Expeditions beyond QCD Phase Boundary at LHC and RHIC

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High energy nucleus-nucleus collision experiments expedit on the QCD phase diagram toward the deconfined partonic phase. PHENIX experiment at RHIC has found a thermal compoment in the direct photon spectrum, suggesting a temperature above the predicted phase boundary at around 170 MeV. The ALICE experiment at LHC started a further scientific expedition in 2009. First physics results and latest analysis status from p+p collisions at $\sqrt{s}$ = 900 GeV, 2.36 TeV and 7 TeV are reported, along with the plans and prospects at ALICE/LHC. The first Pb+Pb running at $\sqrt{s_{NN}}$ = 2.75 TeV is scheduled to begin in November, 2010, with expectations for exciting physics harvests toward global and comprehensive understanding of properties of the deconfined partonic matter, especially via penetrating photon and lepton measurements.

§1. Experimental Expeditions on QCD Phase Diagram

High energy nucleus-nucleus collision experiments expedite on the QCD phase diagram toward the deconfined partonic phase. The lattice QCD predicts the critical temperature around 170 MeV, or the critical energy density around 1 GeV/fm^3.[1] In contrast to the ordinary hadronic phase, partons are expected to deconfine themselves from hadrons on the other side of the boundary, as they must have been in the very early universe at $\sim$ 10 μsec after the big bang.

The programs historically started with fixed target experiments at Bevalac, AGS and SPS, where the regime with high baryo-chemical potential is explored on the diagram. RHIC started its operation in 2000 as the first nucleus-nucleus collider to access the high energy density regime with low baryo-chemical potential. Among the wide variety of physics outcome at RHIC, the most important finding was creation of a new state of nuclear matter, which is hot, dense, strongly-coupled, and with partonic degrees of freedom.[2] The solid knowledge that we have crossed the boundary and reached another phase is an important basis for further scientific expeditions. With LHC since 2009 and RHIC developing further, the field has proceeded to a new stage where the properties of the partonic phase are pursued for comprehensive understanding.

§2. News from RHIC and LHC

2.1. *Thermal photon measurement at PHENIX/RHIC*

Photons are vital probes in many ways in high energy nuclear physics. The reasons include their serving as a thermometer of the nucleus-nucleus collision systems. The spectra of real and virtual photons carry information on the temperature of the emission source. In particular if the system is in thermal equilibrium, it inevitably

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emits a thermal radiation following the Maxwell-Boltzmann distribution.

Experimentally, however, measurement of thermal photons has been technically quite challenging due to a large amount of photons from other sources such as prompt photons from hard QCD processes, *e.g.* compton scattering and annihilation of quarks and fragmentation of color strings; interaction between jets and the medium, *e.g.* jet-photon conversion and bremsstrahlung; thermal photons from the mixed and hadronic gas phases; and most abundantly decay photons from short-lived hadrons. Aside from the hadronic decay photons, which can be statistically subtracted, photons from the hard QCD processes and the hadronic gas phase generally dominate the high and low transverse momentum regions, respectively. At the RHIC energy, however, there is a predicted window at the intermediate transverse momentum around a few GeV/c where the thermal photons from the partonic phase should prevail.

The naïve way to measure the direct photons is to look for an "excess" above photons from hadron decay. PHENIX has found the results in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV to be consistent with perturbative QCD (pQCD) calculations scaled with the number of binary nucleon-nucleon collisions, *i.e.* no thermal photon contribution observed.[3)] It should be stressed that the significance of the result is limited by systematic errors in the low transverse momentum region where the thermal photon component is expected, due to a very small signal-to-background ratio.

PHENIX has hence explored an alternative way to measure direct photons, via "almost real" virtual photons, *i.e.* electron-positron pairs with low invariant masses. The result in p+p collisions well reproduces decay photons from hadrons based on their measured spectra with an additional component in high transverse momentum region from pQCD processes. In Au+Au collisions, on the other hand, an enhancement is observed in the mass region above the π^0 mass. This is expected since there is no virtual photons from Dalitz decay of π^0 in the mass region enhancing the signal-to-background ratio for direct virtual photons by a factor of ~ 5.[4)]

The direct photon spectra measured by PHENIX via the two independent methods, real and virtual photons, are consistent with each other in the overlapping transverse momentum regions, supporting the correctness of the measurements. While the p+p result is consistent with a pQCD expectation down to transverse momentum as low as ~ 1 GeV/c, the Au+Au result exhibits an excess with the inverse slope of $221 \pm 19 \pm 19$ MeV, as shown in Figure 1.[5)] Models assuming the initial temperature ranging $300 - 600$ MeV at times of $0.6 - 0.15$ fm/c are in qualitative agreement with the data, suggesting a temperature well above the phase boundary achieved.

2.2. *First physics run at ALICE/LHC*

The historic first p+p collisions at LHC at $\sqrt{s} = 900$ GeV were observed on November 23, 2009. The beam was then declared stable on December 6 and the ALICE detector complex was fully turned on. About 4×10^5 "good" p+p events were collected at 900 GeV through December 14, with all the detectors included in the data stream and the magnets turned on. The first data have enabled the detectors to be validated in details. Successively, the highest ever collision energy on the earth of 2.36 TeV was achieved, where about 3×10^4 events have been collected at

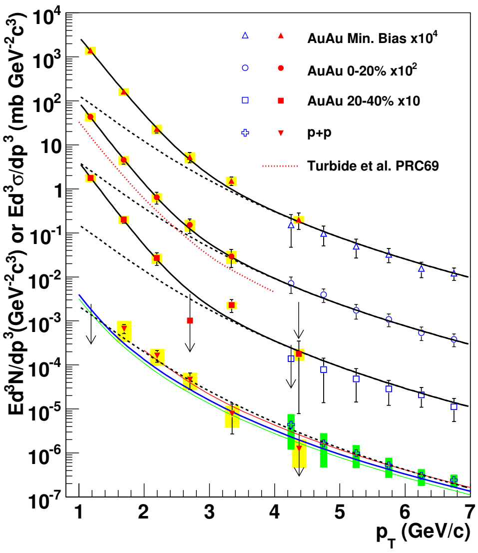

Fig. 1. Transverse momentum spectra of direct photons in p+p and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV measured by RHIC-PHENIX.[5] The open symbols are from real photon measurements; the filled are from the virtual photon method. The three curves on the p+p data represent pQCD calculations; the dashed lines show a fit to the p+p data, scaled with the number of binary nucleon-nucleon collisions.

ALICE. After an end-of-year shutdown, the LHC was recommissioned in early 2010, and p+p collisions at the new record energy of 7 TeV were established on March 30. The LHC has been developing higher luminosity since then, with the latest record of 3×10^{29} cm^{-2} s^{-1}, and has delivered about 2×10^{-2} pb^{-1} of integrated luminosity to ALICE and other experiments, as of the end of May, 2010.

The ALICE experiment at LHC is fully ready to accept the collisions to attack the standing issues remaining at RHIC, *i.e.* global and comprehensive understanding of properties of the deconfined partonic matter, especially via penetrating photon and lepton measurements, such as direct measurement of thermal radiation and systematic measurements of heavy flavors up to the beauty.

§3. First Physics Results from ALICE

Not only celebrating the first physics run, the first physics results from ALICE and LHC have been already published. They include the charged particle densities $dN_{ch}/d\eta$ of $3.10 \pm 0.13 \pm 0.22$ for total inelastic p+p collisions at 900 GeV and $3.51 \pm 0.15 \pm 0.25$ for non-single-diffractive collisions,[6] allowing an extrapolation to p+p collisions at the top LHC energy of 14 TeV, where $dN_{ch}/d\eta$ will be ~ 5.5 for total inelastic and ~ 5.9 for non-single-diffractive. The charged particle densities in p+p collisions at 2.36 TeV and 7 TeV have also been submitted to journals.[7),8]

With the collision data at 900 GeV and 2.36 TeV in hand and at 7 TeV steadily accumulating to $\sim 2 \times 10^8$ minimum-bias p+p events, or ~ 2.6 nb^{-1} of integrated luminosity, recorded as of the end of May, 2010, "next-to-first" physics analysis is in good progress. It includes inclusive and identified particle spectra, antiproton-proton ratio, HBT correlations, mean transverse momentum of produced particles as a function of multiplicity, measurements of short-lived particles via hadronic and photonic decay channels, (mini-)jets, event topology, heavy flavor production, and so forth.

Figure 2 demonstrates the performance of π^0 identification at ALICE, with its two types of photon detectors, PHOS and EMC. For more of the latest progresses, see, *e.g.*, reference 9).

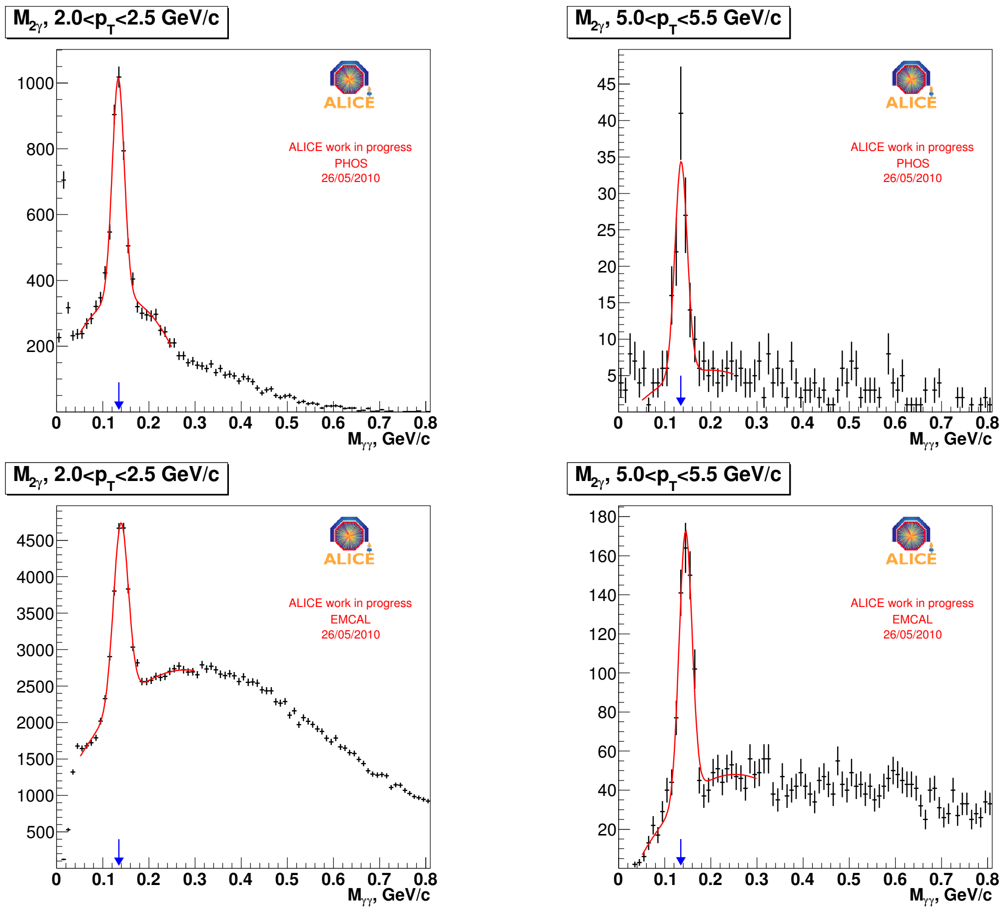

Fig. 2. Invariant mass peaks of π^0 via photon pair measurements. Top: with the PHOS detector; bottom: with the EMC detector. Left: transverse momentum of the pairs from 2.0 GeV/c to 2.5 GeV/c; right: from 5.0 GeV/c to 5.5 GeV/c.

§4. Plans, Schedule, Strategies and Prospects at ALICE/LHC

4.1. *LHC run plans*

LHC plans to continue the current p+p running at $\sqrt{s} = 7$ TeV over the summer of 2010, and then the first Pb+Pb program at $\sqrt{s_{NN}} = 2.75$ TeV is scheduled to begin on November 18, 2010, through December 10. Another long p+p at 7 TeV and the second Pb+Pb at 2.75 TeV are scheduled in 2011. Then after a long shutdown period for 18 to 24 months for hardware works to assure the original design energy of the LHC, Pb+Pb running at the top energy of $\sqrt{s_{NN}} = 5.5$ TeV is expected for about a month in each year along with regular p+p running at 14 TeV. It should also be emphasized that reference runs including p+p at 5.5 TeV, p+Pb ($\sqrt{s_{NN}}$ up to 8.8 TeV), and lighter nucleus-nucleus, *e.g.* Ar+Ar ($\sqrt{s_{NN}}$ up to 6.3 TeV), are planned in the following few years. Those reference runs are vitally important for systematic studies of the complex multi-parton system created in high energy nucleus-nucleus collisions.

4.2. *ALICE status and plans*

The detector configuration of ALICE[10)] in the first physics run in 2009 through 2011 includes full instrumentation of the internal tracking system (ITS), the time projection chamber (TPC), the time-of-flight detector (TOF), the high momentum particle identification detector (HMPID), the muon spectrometer (MUON), and the trigger detectors; partial instrumentation of the transition radiation detector (TRD) (7 sectors out of 18), the photon spectrometer (PHOS) (3 out of 5), and the electromagnetic calorimeter (EMC) (2 out of 5.5); and reduced capacity of the high level trigger (60%). ALICE has hence reached almost full capabilities of hadron and muon measurements, with partially reduced electron and photon capabilities which are to be completed in the next few years. The mid-term plan of ALICE also includes detectors beyond the baseline, *e.g.* an additional EMC coverage and a forward calorimeter (FOCAL).

4.3. *Physics prospects at ALICE*

One of the key measurements at ALICE/LHC, considering the physics outcome at RHIC, is direct measurement of thermal photons in Pb+Pb collisions. ALICE is equipped with the PHOS detector precisely for the purpose. PHOS consists of a highly segmented high resolution electro-magnetic calorimeter, based on lead-tungstate ($PbWO_4$, or PWO) crystals and avalanche photo-diode (APD) semiconductor readout.[10),11)] With the PWO crystals and the APD's cooled and temperature controlled at -25 ± 0.1°C, its energy resolution σ/E is designed to be $(3.3/\sqrt{E\ [\mathrm{GeV}]} \oplus 1.1)\%$ in the very wide energy range from < 100 MeV up to ~ 80 GeV.

Thanks to the higher temperature and longer life time of the created fireball expected at LHC than at RHIC, to the reduced background photons from hadron decay as hadrons with high transverse momenta are suppressed due to energy loss of hard-scattered partons in the partonic medium, and to the superb PHOS detector, direct measurement of thermal photons from the deconfined partonic phase is prospected finally at LHC. It would allow an access to the thermal properties of the created partonic system at the “quark gluon plasma factory”.

An earlier physics prospect via photon measurements at ALICE is neutral meson suppression at very high transverse momentum. With the detector acceptance and statistics expected in the first Pb+Pb running, as well as in the p+p, measurements of quark energy loss is achievable already in the first year with at minimum a comparable quality to what have been reached at RHIC after years of its operation. Figure 3 shows the expected statistical significance of “nuclear modification factor” measurements in the first year at ALICE. The higher reach in transverse momentum and theoretically expected stronger suppression[12)] would allow an even clearer and more systematic measurement of quark energy loss, to investigate the dynamic properties of the partonic phase.

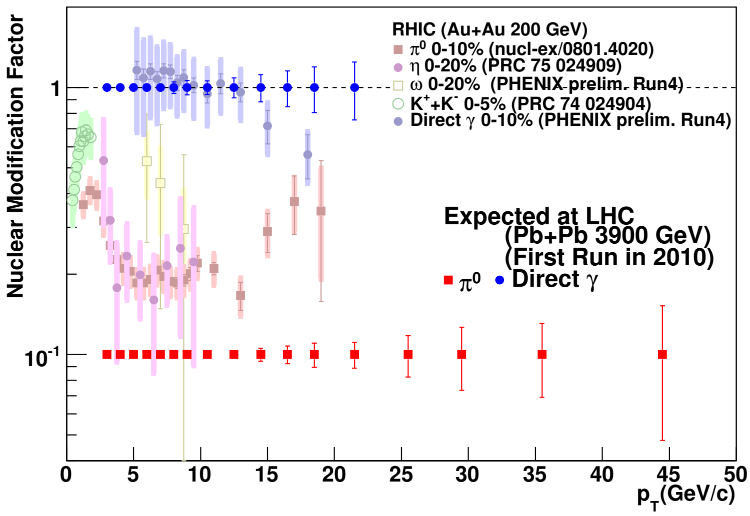

Fig. 3. Expected statistical significance of nuclear modification factor measurements of π^0 and direct photons at ALICE in the first year, as a function of transverse momentum. The reference points are from RHIC-PHENIX.

§5. Summary and Concluding Remarks

PHENIX experiment at RHIC has found a thermal component in the direct photon spectrum via the virtual photon method, in qualitative agreement with models assuming the initial temperature ranging 300 – 600 MeV at times of 0.6 – 0.15 fm/c, suggesting a temperature well above the phase transition which is predicted to occur at around 170 MeV by lattice QCD calculations. With the solid knowledge that we have crossed the boundary and reached another phase, the ALICE experiment at LHC started a further scientific expedition on the QCD phase diagram at the highest ever collision energies. First p+p collisions at $\sqrt{s}$ = 900 GeV and at 2.36 TeV were achieved in 2009, high statistics p+p data at 7 TeV are being accumulated, and the first Pb+Pb running at $\sqrt{s_{NN}} = 2.75$ TeV is scheduled to begin on November 18, 2010, through December 10. Based on the rich outcome at RHIC, even more exciting physics harvests are expected from ALICE/LHC already since the first years, toward global and comprehensive understanding of properties of the deconfined partonic matter, especially via penetrating photon and lepton measurements.

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