Heavy Ions at the LHC: Selected Predictions

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Heavy-ion collisions at relativistic energy have been investigated for many years at various experimental facilities such as the Berkeley Bevalac, the CERN synchrotron SPS, and the Brookhaven relativistic heavy-ion collider RHIC [1]. At RHIC, a maximum centre-of-mass energy of 0.2 TeV (0.2·10^12 electron volt) per particle pair is reached in Au + Au collisions [2]. Numerous theoretical works have been written to interpret the data, or make predictions regarding quark-gluon plasma formation, and other processes of interest such as the presence of a gluon condensate in the initial state. With the advent of the Large Hadron Collider LHC at CERN in Geneva, a new era in this field of research is emerging.

The Large Hadron Collider LHC at CERN

Until now, the LHC has solely been used to investigate proton-proton collisions at center-of-mass energies of up to 7 TeV and relatively low beam intensities: several (presently up to 25) bunches of about 10^11 protons per beam, compared to 2808 bunches to be reached in 2016 at the design luminosity (10^34 cm^−2·s^−1).

At correspondingly low event rates (presently up to 10^4 Hertz), it is still possible to re-discover the known standard-model particles such as the neutral K_s - meson which decays mainly into positive and negative pions in the detectors ATLAS, CMS, LHCb and ALICE, or the neutral Λ-baryon that decays into a proton and a pion. Indeed almost all SM-particles including the W- and Z-boson have been found [3].

There are also some candidate events for the top-quark, which is particularly difficult to detect (Fig. 2). But for the discovery of the Higgs-Boson, and also for super-symmetric or dark-matter particles and mini black holes, one needs much higher collision rates (up to 6·10^8/s).

According to recent results from the Tevatron [4], a Higgs-boson mass range 158 – 175 GeV/c^2 is excluded with 95% confidence limit, making a light Higgs – which is even more difficult to detect - much more probable. It is expected that the discovery potential of the LHC will compete with the Tevatron proton-antiproton collider at Fermilab next year, running up to an integrated luminosity of 1 fb^-1 (Tevatron has analyzed up to 6.7 fb^-1 so far).

Opening the LHC for heavy ions

Collisions of lead ions are scheduled to start in November 2010, first at the injection c.m. energy of 0.32 TeV, then at a centre-of-mass energy per particle pair of 2.76 TeV (corresponding to 7 TeV in a proton-proton collision at the same magnetic-field configuration). There will be two Pb-runs before the shutdown of the LHC in 2012. The highest energy of 5.52 TeV in Pb+Pb, corresponding to 14 TeV in p + p - almost 30 times the maximum RHIC energy (Fig. 3) – will then be reached in 2013. There will eventually be 592 bunches in each beam. The dedicated heavy-ion detector is ALICE - which presently studies QCD with pp collisions -, but there are also heavy-ion groups within ATLAS and CMS.

No heavy-ion beam crossing is so far envisaged for LHCb which mainly studies CP-violation through B-mesons. However, this detector with its excellent particle-identification capabilities at very forward angles, or large rapidities (the Lorentz-invariant analogue of the velocity) $y=0.5\cdot\ln[(E+p)/(E-p)]$ might also turn out to be a good tool to investigate particles produced from Pb+Pb collisions at large rapidities $y= 5 - 8$ where interesting physics is expected to occur that is inaccessible to ALICE because particle identification is restricted there to $y<2$ (the beam rapidity at maximum energy is $y_b = 8.68$).

ALICE and the heavy-ion groups of the other detectors will investigate the state of matter at high temperature and energy density where the confinement of quarks and gluons into hadrons is overcome, and a quark-gluon plasma is formed. Possible signatures for its formation such as the enhancement of strangeness or the suppression of the rate of produced J/Psi-mesons that consist of charm-anticharm quarks have been notoriously difficult to interpret because many effects that are unrelated to QGP-formation (such as hadronic final-state interaction in case of J/Psi suppression) can also cause the observed phenomena.

Still there is general agreement in the heavy-ion community that quark-gluon degrees of freedom essentially determine the state of matter at and above SPS energies (17.3 GeV in the centre-of-mass), with some more direct indications that the crossover from the hadronic to the quark-gluon medium may occur at c.m. energies around 6-8 GeV per particle pair [5].

A new type of quark-gluon plasma

At LHC energies we are far above the crossover energy, and the character of the QGP changes as compared to RHIC energies. New hard probes are expected to be useful to investigate the QGP: High-p_T jets will play a much more pronounced role, as well as heavy quarks. A careful investigation of the quenching of the jets by the quark-gluon medium will reveal much of its properties, as had already been done at RHIC. Collective expansion of the high-density medium will be even faster than at RHIC. The Y-meson (consisting of bottom and antibottom quarks) with a rest mass of 9.5 GeV/c^2 that has not been relevant at RHIC energies may turn out to be a more interesting probe at LHC energies than the J/Psi-meson, which had driven much of the interest at SPS and RHIC.

The investigation of extreme matter at high energy density that is created in a Pb+Pb collision at LHC is essentially based on QCD [6], but typically at smaller Q^2-values (square of the momentum transfer) as compared to the ones studied in p+p. Of special importance are then the high gluon field strength and ensuing gluon saturation effects in the initial state [7], which are expected to have observable consequences.

Gluon saturation

As example for a particularly interesting quantity that is sensitive to the gluon saturation scale one may consider the net-baryon (baryon minus antibaryon) rapidity distribution, which had been determined carefully at SPS and RHIC [8] energies through the measured net-proton distributions (Fig. 4). Here the position of the fragmentation peaks at large rapidities y turns out to be sensitive to the gluon saturation scale [9]: the valence-quark scattering off the gluon condensate has observable consequences. Due to the restriction in the particle identification properties of ALICE to the midrapidity region $y<2$ it will, however, require experimental upgrades to measure the effect. A description for the net-proton rapidity distribution within the relativistic diffusion model (which is not based on QCD, but on nonequilibrium-statistical physics) had been developed in [10].

Many other interesting observables in heavy-ion collisions at LHC energies will stimulate the research in many-body physics at the quark-gluon level once the first results for Pb+Pb collisions in the new energy regime become available.

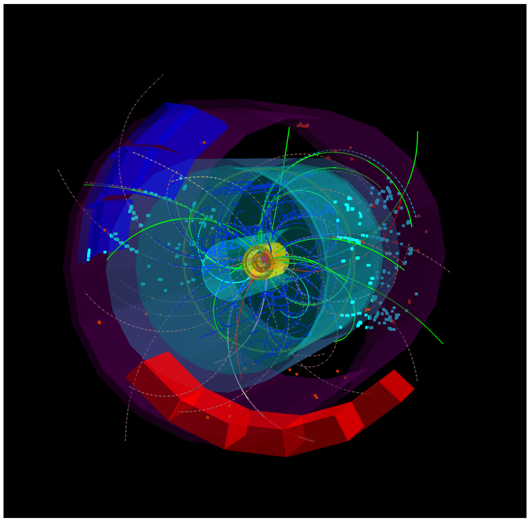

Figure 1: ALICE particle tracks in p+p at the LHC

Particle tracks fly out from the heart of the ALICE experiment from one of the first proton – proton collisions at a total energy of 7 TeV. © ALICE collaboration, CERN. Reproduced with permission.

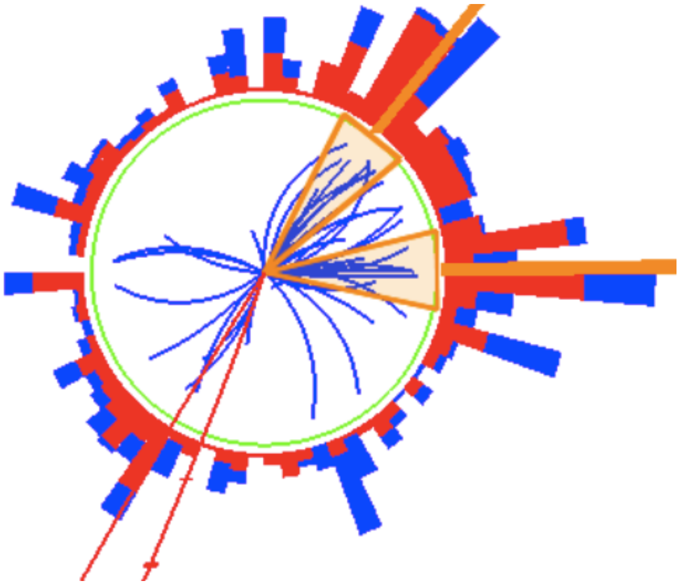

Figure 2: Top-quark candidate event in 7 TeV p+p at the LHC

A candidate for production of a top quark pair in CMS, where both top quarks decay into a W boson and a b quark, and both W particles decay into a muon and neutrino. This results in 2 muons (red tracks), 2 jets tagged as b-quark jets and missing energy (from the escaping neutrinos). © CMS collaboration, CERN. Reproduced with permission.

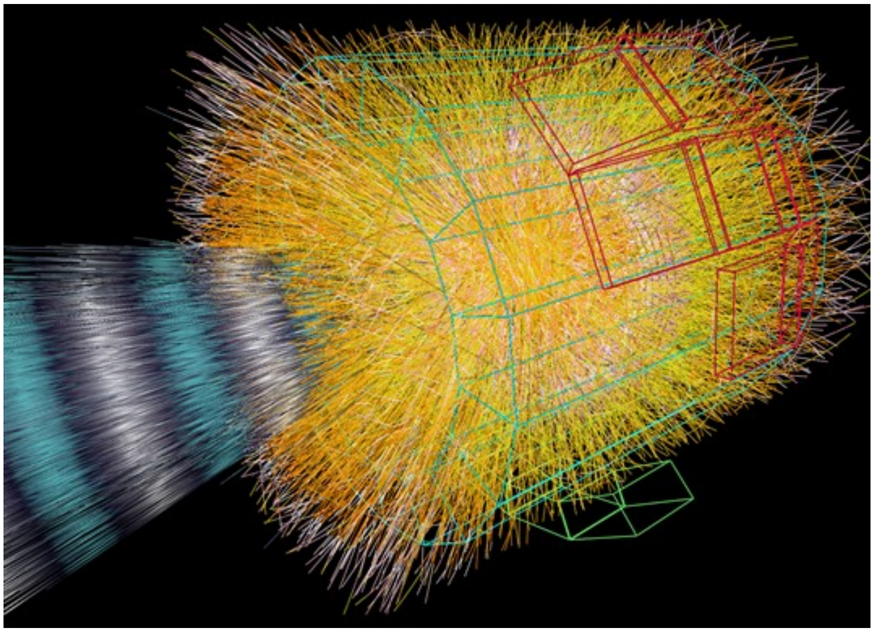

Figure 3: Simulated LHC heavy-ion event in Pb+Pb. Source: ALICE collaboration. © ALICE collaboration, CERN. Reproduced with permission.

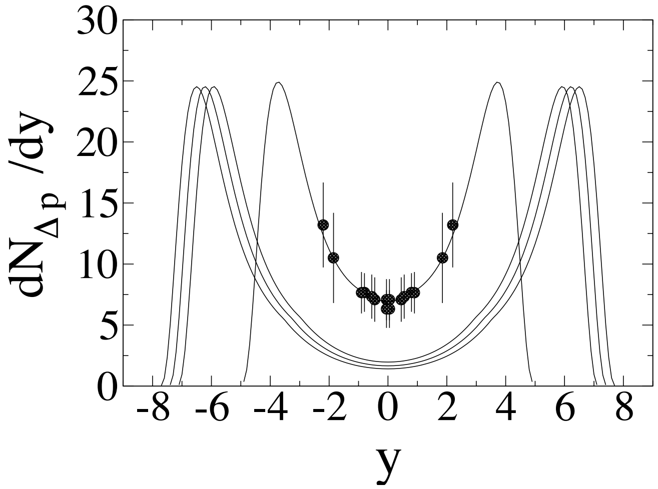

Figure 4: Rapidity distributions of net protons in central heavy-ion collisions

Rapidity distributions of protons – antiprotons in central Au + Au collisions at RHIC energies of 0.2 TeV compared with BRAHMS data [8], and calculations for LHC centre-of-mass energies of 2.8, 3.9 and 5.5 TeV from [9].

Further reading

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