HARD PROBES AT HEAVY-ION COLLIDER ENERGIES: RESULTS FROM PHENIX.

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Hard processes in nucleus-nucleus interactions at relativistic energies are reviewed with emphasis on recent PHENIX results from the first run of the Relativistic Heavy-Ion Collider at BNL. The observed suppression of moderately high p_T hadrons (p_T = 2 - 5 GeV/c) in $\sqrt{s_{NN}}$ = 130 GeV $Au+Au$ central collisions compared to the scaled pp data, is discussed in terms of conventional nuclear and "quark-gluon-plasma" effects. The meson and baryon composition at high p_T, as well as the implications for open charm of the measured single electron spectrum are also presented.

1 Introduction.

High-energy heavy-ion (HI) physics aims at the study of the QCD phase diagram at energy densities where lattice calculations predict a phase transition from hadronic matter to a (deconfined and chirally symmetric) plasma of quarks and gluons (QGP). High-p_T particles (jets, prompt γ) and heavy particles (D, B, J/Ψ) are produced in parton-parton scatterings with large momentum transfers ("hard processes") during the earliest stages of a HI collision ($\tau \propto 1/p_T < 0.1$ fm/c). Such hard probes are thus direct signatures of the partonic phases of the reaction and have attracted much interest because their yields can be quantitatively compared (after scaling with the number of binary inelastic collisions N_{coll}) with: (i) perturbative QCD predictions, and (ii) the available set of baseline "vacuum" ($pp, p\bar{p}$) and "cold-medium" (pA) data. In both cases, any departure (suppression or excess) from the "expected" results provides precious information on the strongly interacting hot and dense medium created during the reaction.

2 Run-1 PHENIX experimental setup.

During the year 2000, ~5 million "minimum bias" $Au+Au$ events (~1 μb of integrated luminosity) at a center-of-mass energy of 130 GeV were collected by the PHENIX experiment at

Brookhaven National Laboratory RHIC collider. The PHENIX detector is specifically designed to measure penetrating probes, such as direct photon radiation, heavy flavors, and jet production, by combining good mass and PID resolution, high rate capability and small granularity, though within a limited angular coverage. PHENIX is composed of 11 detector subsystems divided into: (i) 2 Central Arm spectrometers for electron, photon and hadron measurement at mid-rapidity ($|\eta| < 0.38$, $\Delta\phi = \pi/2$); (ii) 2 forward-backward ($|\eta| = 1.15 - 2.25$, $\Delta\phi = 2\pi$) spectrometers for muon detection; and (iii) 3 global (inner) detectors for centrality and trigger selection. During this Run-1, neutral pions were reconstructed through invariant mass analysis of γ pairs detected in the 3 active sectors of the electromagnetic calorimeter EMCal: two sectors of lead scintillator (PbSc) on the west arm and one sector of lead glass (PbGl) on the east side. In the east arm, trajectories and momenta of charged hadrons were measured by a drift chamber (DC) and two MWPC's with pad readout (PC1 and PC3). Hadron identification was achieved with the time-of-flight detector (TOF) within a third of the azimuthal acceptance of the east arm. Electron detection was done combining the ring-imaging-cerenkov (RHIC) and the EMCal energy and momentum measurements.

3 High-p_T hadron yields. Conventional nuclear effects vs QGP signals.

Due to the large soft particle background produced in HI collisions, the standard jet algorithms in *pp* collisions fail to identify jets below $p_T \sim 40$ GeV/c in $Au + Au$ at $\sqrt{s_{NN}} \sim 200$ GeV. Yet, "jet physics" in HI collisions can still be studied via high transverse momentum hadrons ($p_T >$2 GeV/c) under the assumption that most of these particles result from the fragmentation (*leading particle*) of the partons produced in the hard scattering process. Fig. 1 (left) shows the yield of charged hadrons and π^0 mesons ($p_T >$1.0 GeV/c) emitted at mid-rapidity in central and peripheral collisions compared to the scaled nucleon-nucleon (NN) reference. Whereas in peripheral collisions the yield is well reproduced by the binary-scaled extrapolation of $pp(\bar{p})$ (ISR, UA1, CDF) yields, in central collisions the yields are suppressed by a factor 2 to 3 [1]. This suppression is more visible in the right side of Fig. 1 where the "nuclear modification factor"

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle N_{coll}\rangle (dN/dp_T)_{NN}}, \tag{1}$$

is plotted. The value of $R_{AA}(p_T)$ quantifies the deviation from the nucleon-nucleon extrapolation, i.e. from the absence of nuclear-medium effects, in terms of suppression or enhancement (R_{AA} smaller or larger than unity, respectively). For $p_T < 2$ GeV/c, R_{AA} is expected to be below unity since the bulk of particle production is due to soft processes which scale with the number of participant nucleons (N_{part}) rather than with N_{coll}. Above $p_T = 2$ GeV/c, however, hadron production in pA and AA collisions at lower energies [2,3] is found to be enhanced compared to the binary scaling expectation. This increased high-p_T production in the nuclear medium ("Cronin effect") is due to initial-state multiple (soft & semi-hard) parton interactions before the hard scattering, resulting in a k_T broadening additional to the intrinsic nucleon k_T observed in *pp* collisions. Notwithstanding, PHENIX observes exactly the opposite trend: instead of an enhancement, a suppression of the particle yield is observed above 2 GeV/c.

Apart from the Cronin enhancement, the other initial-state effect that is known to modify the p_T distributions is nuclear shadowing. The region of parton fractional momenta $x_T = 2p_T/\sqrt{s}$ relevant for moderately high-p_T production (2-5 GeV/c) at RHIC is $x_T \sim$ 0.03 - 0.08, where gluons are known to dominate the parton distribution functions (PDFs) in the nucleon. In the nuclei, it has been experimentally observed that the PDFs are depleted compared to the nucleon ones for $x <$0.1. Such a shadowing is usually explained in terms of parton recombinations which effectively reduce the parton density at low x in the nuclei. The most up-to-date parametrizations of nuclear PDFs [4] predict, however, a very small (if any) reduction of the gluon density in

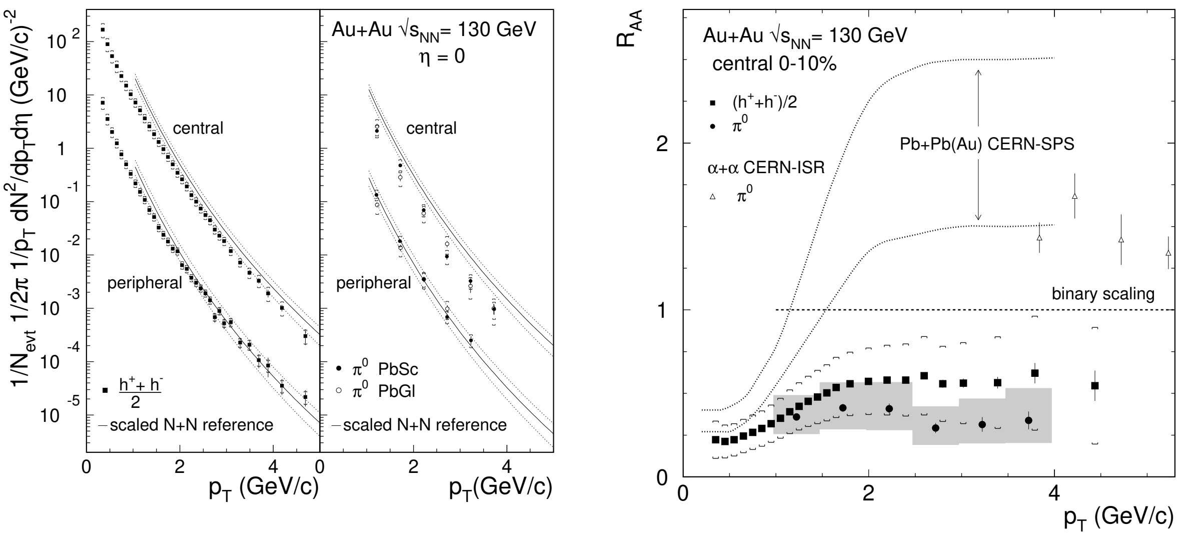

Figure 1: Left: Transverse momentum distribution of charged hadrons and π^0 measured by PHENIX [1] in 10% most central and in 60%-80% peripheral $Au+Au$ collisions. The solid lines are the binary-scaled extrapolation of $pp(\bar{p})$ data. Right: Nuclear modification factor, Eq. (1), for central collisions compared to data at lower energies.

the range of x and Q^2 values compatible with the high-p_T PHENIX results. This fact rules out shadowing as a possible explanation of the observed hadron deficit[a].

The most interesting explanation of the high-p_T suppression relies not on an initial-state nuclear effect but on a final-state *medium* one: "jet quenching". It has been since long predicted [5] that a hot and dense colored medium like a QGP would induce multiple gluon radiation off the fast partons produced in a hard scattering. The resulting energy loss of the parton, dE/dx emitted outside the jet cone before its hadronization, is of the order of a few GeV/fm and would lead to a depletion of the leading-particle inclusive spectra at high p_T. Leading-order pQCD calculations [6,7] including k_T Cronin enhancement, nuclear PDFs, and modified fragmentation functions (FFs) to take into account medium-induced energy loss are able to reproduce the suppression in central collisions with $dE/dx \sim 0.25$ GeV/fm (equivalent to $dE/dx \sim 7$ GeV/fm in a static medium, much larger than the standard energy losses found in *cold* nuclear matter [8]). Peripheral collision spectra, on the other side, are consistent with $dE/dx \sim 0$. PHENIX central $AuAu$ high-p_T results are thus in qualitative agreement with the expectations of parton energy loss in an opaque medium.

4 High-p_T hadron composition.

The spectra [9] of identified $\pi^\pm$ and $p, \bar{p}$ in central $Au+Au$ collisions cross each other at about $p_T = 2$ GeV/c and give a meson to baryon yield ratio of ~1. Such an observation is at variance with NN data (ISR, FNAL) where a baryon/meson ratio of ~0.3 - 0.4 was found at high-p_T. Various interpretations [9] have been proposed to explain such a behaviour ranging from large strong collective radial flow (proportional to the hadron mass) plus hadron rescattering, to more "exotic" mechanisms such as baryon junctions and jet quenching in the pion channel.

[a] Note, however, that the (x, Q^2) scale dependence of nuclear PDFs (specially for gluons) is less known than for nucleons due to the limited range of x, Q^2, A covered in the available lepton-A experiments. Therefore, $p, d+A$ collisions at the same $\sqrt{s}$ as the $Au+Au$ ones are needed at RHIC in order to assess the role of gluon shadowing.

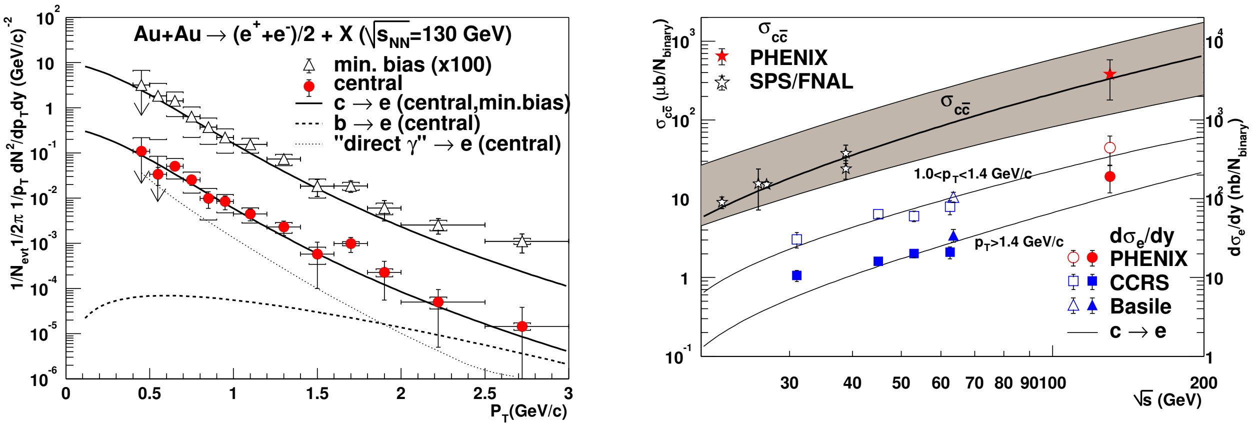

Figure 2: Left: Inclusive electron distribution for central and min. bias $Au + Au$ collisions, after subtraction of the light meson decay background, compared to the scaled pp contribution from open charm meson decays. Right: Inclusive charm cross-section as a function of $\sqrt{s}$ from experimental data, pQCD and PYTHIA calculations [10].

5 Electron yield and charm production.

Single electrons are very interesting observables providing information on several hard probe signals: heavy-flavor (via semi-leptonic decays of open charm and bottom mesons), Drell-Yan/thermal dileptons, and direct γ (through conversion). The inclusive electron spectrum, however, is dominated by light meson backgrounds: Dalitz decays of pseudo-scalars (π^0 and η), soft γ conversions, and di-electron decays of vector mesons. Fig. 2 shows the single electron, $(e^- + e^+)/2$, spectra measured by PHENIX [10] in the p_T range 0.2 - 3.0 GeV/c after subtraction of the "cocktail" background. The resulting spectra for minimum bias and central collisions are consistent with scaled pp Pythia calculations of open charm contributions. Assuming no thermal radiation component (virtual and/or real+conversion) in the spectra, i.e. assuming all $e^{\pm}$ originate in D decays, the obtained charm cross-section (per NN collision) is $\sigma_{c\bar{c}} = 380 \pm 60 \pm 200$ mb for the central sample in agreement with the expectation from binary scaling of pp data and with theoretical calculations (Fig. 2 right). Thus, assuming a modest photon contribution, the measured electron spectra and cross-sections are consistent with simple pp scaled charm production precluding significant nuclear or medium effects on heavy-flavor production.

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References

1. K. Adcox *et al.* (PHENIX Coll.), *Phys. Rev. Lett.* **88**, 022301 (2002).
2. B.Z. Kopeliovich *et al.*, hep-ph/0201010, to appear in *Phys. Rev. Lett.*
3. K. Reygers (WA98 Coll.), nucl-ex/0202018.
4. K. Eskola *et al.*, *Phys. Lett.* B **532**, 222 (2002), and C. Salgado, these Proceedings.
5. M. Gyulassy and M. Plümer, *Phys. Lett.* B **243**, 432 (1990).
6. X.N. Wang, hep-ph/0111404.
7. G. Fai *et al.*, hep-ph/0111211.
8. F. Arleo, these Proceedings.
9. K. Adcox *et al.* (PHENIX Coll.), nucl-ex/0112006, to appear in *Phys. Rev. Lett.*
10. K. Adcox *et al.* (PHENIX Coll.), *Phys. Rev. Lett.* **88**, 192303 (2002).