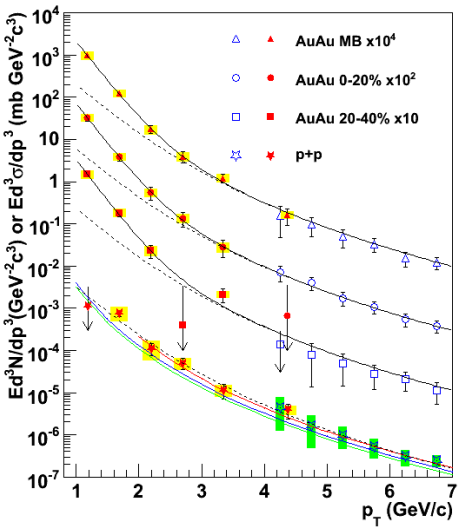
RHIC FY08-09 Highlight I: 'Perfect' Liquid Hot Enough To Be Quark-Gluon Soup

New results from the PHENIX Collaboration (arXiv:0804.4168) confirm that collisions of gold ions traveling at nearly the speed of light have created matter at a temperature of about 4 trillion degrees Celsius — the hottest matter ever produced in a laboratory. The temperature readings reveal that RHIC collisions have surpassed the theoretical boundary beyond which protons and neutrons are expected to "melt" to form a soup of their smaller, normally confined components — subatomic quarks and gluons. Earlier RHIC results had established that the novel matter produced in these violent collisions behaves as a nearly frictionless (or near-perfect) expanding liquid, and that the temperature at a late stage in the collision, when the emerging strongly interacting particles (quark composites called hadrons) have ceased interacting with each other, is about 2 trillion degrees. The latter temperature is near the well-established maximum possible (so-called Hagedorn) temperature attainable by a system composed purely of hadrons.

To determine the perfect liquid's nature, it is important to measure its temperature and other properties at an earlier stage, when the matter first comes into thermal equilibrium. That requires measuring the distribution of particles that are formed early in the collision but emerge without distortion by subsequent interactions on their way out. Particles of light – photons emitted as blackbody radiation – are excellent candidates, just as they are also in cosmic microwave background measurements (Nobel Prize, 2006) of the extremely cold temperatures reached by the universe billions of years ago, but hundreds of thousands of years after the Big Bang. The extremely high temperatures of the matter in RHIC collisions – characteristic of the universe mere *microseconds* after the Big Bang – give rise to much higher energy photons, which may materialize as electron-positron pairs. PHENIX detected such electron-positron pairs and found a clear excess in collisions of gold nuclei, in comparison with collisions of protons (see figure). The excess yield can be explained by blackbody photons emitted over time during the expansion of matter that initially reaches equilibrium at about 4 trillion degrees. The deduced temperature clearly exceeds that attainable by hadrons, and confirms that the constituents of the perfect liquid must be (strongly interacting) quarks and gluons.

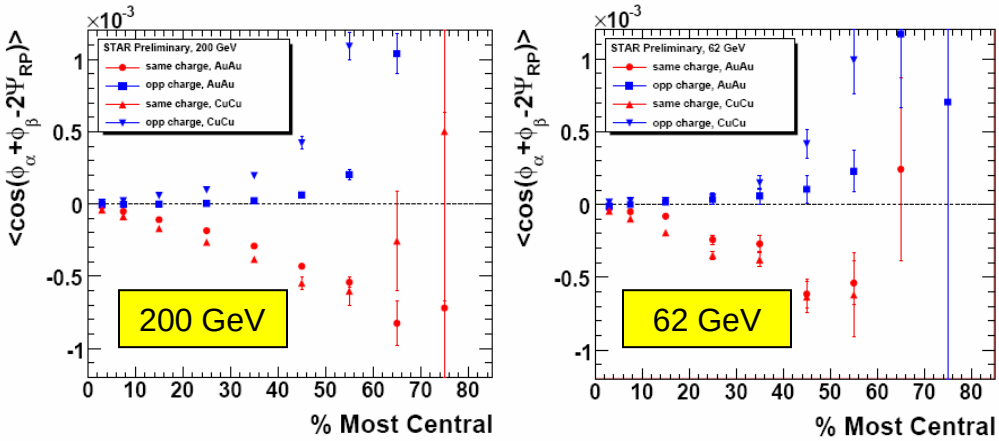


The distribution with respect to transverse momentum (p_T) of low-mass (< 300 MeV) electron-positron pairs measured by the PHENIX detector in proton-proton (bottom dataset) and gold-gold collisions at a center-of-mass energy of 200 GeV per nucleon pair. The yields at p_T below about 4 GeV/c are very consistent with extrapolations from higher momentum for pp collisions, but show a clear excess for gold-gold. The excess is consistent with an origin in the conversion of thermal photons produced at a rate predicted by hydrodynamics calculations for matter first formed at about 4 trillion degrees.

RHIC FY08-09 Highlight II: Does Mirror Symmetry "Melt" Along With Nucleons?

Elementary particle behavior reflects the symmetries inherent in the fundamental laws governing particle interactions, but also the symmetries possessed by the lowest-energy, or "vacuum", state. Sometimes, Nature chooses one among many possible vacuum states of equal energy, "spontaneously" breaking a symmetry of the underlying law (a realization that earned Yoichiro Nambu a share of the 2008 Nobel Prize in Physics). RHIC experiments are exploring the profound possibility that Nature, in matter at very high temperatures, may allow temporary "jumps" to alternative vacuum states, altering the symmetry properties of particle behavior. The melting of neutrons and protons to liberate quarks and gluons has been predicted (D. Kharzeev, Phys. Lett. **B 633**, 260 (2006)) to produce "bubbles" (analogous to those in boiling water), in which jumps to alternative vacuum states spontaneously break the mirror symmetry (parity) normally characterizing strong interactions. New STAR data provide the first evidence favoring this prediction.

STAR measured correlations among charged particles emitted in gold-gold or copper-copper collisions. The crucial observation (see figure) is that, for all but the most head-on collisions, particles of like sign (red points) are more likely to emerge on the same side (above or below) than on opposite sides of the reaction plane defined by the paths of the colliding nuclei. For particles of opposite charge (blue points), the preference is reversed. While the preference is only of order 1%, it suggests a charge separation in each collision that is asymmetric under mirror reflection through the reaction plane. The observed features are qualitatively consistent with the predictions of parity-violating bubbles in hot quark matter, which invoke not only a vacuum transformation, but also a large magnetic field to separate liberated quarks over significant distances. The magnetic field arises naturally from the large orbital angular momentum in non-head-on collisions. Different bubbles may jump to different alternative vacuum states, preferring parity violation of opposite sign, so that the net experimental signal, when averaged over many collision events, no longer *manifestly* violates mirror symmetry. While mundane parity-conserving effects might then, in principle, mock up the predicted signal, STAR analyses have so far ruled out the most obvious mundane sources. This first hint of a profound symmetry transformation will be pursued further in future RHIC measurements.

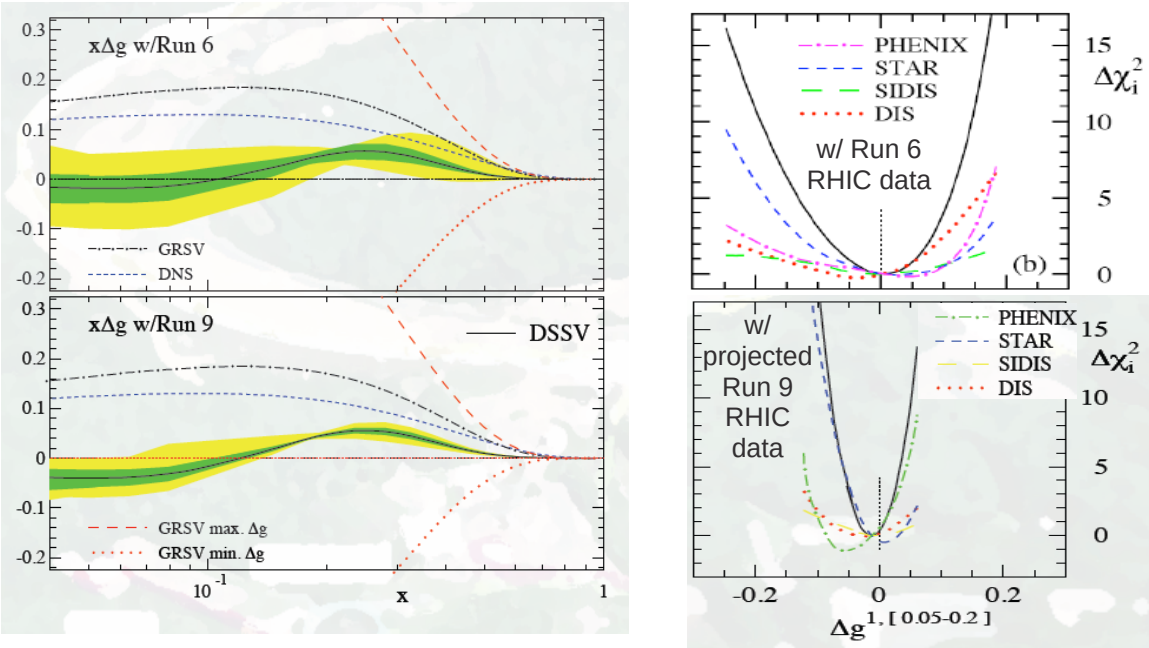


STAR heavy-ion collision data at two energies vs. centrality (head-on collisions at low abscissa values) show the charge correlations described in the text.

RHIC FY08-09 Highlight III: The Spin Puzzle Plot Thickens

Collisions of polarized proton beams at RHIC offer direct sensitivity to any preferential alignment of gluon spins with the overall spin of the proton in which they reside. This sensitivity fuels measurements aimed at resolving the puzzle revealed by earlier experiments on deep inelastic scattering: the quarks and antiquarks, with which high-energy electron and muon beams interact, combine to account for less than 1/3 of the proton's overall spin. A new global quantum chromodynamics (QCD) analysis (de Florian *et al.*, arXiv:0804.0422) of all spin-sensitive scattering data, including for the first time the most impactful RHIC spin results, has now quantified extraction of the gluon contribution to proton spin. The analysis results (see figure) indicate that the RHIC data already constrain, and should soon dominate, the determination of gluon polarization. They suggest that the gluon spin preference may unexpectedly change sign as a function of the fraction of proton momentum carried by the gluon, giving a small net gluon contribution only barely compatible with accounting for a majority of the "missing" proton spin, within present uncertainties that are likely to shrink substantially with 2009 RHIC data.

These results enhance the mystery of the quark-gluon origin of the proton spin, especially when combined with recent calculations solving QCD numerically on a finite lattice of space-time points. These calculations indicate that the net orbital motion of quarks in a proton also contributes little to the missing spin. If confirmed by planned measurements and calculations, these small spin effects call for fresh ideas to resolve the spin puzzle, e.g., by clarifying the orbital motion sensitivity of RHIC transverse spin asymmetries.

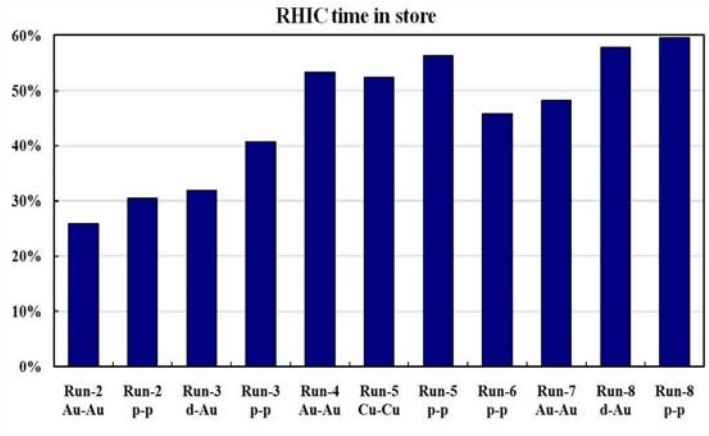


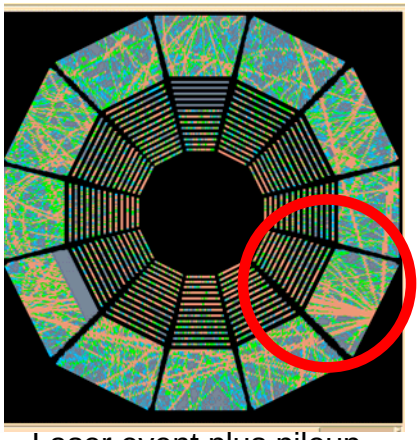
Results of a new global QCD analysis of gluon polarization, incorporating RHIC spin (pion and jet production) data from 2006 (upper frames) and projected for 2009 (lower frames). The colored bands on the left present uncertainties in the extracted gluon polarization, as a function of momentum fraction, while the curves on the right show the deterioration in quality of fit as the gluon spin contribution is varied away from the best fit value, and as one data set is removed at a time from the fitted sample.

RHIC FY08-09 Facility Highlight I: Improving the Efficiency of Data-Taking

Two significant improvements in FY08-09 have substantially upgraded the efficiency with which new physics results can be explored at RHIC. The first results from a major effort, between RHIC Runs 7 and 8, to make repairs to improve the reliability of the collider and injector power supplies. This effort ameliorated the dominant source of unscheduled breakdowns in earlier runs, and allowed RHIC operations to approach, for the first time in 2008 (see left-hand figure below), the facility goal of 60% of the available beam time being spent in collider stores used for nuclear physics data acquisition by the STAR and PHENIX Collaborations. Roughly half of the 40% "missing" time is spent in regularly scheduled periods devoted to machine and detector maintenance and to accelerator physics experiments. The 2008 performance thus represents less than 20% beam time losses to unscheduled breakdowns, a performance level we hope to maintain for this intricate complex of seven accelerators in the coming years.

The second major improvement affects the efficiency for taking useful data by the STAR experiment. By upgrading the front-end electronics readout of the Time Projection Chamber (TPC) that forms the heart of the STAR detector, and making associated changes to their data acquisition software, STAR has been able to increase the rate at which interesting collision events can be recorded by an order of magnitude, from 100 to 1000 per second. The changes were installed for one of 24 sectors of the TPC during RHIC Run 8, and no problems were encountered with the data collected for that sector (see right-hand figure below). In Run 9, for which machine cooldown began on Feb. 2, 2009, this DAQ1000 upgrade is successfully installed for the full TPC. The impact will be especially important for those desired rare events that can be triggered at rates of no more than a few per second, but which nonetheless were collected with only ~50% efficiency previously, due to dead time incurred in handling more abundant event types that had to be studied at the same time. The new system will lead to an immediate gain by a factor of two in collecting those rare events that are central to STAR's physics goals.





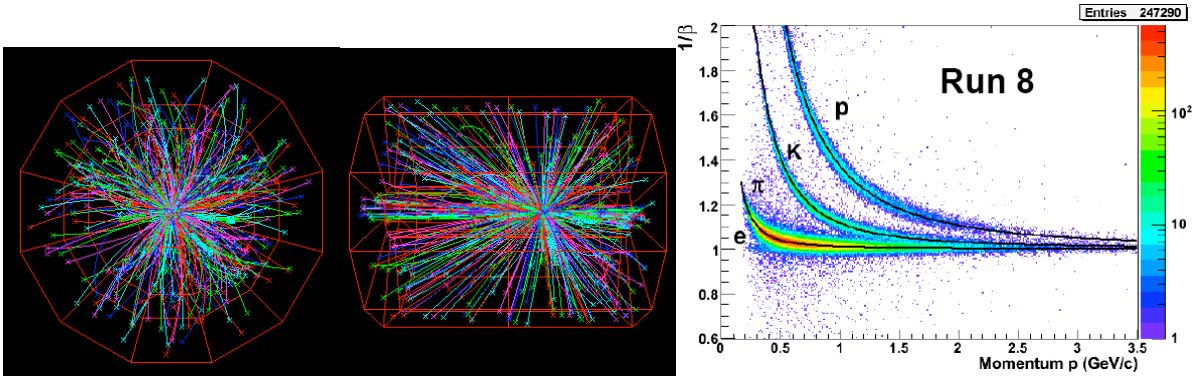
Laser event plus pileup

Left: the percentage of available beam time spent in collider stores for physics data-taking, for RHIC runs from 2002 through 2008. Right: end view of laser-induced tracks recorded by the STAR TPC during 2008, showing complete consistency of data between the one (circled) sector outfitted with the new DAQ1000 readout and the rest of the TPC.

RHIC FY08-09 Facility Highlight II: Developing the Path Toward a Critical Point Search

Many observations indicate that nearly head-on collisions of heavy nuclei at RHIC have produced matter in which quarks and gluons are liberated from their normal confinement within neutrons and protons. However, there is a strong consensus that this change from nucleons to quarks and gluons does not occur abruptly as a function of temperature – it represents a smooth "cross-over" rather than a first- or second-order phase transition – in matter as nearly balanced between quarks and antiquarks as that produced at RHIC to date. There are strong theoretical reasons to expect an abrupt melting of nucleons, more akin to the normal melting of ice at 0° C, in matter with higher net quark density, perhaps reachable in lower-energy RHIC collisions. Of particular interest is a single well-defined "critical" point in temperature and quark density that separates cross-over from first-order phase transitions. Two FY08-09 facility developments represent milestones along the path toward RHIC measurements that might reveal this unique landmark of QCD matter.

In a short test run at the end of RHIC Run 8, the collider produced collisions of gold nuclei at a useful rate, at a collision energy (9.2 GeV/nucleon pair) substantially lower than the machine was designed to operate. The left-hand figure shows a collision event display (one of about 3500) recorded by the STAR detector during its short exposure to these low-energy collisions, already providing early physics results at this energy. Later test runs and possible machine upgrades will be used to commission collisions at even lower energy. Many measurements considered as a function of collision energy to give sensitivity to the nearby presence of the predicted critical point require determination of yield ratios for different outgoing particle types. The addition of a new STAR subsystem to determine the time-of-flight (TOF), and hence the velocity, of detected particles with high resolution, is crucial to attaining the clean particle identification needed for these measurements. The first five of an eventual 120 modules of this TOF detector, installed for RHIC Run 8, provided the sharp identification shown in the right-hand figure. More than ¾ of all the modules are now installed for Run 9, greatly extending STAR's capabilities. A low-energy RHIC scan to search for the critical point should begin in 2010-11.

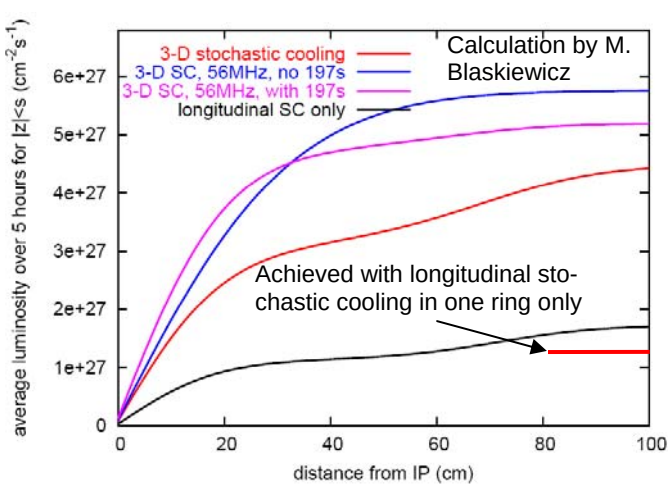


Left: end and side views of the tracks resulting from one 9.2 GeV gold-gold collision observed by the STAR detector during the 2008 run. Right: sharp particle identification loci observed for pions, kaons and protons during Run 8 by comparing particle velocity determined from the first 5 TOF detector modules with momentum from the STAR TPC.

RHIC FY08-09 Facility Highlight III: Extending RHIC's Reach

The 2009 run just starting at RHIC will feature two facility developments that significantly extend the facility's science reach. The run will begin with commissioning of first polarized proton collisions at a center-of-mass energy of 500 GeV. The jump from previous operation at 200 GeV will enable meaningful measurements of parity-violating spin asymmetries in W intermediate vector boson production. The production of W's via the electroweak fusion of a quark from one proton with an antiquark from the other will provide uniquely clean access to the spin orientation preference of up vs. down antiquarks in the quark-antiquark "sea" within a polarized proton. Measurements of W production at RHIC are anticipated to elucidate the mechanism for producing the sea, a question of central importance in understanding nucleon substructure. Both the STAR and PHENIX detectors will get a first opportunity to observe the success of their plans to trigger on and suppress backgrounds for this rare signal. If their planning was robust, first measurements of production cross sections and spin asymmetries should be possible.

The second development is the installation of the first plane of transverse stochastic cooling pickups and kickers in one RHIC ring. The pickups sense particle momentum components perpendicular to the central beam orbit, and feed the signals to high-frequency kickers designed to reduce these undesired components, improving beam quality and longevity in the collider. *Longitudinal* stochastic cooling, correcting for energy, rather than angular, spread within the beam, was already demonstrated for time-bunched beams for the first time in RHIC in 2007. Both longitudinal and transverse cooling are needed to increase the RHIC collision rate sufficiently to quantify properties of the near-perfect hot liquid matter, via measurements for rare processes and multi-particle correlations. Run 9 will test for proper functioning of the transverse cooling apparatus, but observation of the anticipated beam lifetime gain will wait for Run 10, when RHIC again operates with heavy-ion beams. A further 2008 advance in stochastic cooling resulted from simulations (magenta curve in the figure below) demonstrating that a new (56 MHz) superconducting rf system, for which cavity design was started in 2008, could be combined with the existing (197 MHz) RHIC rebunching scheme to reduce the spread of event vertex locations, as needed to better match new, short microvertex detectors planned for both PHENIX and STAR.



Simulations showing projected time-averaged collision luminosity in a 5-hour gold+gold RHIC store, as a function of the distance over which collision vertices are counted, for several incarnations of stochastic cooling and RHIC beam rebunching schemes. The best luminosity within a ±20 cm vertex cut is obtained (magenta curve) with longitudinal and transverse cooling in both rings, and with both 56 and 197 MHz rebunching in effect.