Review

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RESULTS FROM PHENIX AT RHIC WITH IMPLICATIONS FOR LHC

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Results from the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) in nucleus–nucleus and proton–proton collisions at c.m. energy $\sqrt{s_{NN}} = 200$ GeV are presented in the context of the methods of single and two-particle inclusive reactions which were used in the discovery of hard-scattering in p–p collisions at the CERN ISR in the 1970's. These techniques are used at RHIC in A+A collisions because of the huge combinatoric background from the large particle multiplicity. Topics include J/Ψ suppression, jet quenching in the dense medium (sQGP) as observed with $\pi 0$ at large transverse momentum, thermal photons, collective flow, two-particle correlations, suppression of heavy quarks at large p_T and its possible relation to Higgs searches at the LHC. The differences and similarities of the measurements in p–p and A+A collisions are presented. The two discussion sessions which followed the lectures on which this article is based are included at the end.

Keywords: RHIC; strongly interacting quark–gluon plasma (sQGP); heavy ion collisions; jet quenching; collective flow; Higgs mechanism; thermal radiation.

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1. Introduction

High energy nucleus–nucleus collisions provide the means of creating nuclear matter in conditions of extreme temperature and density[1,a] The kinetic energy of the incident projectiles would be dissipated in the large volume of nuclear matter involved in the reaction. At large energy or baryon density, a phase transition is expected from a state of nucleons containing confined quarks and gluons to a state of "deconfined" (from their individual nucleons) quarks and gluons, in chemical and thermal equilibrium, covering a volume that is many units of the confining length scale. This state of nuclear matter was originally given the name Quark–Gluon Plasma (QGP),[3] a plasma being an ionized gas. However the results at RHIC[a] indicated that instead of behaving like a gas of free quarks and gluons, the matter created in heavy ion collisions at nucleon–nucleon center-of-mass (c.m.) energy $\sqrt{s_{NN}} = 200$ GeV appears to be more like a *liquid*. This matter interacts much more strongly than originally expected, as elaborated in peer-reviewed articles by the four RHIC experiments,[4–7] which inspired the theorists[8] to give it the new name "sQGP" (strongly interacting QGP).

In the terminology of high energy physics, the QGP or sQGP is called a "soft" process, related to the QCD confinement scale

$$\Lambda_{\rm QCD}^{-1} \simeq (0.2\ {\rm GeV})^{-1} \simeq 1\ {\rm fm}\,. \tag{1}$$

With increasing temperature, T, in analogy to increasing Q^2, the strong coupling constant $\alpha_s(T)$ becomes smaller, reducing the binding energy, and the string tension, $\sigma(T)$, becomes smaller, increasing the confining radius, effectively screening the potential:[9]

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r \to -\frac{4}{3}\frac{\alpha_s}{r}e^{-\mu r} + \sigma\,\frac{(1-e^{-\mu r})}{\mu}\,, \tag{2}$$

where $\mu = \mu(T) = 1/r_D$ is the Debye screening mass.[9] For $r < 1/\mu$, a quark feels the full color charge, but for $r > 1/\mu$, the quark is free of the potential and the string tension, effectively deconfined.

There has been considerable work over the past three decades in making quantitative predictions for the QGP.[a] The predicted transition temperature from a state of hadrons to the QGP varies, from $T_c \sim 150$ MeV at zero baryon density, to zero temperature at a critical baryon density roughly 1 GeV/fm^3, $\sim$6.5 times the normal density of cold nuclear matter ($\rho_0 = 0.14$ nucleons/fm^3, $\mu_B \simeq 930$ MeV), where

[a]See Ref. 2 for a more extensive list of references.

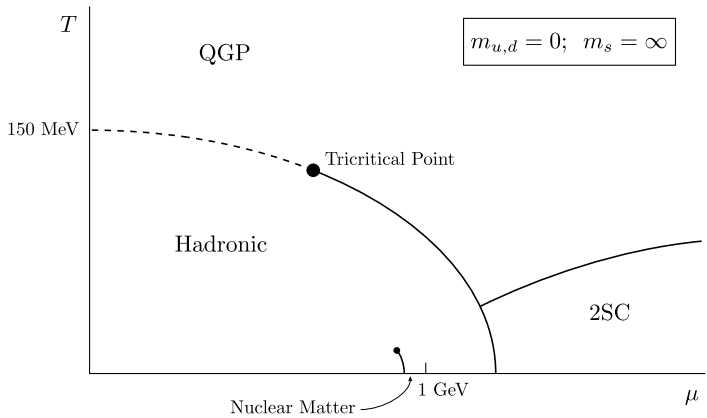


Fig. 1. (left) A proposed phase diagram for nuclear matter.[10] Temperature, T, vs baryon chemical potential, μ.

μ_B is the baryon chemical potential. A typical expected phase diagram of nuclear matter[10] is shown in Fig. 1. Not distinguished in Fig. 1 in the hadronic phase are the liquid self-bound ground state of nuclear matter and the gas of free nucleons.[11]

A nice feature of the search for the QGP is that it requires the integrated use of many disciplines in Physics: High Energy Particle Physics, Nuclear Physics, Relativistic Mechanics, Quantum Statistical Mechanics, and, recently, AdS/CFT string theory.[12,13] From the point of view of an experimentalist, there are two major questions in this field. The first is how to relate the thermodynamical properties (temperature, energy density, entropy, viscosity, etc.) of the QGP or hot nuclear matter to properties that can be measured in the laboratory. The second question is how the QGP can be detected.

One of the major challenges in this field is to find signatures that are unique to the QGP so that this new state of matter can be distinguished from the "ordinary physics" of relativistic nuclear collisions. Another more general challenge is to find the effects which are specific to A+A collisions, such as collective or coherent phenomena, in distinction to cases for which A+A collisions can be considered as merely an incoherent superposition of nucleon–nucleon collisions.[b]

2. Issues in Relativistic Heavy Ion Physics

2.1. *J/Ψ suppression — The original "gold-plated" QGP signature*

Since 1986, the "gold-plated" signature of deconfinement was thought to be J/Ψ suppression. Matsui and Satz[16] proposed that J/Ψ production in A+A collisions will be suppressed by Debye screening of the quark color charge in the QGP.

[b]It should be noted that the requirement of specificity to A+A collisions immediately rules out the QGP in p–p collisions, which is disputable (see Refs. 14 and 15).

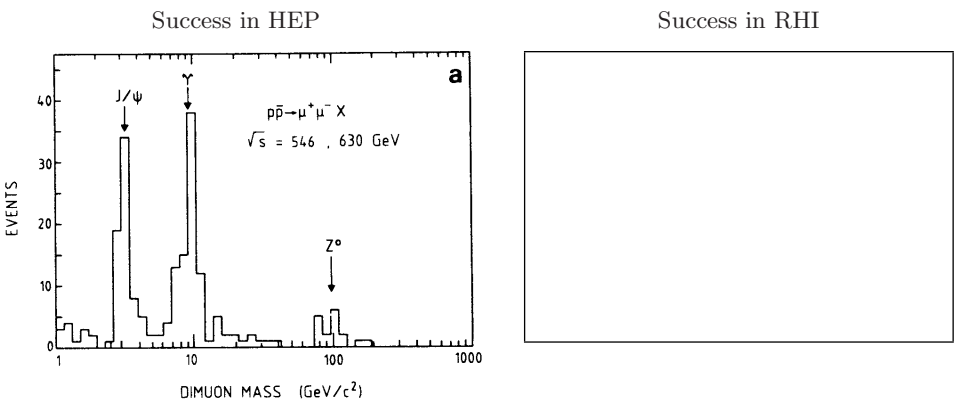


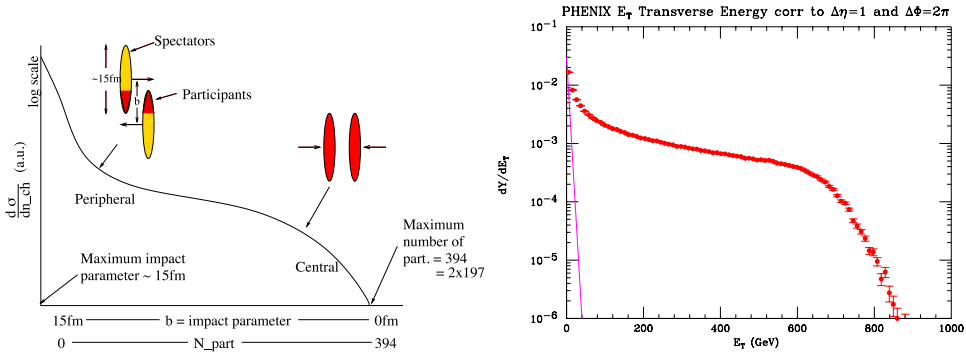
Fig. 2. "The road to success": In High Energy Physics (left) a UA1 measurement[21] of pairs of muons each with $p_T \geq 3$ GeV/c shows two Nobel Prize-winning dimuon peaks and one which won the Wolf Prize. Success for measuring these peaks in RHI Physics is shown schematically on the right.

The J/Ψ is produced when two gluons interact to produce a c, $\bar{c}$ pair which then resonates to form the J/Ψ. In the plasma, the c, $\bar{c}$ interaction is screened so that the c, $\bar{c}$ go their separate ways and eventually pick up other quarks at the periphery to become *open charm*. "Anomalous suppression" of J/Ψ was found in Pb+Pb collisions at the CERN SpS $\sqrt{s_{NN}} = 17.2$ GeV (Refs. 17 and 18) (e.g. see Fig. 18 below). This is the CERN fixed-target heavy-ion program's main claim to fame: but the situation is complicated because J/Ψ are suppressed in $p + \mathrm{A}$ collisions.[19,20]

The search for J/Ψ suppression and thermal photon/dilepton radiation from the QGP drove the design of the RHIC experiments. This author's summary of the different views of dilepton resonances in the High Energy[21] and Relativistic Heavy Ion (RHI)[16] Physics communities since the mid 1980's is shown in Fig. 2.

2.2. *Detector issues in* A+A *compared to p–p collisions*

Another main concern of experimental design in RHI collisions is the huge multiplicity in A+A central collisions compared to p–p collisions. A schematic drawing of a collision of two relativistic Au nuclei is shown in Fig. 3(a). In the c.m. system of the nucleus–nucleus collision, the two Lorentz-contracted nuclei of radius R approach each other with impact parameter b. In the region of overlap, the "participating" nucleons interact with each other, while in the nonoverlap region, the "spectator" nucleons simply continue on their original trajectories and can be measured in Zero Degree Calorimeters (ZDC), so that the number of participants can be determined. The degree of overlap is called the centrality of the collision, with $b \sim 0$, being the most central and $b \sim 2R$, the most peripheral. The maximum time of overlap is $\tau_0 = 2R/\gamma c$ where γ is the Lorentz factor and c is the velocity of light. The energy of the inelastic collision is predominantly dissipated by multiple particle production, where n_{ch}, the number of charged particles produced, is directly proportional[7] to

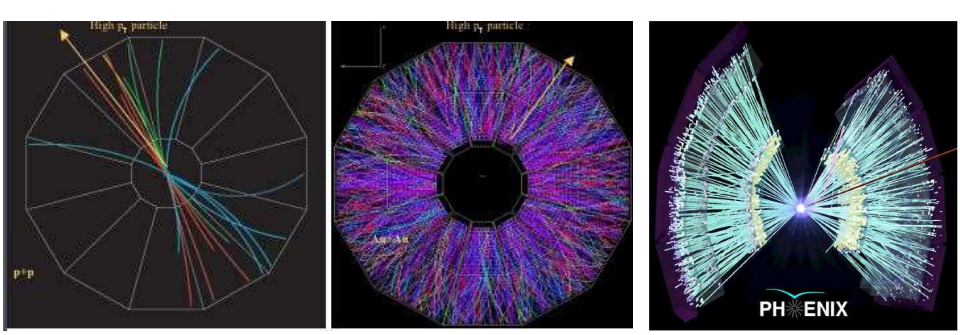


(a) (b)

Fig. 3. (a) Schematic of collision of two nuclei with radius R and impact parameter b. The curve with the ordinate labeled $d\sigma/dn_{\rm ch}$ represents the relative probability of charged particle multiplicity $n_{\rm ch}$ which is directly proportional to the number of participating nucleons, $N_{\rm part}$. (b) Transverse energy (E_T) distribution in Au+Au and p–p collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX.[22]

the number of participating nucleons ($N_{\rm part}$) as sketched in Fig. 3(a). Thus, $n_{\rm ch}$ or the total transverse energy E_T in central Au+Au collisions is roughly A times larger than in a p–p collision, as shown in the measured transverse energy spectrum in the PHENIX detector for Au+Au compared to p–p [Fig. 3(b)] and in actual events from the STAR and PHENIX detectors at RHIC in Fig. 4.

As it is a daunting task to reconstruct all the particles produced in such events, the initial detectors at RHIC[23] concentrated on the measurement of single-particle or multiparticle inclusive variables to analyze RHI collisions, with inspiration from the CERN ISR which emphasized those techniques before the era of jet reconstruction. There are two major detectors in operation at RHIC, STAR and PHENIX, and there were also two smaller detectors, BRAHMS and PHOBOS, which have



(a) (b) (c)

Fig. 4. (a) A p–p collision in the STAR detector viewed along the collision axis; (b) Au+Au central collision at $\sqrt{s_{NN}} = 200$ GeV in the STAR detector; (c) Au+Au central collision at $\sqrt{s_{NN}} = 200$ GeV in the PHENIX detector.

completed their program. As may be surmised from Fig. 4, STAR, which emphasizes hadron physics, is most like a conventional general purpose collider detector, a TPC to detect all charged particles over the full azimuth ($\Delta\phi = 2\pi$) and ± 1 units of pseudorapidity (η), while PHENIX is a very high granularity high resolution special purpose detector covering a smaller solid angle at mid-rapidity, together with a muon-detector at forward rapidity.[c] PHENIX is designed to measure and trigger on rare processes involving leptons, photons and identified hadrons at the highest luminosities with the special features: (i) a minimum of material (0.4% X_0) in the aperture to avoid photon conversions; (ii) possibility of zero magnetic field on axis to prevent de-correlation of e^+e^- pairs from photon conversions; (iii) Electromagnetic Calorimeter (EMCal) and Ring Imaging Cherenkov Counter (RICH) for $e^\pm$ identification and level-1 $e^\pm$ trigger; (iv) a finely segmented EMCal ($\delta\eta$, $\delta\phi = 0.01\times 0.01$) to avoid overlapping showers due to the high multiplicity and for separation of single-γ and π^0 up to $p_T \sim 25$ GeV/c; (v) EMCal and precision time-of-flight measurement for particle identification.

In addition to the large multiplicity, there are two other issues in RHI physics which are different from p–p physics: (i) space–time issues, both in momentum space and coordinate space — for instance, what is the spatial extent of fragmentation? Is there a formation time/distance?; (ii) huge azimuthal anisotropies of particle production in noncentral collisions (colloquially collective flow) which are interesting in their own right but can be troublesome.

2.3. *Collective flow*

A distinguishing feature of A+A collisions compared to either p–p or p+A collisions is the collective flow observed. This effect is seen over the full range of energies studied in heavy ion collisions, from incident kinetic energy of $100A$ MeV to c.m. energy of $\sqrt{s_{NN}} = 200$ GeV.[24] Collective flow, or simply flow, is a collective effect which cannot be obtained from a superposition of independent N–N collisions.

Immediately after an A+A collision, the overlap region defined by the nuclear geometry is almond shaped (see Fig. 5), with the shortest axis along the impact parameter vector. Due to the reaction plane breaking the ϕ symmetry of the problem, the semi-inclusive single particle spectrum is modified by an expansion in harmonics[27,28] of the azimuthal angle of the particle with respect to the reaction plane, $\phi - \Phi_R$,[29] where the angle of the reaction plane Φ_R is defined to be along the impact parameter vector, the x-axis in Fig. 5:

$$\frac{Ed^3N}{dp^3} = \frac{d^3N}{p_T\,dp_T\,dy\,d\phi} = \frac{d^3N}{2\pi p_T\,dp_T\,dy}\left[1 + \sum_n 2v_n \cos n(\phi - \Phi_R)\right]. \qquad (3)$$

The expansion parameter v_2, called elliptical flow, is predominant at mid-rapidity. In general, the fact that flow is observed in final state hadrons shows that thermalization is rapid so that hydrodynamics comes into play before the spatial anisotropy

[c]The detector is so nonconventional that it made the cover of Physics Today, October 2003.

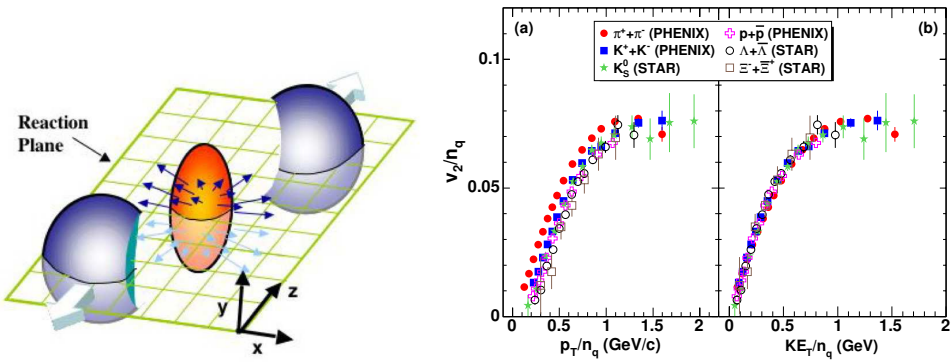


Fig. 5. (left) Almond shaped overlap zone generated just after an A+A collision where the incident nuclei are moving along the $\pm z$-axis. The reaction plane by definition contains the impact parameter vector (along the x-axis)[25] (see discussion session). (right) Measurements of elliptical-flow (v_2) for identified hadrons plotted as v_2 divided by the number of constituent quarks n_q in the hadron as a function of (a) p_T/n_q, (b) KE_T/n_q.[26]

of the overlap almond dissipates. At this early stage hadrons have not formed and it has been proposed that the constituent quarks flow,[30] so that the flow should be proportional to the number of constituent quarks n_q, in which case v_2/n_q as a function of p_T/n_q would represent the constituent quark flow as a function of constituent quark transverse momentum and would be universal. However, in relativistic hydrodynamics, at mid-rapidity, the transverse kinetic energy, $m_T - m_0 = (\gamma_T - 1)m_0 \equiv KE_T$, rather than p_T is the relevant variable, and in fact v_2/n_q as a function of KE_T/n_q seems to exhibit nearly perfect scaling[26] [Fig. 5(b)].

The fact that the flow persists for $p_T > 1$ GeV/c implies that the viscosity is small,[31] perhaps as small as a quantum viscosity bound from string theory,[32] $\eta/s = 1/(4\pi)$ where η is the shear viscosity and s the entropy density per unit volume. This has led to the description of the "sQGP" produced at RHIC as "the perfect fluid."[8]

2.4. *Triangular flow, odd harmonics*

For the first 10 years of RHIC running, and dating back to the Bevalac, all the experts thought that the odd harmonics in Eq. (3) would vanish by the symmetry $\phi \to \phi + \pi$ of the almond-shaped overlap region[33,28] (Fig. 5). However, in 2010, an MIT graduate student and his Professor in experimental physics, seeking (at least since 2006) how to measure the fluctuations of v_2 in the PHOBOS experiment at RHIC, realized that fluctuations in the collision geometry on an event-by-event basis, i.e. the distribution of participants from event-to-event, did not respect the average symmetry. This resulted in what they called "participant triangularity" and "triangular flow," or v_3 in Eq. (3), which they measured using both PHOBOS and STAR data.[34] A Brazilian group had shown in 2009 that v_3, does appear in an

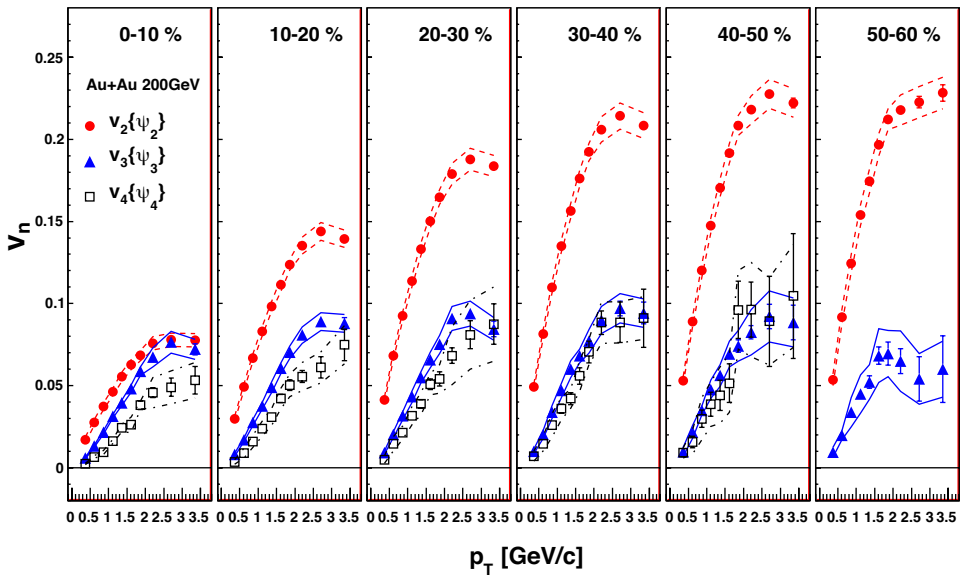


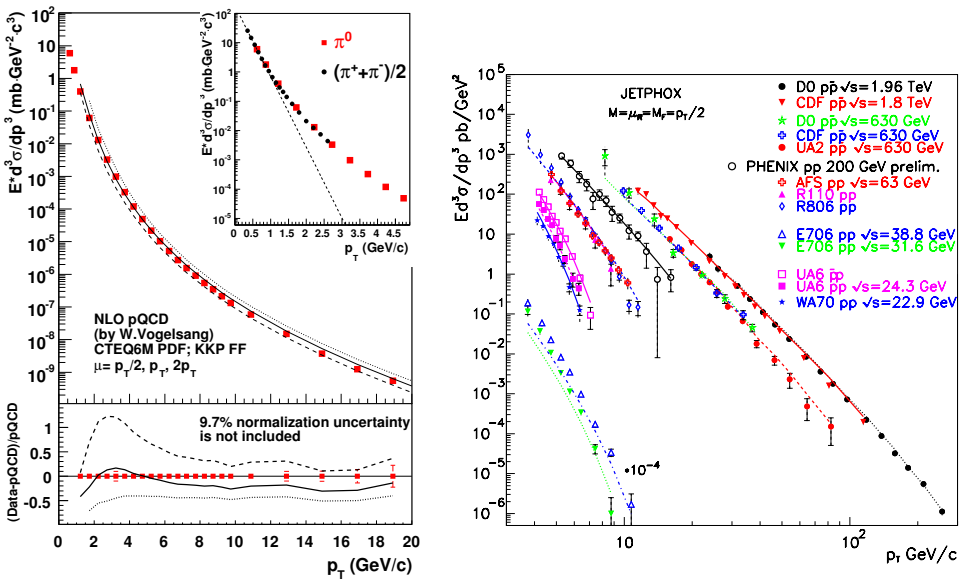
Fig. 6. PHENIX[37] measurements of the v_n parameters using Eq. (3) (with the appropriate reaction plane) as a function of p_T for different centrality slices in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions.

event-by-event hydrodynamics calculation without jets,[35,36] but the MIT group[34] was the first to show it with real data.

Many experiments presented measurements of v_3 at Quark Matter 2011 this year, e.g. Fig. 6,[37] and it was one of the most exciting results of this past year. There are two striking observations from Fig. 6 which indicate that fluctuations of the initial collision geometry are driving the observed v_3: (i) the centrality dependence of $v_3(p_T)$ is weak as one would expect from fluctuations, but $v_2(p_T)$ which is most sensitive to the geometry of the "almond"-shaped overlap region tracks the change in eccentricity with centrality; (ii) for the most central collisions (0–10%), where the overlap region is nearly circular so that all the v_n are driven by fluctuations, $v_2(p_T)$, $v_3(p_T)$, $v_4(p_T)$ are comparable. The fact that the observed collective flow of final state particles follows the fluctuations in the initial state geometry points to real hydrodynamic flow of a nearly perfect fluid (and convinces this author of the validity of hydrodynamics in RHI collisions, of which he had been quite skeptical).

3. Measurements in p–p Collisions at RHIC

In addition to being the first heavy ion collider, RHIC is also the first polarized proton collider. Proton–proton collisions are performed with both beams either longitudinally or transversely polarized.[23,38] The bunch-by-bunch polarization is arranged so that the spin averaged cross-section is obtained to high accuracy if polarization information is ignored. The emphasis on precision EM calorimetry allows PHENIX to excel in the measurement of reactions producing photons, such



(a) (b)

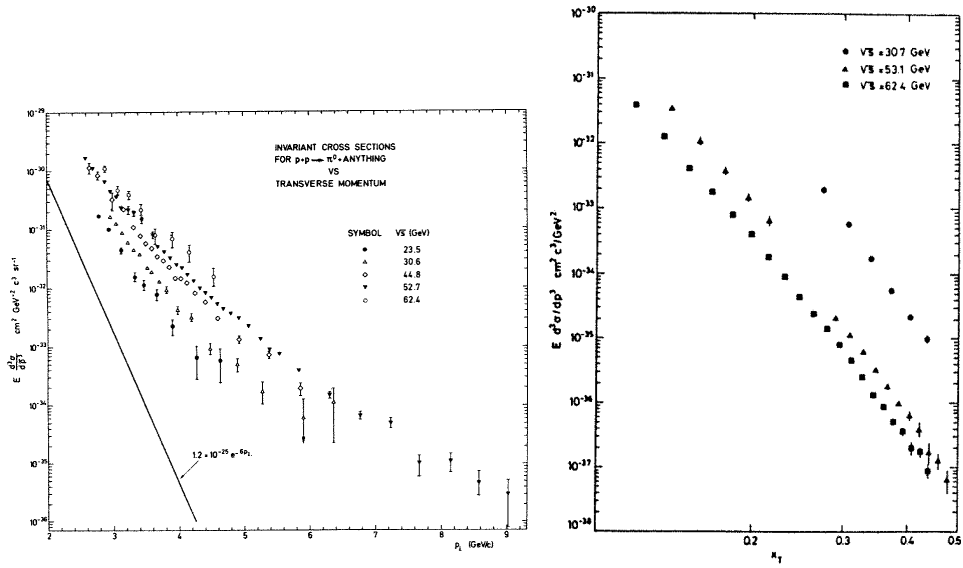
Fig. 7. (a) PHENIX measurement of invariant cross-section of π^0 vs p_T at mid-rapidity in p–p collisions at $\sqrt{s} = 200$ GeV.[39] (b) PHENIX measurement of inclusive direct-single γ in p–p collisions at $\sqrt{s} = 200$ GeV (∘), together with all previous data compared to the theory.[40]

as direct-single-photon production, or particles which decay to photons, $\pi^0 \to \gamma + \gamma$, $\eta \to \gamma + \gamma$, etc.

In order to understand whether an effect observed in A+A collisions exhibits a sensitivity to collective effects or to the presence of a medium such as the QGP, it is important to establish a precise baseline measurement in p–p collisions at the same value of nucleon–nucleon c.m. energy $\sqrt{s_{NN}}$. PHENIX measurements of the invariant cross-section, $Ed^3\sigma/dp^3$, for π^0 and direct-single-γ production in p–p collisions at $\sqrt{s} = 200$ GeV are shown in Fig. 7(a) (Ref. 39) and Fig. 7(b) (Ref. 40), respectively. The inset in Fig. 7(a) shows that the π^0 cross-section is exponential $\sim e^{-6p_T}$ for $p_T < 2$ GeV/c, as originally parametrized by Cocconi,[41,42] which is the region of soft-multiparticle physics. For $p_T > 2$ GeV/c the spectrum is a power law which is indicative of the hard-scattering of the quark and gluon constituents of the proton. The excellent agreement of the measurements with theory is rewarding, although not surprising, since, after all, the discovery of π^0 production at large transverse momentum at the CERN-ISR proved that the partons of deeply inelastic scattering (DIS) interacted strongly with each other.[42,43]

3.1. *The influence of the CERN-ISR*

The ISR discovery[43] [Fig. 8(a)] showed that the e^{-6p_T} dependence at low p_T breaks to a power law with characteristic $\sqrt{s}$ dependence for $p_T > 2$ GeV/c, which is more evident from the log–log plot of subsequent data[44] [Fig. 8(b)] as a function of



(a) (b)

Fig. 8. (a) CCR[43] measurement of the invariant cross-section of π^0 vs p_T at mid-rapidity in p–p collisions for 5 values of $\sqrt{s}$. (b) Later ISR measurement of invariant cross-section of π^0 vs $x_T = 2p_T/\sqrt{s}$ at mid-rapidity in p–p collisions for 3 values of $\sqrt{s}$.[44]

$x_T = 2p_T/\sqrt{s}$. This plot exhibits that the cross-section for hard-processes obeys the scaling law:

$$E\frac{d^3\sigma}{d^3p} = \frac{1}{p_T^{n_{\rm eff}}} F\left(\frac{p_T}{\sqrt{s}}\right) = \frac{1}{\sqrt{s}^{n_{\rm eff}}} G(x_T)\,, \tag{4}$$

where $n_{\rm eff}(x_T, \sqrt{s}) \sim 4$–$6$ gives the form of the force law between constituents as later predicted by Quantum Chromodynamics (QCD) with nonscaling structure and fragmentation functions and running coupling constant.[45] The more familiar equation for the constituent reaction $a + b \to c + d$ (e.g. $g + q \to g + q$) at parton–parton c.m. energy $\sqrt{\hat{s}}$ in "leading logarithm" pQCD[46] is:

$$\begin{aligned}\frac{d^3\sigma}{dx_1\, dx_2\, d\cos\theta^*} &= \frac{s d^3\sigma}{d\hat{s}\, d\hat{y}\, d\cos\theta^*} \\ &= \frac{1}{s}\sum_{ab} f_a(x_1) f_b(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)\,,\end{aligned} \tag{5}$$

where $f_a(x_1)$, $f_b(x_2)$, are parton distribution functions — the differential probabilities for partons a and b to carry momentum fractions x_1 and x_2 of their respective protons [e.g. $u(x_2)$], and θ^* is the scattering angle in the parton–parton c.m. system. The parton–parton c.m. energy squared is $\hat{s} = x_1x_2s$, where $\sqrt{s}$ is the c.m. energy of the p–p collision. The parton–parton c.m. system moves with rapidity $\hat{y} = 1/2\ln(x_1/x_2)$ in the p–p c.m. system and the transverse momentum of a

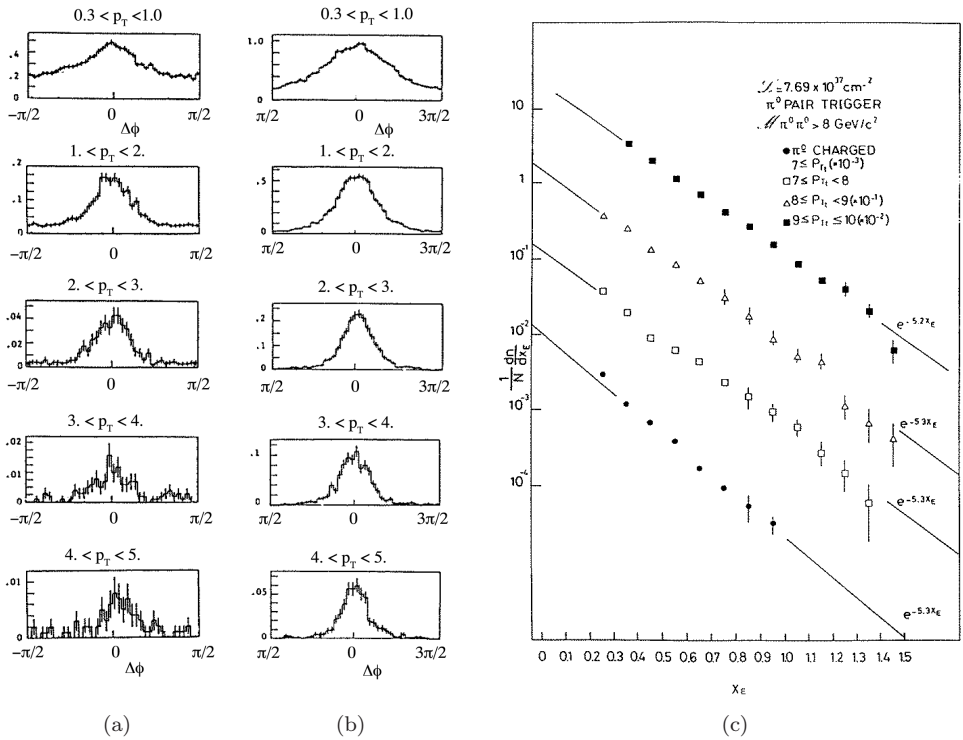
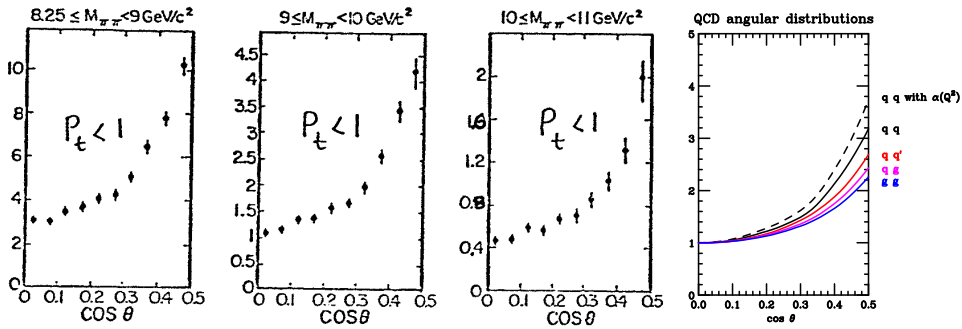


Fig. 9. CCOR[50,51] measurements at $\sqrt{s} = 62.4$ GeV. (a) and (b) Distributions of azimuthal angle ($\Delta\phi$) of associated charged particles of transverse momentum p_{T_a}, with respect to a trigger π^0 with $p_{T_t} \geq 7$ GeV/c, for five intervals of $p_{T_{(a)}}$: (a) for $\Delta\phi = \pm\pi/2$ rad about the trigger particle, and (b) for $\Delta\phi = \pm\pi/2$ about π rad (i.e. directly opposite in azimuth) to the trigger. The trigger particle is restricted to $|\eta| < 0.4$, while the associated charged particles are in the range $|\eta| \leq 0.7$. (c) x_E distributions (see text) corresponding to the data of the center panel.

scattered parton is $p_T = p_T^* = \frac{\sqrt{s}}{2}\sin\theta^*$. Only the characteristic subprocess angular distributions, $\Sigma^{ab}(\cos\theta^*)$ and the coupling constant, $\alpha_s(Q^2) = 12\pi/(25\ln(Q^2/\Lambda^2))$, are fundamental predictions of QCD.[47–49]

Subsequent ISR measurements utilizing inclusive single or pairs of hadrons established that high p_T particles in p–p collisions are produced from states with two roughly back-to-back jets which are the result of scattering of constituents of the nucleons as described by QCD, which was developed during the course of those measurements. These techniques have been used extensively and further developed at RHIC since they are the only practical methods to study hard-scattering and jet phenomena in Au+Au central collisions at RHIC energies.

The di-jet structure of events triggered by a high p_T π^0, measured via two-particle correlations at the ISR, is shown in Fig. 9. The peaks on both the same side [Fig. 9(a)] as the trigger π^0 and opposite in azimuth [Fig. 9(b)] are due to the correlated charged particles from jets. The integrated (in $\Delta\phi$) yield of the



(a) (b) (c) (d)

Fig. 10. (a)–(c) CCOR measurement[53–55] of polar angular distributions of π^0 pairs with net $p_T < 1$ GeV/c at mid-rapidity in p–p collisions with $\sqrt{s} = 62.4$ GeV for three different values of $\pi\pi$ invariant mass $M_{\pi\pi}$. (d) QCD predictions for $\Sigma^{ab}(\cos\theta^*)$ for the elastic scattering of gg, qg, qq', qq, and qq with $\alpha_s(Q^2)$ evolution.

away-side particles as a function of the variable $x_E \equiv -p_{T_a}\cos(\Delta\phi)/p_{T_t} \approx z_a/z_t$, where $z_t = p_{T_t}/\hat{p}_{T_t}$ is the fragmentation variable of the trigger jet (with $\hat{p}_{T_t}$) and $z_a = p_{T_a}/\hat{p}_{T_a}$ is the fragmentation variable of the away-jet (with $\hat{p}_{T_a}$), was thought in the ISR era to measure the fragmentation function of the away-jet [Fig. 9(c)[d]] but was found at RHIC to be sensitive, instead, to the ratio of the transverse momenta of the away-jet to the trigger jet, $\hat{x}_h \equiv \hat{p}_{T_a}/\hat{p}_{T_t}$.[52]

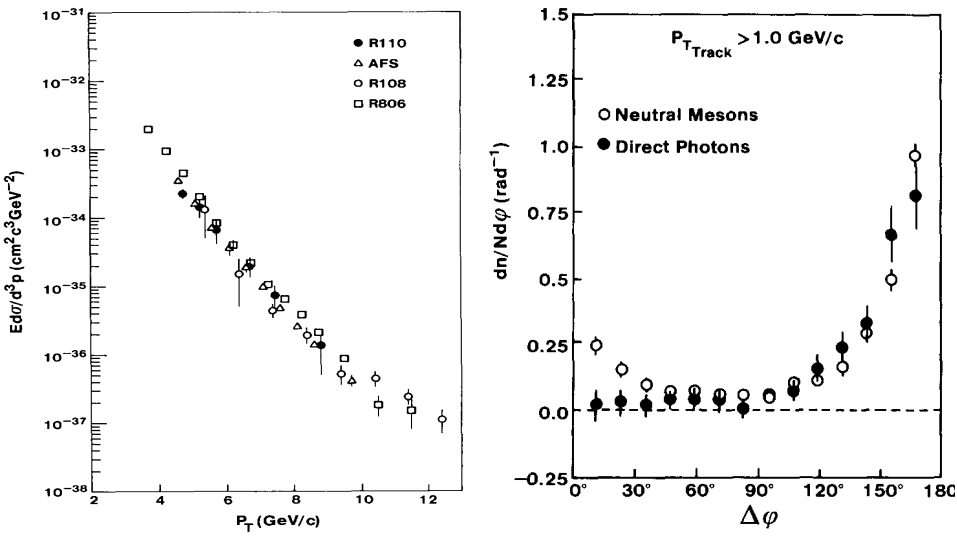
The QCD subprocess angular distribution $\Sigma^{ab}(\cos\theta^*)$ was also first measured with two-particle correlations of π^0 pairs of large invariant mass at the CERN-ISR[53–55] (Fig. 10), in agreement with QCD[47–49,54] at a fundamental level.

3.2. *Other ISR discoveries important at RHIC*

Two other ISR discoveries, direct-single-γ production and direct-single $e^{\pm}$ production, and one near miss, J/Ψ production, are important components of physics at RHIC.

Direct-single-γ production via the inverse QCD-compton process[56] $g+q \to \gamma+q$ is an important probe in A+A collisions because the γ is a direct participant in the reaction (at the constituent level), which emerges from the medium without interacting and can be measured precisely. The cross-sections for direct single-γ production at $\sqrt{s} = 62.4$ GeV (Ref. 57) are shown in Fig. 11(a). Two-particle azimuthal correlations of charged hadrons with neutral mesons (π^0), compared to direct-γ (Fig. 11(b)), show that direct-γ are isolated, with no accompanying same-side particles, while π^0 have accompanying particles since they are fragments of jets from high p_T partons.

[d]Data from Ref. 50 shown in Ref. 51.



(a) (b)

Fig. 11. (a) Compilation of invariant cross-sections of direct-γ production at ISR;[57] (b) azimuthal correlations of neutral mesons and direct-γ with $h^{\pm}$.[57]

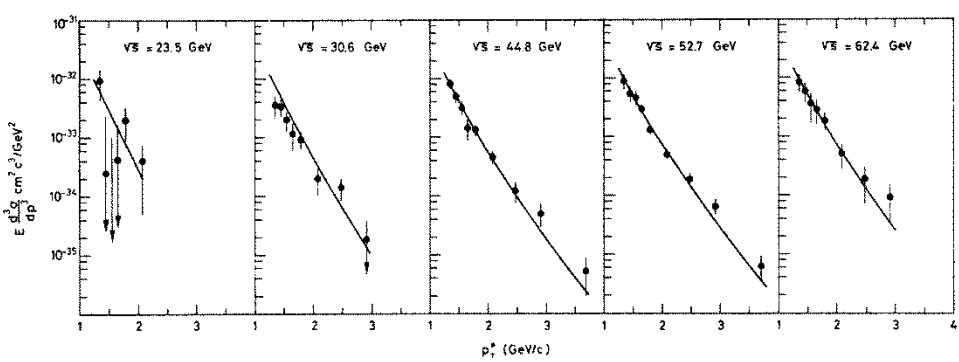
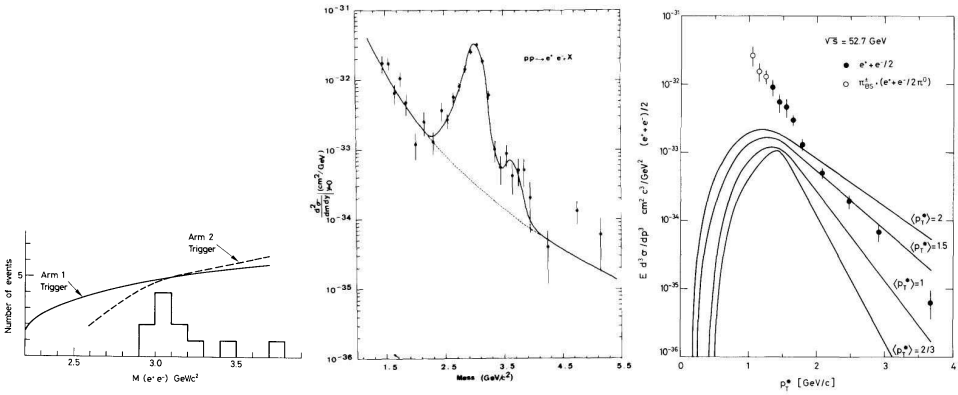


Fig. 12. Invariant cross-sections at mid-rapidity: $(e^{+} + e^{-})/2$ (points); $10^{-4} \times (\pi^{+} + \pi^{-})/2$ (lines).[58]

Direct single-$e^{\pm}$ at a level of $e^{\pm}/\pi^{\pm} \approx 10^{-4}$ for all values of $\sqrt{s}$ at the CERN-ISR were discovered before either the J/Ψ or open-charm[58] (Fig. 12). After the discovery of the J/Ψ in 1974, it was demonstrated that the J/Ψ was not the source of the single-$e^{\pm}$ (Fig. 13), and two years later, when open charm was discovered, it was shown that the direct $e^{\pm}$ were due to the semileptonic decay of charm mesons.[59] Figure 13(a)[60] shows the first J/Ψ at the ISR,[60] Fig. 13(b) shows the best J/Ψ measurement at the ISR[61] while Fig. 13(c)[58] shows that the direct electrons (Fig. 12) are not the result of J/Ψ decay since $\langle p_T \rangle = 1.1 \pm 0.05$ GeV/c.[61]



(a) (b) (c)

Fig. 13. (a) First J/Ψ at ISR;[60] (b) Best $d\sigma_{ee}/dm_{ee}\,dy|_{y=0}$;[61] (c) direct-$e^{\pm}$ data at $\sqrt{s}$ = 52.7 GeV (Fig. 12) with calculated $e^{\pm}$ spectrum for J/Ψ for several values of $\langle p_T \rangle$.[58]

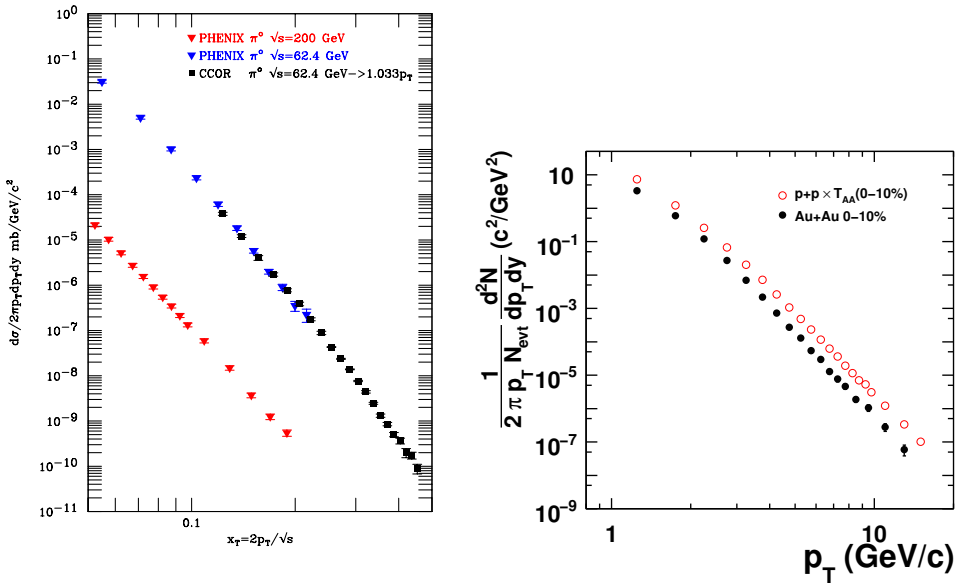
4. From ISR *p–p* to RHIC A+A Physics

Since hard-scattering at high $p_T > 2$ GeV/c is point-like, with distance scale $1/p_T <$ 0.1 fm, the cross-section in p + A (A+A) collisions, compared to p–p, should be larger by the relative number of possible point-like encounters a factor of A (A^2) for p + A (A+A) minimum bias collisions. When the impact parameter or centrality of the collision is defined, the proportionality factor becomes $\langle T_{AA} \rangle$, the average overlap integral of the nuclear thickness functions.

4.1. *Jet quenching from inclusive* π^0 *production*

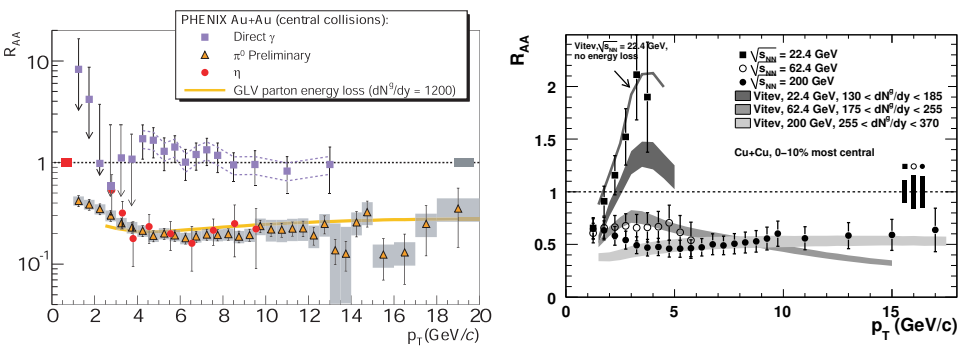
The discovery, at RHIC, that π^0 are suppressed by roughly a factor of 5 compared to point-like scaling of hard-scattering in central Au+Au collisions is arguably *the* major discovery in RHI Physics. In Fig. 14(a), the PHENIX measurement of $Ed^3\,\sigma/dp^3$ for π^0 production in p–p collisions at $\sqrt{s}$ = 62.4 GeV (Ref. 62) is in excellent agreement with the ISR data and the PHENIX π^0 data follow the same trend as the lower energy data, with a pure power-law, $Ed^3\sigma/dp^3 \propto p_T^{-8/1\pm0.1}$ for $p_T > 3$ GeV/c at $\sqrt{s}$ = 200 GeV. In Fig. 14(b), the 200 GeV p–p data, multiplied by the point-like scaling factor $\langle T_{AA} \rangle$ for (0–10%) central Au+Au collisions are compared to the semi-inclusive invariant π^0 yield in central (0–10%) Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV and, amazingly, the Au+Au data follow the same power law as the p–p data but are suppressed from the point-like scaled p–p data by a factor of ~ 5, independent of p_T. The suppression is represented quantitatively by the "nuclear modification factor," $R_{AA}(p_T)$, the ratio of the measured semi-inclusive yield in A+A collisions to the point-like scaled p–p cross-section at a given p_T:

$$R_{AA}(p_T) = \frac{d^2 N^{\pi}_{AA}/dp_T\,dy\,N_{AA}}{\langle T_{AA} \rangle d^2\sigma^{\pi}_{pp}/dp_T\,dy}\,. \tag{6}$$



(a) (b)

Fig. 14. (a) $Ed^3\sigma/dp^3$ vs x_T for PHENIX mid-rapidity π^0 at $\sqrt{s} = 200$ GeV in p–p collisions[39] plus PHENIX[62] and CCOR-ISR[44] measurements at $\sqrt{s} = 62.4$ GeV, where the absolute p_T scale of the ISR measurement has been corrected upwards by 3% to agree with the PHENIX data. (b) π^0 p–p data vs p_T at $\sqrt{s} = 200$ GeV from (a) multiplied by $\langle T_{AA}\rangle$ for Au+Au central (0–10%) collisions compared to semi-inclusive π^0 invariant yield in Au+Au central (0–10%) collisions at $\sqrt{s_{NN}} = 200$ GeV.



(a) (b)

Fig. 15. (a) Nuclear modification factor, R_{AA} for direct-γ, π^0 and η in Au+Au (0–10%) central collisions at $\sqrt{s_{NN}} = 200$ GeV,[63] together with GLV theory curve.[64,65] (b) PHENIX R_{AA} for π^0 in Cu+Cu central collisions at $\sqrt{s_{NN}} = 200$, 62.4 and 22.4 GeV,[66] together with Vitev theory curves.[67]

In Fig. 15(a), $R_{AA}(p_T)$ is shown for π^0, η mesons and direct-γ for $\sqrt{s_{NN}} = 200$ GeV Au + Au central (0–10%) collisions. The π^0 and η mesons, which are fragments of jets from outgoing partons are suppressed by the same amount while the

direct-γ which do not interact in the medium are not suppressed. This indicates a strong medium effect on outgoing partons. Figure 15(b) shows that R_{AA} for central (0–10%) Cu+Cu collisions is comparable at $\sqrt{s_{NN}} = 62.4$ and 200 GeV, but that there is no suppression, actually a Cronin enhancement,[68] at $\sqrt{s_{NN}} = 22.4$ GeV. This indicates that the medium which suppresses jets is produced somewhere between $\sqrt{s_{NN}} = 22.4$ GeV, the SpS Fixed Target highest c.m. energy, and 62.4 GeV.

The measurements at RHIC appear to be in excellent agreement with the theoretical curves.[64,65,67] The suppression can be explained by the energy loss of the outgoing partons in the dense color-charged medium due to coherent Landau–Pomeranchuk–Migdal radiation of gluons, predicted in QCD,[69] which is sensitive to properties of the medium. Measurements of two-particle correlations (discussed below, Sec. 7) confirm the loss of energy of the away-jet relative to the trigger jet in Au+Au central collisions compared to p–p collisions. However, lots of details remain to be understood.

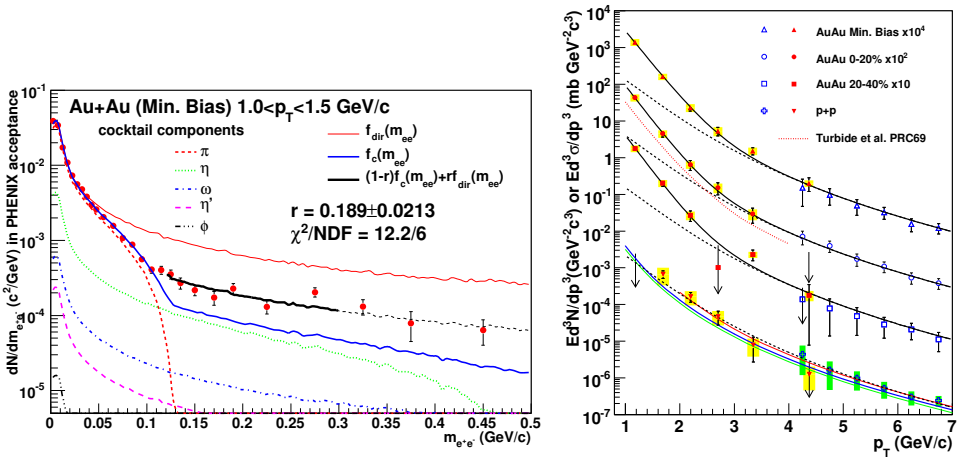
5. Direct Photons at RHIC: Thermal Photons?

5.1. *Internal conversions — The first measurement anywhere of direct photons at low p_T*

Internal conversion of a photon from π^0 and η decay is well-known and is called Dalitz decay.[70] Perhaps less well known in the RHI community is the fact that for any reaction (e.g. $q + g \to \gamma + q$) in which a real photon can be emitted, a virtual photon (e.g. e^+e^- pair of mass $m_{ee} \geq 2m_e$) can also be emitted. This is called internal-conversion and is generally given by the Kroll–Wada formula:[71,72]

$$\frac{1}{N_\gamma}\frac{dN_{ee}}{dm_{ee}} = \frac{2\alpha}{3\pi}\frac{1}{m_{ee}}\left(1 - \frac{m_{ee}^2}{M^2}\right)^3 \left|F\left(m_{ee}^2\right)\right|^2 \sqrt{1 - \frac{4m_e^2}{m_{ee}^2}}\left(1 + \frac{2m_e^2}{m_{ee}^2}\right), \qquad (7)$$

where M is the mass of the decaying meson or the effective mass of the emitting system. The dominant terms of Eq. (7) are — the characteristic $1/m_{ee}$ dependence, and the cutoff of the spectrum for $m_{ee} \geq M$ [Fig. 16(a)].[72] Since the main background for direct-single-γ production is a photon from $\pi^0 \to \gamma + \gamma$, selecting $m_{ee} \gtrsim 100$ MeV/c^2 effectively reduces the background by an order of magnitude by eliminating the background from π^0 Dalitz decay, $\pi^0 \to \gamma + e^+ + e^-$, at the expense of a factor ~ 1000 in rate. This allows the direct photon measurements to be extended (for the first time in both p–p and Au+Au collisions) below the value of $p_T \sim 4$ GeV/c, possible with real photons, down to $p_T = 1$ GeV/c [Fig. 16(b)],[72] which is a real achievement. The solid lines on the p–p data are QCD calculations which work down to $p_T = 2$ GeV/c. The dashed line is a fit of the p–p data to the modified power-law $B(1+p_T^2/b)^{-n}$, used in the related Drell–Yan[73] reaction, which flattens as $p_T \to 0$.



(a) (b)

Fig. 16. (Color online) (a) Invariant mass (m_{ee}) distribution of e^+e^- pairs from Au+Au minimum bias events for $1.0 < p_T < 1.5$ GeV/c.[72] Dashed lines are Eq. (7) for the mesons indicated. Blue solid line is $f_c(m)$, the total di-electron yield from the sum of contributions or "cocktail" of meson Dalitz decays; Red solid line is $f_{\rm dir}(m)$ the internal conversion m_{ee} spectrum from a direct-photon ($M \gg m_{ee}$). Black solid line is a fit of the data to the sum of cocktail plus direct contributions in the range $80 < m_{ee} < 300$ MeV/c^2. (b) Invariant cross-section (p–p) or invariant yield (Au+Au) of direct photons as a function of p_T.[72] Filled points are from virtual photons, open points from real photons.

The relatively flat, nonexponential, spectra for the direct-γ and Drell–Yan reactions as $p_T \to 0$ is due to the fact that there is no soft-physics production process for them, only production via the partonic subprocesses, $g + q \to \gamma + q$ and $\bar{q} + q \to e^+ + e^-$, respectively. This is quite distinct from the case for hadron production, e.g. π^0, where the spectra are exponential as $p_T \to 0$ in p–p collisions [Fig. 7(a)] due to soft-production processes, as well as in Au+Au collisions. Thus, for direct-γ in Au+Au collisions, the exponential spectrum of excess photons above the $\langle T_{AA}\rangle$ extrapolated p–p fit is unique and therefore suggestive of a thermal source.

5.2. *Low p_T vs high p_T direct-γ — Learn a lot from a busy plot*

The unique behavior of direct-γ at low p_T in Au+Au relative to $p + p$ compared to any other particle is more dramatically illustrated by examining the R_{AA} of all particles measured by PHENIX in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (Fig. 17).[e] For the entire region $p_T \leq 20$ GeV/c so far measured at RHIC, apart from the $p + \bar{p}$ which are enhanced in the region $2 \leq p_T \lesssim 4$ GeV/c ("the baryon

[e]Thanks to Sasha Milov for the plot of $R_{AA}(p_T)$ for all PHENIX published and preliminary measurements. With the exception of the internal-conversion direct-γ where the fit to the p–p data is used to compute R_{AA}, all the other values of R_{AA} are computed from Eq. (6) using the measured Au+Au and p–p data points.

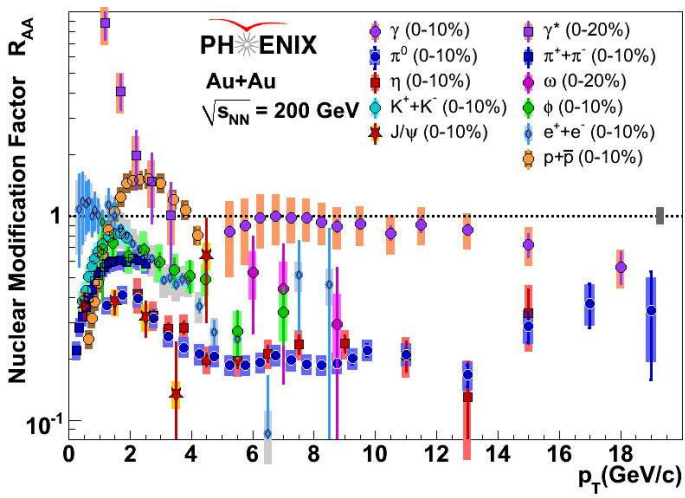


Fig. 17. Nuclear Modification Factor, $R_{AA}(p_T)$ for all identified particles so far measured by PHENIX in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV.[e]

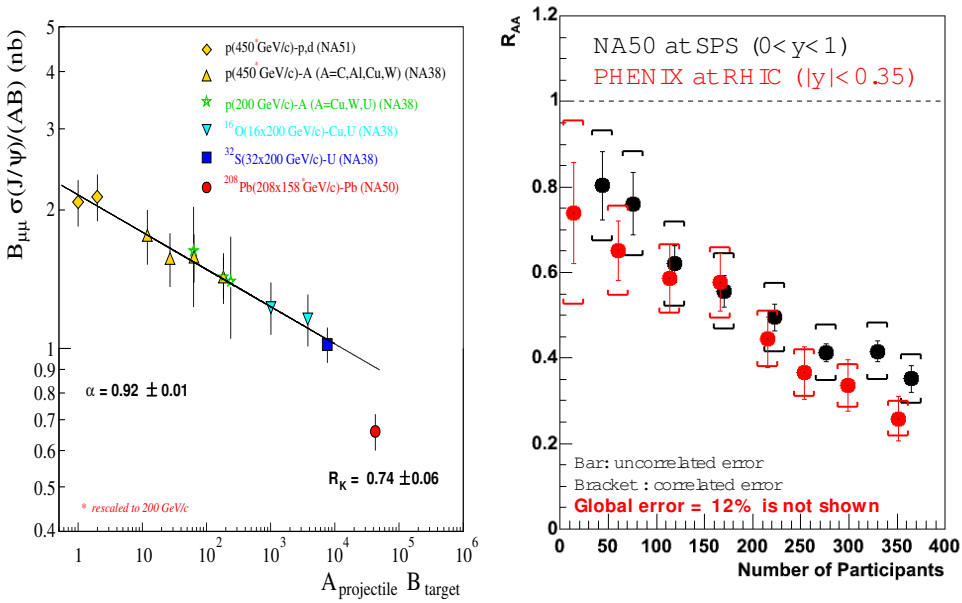
anomaly"), the production of *no other particle* is enhanced over point-like scaling. The behavior of R_{AA} of the low $p_T \leq 2$ GeV/c direct-γ is totally and dramatically different from all the other particles, exhibiting an order of magnitude exponential enhancement as $p_T \to 0$. This exponential enhancement is certainly suggestive of a new production mechanism in central Au+Au collisions different from the conventional soft and hard particle production processes in p–p collisions and its unique behavior is attributed to thermal photon production by many authors (e.g. see citations in Ref. 72).

5.2.1. *Direct photons and mesons up to $p_T = 20$ GeV/c*

Other instructive observations can be gleaned from Fig. 17. The π^0 and η continue to track each other to the highest p_T. At lower p_T, the ϕ meson tracks the $K^{\pm}$ very well, but with a different value of $R_{AA}(p_T)$ than the π^0, while at higher p_T, the ϕ and ω vector mesons appear to track each other. Interestingly, the J/Ψ seems to track the π^0 for $0 \leq p_T \leq 4$ GeV/c; and it will be important to see whether this trend continues at higher p_T.

6. J/Ψ Suppression, Still Golden?

The dramatic difference in π^0 suppression from SpS to RHIC c.m. energy (Fig. 15(b)) is not reflected in J/Ψ suppression, which is nearly identical at mid-rapidity at RHIC compared to the NA50 measurements at SpS [Fig. 18(b)].[74,75] This casts new doubt on the value of J/Ψ suppression as a probe of deconfinement in addition to the previous complication that J/Ψ are already suppressed

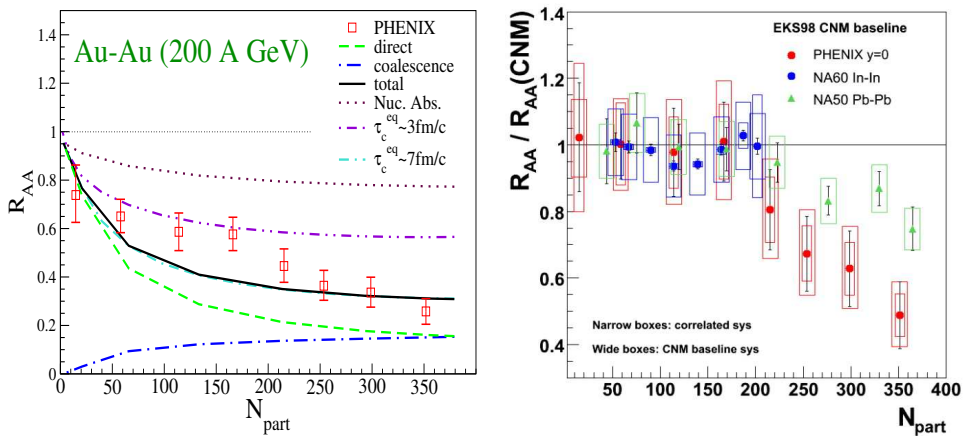


(a) (b)

Fig. 18. (a) Total cross-section for J/Ψ production divided by AB in $A+B$ collisions at 158–200A GeV.[17,18] (b) J/Ψ suppression relative to p–p collisions (R_{AA}) as a function of centrality ($N_{\rm part}$) at RHIC[74,75] and at the CERN/SPS.[17,18]

(compared to point-like scaling) in $p+$ A and $B+A$ collisions [Fig. 18(a)]. One possible explanation is that c and $\bar{c}$ quarks in the QGP recombine to regenerate J/Ψ, miraculously making the observed R_{AA} equal at SpS and RHIC c.m. energies [Fig. 19(a)].[75,76] The good news is that such models predict the vanishing of J/Ψ suppression or even an enhancement ($R_{AA} > 1$) at LHC energies,[77–79] which would be spectacular, if observed.

Even without LHC results, there has been progress recently when, after ~ 20 years (!), $p+$A comparison data for the J/Ψ from the CERN fixed target program at 158A GeV/c finally became available.[80] The cold nuclear matter effect of J/Ψ suppression in $p+$ A collisions is parametrized by an effective absorption cross-section $\sigma_{\rm abs}^{J/\Psi}$ which had been previously measured to be 4.3 ± 1.0 mb at 400 GeV/c proton beam energy and "*assumed to be independent of beam energy*." The actual measurement for 158 GeV $p+$A collisions gives $\sigma_{\rm abs}^{J/\Psi} = 7.6 \pm 0.9$ mb which considerably reduces the "anomalous suppression" effect shown in Fig. 18(a) to such an extent that there is now a clear difference between the CERN SpS and RHIC J/Ψ suppression for the most central A+A collisions relative to the measured Cold Nuclear Matter effect [Fig. 19(b)].[81] Maybe there is still some hope for J/Ψ suppression as a QGP signature, but there is an important lesson for LHC. Comparison of data for p–p and $p+$ A *must* be taken and must be at the same $\sqrt{s_{NN}}$ as the A+A data.



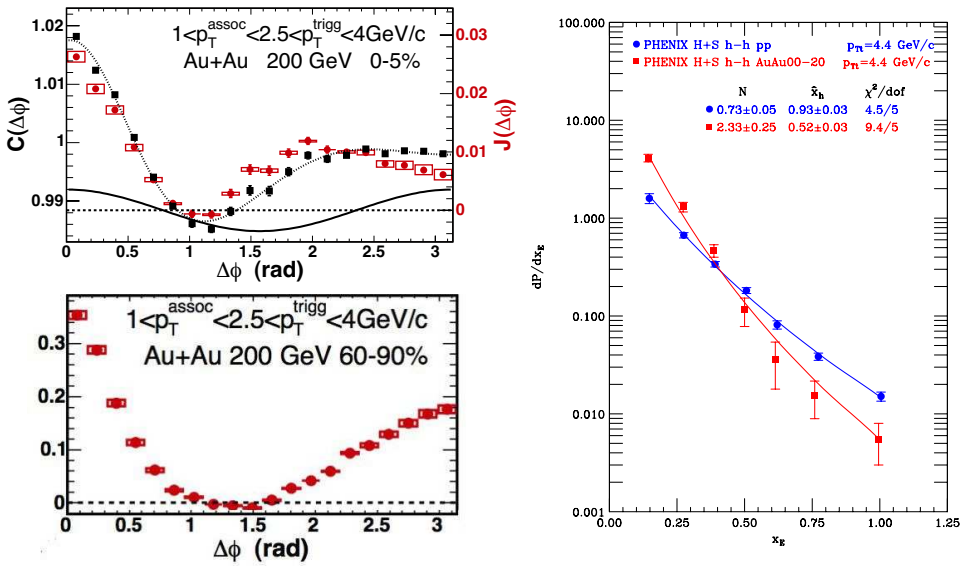
(a) (b)

Fig. 19. (a) PHENIX measurement of R_{AA} as a function of centrality from Fig. 18(b) together with prediction from a coalescence model;[76] (b) R_{AA} of J/Ψ at SpS and RHIC c.m. energies normalized to the measured R_{AA}(CNM) from cold nuclear matter.[81]

7. Two-Particle Correlations

If the π^0 suppression shown in Fig. 15 is in fact explained by the energy loss of the outgoing partons in the dense color-charged medium, this can be confirmed by measurements of two-particle correlations. These measurements are sensitive to the ratio of the energy of the away-jet to the trigger jet, which can be compared in Au+Au collisions and p–p collisions. In analogy to Fig. 9 (above), the two-particle correlations in Au+Au collisions [Fig. 20(a)] show clear di-jet structure in both peripheral and central collisions. The away-side correlation in central Au+Au collisions is much wider than in peripheral Au+Au and p–p collisions, and is further complicated by the large multiparticle background which is modulated in azimuth by the v_2 collective flow of a comparable width to the jet correlation. After the v_2 correction, a double peak structure $\sim \pm 1$ radian from π is evident, with a dip at π radians. This may indicate a reaction of the medium to a passing parton in analogy to a "sonic-boom"[82] and is under active study both theoretically and experimentally. It is evident that v_3, a $\cos 3(\Delta\phi)$ term with lobes at $\Delta\phi = 0$, $2\pi/3$ and $4\pi/3 \approx 0, 2, 4$ radians, could explain the double peak structure at $\pi \pm D$ radian in the two-particle correlations. There is presently lots of activity to confirm in detail; for e.g. whether taking account of the odd harmonics in addition to v_2 and v_4 in the background of Fig. 20(a) will result in narrower Gaussian-like away-jet peaks in Au+Au central collisions like the peaks in peripheral Au+Au and p–p collisions.

The energy loss of the away-parton is indicated by the fact that the x_E distribution in Au+Au central collisions [Fig. 20(b)] is steeper than that from p–p collisions. As noted above, we found in PHENIX[52,83] that the x_E distribution did



(a) (b)

Fig. 20. (a) Azimuthal correlation $C(\Delta\phi)$ of $h^{\pm}$ with $1 \leq p_{T_a} \leq 2.5$ GeV/c with respect to a trigger $h^{\pm}$ with $2.5 \leq p_{T_t} \leq 4$ GeV/c in Au + Au: (top) central collisions, where the line with data points indicates $C(\Delta\phi)$ before correction for the azimuthally modulated (v_2) background, and the other line is the v_2 correction which is subtracted to give the jet correlation function $J(\Delta\phi)$ (data points); (bottom) same for peripheral collisions. (b) $x_E \approx p_{T_a}/p_{T_t}$ distribution for the Au+Au-central data compared to p–p.

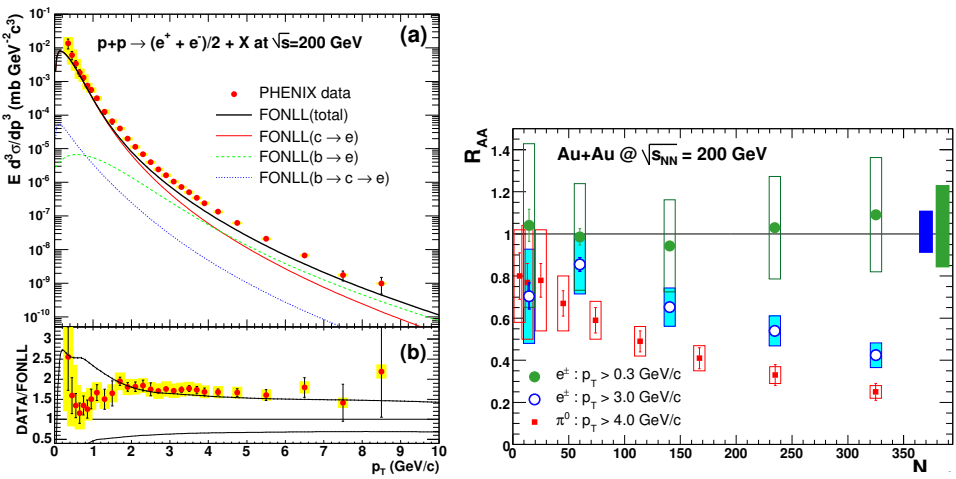
not measure the fragmentation function of the away-jet but is sensitive instead to $\hat{x}_h$, the ratio of the transverse momentum of the away-parton to that of the trigger parton, specifically:[52]

$$\left.\frac{dP}{dx_E}\right|_{p_{T_t}} = N(n-1)\frac{1}{\hat{x}_h}\,\frac{1}{(1+x_E/\hat{x}_h)^n}\,, \tag{8}$$

where N is a normalization factor, and n (= 8.1 at 200 GeV) is the power of the inclusive invariant p_{T_t} distribution.

8. A Charming Surprise

We designed PHENIX specifically to be able to detect charm particles via direct-single $e^{\pm}$ since this went along naturally with $J/\Psi \to e^+ + e^-$ detection and since the single particle reaction avoided the huge combinatoric background in Au+Au collisions. We thought that the main purpose of open charm production, which corresponds to a hard-scale ($m_{c\bar{c}} \gtrsim 3$ GeV/c^2), would be a check of our centrality definition and $\langle T_{AA}\rangle$ calculation since the total production of c quarks should follow point-like scaling. In fact, our first measurement supported this beautifully.[84] However, our subsequent measurements proved to be much more interesting and



(a) (b)

Fig. 21. (a) Invariant cross-section of direct $e^{\pm}$ in p–p collisions[85] compared to theoretical predictions from c and b quark semileptonic decay. (b) R_{AA} as a function of centrality ($N_{\rm part}$) for the total yield of $e^{\pm}$ from charm ($p_T > 0.3$) GeV/c, compared to the suppression of the $e^{\pm}$ yield at large $p_T > 3.0$ GeV/c which is comparable to that of π^0 with ($p_T > 4$ GeV/c).[85]

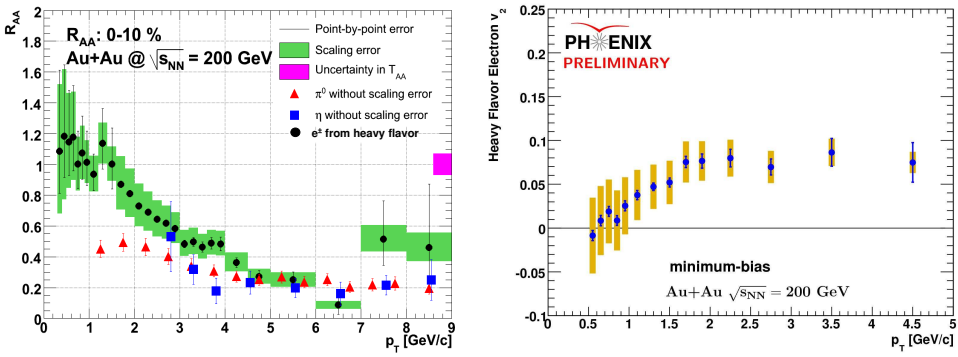
even more beautiful. Figure 21(a) shows our direct-single-$e^{\pm}$ measurement in p–p collisions at $\sqrt{s} = 200$ GeV (Ref. 85) in agreement with a QCD calculation of c and b quarks as the source of the direct-single-$e^{\pm}$ (also called nonphotonic $e^{\pm}$ at RHIC). The total yield of direct-$e^{\pm}$ for $p_T > 0.3$ GeV/c was taken as the yield of c-quarks in p–p and Au+Au collisions. The result, $R_{AA} = 1$ as a function of centrality [Fig. 21(b)], showed that the total $c - (\bar{c})$ production followed point-like scaling, as expected. The big surprise came at large p_T where we found that the yield of direct-single-$e^{\pm}$ for $p_T > 3$ GeV/c was suppressed nearly the same as the π^0 from light quark and gluon production. This strongly disfavors the QCD energy-loss explanation of jet-quenching because, naively, heavy quarks should radiate much less than light quarks and gluons in the medium; but opens up a whole range of new possibilities including string theory.[f]

The suppression of direct-single-$e^{\pm}$ is even more dramatic as a function of $p_T \gtrsim 5$ GeV/c [Fig. 22(a)] which indicates suppression of heavy quarks as large as that for π^0 in the region where the $m \gtrsim 4$ GeV b-quarks dominate. Figure 22(b) shows that heavy quarks exhibit collective flow (v_2), another indication of a very strong interaction with the medium.

9. Zichichi to the Rescue?

In September 2007, I read an article by Nino, "Yukawa's gold mine" in the CERN Courier taken from his talk at the 2007 International Nuclear Physics meeting in

[f]For example, see Ref. 85 for a list of references.



(a) (b)

Fig. 22. (a) R_{AA} (central Au+Au) (b) v_2 (minimum bias Au+Au) as a function of p_T for direct-$e^{\pm}$ at $\sqrt{s_{NN}} = 200$ GeV.[85]

Tokyo, Japan, in which he proposed: "We know that confinement produces masses of the order of a giga-electron-volt. Therefore, according to our present understanding, the QCD colorless condition cannot explain the heavy quark mass. However, since the origin of the quark masses is still not known, it cannot be excluded that in a QCD colored world, the six quarks are all nearly massless and that the colorless condition is "flavor" dependent."

Nino's idea really excited me even though, or perhaps because, it appeared to overturn two of the major tenets of the Standard Model since it seemed to imply that: QCD is not flavor blind; the masses of quarks are not given by the Higgs mechanism. Massless b and c quarks in a color-charged medium would be the simplest way to explain the apparent equality of gluon, light-quark and heavy-quark suppression indicated by the equality of R_{AA} for π^0 and direct-single-$e^{\pm}$ in regions where both c and b quarks dominate. Furthermore RHIC and LHC-Ions are the only place in the Universe to test this idea.

It may seem surprising that I would be so quick to take Nino's idea so seriously. This confidence dates from my graduate student days when I checked the proceedings of the 12th ICHEP in Dubna, Russia in 1964 to see how my thesis results were reported and I found several interesting questions and comments by an "A. Zichichi" printed in the proceedings. One comment about how to find the W boson in $p + p$ collisions deserves a verbatim quote because it was exactly how the W was discovered at CERN 19 years later: "We would observe the μ's from W-decays. By measuring the angular and momentum distribution at large angles of K and π's, we can predict the corresponding μ-spectrum. We then see if the μ's found at large angles agree with or exceed the expected numbers."

Nino's idea seems much more reasonable to me than the string theory explanations of heavy-quark suppression (especially since they cannot explain light-quark suppression). Nevertheless, just to be safe, I asked some distinguished theorists

what they thought, with these results:

- Stan Brodsky: "Oh, you mean the Higgs field cannot penetrate the QGP."
- Rob Pisarski: " You mean that the propagation of heavy and light quarks through the medium is the same."
- Chris Quigg (Moriond 2008): "The Higgs coupling to vector bosons γ, W, Z is specified in the standard model and is a fundamental issue. One big question to be answered by the LHC is whether the Higgs gives mass to fermions or only to gauge bosons. The Yukawa couplings to fermions are put in by hand and are not required." "What sets fermion masses, mixings?"
- Bill Marciano:"No change in the t-quark, W, Higgs mass relationship if there is no Yukawa coupling: but there could be other changes."
- Steve Weinberg: "Lenny Susskind and I had a model, Technicolor (or Hypercolor), that worked well in the vector boson sector but did not give mass to the fermions."

Nino proposed to test his idea by shooting a proton beam through a QGP formed in a Pb+Pb collision at the LHC and seeing the proton "dissolved" by the QGP. My idea is to use the new PHENIX VTX detector, installed in 2011, to map out, on an event-by-event basis, the di-hadron correlations from identified b–$\bar{b}$ di-jets, identified c–$\bar{c}$ di-jets, which do not originate from the vertex, and light quark and gluon di-jets, which originate from the vertex and can be measured with π^0-hadron correlations. A steepening of the slope of the x_E distribution of heavy-quark correlations as in Fig. 20(b) will confirm in detail (or falsify) whether the different flavors of quarks behave as if they have the same energy loss (hence mass) in a color-charged medium. If Nino's proposed effect is true, that the masses of fermions are not given by the Higgs particle, and we can confirm the effect at RHIC or LHC-Ions, this would be a case where we Relativistic Heavy Ion Physicists may have something unique to contribute at the most fundamental level to the Standard Model, which would constitute a "transformational discovery." Of course the LHC could falsify this idea by finding the Higgs decay to b–$\bar{b}$ at the expected rate in p–p collisions. Clearly, there are exciting years ahead of us!

Acknowledgments

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Appendix. Discussions

This appendix contains discussions among author and participants at the Erice 2009 International School of Subnuclear Physics.

A.1. *Discussion I*

Chairman: G. 't Hooft. Scientific Secretaries: M. A. Ahmad and V. N. Uvais.

Y. Klopot:

Could you please give some details on how in heavy ion collisions one can extract the ratio of shear viscosity to entropy density?

M. J. Tannenbaum:

I don't wish to discuss this today. Ask me again tomorrow.

H. Perrey:

In the PHENIX what difference would it make to be able to measure at full azimuth, 2π instead of π?

M. J. Tannenbaum:

For detection of a single particle near mid-rapidity, simply a factor of 2 for the azimuthal acceptance. For two-particle detection like the J/ψ, or for correlations, we might gain a larger factor, possibly 4 by extending to full azimuth, depending how correlated the particles of interest are in azimuth — the less correlated back-to-back, the more we would gain. In rapidity, if we could have afforded to build our detector to cover $|\eta| < 1.05$, like STAR, we could have gained another factor of 3 in acceptance for single particles. We also have a forward detector for muons which covers 2π in azimuth and $1.2 < |\eta| < 2.2$, primarily for J/ψ, Drell–Yan and W boson measurements. We also have two small electromagnetic calorimeters covering 2π in azimuth and $3.1 < |\eta| < 3.7$ for measurements in the forward cone. Personally, I like to measure at mid-rapidity because this emphasizes hard-scattering which occurs at large p_T, while in the forward direction p_T is limited by conservation of energy; and hard-scattering occurs with particles of large energy $= (\sqrt{\hat{s}})/2$, where $(\sqrt{\hat{s}} = 2p_T/\sin\theta^*)$ is the c.m. energy and θ^* the scattering angle for the parton–parton scattering. At mid rapidity, a parton has $p_T = E = (\sqrt{\hat{s}})/2$, and the kinematics of the parton are simple even with a single particle detected: $x_1 \approx x_2 \approx x_T = 2p_T/\sqrt{s}$, where $\sqrt{s}$ is the c.m. energy of the p–p collision. In the forward direction, the limited p_T and large energy forced by the kinematics puts the particles from hard-scattering in the region of low p_T dominated by soft processes such as diffraction dissociation. Also the so-called 'higher twist' QCD process come into play and complicate things further.

In general, I personally don't like to measure at forward rapidity — it's too complicated, with one exception. We can measure the gluon structure function in nuclei at low values of parton x by this method. The reaction we use is $g+q \to \gamma+q$. This will be my first slide tomorrow. The beauty of this reaction is that the γ comes straight out of the medium in a heavy ion collision without interacting, in distinction to the ougtoing q (or g) from hard-scattering. We have discovered that

the q and g interact with the medium produced in A+A collisions at RHIC and lose energy, which suppresses the spectrum of particles, such as π^0, from the parton fragmentation by a factor of 5 relative to binary-scaling from p–p collisions. By contrast, the direct-γ are not suppressed, which shows that the suppression is a final state effect, caused by the medium.

The binary-scaling assumes that the probability of finding a g (and q) in a nucleus A is simply A times that in a nucleon. We know that for small values of x, the probability is less than A — this is called shadowing. It is possible that direct γ will be suppressed in A+A collisions at LHC due to initial state shadowing thus vastly complicating the study of the medium (QGP). For instance, for a 10 GeV direct γ at mid-rapidity at RHIC, the parton $x \approx x_T = 10/100 = 0.1$, while the same 10 GeV photon at the LHC will have $x = 10/2750 = 0.0036$. We can achieve a low x at RHIC by detecting both the direct γ and its quark jet at forward rapidity, $y_1 = y_2 = y$, in which case $x_1 = x_T e^{-y}$ and $x_2 = x_T e^{y}$. So, for $y = 4.0$ we can reduce x_1 by a factor of 55 (kinematics permitting), making up the ratio of energies of RHIC to the LHC and enabling us at RHIC to measure the gluon structure function in Au, at a value of x which is useful at the LHC.

R. Preghenella:

I have a rather technical question about elliptical flow measurement at PHENIX. How do you determine the reaction plane? Do you have a dedicated detector?

M. J. Tannenbaum:

Yes, we have three detectors to determine the reaction plane. The first detector is the beam–beam counter (BBC). We have two identical counters with 64 channels of quartz cerenkov counters located on each side of the interaction point at $3.0 < |\eta| < 3.9$. We measure the reaction plane in the detector by looking at the asymmetry of the azimuthal distribution of counts. To measure the resolution we compare the upstream and downstream counters. We also have a forward EM calorimeter that Mickey Chiu built which is just behind the BBC and measures the asymmetry of the energy. We recently added R $\times$ NP which is a pair of highly segmented scintillator Pb sandwich counters covering $1.2 < |\eta| < 2.8$. Using the 3 sets of counters gives us a factor of four better resolution on the angle of the reaction plane than our early measurements using the BBC only.

R. Preghenella:

You told us about $N_{\rm ch}$ scaling with $N_{\rm part}$ using different models which work at different energies. What is the role of QGP quenching effects on this? Could it be the reason why one has to change model?

M. J. Tannenbaum:

In some sense it is possible that the QGP could change the total multiplicity; so in principle, you are absolutely correct. However, I don't know what effect it will make,

how the multiplicity would or should be changed. People who make calculations just assume that the multiplicity is the entropy. The measured multiplicity is consistent with simple scaling from p–p to $\mathrm{Au}-\mathrm{Au}$ collisions. If you're right, there might be some effects. We mostly look for the non-statistical fluctuations in multiplicity to see such effects, but we observe very little of such fluctuations, they're tiny — mostly due to the Bose–Einstien effect. So, the answer is yes. On should expect effects on the final multiplicity due to QGP formation, but so far we have not seen anything.

S. Yasnopolskiy:

Using PbGl crystals at EmCal of PHENIX, do you have to keep them at low temperatures for better performance as it was originally designed for PbWO crystals at PHOS of ALICE experiment? If yes, have you also had long lasting problems with the cooling system?

M. J. Tannenbaum:

Our PbGl calorimeter comes from the WA98 Experiment. We keep all our calorimeters at room temperature, including the PbWO crystals of the MPC. We have forced air cooling to dissipate the heat from the electronics for the central calorimeters which in general works fine. For the MPC we can't apply cooling and they are kept at a relatively constant temperature by the large mass of the iron piston of the Muon spectrometer in which they are embedded. We don't have any major problems with our forced air cooling system.

L. Dixon:

What causes the transition from $n = 8$ to $n = 4$ or 5 in the index of the single hadron inclusive p_T spectra you showed?

M. J. Tannenbaum:

Going to larger p_T than the original CCR measurement and using only the two largest values of $\sqrt{s} = 52.7$ and 62.4 GeV caused the effective index n_{eff} from x_T scaling to change from 8 to 5. Even at large $x_T > 0.30$, including the $\sqrt{s} = 30.7$ GeV in the calculation gives values of $n_{\mathrm{eff}} = 7$ (and 8 at lower x_T) rather than 5. Staying away from the lowest p_T and lowest $\sqrt{s}$ did the trick.

A.2. *Discussion II*

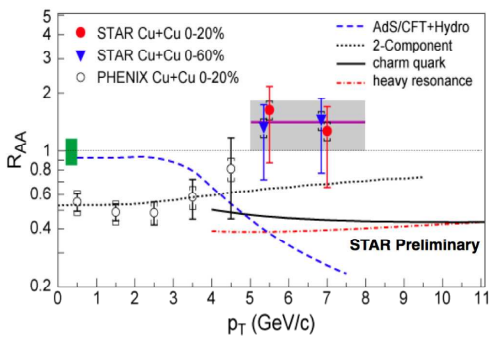
Chairman: A. Zichichi. Scientific Secretaries: M. Kurkov, S. Yasnopolskiy.

M. J. Tannenbaum (*additional comments to the letures*):

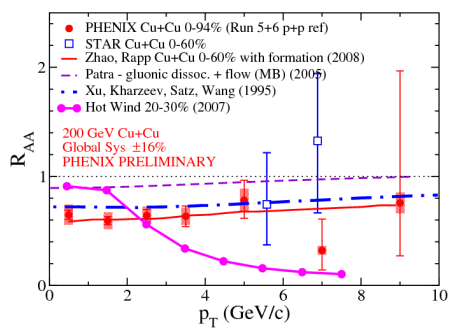
Before taking questions, I would like to make a few comments on some unresolved issues between STAR and PHENIX that may not be clear from the lectures. Paul Sorensen presented STAR's view on the J/ψ suppression in Cu+Cu. On a semi-log plot, STAR presents only two points at $p_T = 5$ and 7 GeV/c which show

$R_{AA} > 1$ with huge errors with the claim that the data are consistent with no J/ψ suppression at high p_T. However since Quark Matter 2009, PHENIX has added two more points to this plot at $p_T = 7$ and 9 GeV/c which are consistent with all the PHENIX measurements at lower p_T and indicate a constant value of $R_{AA} \sim 0.6$ from $0 < p_T < 9$ GeV/c. I think that STAR's emphasis on the rising R_{AA} here was misleading. Predictions show both a rising and falling $R_{AA}(p_T)$ while the PHENIX and STAR data together are consistent with a constant $R_{AA}(p_T)$.

STAR's view



PHENIX's view post QM2009



P. Sorensen:

There are different points here.

M. J. Tannenbaum:

I'm talking about these new PHENIX data points at 7 and 9 GeV/c.

P. Sorensen:

So we are not ignoring these two data STAR points.

M. J. Tannenbaum:

I'm not ignoring them, but whichever ones you use the STAR and PHENIX points are consistent, but STAR has huge errors.

P. Sorensen:

Yeah, but those are different than the ones on the final plot.

M. J. Tannenbaum:

I don't know, I did not make this plot. Anyway, just look at the (PHENIX) red points.

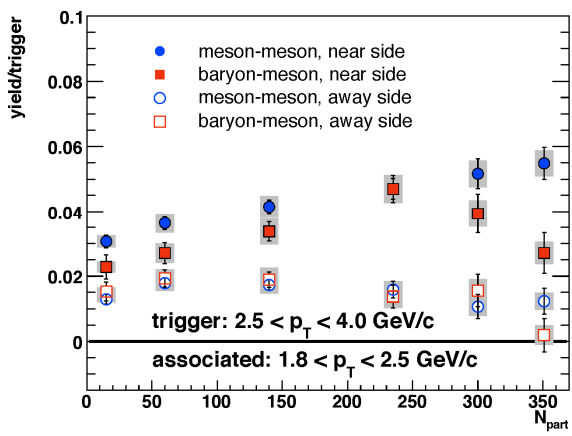
P. Sorensen:

I have it zero to sixty.

M. J. Tannenbaum:

Anyway, it's PHENIX's view of this.

Second comment — a really interesting point made by Paul [Sorensen] is Stan Brodsky's idea about color transparency. I show the PHENIX measurement of two-particle correlations for identified mesons associated to identified baryon and meson triggers in the region of the baryon anomaly $2.5 < p_{Tt} < 4.0$ GeV/c which I did not discuss in my lecture but which Paul mentioned. For this range of p_{Tt}, the p/π ratio is 1 in central Au+Au collisions instead of the value of 0.3 measured in p–p collisions. For this plot the mesons are the sum of π and K and the baryons are protons + antiprotons. With the exception of the most central point for the near-side, there is no difference in the correlations to a baryon or a meson trigger.

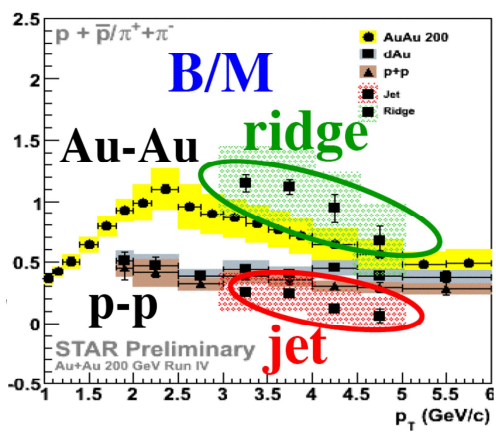


Since we know that the inclusive π mesons come from jets and satisfy the correct x_T scaling, while the inclusive protons have anomalous x_T scaling, the fact that the associated mesons are the same for trigger baryons and mesons means that the baryons also come from jets with the exception of the most central point where there are definitely fewer mesons associated to the baryon trigger than to the meson trigger. This could imply that some protons come out unaccompanied for the most central collisions, possibly consistent with Brodsky's prediction of the higher twist process $u + u \to p + \bar{d}$, where the proton comes out unaccompanied and doesn't interact with the medium due to 'color transparency' but the $\bar{d}$ fragments into an away-jet. I like the Paul's point: this prediction can be further tested by measuring the v_2, since the 'color transparent' protons which don't interact with the medium should show zero v_2. This should reduce the total proton v_2 relative to the pion v_2 as $N_{\text{part}} \to 350$.

M. J. Tannenbaum:

I have another point. Here is the famous plot from STAR which shows the Baryon to Meson ratio (B/M) of associated same-side particles to a non-identified hadron

trigger, $h^{\pm}$, with $p_{Tt} > 4.0$ GeV/c in both the ridge region (large $\Delta\eta$) and the jet region (small $\Delta\eta$) in comparison to the inclusive B/M ratio in p–p and Au+Au collisions (the dramatic difference in this ratio in Au+Au compared to p–p is the Baryon Anomaly which I previously mentioned). From this plot, STAR states that: the baryon to meson ratio in the ridge region is close to inclusive Au+Au and in the jet region is close to pp. However what they [STAR] really mean is that the baryon to meson ratio in the conditional yield of same side correlations to an $h^{\pm}$-trigger with $p_{Tt} > 4.0$ GeV/c is close to the inclusive yield for p–p in the jet region and close to Au+Au in the ridge. They are not making a claim for the inclusive B/M ratio in the jet region, only the associated B/M ratio to a non-identified hadron trigger. When said in this precise way, the STAR result is clearly in agreement with PHENIX observation that both the meson and baryon triggers in the region of the baryon anomaly have associated particles which are consistent with the meson and baryon triggers both coming from jets (except maybe for the most central point). STAR ignored the large proton component in the trigger and did not add it to the associated particle yield to get the correct comparison to the inclusive yield. The STAR result for the associated same side B/M ratio in the jet region for an $h^{\pm}$-trigger with $p_{Tt} \sim 4.0$ GeV/c is in reasonable agreement with a recent PHENIX publication [*Phys. Rev. Lett.* **101**, 082301 (2008)].



M. J. Tannenbaum (*a further comment*):

Yesterday somebody asked me the question: "How to measure η/s?" which I didn't wish to answer then. Today, Paul Sorensen showed how this was derived by PHENIX in *Phys. Rev. Lett.* **98**, 172301 (2007) from the $R_{AA}(p_T)$ and $v_2(p_T)$ of non-photonic electrons from heavy quark decay. Thanks Paul. However, please note that the PHENIX derivation is totally model dependent, too model dependent for my taste; that's why I prefer to leave it to the theorists. What one needs is a full hydro calculation which describes the initial state E_T or multiplicity distribution, the p_T spectra, and $v_2(p_T)$ for all identified particles. Also, at present there is still lots

of model dependence for the eccentricity as well as the color charge density of the medium (QGCW as Zichichi calls it) as a function of time. Also we don't know the detailed physics of energy loss in the QGP. So there is a lot to learn and theorists are welcome to bring their models.

D. Tapia Takaki:

What are the future plans at PHENIX concerning very low p_T (less than 3 GeV) direct photons?

M. J. Tannenbaum:

The publication was submitted, but one referee had many criticisms with which we didn't agree, which caused us lots of additional work to respond. In about a month we are going to resubmit it to the journal and I hope it will have been published by the end of the year.

Every particle species produced in a p–p-collision has an exponential p_T distribution as $p_T \to 0$ except for direct-γ. The exponential distribution comes from soft processes such as diffraction dissociation; but we determined that in p–p collisions direct-γ are are not exponential as $p_T \to 0$, they are only produced by the hard process $g + q \to \gamma + q$. In other words, if you measure π^0 and direct-γ in p–p collisions, they both have a power law at high p_T, but as $p_T \to 0$ the π^0 becomes exponential but the direct-γ does not — the slope is nearly flat. Some people believe that p–p collisions are thermal because of the exponential; but I don't believe that an exponential distribution implies a thermal system — it is necessary, but not sufficient. Thus, an exponential distribution in Au−Au-collisions doesn't necessarily mean thermal, either. However, if the exponential distribution of low p_T direct-γ in Au+Au is really thermal emission, this implies radiation from the medium and thus these γ should have the v_2 that is characteristic of the medium, while direct-γ from hard-processes have zero v_2. So we plan to measure the v_2 of direct photons between 1 and 3 GeV. If the low-p_T photons are thermal they should have the same v_2 as the medium.

M. Marienfeld:

Could you comment on the reasons for using the specific element in heavy ion collisions. For example why did you use gold, why will LHC use lead?

M. J. Tannenbaum:

We started using gold in AGS experiments because the ordinary (24 karat) gold that you buy in a jewelry store is isotopcally pure; and since we used gold at AGS we know how to inject it, we know how to strip it of all its electrons, we know how to do everything. That's why we use it at RHIC. It will be interesting when we go to uranium, because uranium has a shape of a rugby ball, and hence when you make a central collision you have an asymmetric overlap which gives huge v_2 (normally v_2 equals 0 for central collisions for spherical nuclei); we are looking forward to it.

M. Marienfeld:

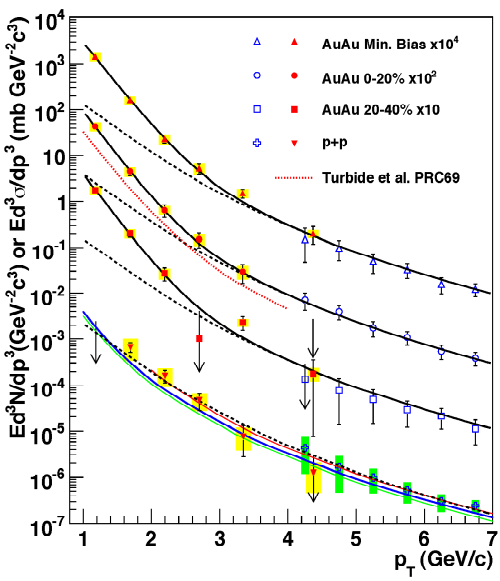
What element would you favor if there were no problems of purity or availability?

M. J. Tannenbaum:

Gold is fine. In fact I wanted element 256, but the nuclear physicists couldn't do this for me.

M. Chiu:

For the "thermal photons" at low p_T, are there any measurements which one can do to constrain many models which now describe the data so that we can use the thermal photons to extract quantitative information about the QGP? The photons are very important since they would carry the information about the early stages without being biased by final state effects.



M. J. Tannenbaum:

I don't think we can do it yet for the photon signal, because the exponential slope doesn't vary much for the three cases — peripheral, central and inclusive — which is rather suspicious. Maybe we will get a better idea if we have a better measurement versus centrality so that we could see the difference. The other test that I discussed above is the measurement as a function of angle to the reaction plane, v_2, which is zero for the direct-γ from hard-scattering which do not interact with the medium, while thermal γ are generated in the medium and so should exhibit the v_2 of the medium, which should be similar to the v_2 observed for hadrons. These are the only two ways I know, so far. I think we are stuck with them, because I don't see

any measurements that we can make to pick out photons coming from the original time, which is $\sim 10^{-23}$ seconds in comparison to the 16–17 nsec for photons to get to out detectors which we measure with $\sim$100 psec resolution.

M. Chiu:

Can't you do something like use HBT?

M. J. Tannenbaum:

That's an excellent point. People are trying to do HBT-correlations for photons, but they are extremely difficult.

R. Ichou:

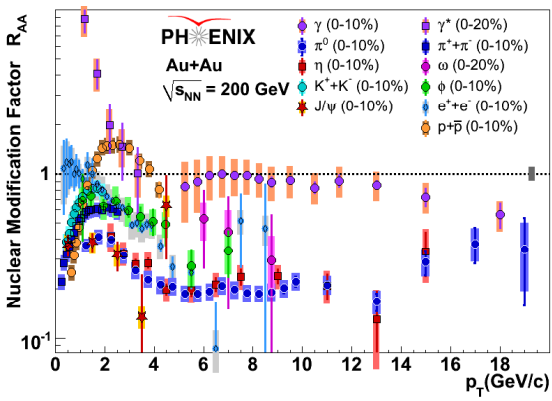
What do you think is the best measurement at LHC to help clarify the open issues at RHIC in the π^0 or jet quenching sector?

M. J. Tannenbaum:

The good thing about ALICE is that you have identified particles. But your calorimeter is unfortunately nearly the same as ours, so I do not think you will be able to do better than we do at 20 GeV. We see that the direct-γ seems to be suppressed at 20 GeV/c approaching the π^0 suppression, but it could easily be a detector effect. We have problems with π^0's because the photons merge and I am not sure about the efficiency of our cuts. However, suppression of direct-γ also could be due to the initial state structure function; we are working on that. The equality of R_{AA} for π^0 and γ at 20 GeV at RHIC would imply an initial state effect, which would mean that the medium effect is insignificant for $p_T \sim 20$ GeV/c. I think the measurements from 10 to 20 GeV at LHC would be interesting, and going above 20 GeV even more interesting. However, because of the low x values for this p_T range at the LHC, direct photons will likely be suppressed due to shadowing in the structure function, so comparison with π^0's to show suppression by the medium will not be as obvious as at RHIC; and besides, the direct-γ measurement is very difficult. Thus you will need extensive p–p and p+Pb collision data at the same $\sqrt{s}$ for the π^0 comparison. A measurement of v_2 is probably easier because you don't need comparison data. Another thing you could do is a p/π ratio vs p_T and centrality. Typically, from jet fragmentation it is 0.3 and you will probably get lots of data in p–p collisions to verify this. The baryon anomaly [peak at 2 GeV on figure] is due to the fact that the p/π ratio is 1 in Au+Au at RHIC in this range instead of 0.3. This is still not explained so the behavior of the baryon anomaly at the LHC is important and should clarify our understanding. Also $p/\bar{p}$ tells you the baryon chemical potential straightaway.

P. Aschieri:

Given the importance of the impact geometry in obtaining the properties of the quark–gluon plasma, is there the possibility of varying this impact geometry?



M. J. Tannenbaum:

In a fixed target experiment it is very easy, but in a collider the situation is different because charged fragments get swept away from the collision axis. The only thing you can detect in a zero-degree calorimeter are free neutrons. We tried to detect all the charged fragments in an external calorimeter, but not very successfully. I don't know if it is possible to do it at LHC. I agree with your point: we don't have a direct measurement of the overlap region, what the ellipse is. In principle we know how to do it at RHIC, but we haven't succeeded in practice. However, I am confident that our measurement of collision centrality (hence impact parameter) by the percentiles of the multiplicity distribution is accurate to within our stated errors, so quite good.

P. Aschieri:

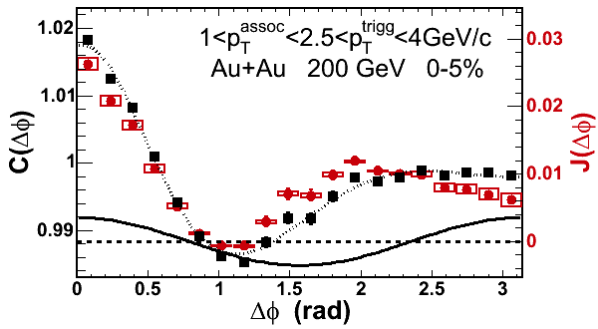
I was thinking thinking about varying the ion's shape via e.g. polarizing them.

M. J. Tannenbaum:

If we take a nucleus like U^{238}, which has a football shape and spin, we could in principle have collisions with the U^{238} nuclei both transversely or longitudinally polarized. In RHIC, we have spin rotators so we can have either transverse or longitudinal polarized beams and we have the so-called Siberian Snakes to preserve the polarization. Each half turn around the ring, we flip the spin, so whatever imperfection develops in one half turn is canceled out in the other. Thus we preserve polarization with protons exceedingly well. I don't know what the spin of U^{238} is but I am sure that it is much less than 238/2. Unless something has roughly the magnetic moment of a proton, it's very hard to preserve its polarization, but if you find the right nucleus, in principle you can do it.

Y. Klopot:

You told us about away side and near side correlations. How are these quantities measured in an actual experiment?



M. J. Tannenbaum:

Here is a typical plot of the azimuthal angle difference $\Delta\phi$ of two particles, a trigger particle with p_{Tt} and an associated particle with p_{Ta}. This angle difference ranges from 0 to 2π radians and we fold the distribution around π radians in the plot. The filled squares are the actual conditional yield $C(\Delta\phi)$ of associated $h^{\pm}$ with $1 < p_{Ta} < 2.5$ GeV/c per trigger $h^{\pm}$ with $2.5 < p_{Tt} < 4.0$ GeV/c, corrected for the azimuthal acceptance, but only for particles in the range $|\eta| < 0.35$. The red filled circles are the correlation due to the di-jet nature of the events, what we call the jet function, $J(\Delta\phi)$, which is $C(\Delta\phi)$ corrected for v_2 (the cosine curve), which is subtracted since v_2 is the correlation of each particle to the event plane, not to each other. This correction can be measured using correlations of particles from different events which have the same event plane angle.

We define the same-side correlation as the region $|\Delta\phi| < \pi/2 = 1.57$ radians from the trigger, the left region of the plot, and the away side as $|\Delta\phi - \pi| < \pi/2$. For the same-side yield we simply integrate the yield in the peak. However, note that in Au+Au collisions the away-side peak is wide and spills over to the same side. For the away-side yield we quote the region of integration in $\Delta\phi$, sometimes over the whole "away" peak, sometimes only over the away-side, $|\Delta\phi - \pi| < \pi/2$. In both cases we only measure the yield in the limited η range, $|\eta| < 0.35$, of our detector. The absolute yield is not correct (STAR is much better on this issue); but the relative yield for Au+Au and p–p is fine.

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