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The ALICE experiment at the LHC

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Abstract: After a general introduction on the Quark Gluon Plasma and a short overview of the experimental results obtained so far with heavy-ion collisions at the SPS and at the RHIC, the physics goals of the ALICE experiment at the LHC are presented.

1. Introduction

Lattice calculations of Quantum ChromoDynamics (LQCD) predict a phase transition of nuclear matter from a hadron gas to a new state of matter for which quarks and gluons are deconfined from the hadrons and are liberated to roam freely [1]. This new state of matter was called the Quark Gluon Plasma (QGP) in the late seventies [2]. According to Big-Bang cosmology, the Universe was in a QGP state until a few microseconds old. This QGP might also be present in the core of neutron stars, although with a different temperature and baryonic chemical potential [3]. For vanishing baryonic chemical potential (and two flavor QCD), LQCD indicates that the phase transition takes place at a critical temperature $\mathrm{T_c} = 173 \pm 15$ MeV which corresponds to a critical energy density $\varepsilon_\mathrm{c} = 0.7 \pm 0.3$ GeV/fm^3 [1]. This transition is expected to be of cross-over type, i.e. without discontinuities in the first and second derivatives of the thermodynamical variables. For non-zero baryonic chemical potentials, LQCD predicts a first order phase transition line and a critical point where the phase transition would be of second order. Two additional important aspects are revealed by LQCD calculations: i) the phase transition coincides with the restoration of the chiral symmetry and ii) even for very large temperatures, the QGP doesn't behave like an ideal gas.

High-energy heavy-ion collisions provide the only experimental tool to explore, in laboratory, the QCD phase diagram and to recreate and study the QGP. It is indeed expected that during an heavy-ion collision, the temperature reached by the strongly interacting matter is sufficiently large to produce the QGP (with a limited life time and size). This experimental exploration of the phase diagram has started 30 years ago with heavy-ion beams delivered at various energies by different accelerators. The progress accomplished so far is schematically summarized in Fig. 1.

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After a short overview of the experimental signals of the QGP measured at the CERN-SPS and the BNL-RHIC, the future experimental program for the study of the QGP with the ALICE detector at the CERN-LHC is discussed. This program aims at investigating the properties of the QGP at very large temperatures and close-to-vanishing baryonic chemical potential[2].

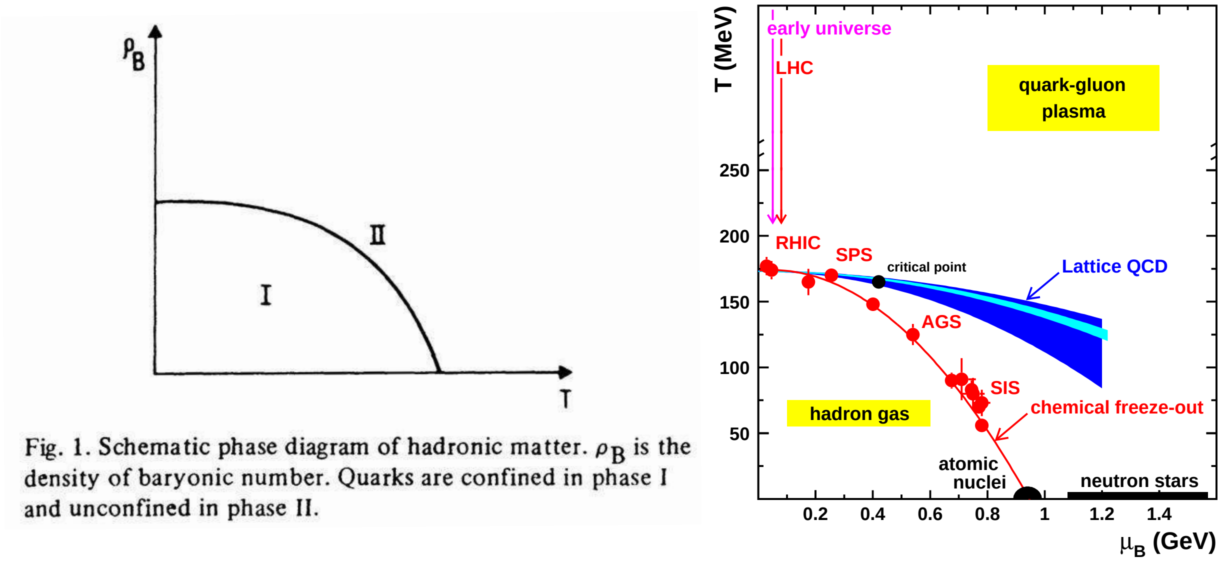

Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

Figure 1. Left: one of the first version of the QCD phase diagram proposed in 1975 (extracted from [5]). Authors of [5] comment "…we expect a phase diagram of the kind indicated in Fig. 1. The true phase diagram may actually be substantially more complex…". Right: simplified version of the QCD phase diagram in 2006 (adapted from [6]). At large baryonic chemical potentials and small temperatures, new phases based on the color superconductivity property of nuclear matter are predicted [7]. These phases are not shown on the figure.

2. The QGP at the SPS

The SPS has delivered heavy-ion beams at nucleon pair center-of-mass energy $\sqrt{s_{\mathrm{NN}}} = 6.7 - 17.2$ GeV from 1986 to 2004. Data collected by the seven heavy-ion experiments allowed to draw the following conclusions derived, for most of them, from central Pb–Pb collisions:

i) The energy density of the system, estimated to reach up to 3.3 GeV/fm^3, is larger than the critical energy density predicted by LQCD; ii) The chemical freeze-out temperature of the system of 168 MeV coincides with the critical temperature. This suggests that the system has reached the deconfined region of the QCD phase diagram; iii) As predicted by

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[2] Details about other experimental programs oriented towards the exploration of the intermediate range of the QCD phase diagram are presented in [4].

heavy-quark resonance melting due to color screening in a deconfined medium, the yield of measured J/ψ is smaller than that expected from a hadron gas; iv) An excess of low mass dilepton is observed and interpreted as a consequence of partial chiral symmetry restoration; v) An excess of (multi-strange-)hyperon production is observed with respect to *pp* collisions, as expected from the reduction of the threshold for strangeness production in the QGP; vi) An excess of direct photons, which would result from the thermal radiation of the deconfined medium, is observed at intermediate transverse momenta.

These observations motivated the publication of a press release on February 10^{th} 2000 announcing that "The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. [...] We now have evidence of a new state of matter where quarks and gluons are not confined." [8]. It should be noted that these observations however do not allow to claim without ambiguity the discovery of the QGP. First of all, some of the measurements can be reproduced by hadronic models which incorporate additional effects but not necessarily resulting from the QGP. Secondly, some aspects in the data are not understood yet and are still a matter of debate. A striking example is given by the J/ψ suppression pattern which is correctly described by three QGP models in Pb–Pb collisions although none of these models is able to describe the same data in the In–In system [9].

3. The QGP at the RHIC

The RHIC has started delivering heavy-ion beams in 2000. Since then, the four experiments installed at RHIC have collected data for various systems at energies $\sqrt{s_{\rm NN}} = 20 - 200$ GeV. Data collected during the four first years of RHIC operation have already led to an enormous number of publications[3]. The achievement, shortly described below, has been recently summarized both from the experimental side [10] and from the theoretical side [11]:

i) The energy density of the system is up to 5.4 GeV/fm^3 and possibly higher; ii) The chemical freeze-out temperature of the system is 177 MeV; iii) The intensity of the elliptic flow and its dependence to particle mass and transverse momentum are correctly reproduced by hydrodynamical calculations which assume a rapid thermalization of the system and use an equation-of-state of a quasi-perfect fluid derived from LQCD calculations. This fluid which is characterized by a low viscosity and a strong degree of thermal equilibrium has been called sQGP (Strongly interacting QGP); iv) The transverse momentum dependence of elliptic flow is identical for several particle species when intensity and transverse momentum are normalized to the number of quark constituents. This reveals the partonic degree of freedom of the system; v) Hadron yield at high transverse momentum is, in central Au–Au collisions, about 5 times smaller than the corresponding yield measured in *pp* collisions and extrapolated via binary scaling whereas photons yield is not suppressed. This indicates an important energy loss of partons flying through a dense medium characterized by a high gluon density; vi) The previous observation is confirmed by the reduction of back-to-back correlations at high transverse momentum in the same central Au–Au collisions whereas these correlations are observed in *pp* and *d*–Au

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[3] By August 14^{th} 2006, there were 79(42) articles published in Phys. Rev. Lett. (Phys. Rev.) and 491 entries in `http://arXiv.org`.

collisions.

These results have been published simultaneously with a press release on April 8th 2004, in which, like in the CERN press release four years earlier, the creation of a new state of matter is announced [12]. The new state of matter however could differ from that produced at CERN since it behaves more like a liquid than like a gas. Although this behavior is in line with the recent predictions from LQCD calculations mentioned in the introduction, some aspects in the data are not well understood. This, added to the lack of non-ambiguous evidence for the QGP formation, is well illustrated in the conclusions of the summary by the experimental collaborations [10]: "...we judge that the QGP discovery claim based on RHIC measurements to date would be premature." (STAR Collaboration) [10]; "There is not yet irrefutable evidence that this state of matter is characterized by quark deconfinement or chiral symmetry restoration, which would be a direct indication of quark-gluon plasma formation." (PHENIX Collaboration) [10]. However, it is essential to stress that due to the spectacular and non-expected behavior of the state of matter produced at RHIC, its study goes far beyond the simple goal of assigning it the name QGP (or sQGP): "...it is clear that the matter that is created at RHIC differs from anything that has been seen before. Its precise description must await our deeper understanding of this matter." (BRAHMS Collaboration) [10].

Efforts are now concentrated on the analysis of hard probes which became accessible in the last two years of operation. This includes, in particular, the study of the interaction of hidden and open heavy flavors with the medium, as well as photon and jet production.

4. The QGP at the LHC

With a nucleus-nucleus center-of-mass energy nearly 30 times larger than the one reached at RHIC, the LHC will provide the biggest step in energy in the history of heavy-ion collisions and will open a new era for studying the properties of strongly interacting matter under extreme conditions (Tab. 1).

Such a high energy represents a challenge for designing and operating detectors since the charged particle density at mid-rapidity could be as large as 4000. However, this new energy regime will lead to a much higher energy density, to a faster equilibration and to a bigger and longer life time of the deconfined system then resulting in an enhanced role of the QGP over final state hadronic interactions [13]. Note from Tab. 1, that the life time of the QGP at LHC is expected to be as large as the life time of the entire heavy-ion collision at the SPS. The higher temperature and close to vanishing baryonic potential of the system will make it closer to the conditions of the primordial Universe. Moreover, the comparison with LQCD calculations will be easier in such conditions for which perturbative theory works well. In fact, the decreasing role of non-perturbative effects with increasing temperature is demonstrated by the decreasing of the strong coupling constant which is estimated to be 0.43, 0.3 and 0.23 at $\mathrm{T} = \mathrm{T_c}$ (SPS), $2\mathrm{T_c}$ (RHIC) and $4\mathrm{T_c}$ (LHC), respectively [14]. On the other hand, heavy-ion collisions at the LHC access unprecedented small Bjorken-x values where low momentum gluons are expected to be close to saturation and lead to a significant shadowing effect (Fig. 2 left). As a consequence (high density) parton distributions are expected to dominate particle production. Another exciting aspect of this new energy regime is the massive production rate of hard

machine	SPS	RHIC	LHC
$\sqrt{s_{\rm NN}}$ (GeV)	17	200	5500
$\mathrm{dN_{ch}/dy}\vert_{y=0}$	400	750	2000 – 4000
$\tau^0_{\rm QGP}$ (fm/c)	1	0.2	0.1
$\mathrm{T_{QGP}/T_c}$	1.1	1.9	3.0 – 4.2
ε (GeV/fm^3)	3	5	15 – 60
$\tau_{\rm QGP}$ (fm/c)	≤ 2	2 – 4	≥ 10
$\tau_{\rm f}$ (fm/c)	~ 10	20 – 30	30 – 40
$\mathrm{V_f}$ (fm^3)	$\sim 10^3$	$\sim 10^4$	$\sim 10^5$
$\mu_{\rm B}$ (MeV)	250	20	1
$\mathrm{N}_{c\bar{c}}$	0.2	10	130
$\mathrm{N}_{b\bar{b}}$	–	0.05	5
processes	soft →	semi-hard →	hard

Table 1
Main characteristics of central heavy-ion collisions at SPS, RHIC and LHC. Shown are (from top to bottom), the maximum available energy per nucleon pair in the center-of-mass for Pb–Pb or Au–Au collisions ($\sqrt{s_{\rm NN}}$), the charged particle density at mid-rapidity ($\mathrm{dN_{ch}/dy}\vert_{y=0}$), the equilibration time of the QGP ($\tau^0_{\rm QGP}$), the ratio of the QGP temperature to the critical temperature ($\mathrm{T_{QGP}/T_c}$), the energy density (ε), the life time of the QGP ($\tau_{\rm QGP}$), the life time of the system at the freeze-out ($\tau_{\rm f}$), the volume of the system at the freeze-out ($\mathrm{V_f}$), the baryonic chemical potential ($\mu_{\rm B}$), the number of $c\bar{c}$ pairs ($\mathrm{N}_{c\bar{c}}$), the number of $b\bar{b}$ pairs ($\mathrm{N}_{b\bar{b}}$) and the importance of soft and hard processes (adapted from [13]).

processes[4] which are sensitive probes of the collision dynamics at both short and long timescales. This is illustrated in Fig. 2 (right) where it can be seen that, in the semi-hard range ($10 \lesssim p_{\rm t} \lesssim 20$ GeV/c), the LHC allows to reach a statistics considerably larger than the one accessible at RHIC and in the hard range ($p_{\rm t} \gtrsim 20$ GeV/c), the LHC allows to explore a region which is not accessible by any other hadronic machine. Note also the drastic increase of the expected number of produced heavy-quark pairs from RHIC to LHC (Tab. 1). These hard processes can be calculated using perturbative QCD and will represent, at the LHC, an ideal high statistics tool for a detailed characterization of the deconfined medium.

The LHC will be operated seven months per year in pp mode at $\sqrt{s} = 14$ TeV and one month per year in heavy-ion mode at $\sqrt{s_{\rm NN}} = 5.5$ TeV (for Pb–Pb collisions). The

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[4] "Qualitatively, in minimum-bias events SPS is 98% soft, 2% hard, RHIC is 50% soft, 50% hard and LHC is 2% soft, 98% hard." [14].

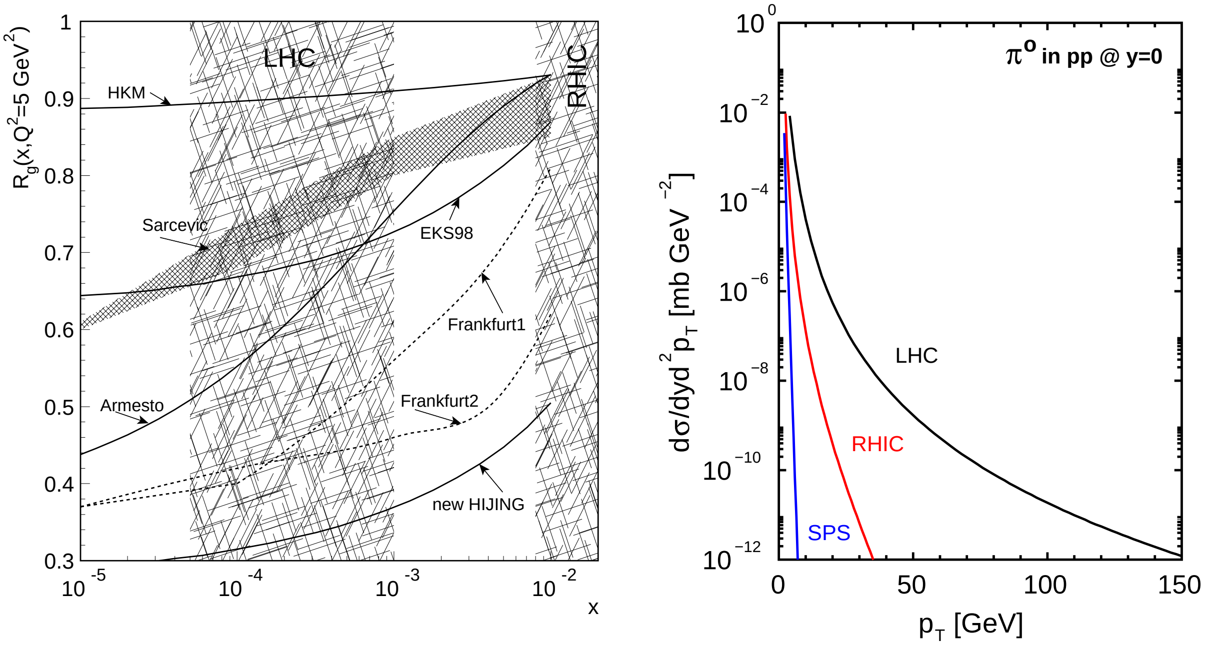

Figure 2. Left: various model predictions for the ratio of the gluon distribution function in a Pb nucleus to the one in a proton as a function of x for $Q^2 = 5$ GeV^2. The hashed areas indicate the x range accessible at RHIC and LHC (extracted from [15]). Right: predicted differential π^0 production cross-section in pp collisions at SPS, RHIC and LHC (adapted from [16]).

corresponding estimated effective running time is 10^7 s and 10^6 s for pp collisions and heavy-ion collisions respectively. The expected luminosity for Pb–Pb collisions is about $5 \cdot 10^{26}$ cm^{-2}s^{-1} which results in a minimum-bias interaction rate of 4 kHz. In order to achieve a comprehensive understanding of heavy-ion collisions, the physics program includes light-ion collisions for scanning the energy density as well as pp and proton(-like)-nucleus collisions which provide reference data for nucleus-nucleus collisions. Three of the four LHC experiments will take heavy-ion data: i) ALICE (see below) is the dedicated detector for heavy-ion physics, ii) CMS (Compact Muon Solenoid) is designed for pp physics but has a strong heavy-ion program focused essentially on jets and quarkonia measurements at large transverse momentum and iii) ATLAS (A Toroidal LHC ApparatuS) has a physics program similar to that of CMS.

4.1. ALICE physics program and detector overview

ALICE (A Large Ion Collider Experiment) is the only LHC experiment dedicated to the study of nucleus-nucleus collisions [15,17]. The ALICE Collaboration currently includes more than 1000 physicists from 80 institutes in 30 countries. The ALICE experiment is designed to ensure simultaneous and high precision measurements of numerous observables based of hadrons, leptons and photons, in a broad acceptance.

The detector (Fig. 3) consists of a central part, a forward muon spectrometer and for-

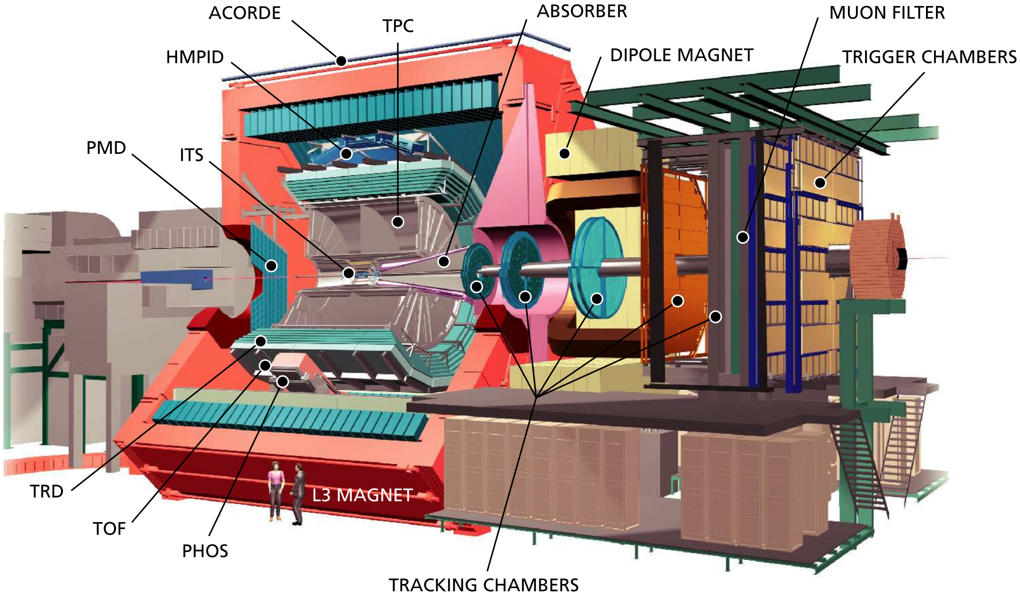

Figure 3. Layout of the ALICE detector.

ward/backward small acceptance detectors. The central part of ALICE consists of four layers of detectors placed in the solenoidal field ($B < 0.5$ T) provided by the LEP L3 magnet. From the inner side to the outer side, these detectors are i) the Inner Tracker System (ITS) consisting of six layers of silicon detectors, ii) the large-volume Time Projection Chamber (TPC), iii) the high-granularity Transition Radiation Detector (TRD) and iv) the high-resolution Time of Flight system (TOF) based on multi gap resistive plate chambers. They provide charged particle reconstruction and identification in the pseudo-rapidity range $|\eta| < 0.9$, with full azimuthal coverage and a broad $p_{\rm t}$ acceptance. The ALICE central barrel will later be also equipped with a large acceptance ($|\eta| < 1.4$, $\Delta\Phi = 110°$) Electro-Magnetic Calorimeter (not shown in Fig. 3). These large area devices are complemented by two smaller acceptance detectors: the High Momentum Particle Identification (HMPID) and the PHOton Spectrometer (PHOS). In the forward/backward region, additional detectors (T0, V0 and FMD, not shown in Fig. 3) allow fast characterization and selection of the events as well as charged particle measurement in the pseudo-rapidity range $-3.4 < \eta < 5.1$. At large rapidities, photon multiplicity and spectator nucleons in heavy-ion collisions will be measured by the Photon Multiplicity Detector (PMD) and the Zero-Degree Calorimeters (not shown in Fig. 3), respectively. Finally a forward muon spectrometer covering the pseudo-rapidity range $2.4 < |\eta| < 4.0$ complements the central part. It consists of a front absorber, a dipole magnet, ten high-granularity tracking chambers, a muon filter and four large area trigger chambers.

As an illustration of the ALICE capabilities for measuring rare signals, the expected performances of the detector in the quarkonium sector are shown in Fig. 4. Quarkonium states will be measured both in the dimuon and the dielectron channels. The acceptance will allow the reconstruction of differential distributions down to low $p_{\rm t}$ in most cases.

The resolution of the apparatus, better than 100 MeV/c^2 for M $\sim$ 10 GeV/c^2, will allow the separation of the different resonance states. More details about the ALICE detector, its operation as well as its expected performances in the various physics channels can be found in [15,17].

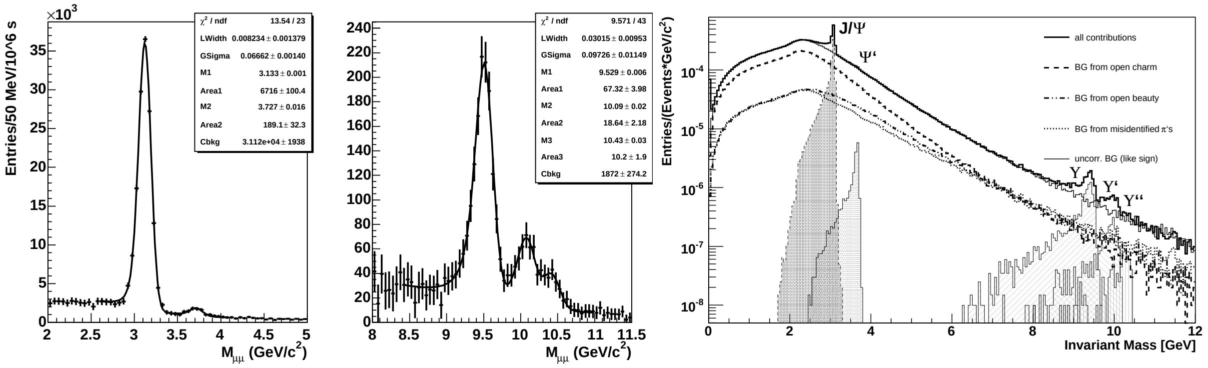

Figure 4. Invariant mass spectra of low mass dimuon (left), high mass dimuon (middle), and dielectron (right), expected to be measured with the ALICE detector within a month of Pb beams (extracted from [17]). In the left and middle plots, the non-correlated background is subtracted from the total spectrum assuming a perfect subtraction i.e. the statistical error of the "full" spectrum is assigned to the remaining spectrum of the sum of the correlated sources.

5. Summary

In about two years from now, heavy-ion collisions at the LHC will undoubtedly open a new and unique era for the exploration of the QCD phase diagram with unprecedented qualitative and quantitative gains for the study of the QGP at large temperature and small baryonic chemical potential. The novelties brought by this new energy regime are i) the access to a regime of very small Bjorken-x values characterized by a saturation of low momentum gluons, ii) the large temperature for which the characteristics of the system get closer to those of an ideal gas, iii) the small baryonic chemical potential which becomes similar to that of the early Universe and iv) the abundant production rate of hard processes which can be used, for the first time, as high statistics probes of the medium. After more than 10 years of intensive detector R&D and construction, the ALICE experiment is currently in its installation phase.

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