Experimental Summary

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1. Introduction
This paper gives highlights of the experimental results shown at this conference. As additional reference the four experimtental papers summarizing the results from the first 3 years of RHIC running will be used [1, 2, 3, 4]. This summary is a highly personal selection of topical results and does not claim to be of comprehensive nature. The author apologizes to all conference participants who contributed interesting results that are not mentioned here.

2. Global observables and initial condition
Transverse energy production was studied by PHENIX and STAR [5, 6] and measured as 600 GeV per unit pseudorapidity for the most central 5 % of Au + Au collisions (unless mentioned otherwise, here always results at the top RHIC energy of \( \sqrt{s} = 200 \text{ GeV} \) are used). Using the Bjorken estimate and, very conservatively, a value \( \tau_0 = 1 \text{ fm/c} \) gives for the initial energy density \( \epsilon_0 = 5.5 \text{ GeV/fm}^3 \). Choosing instead the saturation scale as the measure for \( \tau_0 = 1/Q_0 = 0.14 \text{ fm/c} \) gives a value 7 times larger. Most likely these two values bracket the time scale of equilibration. In any case, the initial energy density significantly exceeds the critical energy density for the phase transition obtained by lattice QCD [7] as \( \epsilon_c = 0.7 \text{ GeV/fm}^3 \).

Charged particle production is addressed by all four experiments. The total charged particle multiplicity for the most central 5 % of Au + Au collisions at full RHIC energy was determined by BRAHMS [8] to 4600. The corresponding number measured by PHOBOS [9] is 5300 for the most central 6 %. This leads to a total hadron multiplicity of about 7500. As discussed by Roland [10] at this conference, the concept of limiting fragmentation holds very accurately for charged particle production over 3-4 units away from beam rapidity comparing SPS and RHIC energies. Mohanty [11] showed that photons (dominantly from \( \pi^0 \) decay) also exhibit this behavior. Assuming that this extends to LHC energy, Roland [10] estimated an upper limit of 1300 - 1800 for \( dN_{\text{ch}}/d\eta \) for Pb + Pb collisions at LHC.

The centrality dependence of charged particle multiplicity distributions and, in particular, its logarithmic growth with number of participants have been taken as signs of gluon saturation and in that respect support the relevance of the concept of color glass condensate at RHIC energies. Recent calculations by Salgado [12] show that this approach works just as well for data at top SPS energy and this casts some doubt whether color glass condensate is indeed the correct underlying physical concept. In the talk of Hofmann the scaling of charged particle multiplicity with beam energy was compared to heavy ion data at lower beam energy as well as to pp and \( e^+e^- \) data [13, 3]. The heavy ion data from top SPS energy upwards are found to agree after participant scaling with pp data at twice the center of mass energy. This is indicative of the large degree of stopping in a heavy ion collisions. The energy deposition and therefore
the energy available for particle production is comparable to an \( e^+e^- \) collision at the same c.m.
energy. This is reflected quantitatively in the BRAHMS data on projectile nucleon rapidity shift
as shown by Debbe [14, 15]. The best estimate for the mean beam nucleon rapidity shift is 2.0
\( \pm \) 0.4 units, very close to the asymptotic value determined by Busza and Goldhaber [16] and
later Busza and Ledoux [17] from central pA collisions. Of the incident beam energy 73 \( \pm \) 6 \%
is available for heating of the fireball and particle production.

3. Hadron production
In the talk of Braun-Munzinger [18] it was shown, that RHIC data on hadron production at
mid-rapidity can be very accurately reproduced as the particle yields of a chemically equilibrated
system in terms of a grand canonical ensemble (see [19] for a complete set of references). A
temperature of 177 \( \pm \) 5 MeV is needed and this value is practically unchanged from \( \sqrt{s} = 130 \) and
17.3 GeV, while the baryon chemical potential drops continuously with increasing beam energy
and has fallen, for top RHIC energy, to 29 \( \pm \) 5 MeV. It appears that from top SPS energy on a
constant temperature characterizes hadron yields, while at lower SPS energies the temperature
is significantly lower; at \( \sqrt{s} = 8.8 \) GeV it is only 148 \( \pm \) 5 MeV. A possible explanation how the
system can achieve equilibrium apparently in a very short time even for hadrons with multiple
(triple) strangeness and antinuclei was presented by Braun-Munzinger [20]; due to the rapid
increase in density in the immediate vicinity of the phase transition multiparticle collisions
become very important and can drive even \( \Omega \) yields into equilibrium within a fraction of a fm/c.

The systematic behavior of hadro-chemical freeze-out parameters with beam energy as shown
by Braun-Munzinger [19] leads to maxima of certain particle ratios for intermediate beam
energies driven by the interplay of increasing temperature and decreasing baryon chemical
potential; examples are the ratio \( K^+ / \pi \) with a broad maximum around \( \sqrt{s_{\text{nn}}} \approx 10 \) GeV and
the ratio \( \Lambda / \pi \) with a pronounced peak at \( \sqrt{s_{\text{nn}}} = 5 \) GeV. In the talk of Friese (Fig.4 in [21])
the measured excitation function of such ratios by NA49 was shown and put into context with
lower and higher beam energy data. The observed ratio \( \Lambda / \pi \) follows the expected trend with
the pronounced maximum with good precision. In the ratio \( K^+ / \pi \) the data appear to show
a sharper maximum and, in particular, the NA49 data points at 80 and 158 A GeV/c beam
momentum appear to lie nearly two standard deviations below the thermal model prediction.
While there has been much speculation about the physics behind this deviation at this stage
it remains an experimental question requiring confirmation. It should be noted that the ratios
\( K^- / \pi \) and \( K^0_s / h^- \) do not show anything unusual.

4. Azimuthal Anisotropies
In has been observed for already quite some time that the elliptic flow parameters \( v_2 \) as function
of transverse momentum and for different particle species can be remarkably well reproduced
by hydrodynamics calculations [22, 23, 24]. The data are described quantitatively up to about
2 GeV/c in transverse momentum. The elliptic flow observable for more massive particles like
protons or Lambdas even exhibits sensitivity to the equation of state favoring an equation of
state with a QGP - hadronic matter phase transition [22]. As pointed out e.g. by McLerran at
this conference, it requires strong interactions at short times for the hydrodynamic description
to work so well. This could happen for instance if the initial state is a color-glass condensate.
Considering the beam energy dependence of elliptic flow, the data show a continuous increase.
When plotting the elliptic flow coefficient divided by the eccentricity as function of the charged
particle rapidity density per cross sectional area, the data appear to scale and to increase about
linearly (see Fig. 25 in [25]. The hydrodynamics results, conversely, show a weak drop with beam
energy and at top RHIC energy data and calculations meet. The significant overprediction of
data by hydrodynamics at SPS energy is linked to the equation of state used, which has a softest
point such that there is a maximum in \( v_2 \) at SPS energy and a minimum at full RHIC energy [4].
As shown by Jacak (Fig.4 in [26]) the elliptic flow increases in data by about 50% from SPS energy to \( \sqrt{s_{\text{nn}}} = 62.4 \text{ GeV} \) and then remains about constant for larger beam energies although the energy density there increases about 30%, supporting a soft equation of state. In the talk by Jacak were also shown the results of various hydrodynamics calculations together with transverse momentum spectra and elliptic flow for protons and pions (Fig.5 in [26]). While qualitatively all calculations that incorporate a phase transition between QGP and hadronic phase reproduce the overall features shown by the data, there are significant deviations in detail. This has to do with how the hadronic phase and freeze-out are treated. Common to all calculations is a rapid equilibration on a time scale of 0.5-1 fm/c.

Another type of scaling has been discovered in the elliptic flow data at RHIC: when normalizing both the flow coefficient \( v_2 \) and the transverse momentum to the number of constituent quarks in a hadron, the data for different hadronic species scale for transverse momenta above about 2 GeV/c as shown by Xu (Fig.3 in [27]). This has been interpreted as partons in the QGP carrying the flow information and preserving it in coalescing [27].

5. Jet quenching

One of the highlights of the RHIC program is the observation of the suppression of production of hadrons at high transverse momentum. This was addressed in several presentations at this conference. When normalizing the transverse momentum spectra observed in Au + Au collisions to the corresponding pp spectra multiplied with the number of binary collisions, a suppression factor \( R_{AA}(p_t) \) is obtained. Similarly central and peripheral Au + Au collisions can be compared. It is observed in all four experiments [1, 2, 3, 4] that for central Au + Au collisions production of pions/charged hadrons is suppressed by a factor 4-5 for transverse momenta in excess of 4 GeV/c. There is reasonable agreement between the experiments, although around 2.5 GeV/c a 20% difference between the STAR data and those of the other experiments is noted (see e.g. Fig.2 of [28]). Since the suppression is not seen in d + Au collisions [1, 2, 3, 4], it is obviously an effect induced by the medium the parton or jet traverses.

Presumably the suppression is due to medium induced radiative energy loss of the parton before it fragments and hadronizes as was predicted [29, 30]. Calculations employing a large initial gluon rapidity density of about 1100 can account for the data [31]. The beam energy dependence of the \( R_{AA} \) factor was presented recently by d’Enterria [32] and it appears that the suppression evolves in a very smooth way from top SPS energy onwards. The \( R_{AA}(p_t = 4\text{ GeV/c}) \) value of 1.0 measured at the SPS represents already a slight suppression as compared to the normal Cronin enhancement [32]. Going from \( \sqrt{s_{\text{nn}}} = 17.3 \) to 62.4 to 200 GeV the gluon rapidity density needed grows from 400 to 650 to 1100 [31]. Alternatively this suppression can be described by increasing and large opacities of the medium traversed [33].

These high initial gluon densities correspond to an initial temperature of about twice the critical temperature and to initial energy densities \( \epsilon_0 = 14 - 20 \text{ GeV/fm}^3 \) well in line with the initial conditions needed for the hydrodynamics calculations to describe spectra and elliptic flow (see section 4) and bracketed by the estimates based on the Bjorken formula (see section 2).

It was observed since some time that the high \( p_t \) suppression pattern is different for different hadronic species. This is very cleanly demonstrated by recent STAR data on the ratio \( \Lambda/K^0 \) which was shown by Lamont [34] as function of \( p_t \) for different centralities. For central collisions this ratio peaks at \( p_t \approx 3 \text{ GeV/c} \) at a value of 1.6, close to the ratio 3/2 expected in quark coalescence models. However, such models at present give quantitatively only a rough description of the data as shown in Fig. 2 of [34]. In the talk of Jacak a similar rise of the ratio for proton over pion \( p_t \) spectra is shown for d + Au collisions (see Fig. 2 in [26]) and the question arises why (constituent) quark coalescence would be an appropriate description for a d + Au collision. To test the coalescence hypothesis jet partners have been looked for for a high \( p_t \) meson or baryon both on the near and on the away side. The fact that within present measurement accuracy a
jet partner is equally likely for a trigger baryon or meson [35] (very similar data from STAR where shown by Mischke and Mironov at this conference) does not strengthen the valence quark coalescence scenario.

In $d + Au$ collisions no suppression is seen in central collisions at mid-rapidity. Recent data by BRAHMS on $R_{dAu}$ as function of pseudo-rapidity shown that a significant suppression sets in at forward rapidities [36]. This is supported by similar data from PHOBOS [37]. It has been suggested that this could be a manifestation of the color glass condensate visible as one probes smaller values of $x$ and a corresponding analysis describes the data well [38]. On the other hand, the same data can be described equally well in terms of the parton coalescence picture [39]. In the talk by Vitev it was shown, that the same feature is exhibited by $d + Au$ data at $\sqrt{s} = 19.4$ GeV. This sheds doubt on both the color glass and the quark coalescence descriptions and points to alternative explanations such as put forward by Kopeliovich et al. [40] e.g. in terms of energy loss of the incoming parton.

Parton thermalization is displayed in a very clean way by recent results of the STAR collaboration [41, 42]. Evaluating the mean transverse momentum in a cone opposite to a high $p_T$ trigger particle as a function of centrality, a gradual decrease for more central Au + Au collisions is observed and in the most central collisions a value very close to the inclusive mean $p_T$ is reached (see Fig. 2 in [42]). To actually connect the high energy parton energy loss to the radiated gluons Vitev calculated di-hadron correlations (see Fig. 3 in [31]). Comparing calculations with and without the so-called gluon feed-back to STAR data [41] shows that quenching of the away-side jet at high $p_T$ is accompanied by a simultaneous strong enhancement at $p_T$ below 2 GeV/c.

In azimuthal correlations of two high $p_T$ particles it was seen that the away-side peak disappears in central Au + Au collisions. Recently it was shown that the effect is very strong in case the away-side jet is emitted out of the reaction plane and much weaker for emission in the reaction plane [43]. This supports the strong correlation of the suppression with the length of matter traversed by the parton. When lowering the $p_T$ cut on the correlated hadron, a very broad structure appears on the side opposite to the trigger particle. This was shown by Mischke for a cut on the correlated hadron of $p_T = 0.15 - 4.$ GeV/c (see Fig. 1 in [42]). This calls to mind a similar observation at SPS energy by CERES [44] where for a condition $p_T \geq 1.2$ GeV/c also very strong broadening of the away-side structure with increasing collision centrality was observed. In the talk of Jacak a tantalizing observation was shown [45]: For a trigger particle $p_T$ of 4-6 GeV/c and a correlated particle $p_T$ of 1.0 - 2.5 GeV/c the away-side peak seen in peripheral Au + Au collisions develops actually into a hole at $\Delta \phi = \pi$ for more central collisions while a very broad peak appears with a maximum at $\Delta \phi = \pi - 1$ as can be seen in Fig. 8 of [26]. Could this be the Mach cone due to the sonic boom of the quenched jet? This goes back to an idea developed by Stöcker et al. for nucleons and nuclei emitted in nuclear reactions in the mid 1970ies (see references [14,15] in [46]) and was suggested for the current scenario of a parton traversing a quark-gluon plasma [47, 48]. If this could be established it would have far reaching consequences since it would be an observable linked directly to the speed of sounds of the quark-gluon plasma and thereby its equation of state. At present it remains an experimental challenge to establish an actual cone topology in two dimensions.

6. Open charm and charmonia

Open charm has been measured indirectly from the inclusive electron $p_T$ spectra after subtracting known contributions from photon conversions and light hadron decays by PHENIX [49]. Recently similar measurements have become possible at high $p_T$ for STAR using the calorimeter [34]. The spectrum remaining after subtraction is dominated \(^1\) by open charm

\(^1\) A possible contribution to the electron spectrum from the Drell-Yan production process cannot be ruled out at present, though.
and beauty contributions but the method is limited by the systematic error introduced by the subtraction. A significant step ahead will come in the future when silicon micro-vertex-detectors will be implemented. Nevertheless, very interesting results have come already from the present method. In the talk of Jacak results for an elliptic flow analysis of the open charm decay electrons were shown (see Fig. 6 of [26]). There is a significant nonzero value in the transverse momentum range 0.4 - 1.6 GeV/c. At this meeting STAR data were shown by Lamont [34] that complement the PHENIX results and extend the overall transverse momentum coverage by adding the range $p_t = 1.5 - 3.0$ GeV/c. Together the data paint a consistent picture that indeed the electrons from open charm decay exhibit elliptic flow. What is more, the data are described quantitatively by a calculation [50] based on thermalization and elliptic flow of the charm quark (see Fig. 7 of [34]): the corresponding calculation with no charm quark flow (and hence only an effect from the flow of the light quark in a D meson) is a factor two below the data, although with the presently still large error bars this is an effect of only a few standard deviations. The present data can be taken as an indication that the charm quark thermalizes to a significant degree. Note that this is a necessary prerequisite for any formation of charmed hadrons by statistical hadronization [51]. On the other hand, in that case also jet quenching should be observed for charmed hadrons. Indeed in the talks by Hamagaki and Tabaru [52] it was shown that electron spectra after the subtraction of contributions from conversion and light hadron decays show high $p_t$ suppression for central collisions. The $R_{AA}$ factor drops practically as low as for pions at $p_t$ of 4 GeV/c, i.e. to values of about 0.2 (see Fig.7 in [26]). In a recent publication [53] the suppression for electrons from D meson decay was studied for different transport coefficients and in the talk of Jacak it was shown, that the present data would be consistent with a calculation using a transport coefficient of 14 GeV$^2$/fm (see Fig. 2 of [53]) at the upper end of the range needed to reproduce the data for pions. This is very surprising, in particular also in view of the fact, that at $p_t$ of about 4 GeV/c also the contribution of b-quarks to the electron spectrum should become sizeable.

The overall charm production cross section at RHIC energy has been measured indirectly by PHENIX [49] for $\sqrt{s} = 130$ and 200 GeV from the inclusive electron spectra in the way described above for Au + Au collisions and at full RHIC energy also for d + Au and pp collisions [54]. It is found that the integrated charm cross section, when scaled with the number of binary collisions, agrees for all three collisions systems [52]. The value is about 30% above a NLO pQCD calculation (as shown e.g. by Lamont [34] in these proceedings) but agrees within errors. In STAR, D mesons have been reconstructed via their hadronic decay to $K\pi$ in d + Au collisions and a charm cross section per nucleon nucleon collision has been extracted [55]. It is twice as large as the PHENIX value by about two standard deviations. This obvious experimental discrepancy needs to be resolved; most likely this will come only with the future charm measurement using the displaced vertex feature.

For charmonia there were final results for NA50 at the CERN SPS presented at this meeting by Quintans [56]. Analysing all pA data, a cross section for normal nuclear absorption of 4.1±0.4 mb was extracted [57]. To this normal nuclear suppression all results from heavy ion collisions can be compared. It turns out that S + U data as well as data from peripheral Pb + Pb collisions agree with this normal nuclear absorption curve. For transverse energies above 40 GeV or a length of nuclear matter seen by the $J/\psi$ of $L \leq 7$ fm the points from Pb + Pb collisions fall increasingly below this normal nuclear absorption curve. The range of $L = 5.3 - 8$ fm covered by the new NA60 experiment for In + In collisions is exactly in the interesting region where the deviation is starting. First data were shown by Seixas at this meeting (although not contained in these proceedings) and they confirm well the systematic trend seen in Pb + Pb collisions. Nothing has changed on the front of theoretical interpretation. The suppression can be explained by disappearance of the $J/\psi$ (or possibly only the charmonia states that feed it) in a hot colored medium or by interaction with comovers, albeit with a very large density of more
than $1/{\text{fm}^3}$, i.e. a value not deemed achievable for a hadron gas.

7. Direct photons
Direct photons in pp collisions have been measured at top RHIC energy by PHENIX [58]. It was shown at this conference by Cole and Bathe (see Fig. 1 in [59]) that they agree well with a NLO pQCD calculation by Gordon and Volgelsang [60]. The data are still statistics limited plus there is some remaining scale uncertainty. Here additional high luminosity pp running is desirable. For Au + Au collisions, the measurement by PHENIX [61] shown at this meeting by Bathe and Jacak agrees also well with the same NLO pQCD calculation. There is no definitive answer yet whether $k_t$ broadening is needed. The centrality dependence is well reproduced over the entire range in $p_t$ covered out to 13 GeV/c just by scaling with the number of collisions (see Figs. 2,3 in [59]). Comparing this to the observed high $p_t$ suppression seen for hadron spectra (see above) confirms that this is indeed a final state effect due to the medium that should not and apparently does not affect photons. Comparing the measured $\gamma/\pi^0$ ratio to the expected one due to hadronic decays a direct photon component is apparent for $p_t$ above 4 GeV/c. With systematic errors of 10 % this means that at the present stage there is unfortunately no sensitivity yet to thermal photons radiated by the plasma; they are expected to dominate over direct hard photons below about 3 GeV/c. To achieve the required sensitivity of a few % in $\gamma/\pi^0$ in the range $p_t = 1-3$ GeV/c requires a quantum jump in the quality of the experimental data. Nevertheless, this very difficult measurement is very desirable.

8. Fluctuations and correlations
For this interesting subject I refer to the authoritative review given by Voloshin in these proceedings [62]. Here only very few points are picked up. Transverse momentum fluctuations have been studied at the SPS and at RHIC and many different observables have been proposed and have been used to quantify these fluctuations. Nonstatistical fluctuations have been seen at all energies from $\sqrt{s_{nn}} = 8$ to 200 GeV. Voloshin has proposed to use the momentum correlator as a measure. In this quantity all present measurements give a relative fluctuation of 1 % without any hint to increased fluctuations possibly indicating the vicinity of a critical point (see Fig. 4 of [62]). The question was raised by Koch at this meeting whether possibly the data cover not the optimal region in $p_t$. Another possibility is that the data integrated over opening angles average over too many different contributions to correlations which might lead to a loss in sensitivity [63]. Voloshin pointed out that, nevertheless, the current data are very useful because they are sensitive to velocity profiles for the expansion of the fireball as demonstrated in his Fig.5. This should indeed be exploited more to get quantitative results that then constrain the interpretation of transverse momentum spectra and two particle correlations.

A very tantalizing preliminary NA49 result on the charged kaon to pion multiplicity fluctuations was shown by Friese (see Fig.6 in [21]): at the smallest SPS energies the fluctuations are larger than expected in contrast to the fluctuations in the proton to pion ratio that look ’normal’. It would be extremely desirable to confirm this very difficult and, if confirmed, possibly far reaching measurement with better particle identification capability.

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