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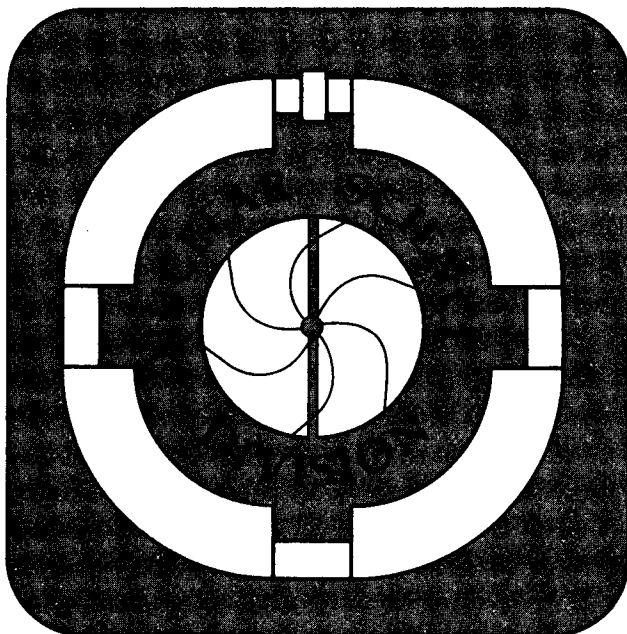
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## Relativistic Heavy Ion Collider: Physics and the STAR Experiment

J.W. Harris and the STAR Collaboration

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**Relativistic Heavy Ion Collider:  
Physics and the STAR Experiment**

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September 1992

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# **Relativistic Heavy Ion Collider: Physics and the STAR Experiment**

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## **ABSTRACT**

An overview of the Relativistic Heavy Ion Collider (RHIC) and its experimental program is presented. The physics capabilities of STAR, one of two large experiments planned for RHIC, are described through simulations of the measurements anticipated in STAR. The STAR experiment will concentrate on hadronic observables in the search for the Quark-Gluon Plasma (QGP). An emphasis will be placed on event-by-event observables in an attempt to extract thermodynamic variables of individual events and to be able to identify special events characteristic of QGP formation.

## **INTRODUCTION**

In the collisions of nuclei at extremely high energies the baryon and energy densities are expected to reach critical values where the quark constituents of the incident nucleons, bound in nuclei, form an extended volume of freely interacting quarks, antiquarks and gluons known as the quark-gluon plasma (QGP). After formation the system is expected to evolve dynamically from a pure plasma or mixed phase (of plasma and hadronic matter) through expansion, cooling, hadronization and freeze-out. To be able to establish that such a new, transient state of matter has been formed it will be necessary to identify and study QGP signatures and the space-time evolution of the collision process. This requires an understanding of the microscopic structure of hadronic interactions, at the level of quarks and gluons, at high temperatures and high densities.

## **PIONEERING THEORETICAL DEVELOPMENTS**

The primary motivation for studying nucleus-nucleus collisions at relativistic energies is to understand the equation of state of nuclear, hadronic and partonic matter at high temperatures and densities. Early speculations of possible exotic states of matter focused on the astrophysical implications of abnormal states of dense nuclear matter.<sup>1,2,3</sup> Subsequent field theoretical calculations, assuming chiral symmetry in the  $\sigma$  model, resulted in predictions of abnormal nuclear states and excitation of the vacuum.<sup>4</sup> This generated an interest in transforming the state

of the vacuum by using relativistic nucleus-nucleus collisions.<sup>5,6</sup> Shortly thereafter, a deconfinement phase transition to quark matter or a quark-gluon plasma<sup>7,8,9</sup> was predicted. At the same time there were also predictions of phase transitions resulting from pion condensation in nuclear matter<sup>10</sup> with possible formation of the condensate in relativistic nucleus-nucleus collisions.<sup>11</sup> Many theoretical developments have evolved the field to its present state of understanding.<sup>12</sup> Presently, perturbative quantum chromodynamics (QCD) is being used to predict observables in experiments at ultrarelativistic energies and to calculate the properties of the high parton density matter, sometimes referred to as QCD matter, resulting from parton cascades in these collisions.<sup>13</sup>

## THE RELATIVISTIC HEAVY ION COLLIDER

Lattice QCD predictions<sup>14,15,16</sup> exhibit a phase transition from hadronic matter to a plasma of deconfined quarks and gluons, the quark-gluon plasma (QGP), at a temperature near 250 MeV. This phase of matter must have existed shortly after the Big Bang and may exist in the cores of dense stars. An important question is whether this predicted state of matter can be created and studied in the laboratory.

The Relativistic Heavy Ion Collider (RHIC)<sup>17</sup> is being constructed at Brookhaven National Laboratory to address this question. A schematic diagram of the RHIC accelerator complex is displayed in Fig. 1. Nuclear beams are accelerated from the tandem Van de Graaff accelerator through a transfer line into the AGS Booster synchrotron and into the AGS, which serves as an injector for RHIC. RHIC will accelerate nuclei over a range of energies. Fig. 2 summarizes the capabilities of the accelerator. Completion of the RHIC accelerator and operation for experiments is planned for 1997. In addition to the colliding beams described in Fig. 2, there is a proposal<sup>18</sup> to inject and accelerate polarized protons at RHIC in order to study the spin content of the proton.

## RHIC EXPERIMENTS

Collisions of the heaviest nuclei at impact parameters near zero are expected to produce approximately 1000 charged particles per unit pseudorapidity at RHIC.<sup>19</sup> This presents a formidable environment in which to detect the products of these reactions. The experiments will take various different approaches to search for the QGP.

At present there are four experiments being considered for the first round at RHIC. There are two large experiments - the Solenoidal Tracker At RHIC (STAR) and the PHENIX experiment - and two smaller ones planned. The STAR experiment will concentrate on measurements of hadron production over a large solid angle in order to perform measurements to study observables on an event-by-event basis. The PHENIX experiment will concentrate on measurements of lepton and photon production as well as have the capability of measuring hadrons. The smaller experiments presently being considered are a forward and midrapidity hadron spectrometer and a compact multiparticle spectrometer (PHOBOS). A brief description of each experiment will be presented along with a more detailed description of STAR.<sup>20</sup>

## Forward and Midrapidity Hadron Spectrometer

The physics goals of this experiment<sup>21</sup> are to achieve a basic understanding of relativistic heavy ion collisions at RHIC through a systematic study of AA collisions from the peripheral to the most central in impact parameter. A diagram of the forward and midrapidity spectrometers is shown in Fig. 3. The spectrometers will measure and identify particles, primarily charged  $\pi$ , K and p, and their momenta with high statistics over a small solid angle and over a wide range of rapidity and transverse momentum. This experiment will extract the net baryon densities as a function of rapidity, energy densities and temperatures to determine whether thermal and chemical equilibrium are reached in these collisions. It will also be able to study both high and low transverse momentum processes.

## The PHOBOS Experiment

The physics goals of the PHOBOS experiment<sup>22</sup> are to measure single particle spectra and correlations between particles with low transverse momenta. Charged particles will be measured and identified in the range  $0 \leq y \leq 1.5$  and  $15 \text{ MeV}/c \leq p_t \leq 600 \text{ MeV}/c$  for pions and  $45 \text{ MeV}/c \leq p_t \leq 1200 \text{ MeV}/c$  for protons. The range of particles to be studied include  $\gamma$ ,  $\pi^\pm$ ,  $K^\pm$ , p,  $\bar{p}$ ,  $\phi$ ,  $\Lambda$ ,  $\bar{\Lambda}$ , d and  $\bar{d}$ . Particle ratios,  $p_t$  spectra, strangeness production ( $K^\pm$ ,  $\phi$ ,  $\Lambda$ ,  $\bar{\Lambda}$ ) and particle correlations will be studied. A multiplicity detector will allow the classification of events by global event characteristics. An illustration of the experiment is shown in Fig. 4.

## The PHENIX Experiment

The physics goals of PHENIX<sup>23</sup> are to measure as many potential signatures of the QGP as possible as a function of a well defined common variable such as impact parameter or pseudorapidity density. The studies can be divided into three categories: basic QCD phenomena, basic collision dynamics and the thermodynamic features of the initial state.

The variables to be measured are lepton pairs (di-electrons and di-muons), photons and hadrons. The experiment will be sensitive to small cross section processes such as the production of the  $J/\psi$ , Y and high  $p_t$  spectra. It will also have the capability for high rates with pp and pA collisions.

A diagram of the PHENIX detector is displayed in Fig. 5. The magnet has an axial field with tracking chambers and detectors for the identification of electrons, muons, photons and hadrons. There are two arms for dielectron measurements with approximately 1 steradian acceptance at midrapidity and a separate forward muon spectrometer as shown in Fig. 5. Photons and hadrons will be measured at midrapidity with approximately 0.5 steradian acceptances.

## The STAR Experiment

The STAR experiment<sup>24,25,26</sup> will search for signatures of QGP formation and investigate the behavior of strongly interacting matter at high energy density. A flexible detection system will be utilized to simultaneously measure many experimental observables. The experiment will exploit two aspects of hadron production that are fundamentally new at RHIC: correlations



between *global observables on an event-by-event basis* and the use of *hard scattering of partons* as a probe of the properties of high density nuclear matter.

The event-by-event measurement of global observables – such as temperature, flavor composition, collision geometry, reaction dynamics, and energy or entropy density fluctuations – is possible because of the very high charged particle densities,  $dn_{ch}/d\eta \approx 1000$  expected in nucleus-nucleus collisions at RHIC. This will allow novel determination of the thermodynamic properties of single events. Full azimuthal coverage with good particle identification and continuous tracking is required to perform these measurements. Correlations between observables will be made on an event-by-event basis to isolate potentially interesting event types.

Measurable yields of high  $p_t$  particles and jets at RHIC will allow investigations of hard QCD processes via both highly segmented calorimetry and high  $p_t$  single particle measurements. A systematic study of particle and jet production will be carried out over a range of colliding nuclei from  $p + p$  through  $Au + Au$ , over a range of impact parameters from peripheral to central, and over the range of energies available at RHIC. Measurements of the remnants of hard-scattered partons will be used as a penetrating probe of the QGP, and will provide important new information on the nucleon structure function and parton shadowing in nuclei.

Measurements will be made at midrapidity over a large pseudo-rapidity range ( $|\eta| < 2$ ) with full azimuthal coverage ( $\Delta\phi = 2\pi$ ) and azimuthal symmetry. The detection system is shown in Fig. 6. It will consist of a silicon vertex tracker (SVT) and time projection chamber (TPC) inside a superconducting solenoidal magnet for tracking, momentum analysis and low  $p_t$  particle identification via  $dE/dx$ ; a time-of-flight system surrounding the TPC for particle identification at higher momenta; and electromagnetic calorimetry outside the solenoid to trigger on and measure jets, and to measure the transverse energy of events. The tracking and particle identification are needed mainly to study the low  $p_t$  physics, and the calorimetry to study the high  $p_t$  physics.

## PHYSICS OF STAR

### Particle Spectra

As a consequence of the high multiplicities in central nucleus-nucleus events, the slope of the transverse momentum ( $p_t$ ) distribution for pions and the  $\langle p_t \rangle$  for pions and kaons can be determined *event-by-event*. Thus, individual events can be characterized by a slope parameter  $T_0$  or "temperature" to search for events with extremely high temperature, predicted<sup>27</sup> to result from deflagration of a QGP. Displayed in Fig. 7 are two spectra generated by the Monte Carlo method from Maxwell-Boltzmann distributions with  $T = 150$  and  $250$  MeV, each containing 1000 pions. This is the average number of pions of a given charge sign expected in the acceptance  $|\eta| < 1$  of this experiment for central  $Au + Au$  collisions. The slopes of spectra with  $T = 150$  and  $250$  MeV derived from fits using a Maxwell-Boltzmann distribution, also shown in Fig. 7, can easily be discriminated at the single event level. The determination of  $\langle p_t \rangle$  for pions can be made very accurately on the single event basis in this experiment, over the expected range of multiplicities in central collisions from  $Ca + Ca$  to  $Au + Au$ . Even for kaons, with  $\sim 200$  charged kaons per event in the acceptance for central  $Au + Au$  events,  $\langle p_t \rangle$  can be determined accurately for single events.

*Inclusive*  $p_t$  distributions of charged particles will be measured with high statistics to investigate effects such as collective radial flow<sup>28</sup> and critical temperature<sup>29</sup> at low  $p_t$ , and mini-

jet attenuation<sup>30,31</sup> at high  $p_t$ . The  $p_t$  spectra of baryons and anti-baryons at midrapidity are particularly interesting for determining the stopping power of quarks. The difference between the  $p_t$  spectra obtained for p and  $\bar{p}$  or  $\Lambda$  and  $\bar{\Lambda}$  will reflect the redistribution in phase space of valence quarks from the nucleons of the target and projectile. This measurement of the net baryon number and net charge is important for establishing the baryo-chemical potential  $\mu_B(y)$  at midrapidity.<sup>32</sup>

## Strangeness Production

There have been many predictions regarding signatures of the QGP. One of the first predictions of a signature for the formation of a QGP was the enhancement in the production of strange particles resulting from chemical equilibrium of a system of quarks and gluons<sup>33</sup>. A measurement of the  $K/\pi$  ratio provides information on the relative concentration of strange and nonstrange quarks, i.e.  $\langle (s + \bar{s}) / (u + \bar{u} + d + \bar{d}) \rangle$ . This has been suggested<sup>34</sup> as a diagnostic tool to differentiate between a hadronic gas and a QGP, and to study the role of the expansion velocity. The  $K/\pi$  ratio will be measured *event-by-event* with sufficient accuracy to classify the events for correlations with other event observables. Another unique feature of STAR is its ability to measure strange and anti-strange baryons (e.g.  $\bar{\Lambda}$ ,  $\Lambda$ ,  $K^0_s$ ) over a wide rapidity interval about midrapidity. Enhancements to the strange antibaryon content due to QGP formation have been predicted.<sup>35</sup> Invariant mass distributions of  $K^0_s$  which will be measured in STAR from the decay  $K^0_s \rightarrow \pi^+\pi^-$  are shown in Fig. 8. Furthermore, multiply-strange baryons ( $\Xi^-$ ,  $\bar{\Xi}^-$ ,  $\Omega^-$ ) may be more sensitive to the existence of the QGP.<sup>36</sup> An example of the mass spectrum expected from the decay  $\bar{\Xi}^- \rightarrow \Lambda\pi^-$  with  $\Lambda \rightarrow \pi^-p$  in the STAR experiment is shown in Fig. 9.

The production cross section of  $\phi$ -mesons can be measured *inclusively* from the decay  $\phi \Rightarrow K^+ + K^-$ . Displayed in Fig. 10 is an invariant mass spectrum, in the region of the  $\phi$  mass, constructed from all possible combinations of identifiable  $K^+$  and  $K^-$  in the acceptance  $|\eta| < 1$ . The momentum resolution and tracking efficiencies of the STAR tracking system are included in the simulation. The mean number of reconstructed  $\phi$ 's in Au + Au central events at RHIC is 6 per event in the STAR detector. Measurement of the yield of the  $\phi$ , which is an  $s\bar{s}$  pair, places a more stringent constraint on the origin of the observed flavor composition<sup>37</sup> than the  $K/\pi$  ratio and is expected to be more sensitive to the presence of a QGP. The  $\phi$  production rate is also expected to be extremely sensitive to changes in the quark masses<sup>38,39,40</sup> due to a chiral phase transition at high energy densities, which is predicted in lattice QCD calculations.<sup>41,42</sup>

## Hanbury-Brown and Twiss (HBT) Interferometry

Correlations between identical bosons provide information on the freezeout geometry,<sup>43</sup> the expansion dynamics<sup>44</sup> and possibly the existence of a QGP.<sup>45</sup> It would be unprecedented to be able to measure the pion source parameters via pion correlation analysis on an *event-by-event* basis and to correlate them with other event observables. In an individual event with 1000 negative pions within  $|\eta| < 1$ , the number of  $\pi^-\pi^-$  pairs is  $n_{\pi^-}(n_{\pi^-}-1)/2 = 500,000$ . The two-pion correlation statistics for a single central Au + Au event at RHIC will be similar to the accumulated statistics published in most papers on the subject. An empirical relation for the transverse radius ( $R_t$ ) of the pion source at midrapidity as a function of the rapidity density ( $dn/dy$ ) has been derived from the existing pion correlation data<sup>46</sup> shown in Fig. 11. This relation,  $R_t \sim (dn/dy)^{-1/3}$ , suggests that rather large source sizes,  $R_t \sim 10$  fm, will be measured in

central Au + Au collisions at RHIC. An example of a simulated correlation measurement in STAR for a single Au + Au central collision event at RHIC is shown in Fig. 12.

The correlations of like-sign charged kaons or pions will be measured on an *inclusive* basis to high accuracy. The dependence of the source parameters on the transverse momentum components of the particle pairs will be measured with high statistics. Measurement of correlations between unlike-sign pairs will yield information on the Coulomb corrections and effects of final state interactions. The *inclusive* measurement of KK correlations will complement the  $\pi\pi$  correlation data. The KK correlation is less affected by resonance decays after hadronic freeze-out than the  $\pi\pi$  correlations<sup>47</sup>, thus interpretation of the KK correlation measurements is much less model-dependent than that of the  $\pi\pi$  data. Since K's are expected to freeze out earlier<sup>48</sup> than  $\pi$ 's in the expansion, the K source sizes are expected to be smaller than those of the  $\pi$ 's. Depending upon the baryo-chemical potential and the existence of a QGP, the  $K^+$  and  $K^-$  are also expected to freeze out at different times. Thus, separate measurements of the  $K^+K^+$  and  $K^-K^-$  correlation functions will be of interest.

### Electromagnetic Energy

One-third of the energy produced at midrapidity in these collisions will be electromagnetic (EM) energy. The hadronic energy can be measured by charged particle tracking. The EM energy must be measured using calorimetry. The measurement of EM energy vs. charged-particle energy is an important correlation to measure in the search for the QGP and other new physics. The unexplained imbalance between charged particle and neutral energy observed in Centauro and other cosmic ray events emphasizes the need for EM/charged particle measurements.<sup>49</sup> Discussions of quark-gluon scattering within the QGP (e.g.,  $qg \rightarrow \gamma q$ ) also point to the importance of measuring the electromagnetic energy as a possible signature of special events.<sup>50</sup>

### Fluctuations in Energy, Entropy, Multiplicity and Transverse Momentum

It has long been known that a prime, general indicator of a phase transition is the appearance of critical dynamical fluctuations in a narrow range of conditions. It is worth emphasizing that such critical fluctuations can only be seen in individual events where the statistics are large enough to overcome uncertainties ( $\sqrt{N}$ ) due to finite particle number fluctuations. The large transverse energy and multiplicity densities at midrapidity in central collisions allow *event-by-event* measurement of fluctuations in particle ratios, energy density, entropy density and flow of different types of particles as a function of  $p_t$ , rapidity, and azimuthal angle. They also allow measurements of local fluctuations in the magnitude and azimuthal distribution of  $p_t$ . These fluctuations have been predicted to arise from the process of hadronization of a QGP.<sup>51</sup>

### Parton Physics from Jets, Mini-Jets and High $p_t$ Single Particles

The goal of studying products of hard QCD processes produced in relativistic heavy ion collisions is to use the propagation of quarks and gluons as a probe of nuclear matter, hot hadronic matter and quark matter. Since the hard scattering processes are directly calculable in QCD, a measurement of the yield of hard scattered partons as a function of their transverse energy should be sensitive to their interaction with the surrounding matter. The partons in a single hard scattering (dijet) whose products are observed at midrapidity must traverse distances

of several fermi through high density matter in a nucleus-nucleus collision. The energy loss of these propagating quarks and gluons is predicted<sup>52</sup> to be sensitive to the medium and may be a direct method of observing the excitation of the medium, i.e., the QGP. Passage through hadronic or nuclear matter is predicted to result in an attenuation of the jet energy and broadening of jets. Relative to this damped case, a QGP is transparent and an enhanced yield is expected. The yield of jets will be measured as a function of the transverse energy of the jet. The jet events can also be correlated with other *event-by-event* observables to deduce information on the dynamics of the collision process.

Mini-jets are expected to be produced copiously in collisions at RHIC.<sup>53,54</sup> As is the case for high  $p_t$  jets, the observed yield of mini-jets is expected to be influenced strongly by the state of the high density medium through which they propagate. It is important to study the degree of fluctuation of the transverse energy and multiplicity as a function of rapidity and azimuthal angle ( $d^2E_t/dy d\phi$  and  $d^2n/dy d\phi$ ) *event-by-event*, which should be strongly affected by mini-jets.<sup>55</sup> The *inclusive*  $p_t$  distributions of hadrons at  $p_t > 3$  GeV/c will also be influenced by jets and mini-jets as can be seen in Fig. 13.<sup>56</sup>

### Correlations between Event Observables

It should be emphasized that the capability of measuring several different observables event-by-event is unique to this experiment. Events can be characterized event-by-event by their temperature, flavor content, transverse energy density, multiplicity density, entropy density, degree of fluctuations, occurrence of jets and possibly source size. The presence of a QGP is not likely to be observed in an average event, nor is it expected to be observed in a large fraction of events. Since there is no single clearly established signature of the QGP, access to many observables simultaneously will be critical for identifying the rare events in which a QGP is formed.

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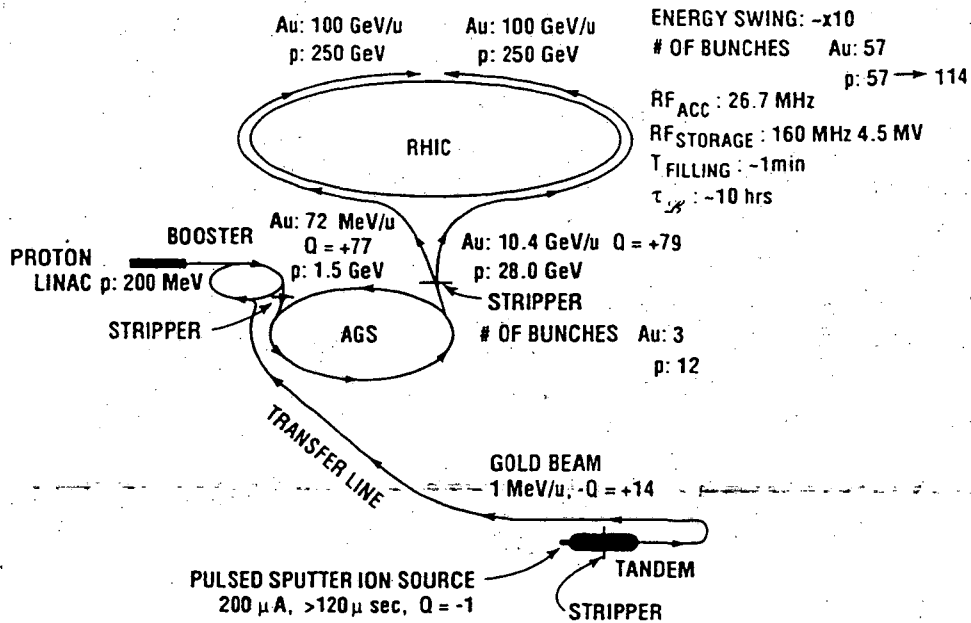
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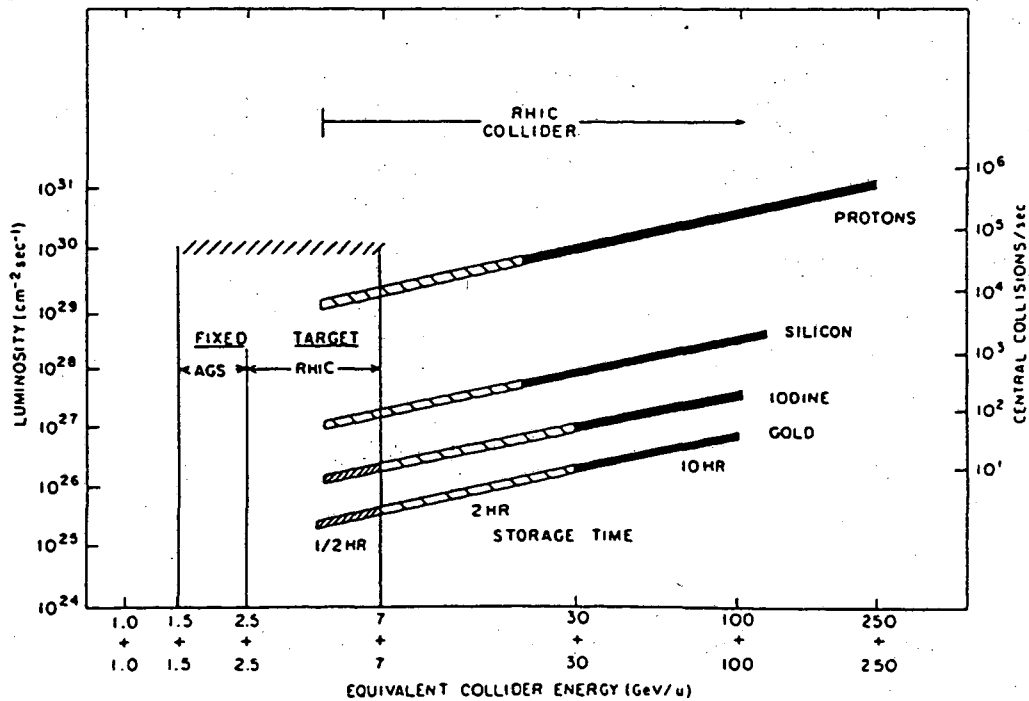
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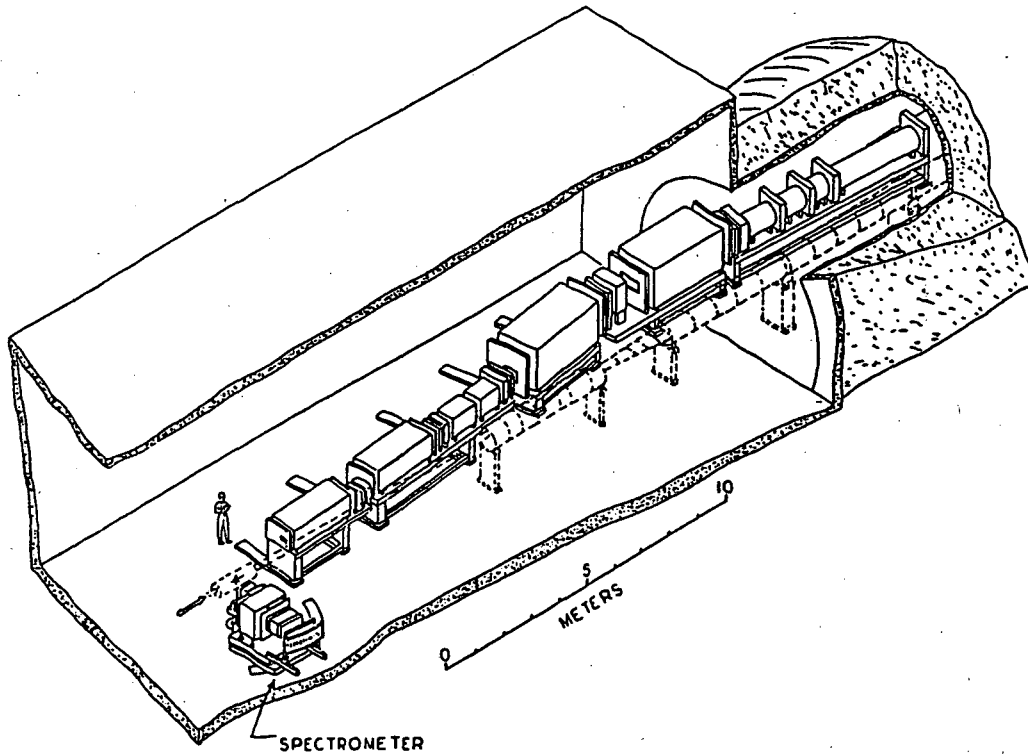
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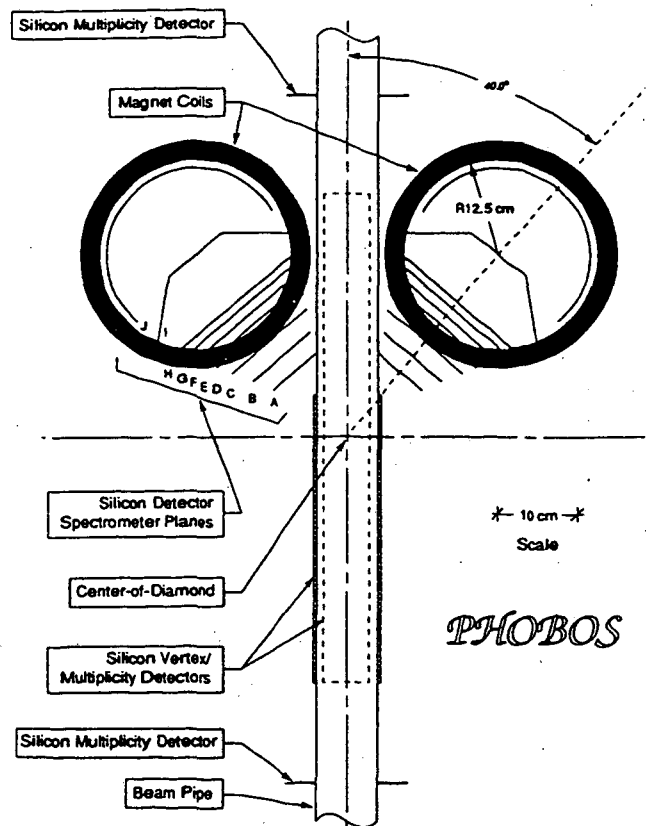
**Figure 1.** Diagram of the Relativistic Heavy Ion Collider (RHIC) accelerator complex. Nuclear beams are accelerated from the tandem Van de Graaff, through the transfer line into the AGS Booster and AGS prior to injection into RHIC. Some details of the characteristics of proton and Au beams are also indicated after acceleration in each phase.



**Figure 2.** The design luminosity and number of central collisions per second, for impact parameters less than 1 Fermi, are plotted as a function of the colliding beam energies for various projectiles.



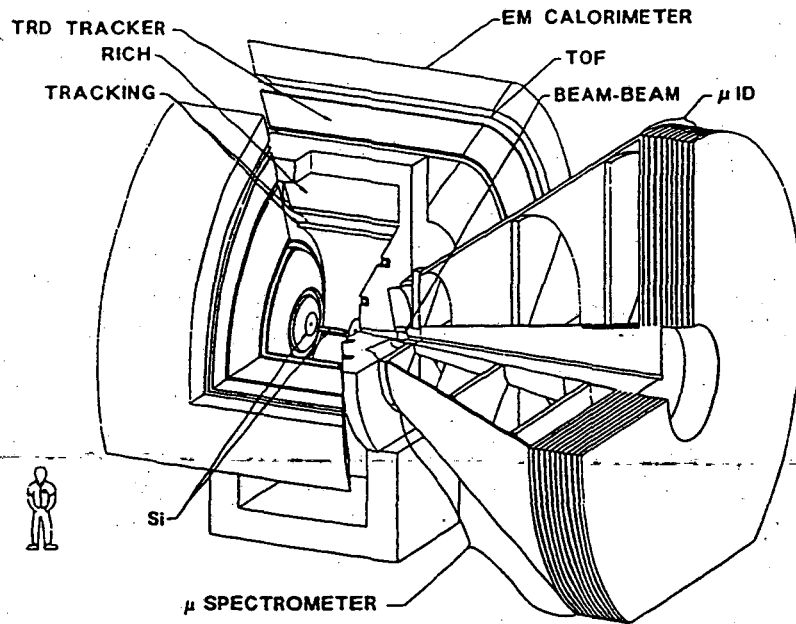
**Figure 3.** A diagram of the forward and midrapidity spectrometer experiment in the narrow angle hall at RHIC.



**Figure 4.** A diagram of the PHOBOS two-arm multiparticle spectrometer. The two arms are located on opposite sides of the beam pipe. Each arm has a 6 Tesla magnet represented by the coils with silicon detector planes for tracking.

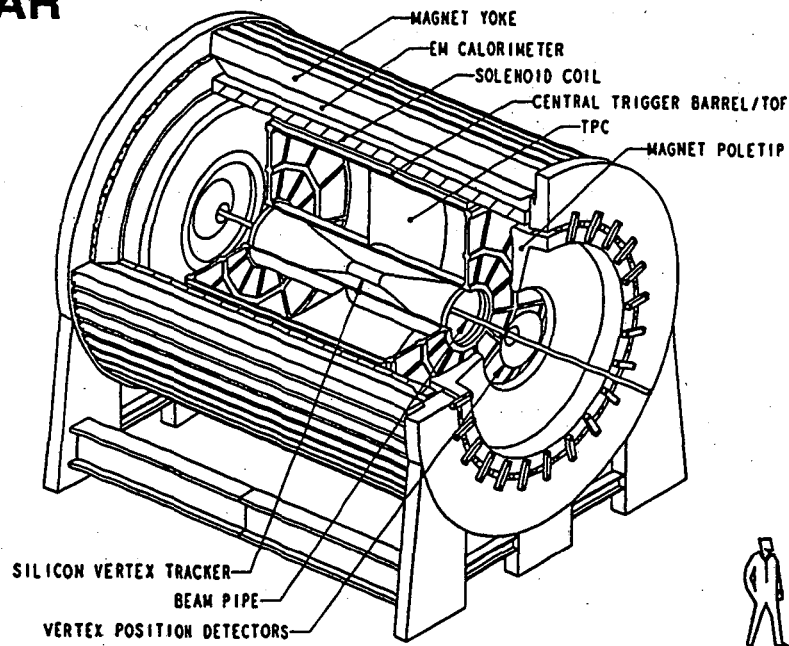


# PHENIX

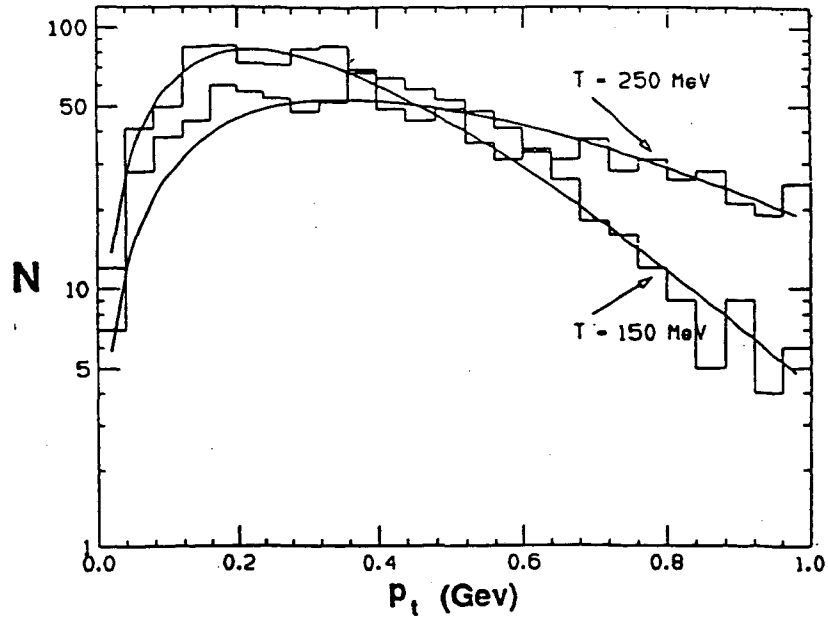


**Figure 5.** A diagram of the PHENIX experiment at RHIC. The beams collide along the horizontal direction in the center of the detector. The detector components are labeled.

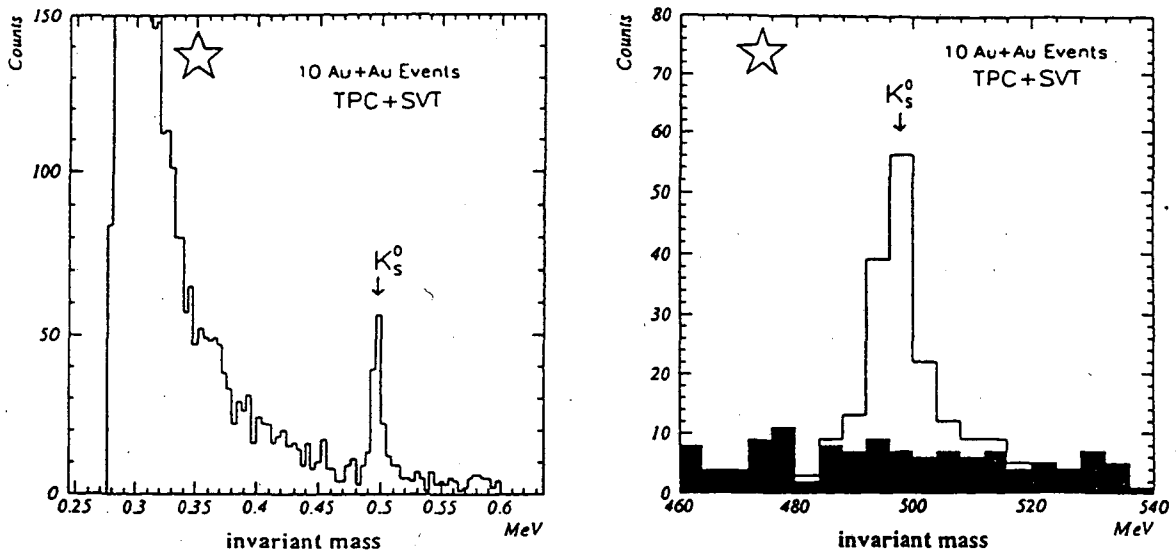
# STAR



**Figure 6.** Conceptual layout of the STAR experiment, with cylindrical symmetry around the beam axis. See text for description.



**Figure 7.** Simulation of the  $p_t$  spectrum for one event generated using a Boltzmann distribution of 1000 pions. The histograms correspond to single events generated with  $T = 150$  MeV and 250 MeV. The curves are fits to the histogram using a Maxwell-Boltzmann distribution.



**Figure 8.** Simulated invariant mass distribution for  $K_S^0 \rightarrow \pi^+\pi^-$  measured in STAR for 10 central Au + Au events at RHIC. The right-hand side is an expanded view in the region of the  $K_S^0$  mass. The shaded area represents the contribution from random combinatorial background.

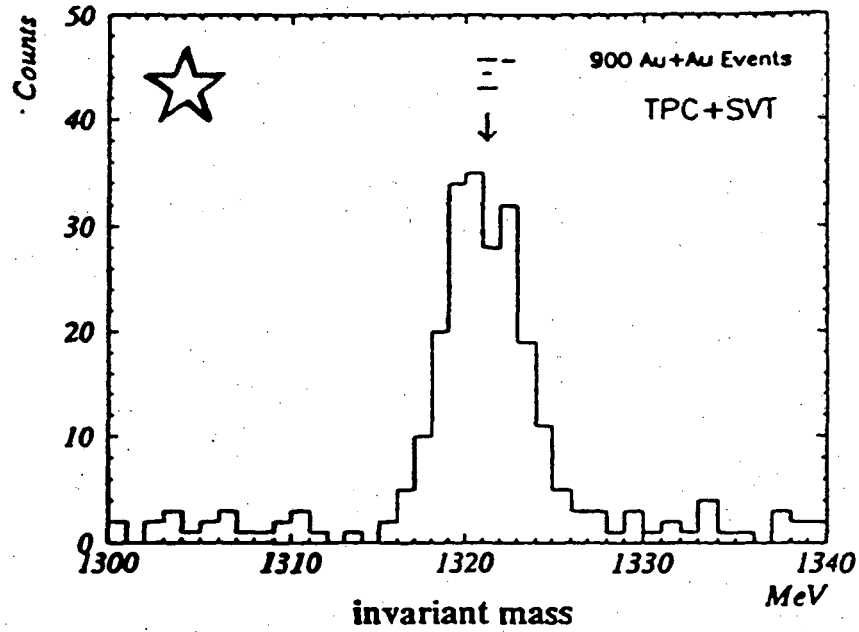


Figure 9. Simulated invariant mass distribution from the decay  $\Xi^- \rightarrow \Lambda \pi^-$  with  $\Lambda \rightarrow \pi^- p$  measured in STAR for 900 central Au + Au events at RHIC.

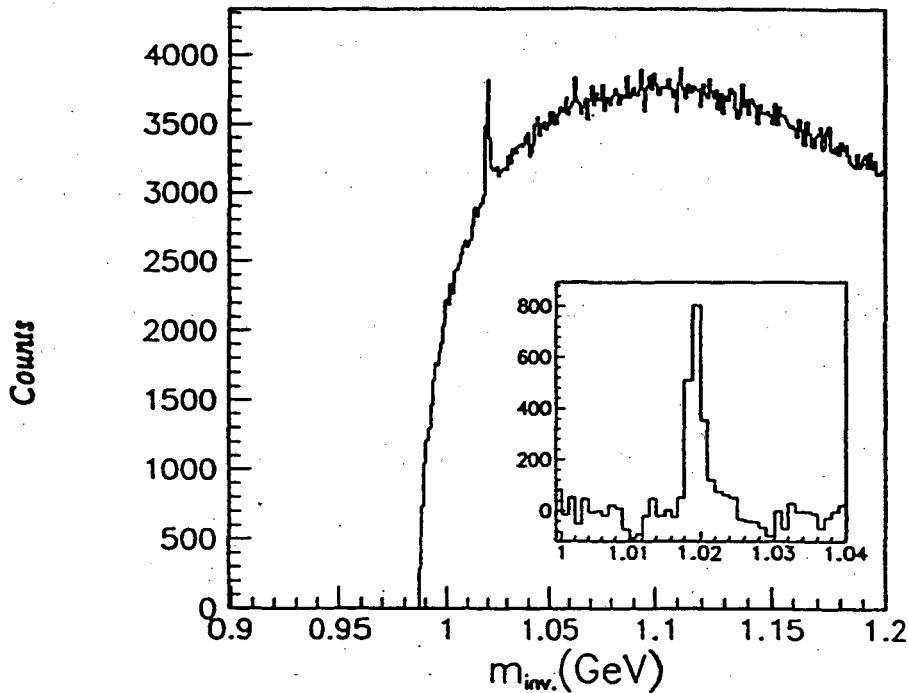
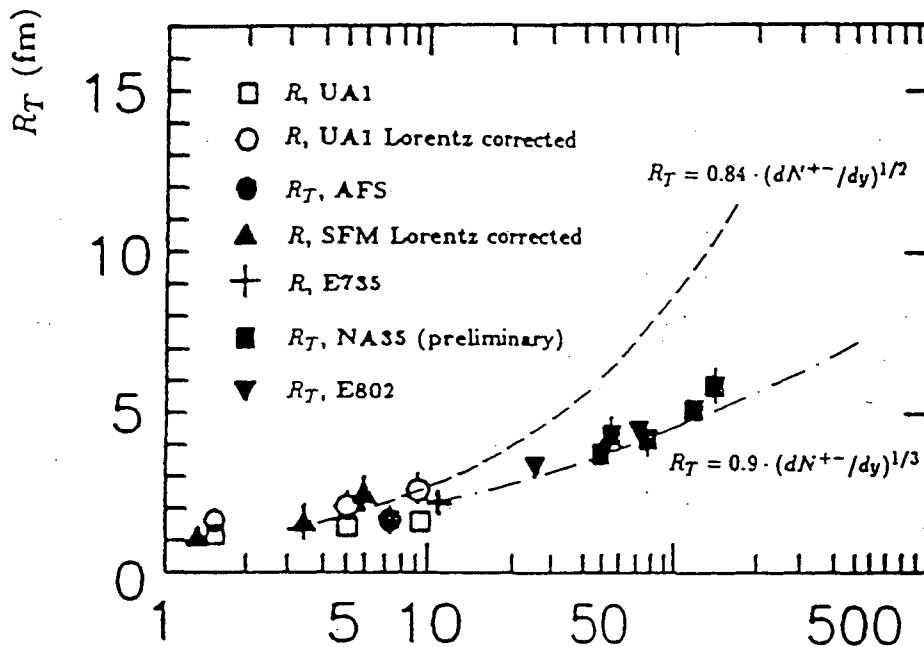
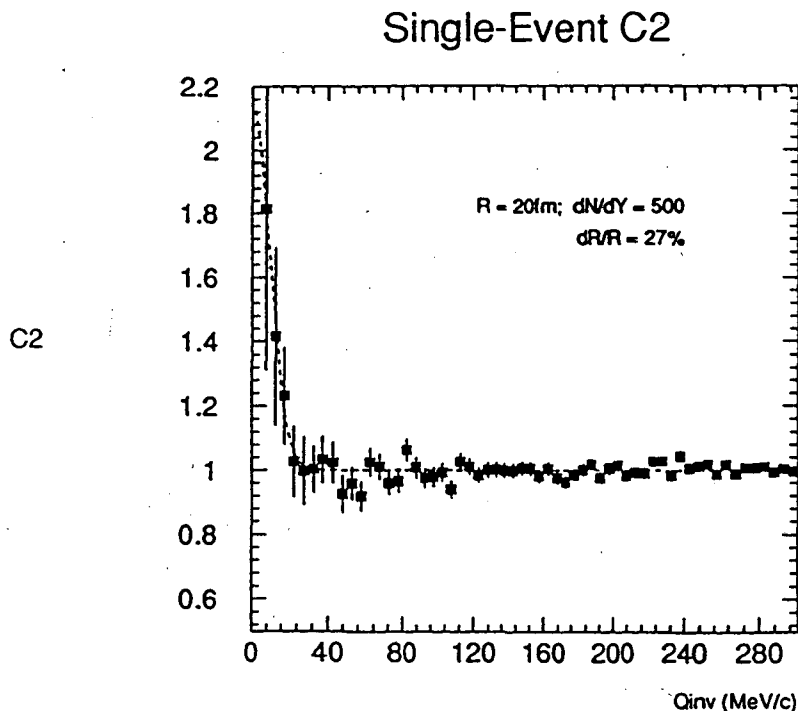


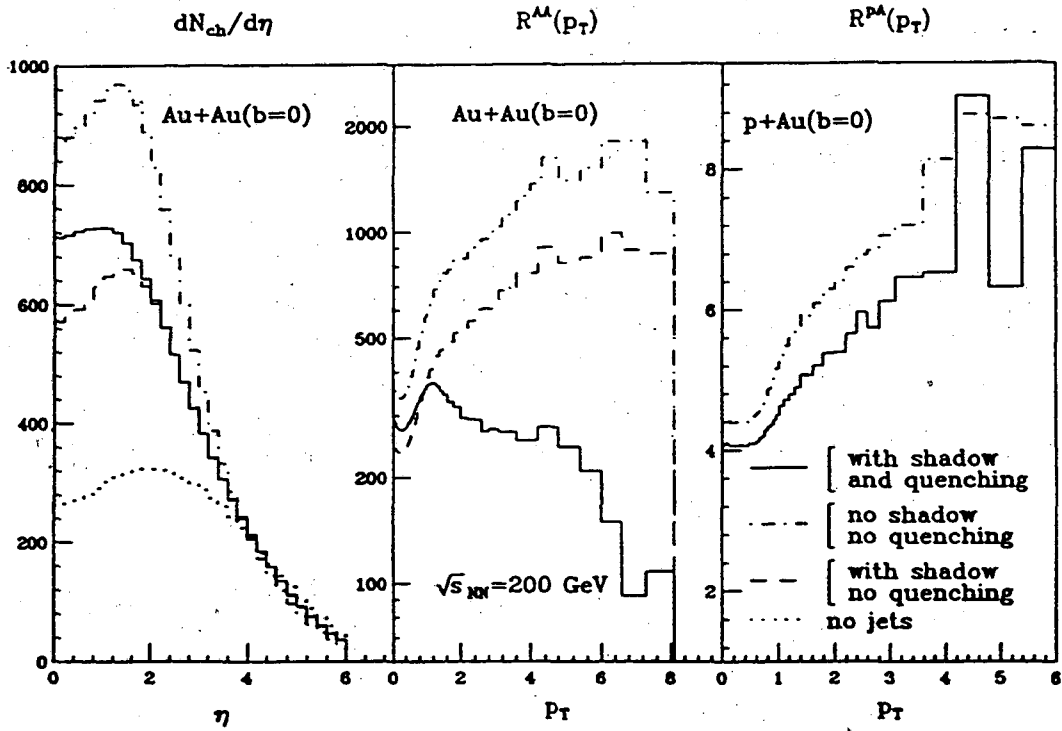
Figure 10. Invariant mass distribution for all identifiable  $K^+K^-$  pair combinations simulated in the acceptance  $|\eta| < 1$  of STAR for 500 Au + Au central events at RHIC. The  $\phi$  signal is the narrow peak at 1.02 GeV. The inset is the result of a subtraction of  $K^+K^-$  pairs formed from  $K^+$  and  $K^-$ , each from a different event, from the true  $K^+K^-$  pairs of the main part of this figure. The simulation has no width for the  $\phi$  and the contribution of the detector to the measurement of the  $\phi$  is observed to be minimal compared to the true width of  $\Gamma = 4.4$  MeV.



**Figure 11.** The correlation between the transverse source radii, derived from two-pion correlation measurements, and the charged-particle rapidity density at midrapidity. Measurements from the Sp  $\bar{p}$ S collider, ISR collider, Tevatron collider, Brookhaven AGS heavy ions and the CERN SPS heavy ions are presented. Two parameterizations corresponding to  $R_t \sim (dn/dy)^{-1/2}$  and  $R_t \sim (dn/dy)^{-1/3}$  are shown.



**Figure 12.** Correlation measurement for a single event simulated with  $R_{inv} = 20$  fm and  $dN_{\pi^-}/d\eta = 500$  in STAR at midrapidity.



**Figure 13.** Results from HIJING calculations on the dependence of the inclusive charged hadron spectra in central Au + Au and p + Au collisions on minijet production (dash-dotted), gluon shadowing (dashed) and jet quenching (solid) assuming that the gluon shadowing is identical to that of quarks (see Ref. 56 for details).  $R^{AB}(p_T)$  is the ratio of the inclusive  $p_T$  spectrum of charged hadrons in A + B collisions to that of p + p.

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