LHC experiments

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The Large Hadron Collider (LHC) will in 2007 start colliding proton and lead beams at $\sqrt{(s)} = 14$ TeV and $\sqrt{(s_{NN})} = 5.5$ TeV, respectively. The accelerator and the experiments are under construction and detailed studies of the physics program are being prepared. I will in this paper review the current status of the experiments and the heavy ion physics aspects that are unique at LHC.

1. Introduction

About 1100 participants are presently involved in the prepration for the heavy ion program at the Large Hadron Collider (LHC) and the community is constantly growing. The experiments are in the construction phase and intensive studies of the physics potential are ongoing. ALICE (A Large Ion Collider Experiment), the only experiment with the main focus on heavy ion collisions at LHC, is engaging a major part of the community. The two experiments, ATLAS (A Toroidal LHC ApparatuS) and CMS (Compact Muon Solenoid), dedicated to proton-proton physics have approved heavy ion programs.
The LHC running scenario, the uniqueness of the LHC heavy ion program, the status of the LHC machine and the experiments will be reviewed. A few selected physics topics will also be discussed.

2. LHC running scheme

The yearly running scheme of LHC will be to have proton-proton (pp) collision most of the year and 1 month of heavy ion running. The LHC is scheduled to start operate in the summer of 2007 with pp collisions at the nominal energy of $\sqrt{(s)} = 14$ TeV but with a lower luminosity than the design value of 10^{34} cm^{-2} s^{-1}. Alice will make full use of the pp running, even though at luminosities below 10^{31} cm^{-2} s^{-1}, to collect reference data but also to pursue a pp physics program complementary to the studies by the ATLAS and CMS experiments. All three experiments, during the initial phase of the LHC, will collect pp data and plans for an early short low luminosity pilot run with heavy ion collisions (PbPb). A few days of running will give enough data to study global propoerties of the heavy ion collisions and to measure large cross-section phenomena. The 2008 LHC running will, besides pp collisions, include a long heavy-ion run at 1/20 of the design luminosity (10^{27} cm^{-2} s^{-1}). Plans for the years after including pA, light ions and different energies have been developed.

3. Properties in the LHC energy regime

The main goal in the field of relativistic heavy ion collisions is to create and study an extremely dense and hot subatomic system called the Quark Gluon Plasma (QGP). QCD, the theory of strong interaction, provides quantitative estimates of the critical temperature at which the phase transition from hadronic to quark matter should occur. Once established, the QGP provides a unique laboratory to study bulk properties of quark matter as well as the fundamental interaction of coloured objects in a coloured medium. PbPb collisions, with a center-of-mass energy about a factor 30 higher than at RHIC, will provide a qualitative new environment for studying nuclear matter under extreme conditions. The higher energy will improve with large factors all parameters relevant for the formation of the Quark Gluon Plasma (QGP). The created system will be hotter, bigger, denser and longer lived. The initial temperature will largely exceed the critical temperature predicted by lattice QCD [1] for QGP formation. The expected muliplicity in central PbPb collisions at LHC, based on extrapolation from RHIC data, will be between 1500 - 6000 charged particles per unit of rapidity. This extrapolation is affected by large uncertainties since the particle production at LHC will be dominated by hard processes, and the energy dependence for these processes in nuclear collisions is not very well known. The ALICE experiment has been optimized for 4000 charged particles per unit of radidity and checked still with good performance up to 8000 particles per unit of rapidity. ATLAS and CMS (checked up to 7000 particles per unit of rapidity) will provide good performances over the expected range. The higher energy available at LHC opens up a new domain of small Bjorken x (x = 10^{-2} - 10^{-5}) characterized by high density saturated gluon distributions. Hard processes will dominate in the collisions. Low energy jets ($p_t <$ 10 GeV/c) will be produced with very high rates and they will dominate the bulk properties of the colliding system. Measurements of these low energy jets may be important for understanding the thermal evolution of the system. Very hard probes (jets with $p_t >$ 20 GeV/c), abundantly produced, will make it possible to perform detailed studies of their interaction with the dense medium as well as studies of the jet fragmentation function. Weakly interacting probes like direct photons and gauge bosons are produced at rates sufficient to study jet tagging and nuclear parton distribution functions at very high Q^2. In addition to the new information provided by the hard probes, the very high multiplicities expected at LHC, will allow for measurements on an event-by-event basis such as particle composition, spectra, flow and non-statistical fluctuation connected to critical phenomena.

4. LHC and the experiments

The first LHC dipole magnet went down into the tunnel in March 2005 for installation. About 1000 of the 1300 dipoles are produced and about 300 of them are installed today. The machine installation is scheduled to be finished in early 2007 to provide the first pp collisions in the summer of 2007. The industrial production of standard components is compatible with this schedule but a ramping up of the installation activities is crucial to maintain the very tight schedule. The progress of the installation can be found on the LHC dashboard [2].

The ALICE experiment [3] is in the process of being installed in the P2 cavern of the

LHC. The central part of the detector will be housed in the LEP L3 magnet which has a moderate solenoid magnetic field (nominal value of 0.5 T). The central tracking system in ALICE covers the pseudo-rapidity range $|\eta| < 0.9$ and full azimuth. The Inner Tracking System ITS placed closest to the interaction point is composed of 6 layers of Si detectors of different technologies. The beam test performance of the ALICE Silicon Pixel Detector (SPD) was presented at this conference [4]. Outside the ITS is the Time Projection Chamber (TPC) which is the main tracking device of ALICE. The TPC is constructed of 4 cylindrical vessels 5 m long. The readout is done using conventional multiwire proportional chambers with cathode pads.The laser calibration system for the TPC was presented at this conference [5]. The TPC is surrounded by the Transistion Radiation Detector (TRD) for electron identification and the Multi-gap Resistive-Plate Chamber detector (MRPC) for time-of-flight measurements. ALICE has in the forward direction a spectrometer which consists of a complex hadron absorber, a 3 Tm dipole magnet, 5 planes of tracking chambers and 2 planes of trigger chambers. This spectrometer will perform high quality measurements of o'nium (J/ψ, Υ) states with a resolution of 100 MeV/c^2 at the Υ mass. A presentation of the physics perspectives with the ALICE muon spectrometer was given at this conference [6]. The central detector part is completed by specialized detector systems for identification of photons (PHOS) and high momentum charged particles (HMPID). ALICE has various detector systems at large rapidities on both sides of the interaction point. These detector systems will provide information for triggering, event selection, global properties and event-by-event studies. The ALICE Forward Multiplicity Detector (FMD) was presented at this conference [7], [8]. The complete detector system of ALICE will track with high spatial and momentum resolution and identify hadrons, leptons and photons produced in the central region in heavy ion and pp collisions. The software reconstruction algoritm enables the reconstruction of charged particle tracks with an almost 100 % efficiency over the full momentum range. Particle identification over a broad range of momenta is very important for most of the observables anticipated in ALICE. A schematic view of the ALICE detector is shown in figure 1.

The ATLAS [9] and CMS [10] detectors were optimized to perform high quality measurements in pp collisions of leptons, hadronic jets and high energy photons. The two detectors are based on very similar concept and differ mainly by the choice of detector technologies. The design, however, provides adequate performances for measuring high p_t phenomena in heavy ion collisions. Both detectors have, closest to the interaction point, large coverage ($|\eta| < 2.5$) trackers composed of multi layer Si detectors of pixel and strip technologies with high granularity. These tracking systems, placed in a high solenoid magnetic field (2 T for ATLAS and 4 T for CMS), provide high precision tracking of charged particles. The software algoritms reconstruct tracks with an efficiency of about 80 % (p_t > 1 GeV/c) at a density of 5000 charged particle per unit of rapidity, increasing to higher efficiency for lower particle densities. The resolution in momentum is in both ATLAS and CMS a few percent for low momentum particles. Outside the inner tracking systems is in both experiments fine grained high resolution calorimeters with hermetic coverage of $|\eta| < 5$. Large acceptance ($|\eta| < 3.0$) muon spectrometers complete the central set-up of both ATLAS and CMS. Different aspects on heavy ion collisions with the ATLAS and CMS detectors were presented at this conference [11],[12].

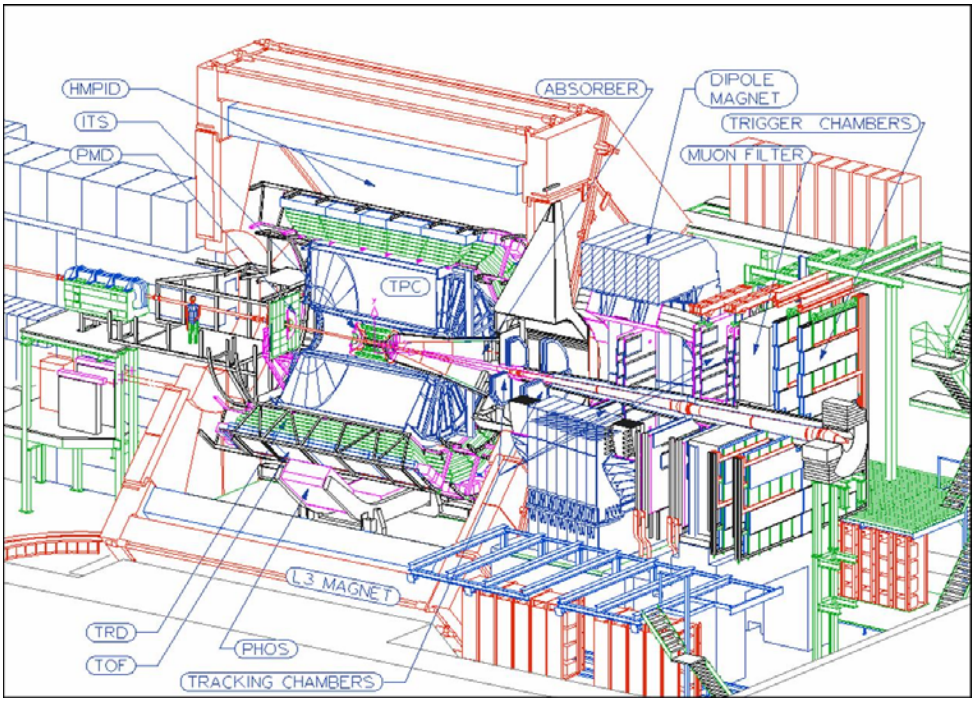

Figure 1. A schematic view of the ALICE detector.

The three experiments complement each other and make it possible to explore all the probes relevant for the studies of the properties of hot and dense nuclear matter. The ability to identify particles over a broad momentum range from very low (<100 MeV/c) to very high (<100 GeV/c) makes ALICE unique to correlate soft processes, which characterize the bulk properties of the hot and dense system, with the hard processes that probes the medium. ATLAS and CMS will extend the momentum range to values of several hundreds GeV/c where they exceed ALICE in identifying inclusive and tagged jets.
The very challenging task for the three experiments is the construction and commissioning of the detectors to be ready for the first pp collisions in the summer of 2007.

5. Physics potential

I will in the following discuss some observables that will be accessible at LHC because of the large increase in the cross section for hard probes. The energy scale at which the hard probes are produced is well above the characteristic scale of the medium such as the medium temperature and the hadron mass. The production occurs on a very short time scale and distance and carries, therefore, information also on the early history of the collisions. One of the most relevant signature is the medium modification of jet observables which are carrying information on the energy density of the hot and dense system created in the heavy ion collisions. The o'nium bound states will be produced at very high rates at LHC offering the possibility to study over a broad mass range the medium induced suppression patterns as observed both at SPS and RHIC.

5.1. Jets

The large production cross sections for hard processes will result in a copious production of jets with high transverse momentum at LHC. During a typical year of heavy ion running (effective 10^6 s) about 10^5 jets with transverse momentum larger than 100 GeV/c will be detected within $|\eta| < 1$. The suppression of high transverse momentum partons (jet quenching) will at LHC be the most attactive observable for studies of the parton energy loss. This supression is a result of various effects like initial state scattering, shadowing and final state effects. The dependence of the suppression pattern on transverse momentum has been predicted with different results. One calculation [13] shows a strong dependence on p_t over a wide range in p_t (2-100 GeV/c) while another [14] shows an almost flat behaviour similar to the observation at RHIC. The high production rate of jets at LHC will allow for extensive studies of the suppression pattern and the LHC experiments should be in a good position to distinguish between the two predictions.
Jets created by high energy partons are easily identified even under the very severe background conditions from hadrons that are formed in heavy ion collisions. ALICE will achieve reconstruction efficiencies, using common jet algorithms taking the background from heavy ion collisions into account (reduced cone size, p_t cut), of about 80 % for 50 GeV/c jets inceasing to about 100 % for 100 GeV/c jets. The fake jet identification will under these conditions be at the level of a few percent. The ATLAS and CMS experiments will extend the range of jet measurements to about 350 GeV/c with a reconstruction efficiency of about 100 % for $p_t > 80$ GeV/c. Calculations [15] show that a 100 GeV/c jet loses about 20 % of the energy but only 3 % will be radiated outside a cone of radius 0.3. Studies of this effect require measurements and identification of charged hadrons down to very low momenta.
The measurement of the fragmentation function and its sensitivity to identify the energy loss and the radiated energy is crucially dependent on the precision in the jet energy measurements. These measurements are limited by the underlying event and the radiated energy across the cone boundaries. One method to perform such studies is to tag the jets with weakly interacting particles like Z^0 or photons produced in the reactions qg -> qX and $q\bar{q}$ -> qX where X = Z^0 or γ. The production of γ - jet events in heavy ion collisions will be about 10^6 events with $E_\gamma > 50$ GeV per month. This coincidence technique will allow to localize the jet and measure the fragmentation function without reconstructing the jet energy. The γ - jet measurements will be affected by the large background of photons especially from neutral pions while tagging with Z^0 would provide an almost background free signal. The ATLAS and CMS experiments are well suited for the latter studies but the rather low production rate will make these measurements very challenging.

5.2. Heavy quarks

Heavy quarks as well as the high p_t jets are produced in hard processes at a very early time and will therefore probe the hot and dense system created in heavy ion collisions. The high temperature of the system generates heavy quark-anti-quark pairs which form bound o'nium states (J/ψ, Υ). These states can be dissolved if the plasma energy is similar to the binding energy of the states. The production rate of o'nium states will be very high at LHC which should allow for spectroscopy studies of these states. The ATLAS and CMS experiments have larger acceptance and somewhat better resolution than ALICE and perform the measurements of o'nium states in the central rapidity region. ALICE, on the other hand, measures in the forward rapidity region with lower background and a much lower p_t. These facts make the three expriments complementary and the performance figures are very similar with a mass resolution of 100 MeV/c^2 at the Υ mass. The temperature of the formed system at LHC will be sufficiently high to dissolve the most tightly bound state. This opens up the possibilty to study the suppression pattern of J/ψ, ψ', Υ, Υ' and Υ'' which dissolve at different temperatures above the critical temperature. The expected performance of o'nium states measurements for the three experiments is shown in figure 2.

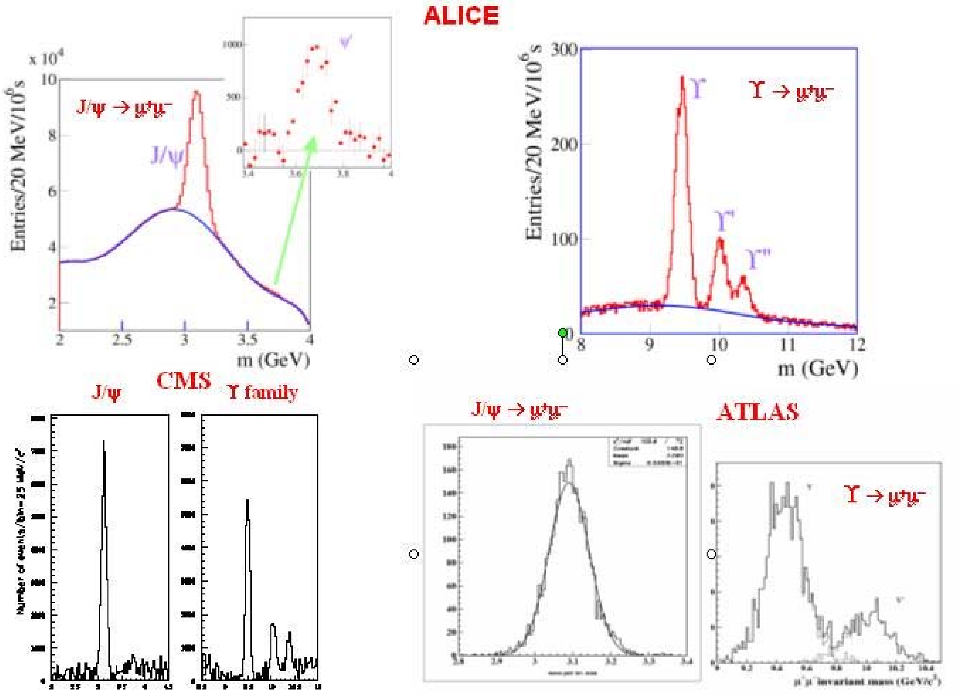

Figure 2. J/ψ and Υ families in the ALICE, ATLAS and CMS experiments.

Heavy quarks produced in hard processes will like light quarks probe the dynamics of the hot and dense system and will loose a large amount of energy due to multiple scattering and radiative energy loss. The nuclear modification factor for hadrons from light and heavy quarks will thus give information which can constrain the interpretation of the quenching effects in terms of energy loss. ALICE with its excellent vertexing capabilities, identification of charged hadrons and momentum resolution measure the D mesons through the reconstruction of the hadronic decay D^0 -> K^- π^+. Calculations show that one month of heavy ion running will give enough events to measure the p_t spectrum for D^0 meson up to about 15 GeV/c. The calculations are based on an energy loss model [16] which takes an approximation of the dead-cone effect into account. The p_t spectra for D mesons in pp and PbPb collisions are shown in figure 3. The ratio of nuclear modification factors for D mesons and for unidentified charged hadrons is found to be a very sensitive probe of the medium properties. Studies are underway to investigate the possibility to do similar measurements of the production of B mesons.

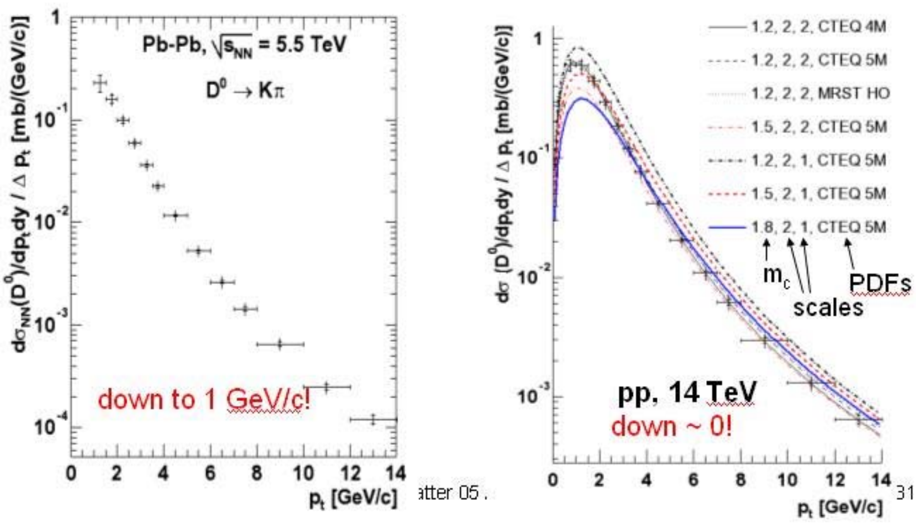

Figure 3. Transverse momentum spectra for D meson in pp and PbPb collisions.

5.3. Prompt photons

Prompt photons and light neutral mesons will in ALICE be measured in a limited solid angle using a spectrometer based on $PbWO_4$ cristals (PHOS). The identification of prompt photons is limited by the background of photons mainly coming from π^0 decay. Procedures for selecting prompt photons among the inclusive photons have been established and these are Shower Shape Analysis (SSA) [17] and the Isolation Cut Method (ICM). In the SSA method, photons are identified by analysing the shape of the shower in PHOS and in the ICM method, photons are tagged and identified as prompt if they appear isolated, i.e without any charged particle nearby. The two methods have shown to be very effective in identifying prompt photons measured by PHOS. The estimated spectrum of identified prompt photons in a standard year of LHC running is shown in figure 4. Based on this estimated high p_t (> 20 GeV/c) photons should be well within the reach of ALICE.

6. Conclusion

We are looking forward to a timely completion of the LHC accelerator and of the experiments. All construction is progressing well and the goal of having the first pp

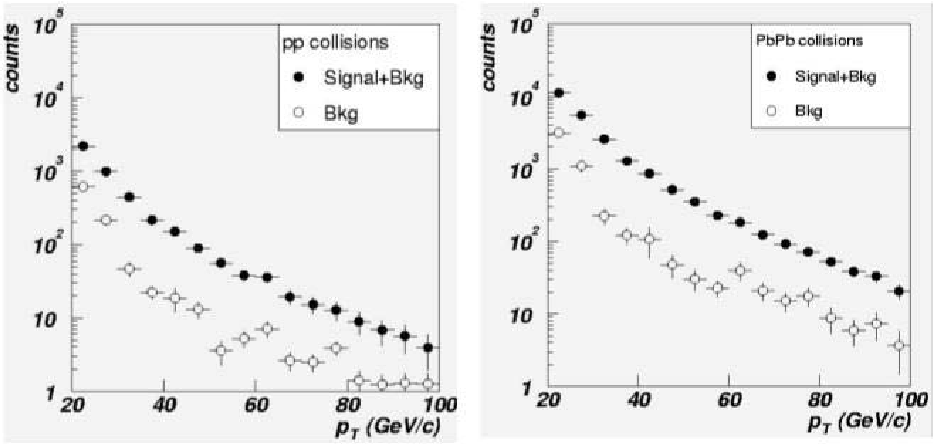

Figure 4. Spectra of identified prompt photons in pp and PbPb collisions.

collisions in the summer of 2007 followed by an early pilot run with heavy ions seems feasible. LHC will open up a new regime for studies of the structure of matter under extreme conditions. I would like to express my thanks to many colleagues in ALICE, ATLAS and CMS for providing me with material for this presentation.

REFERENCES

1. F. Karsch et al. Phys Lett B478 (2003) 447
2. http://lhc.web.cern.ch/lhc
3. http://aliceinfo.cern.ch/
4. D. Elia to be published in Czech J Phys
5. G. Renault to be published in Czech J Phys
6. P. Crochet these proceedings
7. K. Gulbrandsen these proceedings
8. C.H. Christensen to be published in Acta Physics Hungarica
9. http://atlas.web.cern.ch/Atlas
10. http://cmsinfo.cern.ch
11. M.J. Murray these proceedings
12. P. Nevski these proceedings
13. I. Vitev and M. Gyulassy Phys Lett 89 (2002) 252301
14. K.J. Eskola et al. Nucl Phys A747 (2005) 511
15. C.A. Salgado and U.A. Wiedemann Phys Rev Lett 93 (2004) 042301
16. C. Salgado and U. Wiedemann Phys Rev D68 (2003) 199
17. G. Conesa et al. Nucl Instr and Meth A537 (2005) 363