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STUDY OF HIGH MASS DIMUON PRODUCTION IN HEAVY ION COLLISIONS WITH CMS

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High invariant mass muon pair production in Pb–Pb collisions with CMS detector at LHC has been considered. Various sources of dimuons have been included into the analysis. It is shown that for an appropriate set of cuts on the transverse momenta of μ, on the invariant mass of the muon pairs and on the hadronic/electromagnetic energy deposited into the calorimeters, one can separate the contribution of the semileptonic decays of open beauty particles. The latter process can be used as a reference for measuring the suppression of $b\bar{b}$ quarkonium states in nucleus-nucleus collisions.

The investigation has been performed at the Laboratory of High Energies, JINR.

Изучение образования димюонов с большой массой в соударениях тяжелых ионов с помощью CMS

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Рассматривается образование мюонных пар с большой инвариантной массой в Pb–Pb соударениях с помощью установки CMS на LHC. Анализировались разные источники димюонов. Показано, что при соответствующих ограничениях на поперечный импульс μ, инвариантную массу мюонных пар и энергию в адронном и электромагнитном калориметрах удается выделить полулептонные распады очарованных частиц. Этот процесс может быть использован при измерении подавления выхода связанных состояний $b\bar{b}$ в ядро-ядерных соударениях.

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1. Introduction

The main motivation of heavy ion experiments at LHC is the observation and study of the phase transition from hadronic matter to the plasma of deconfined quarks and gluons (quark-gluon plasma, QGP). For heavy nuclei $A \sim 200$, at the centre of mass energies of about 5.5 TeV/nucleon the energy density in central nucleus-nucleus collisions should be well above the expected phase transition value, thus allowing one to probe QGP in the asymptotically free ideal gas form [1,2]. Several measurable effects have been suggested in order to establish the existence of QGP and investigate its properties [2–5]. Some recent investigations imply that direct probes of QGP should be hard enough in order to resolve subhadronic scales and distinguish confined and deconfined media [6]. So, the two topics most widely discussed in the context of QGP manifestations are heavy quarkonium production and high transverse momentum jets.

According to the expectations [1,7], the formation of the states with hidden charm and beauty J/ψ, ψ', Υ, Υ',... in QGP should be suppressed if compared to the hadron-hadron collisions. Moreover, because of the different sizes and formation times for various quarkonium states, the degree of suppression is expected to vary from one quarkonium state to another. However, very similar effects can be caused by other reasons, like significant production of χ states and/or absorption of quarkonium in the dense hadronic matter. Υ family production at LHC looks rather promising [8], especially if these measurements are complemented by the studies of other related characteristics, like the relative suppression between various vector states and open beauty production, and the dependence of the above ratios on the energy density in the collisions.

We argue that the process of open beauty production is a convenient reference process for studying Υ family suppression. Though some fine characteristics of this process should be affected by QGP and final state interactions, one expects that the overall inclusive cross section of open beauty production remains unchanged, apart from a relatively small increase caused by quarkonium dissociation. The production mechanisms for the two processes are quite similar (both quarkonium and open beauty are mainly produced in gluon-gluon collision subprocesses), and so are the detection techniques (both rely heavily on muon detection and measurement). Thus one hopes that both theoretical and experimental systematic errors could be reduced in the ratio. As shown below, high invariant mass lepton pairs from semileptonic decays of *b*-hadrons have a good experimental signature with a potentially well controllable background.

Another choice of the reference process could be Z boson production [9], which is completely free of final state interaction effects. However, in this case there are some drawbacks: the production mechanism is mainly dominated by initial quarks and antiquarks, and the Z mass is significantly higher than that of quarkonium.

The other process of particular interest for heavy ion physics is the production of high transverse momentum jets. One expects that the initial partons – originators of the high P_T jets in a two-jet event – should acquire a significant additional transverse momenta as a result of multiple rescattering off the QGP constituents. This leads to certain measurable effects like P_T disbalance [10,11], acoplanarity [12,13] and transverse energy-energy correlations [14]. The average additional transverse momentum is of order of few GeV, almost independent of the jet energy. One expects that similar effects should hold for *b*-quark initiated jets as well. It should be mentioned, however, that in central heavy ion collisions these measurements are complicated by the ambiguities of the jet definition and the large transverse energy flow due to the huge number of non-jet particles. If semileptonic decays are used to detect and measure events with $b\bar{b}$ pairs, the two leptons from b-hadron decays should also inherit the additional transverse motion originating from multiple rescattering of the parent b-quarks off the constituents of QGP and/or the hadronic matter. This method is free of above-mentioned complications inherent to jet measurements. However, the lepton obtains an additional transverse momentum in the b-hadron weak decay process. The resulting smearing of the dense matter effects can be dangerous and requires further investigation.

On the experimental side, one has to study the ability of the LHC detectors to identify and measure relevant processes. The CMS detector [15] with its good muon system and calorimetry looks very promising for investigating these problems.

In the following, we present the results of our study of the processes which can lead to the production of high mass dimuons in Pb–Pb interactions at LHC. The aim of the work was to show that the contribution of the open beauty decays can be separated out in a wide range of the dimuon invariant masses and muon transverse momenta. The expected statistics should be enough to use the above cross section as a reference process for Υ family suppression measurements, as well as to study some fine details of the b-jet transverse distributions.

2. General Considerations

The main sources of high mass dimuons in heavy ion collisions are shown below:

1. production of heavy quark bound states;
2. Drell-Yan and Z production;
3. decays of heavy flavours ($c\bar{c}$, $b\bar{b}$, $t\bar{t}$);
4. *WW*, *WZ* and *ZZ* production;
5. decays of π and K mesons.

The possibilities of detecting Υ family $\mu^+\mu^-$ decays with the CMS detector have been studied in [16]. The Z-boson production in heavy ion collisions with the implication to QGP manifestations has been considered in [9]. We have performed the Monte Carlo simulation of the processes 2–5 for lead-lead collisions at LHC, with the CMS detector [17].

At LHC heavy ions will be accelerated up to the energies $E = E_p \times (2Z/A)$ per nucleon pair, where $E_p = 7$ TeV is the proton beam energy for LHC. In the case of Pb nuclei the energy per nucleon pair will be 5.5 TeV and the design luminosity for a single experiment is about $L \approx 1.0 \times 10^{27}$ cm^{-2}s^{-1}. For the lighter ion beams the luminosity can be much higher, e.g., the ratio of luminosities $L_{\mathrm{Ca}}/L_{\mathrm{Pb}} = 2500$. The expected total cross section for Pb–Pb interaction is about 7.5 b, which leads to the event rate of 7.5 kHz.

The Drell-Yan, *Z*, heavy flavour, *WW*, *WZ* and *ZZ* pair production cross sections in nucleus-nucleus collisions were obtained from those in *pp* interactions at the same energy ($\sqrt{s} = 5.5$ TeV) using the parametrization $\sigma_{AA} = A^{2\alpha} \times \sigma_{pp}$, with $\alpha = 0.95$. The cross sections in *pp* collisions were evaluated with the PYTHIA Monte-Carlo simulation program [18].

Only leading order processes were simulated and the default structure functions CTEQ2L were used, with the *k*-factor equal to 1. For these reasons the obtained cross sections are somewhat smaller than corresponding results of next-to-leading order calculations (by a factor of 5 for $c\bar{c}$, and 2.5 for $b\bar{b}$ production [19]). However, we have checked that for the high P_T region the difference is only of the order of two for both processes. It should be mentioned that the measurements of open beauty production in $p\bar{p}$ collisions at the Tevatron [20,21] are consistent with each other, being higher than NLO QCD predictions, close to the upper edge of the theoretical uncertainty. For tt and Z production, the difference between the PYTHIA prediction and the experimental data from FNAL $p\bar{p}$ collider is less than 1.5. We did not make any correction of the obtained cross sections, but one has to have this difference in mind.

In order to cover the total phase space with approximately equal statistics, the simulation of $c\bar{c}$ and $b\bar{b}$ production was performed in ten intervals of the transverse momentum of final heavy quarks.

The cross sections for W and Z pair production are very low, so that their contributions to dimuon mass distribution are negligible at all invariant masses.

Neither the effects of the deflection for the parton structure functions in a nucleus relative to a free nucleon, nor the energy losses of heavy quarks in dense matter have been taken into account. No background from cosmic ray muons has been considered. We believe that the latter can be suppressed using the timing information from muon chambers and beam crossing.

3. Simulation Details

The charged particle density in mid-rapidity range for the central Pb–Pb collisions at LHC are expected to be between 3000-8000. In our analysis we have used the extreme number 8000 of charged particles emitted per unit of rapidity. This corresponds to $(dN_{\mathrm{ch}}/dY)_{Y=0} \approx 2500$ charged particles per minimum bias Pb–Pb collision.

The rapidity distributions of π and K mesons have been obtained according the HIJING [22] event generator with the shadowing and jet quenching effects. The rapidity spectra of these particles can be described by the sum of two Gaussian functions. It should be mentioned that invariant mass distribution of dimuons from pion and kaon decays is very sensitive to the shape of the transverse momentum spectra of these particles. For the P_T distribution of pions the following parametrization was used [23,24]:

$$dN_\pi/dP_T^2 = \exp\left(-\sqrt{M_\pi^2 + P_T^2}/T\right) \quad \text{for} \quad R_T < P_T^{\mathrm{lim}}, \tag{1}$$

$$1/(1 + P_T/P_T^0)^n \quad \text{for} \quad P_T > P_T^{\mathrm{lim}}. \tag{2}$$

The transverse momentum spectra of K mesons have been obtained from the pion distribution:

$$dN_K/dP_T^2 = \left(\left(\sqrt{M_\pi^2 + P_T^2} + 2\right)/\left(\sqrt{M_K^2 + P_T^2} + 2\right)\right)^m \times dN_\pi/dP_T^2. \tag{3}$$

The values of the parameters are: $T = P_T^0 = 0.16$ GeV/c, $P_T^{\lim} = 1.1$ GeV/c, $n = 5.1$ and $m = 12.3$, obtained from the fit of pion and kaon transverse momentum distributions from HIJING for Pb–Pb minimum bias collisions.

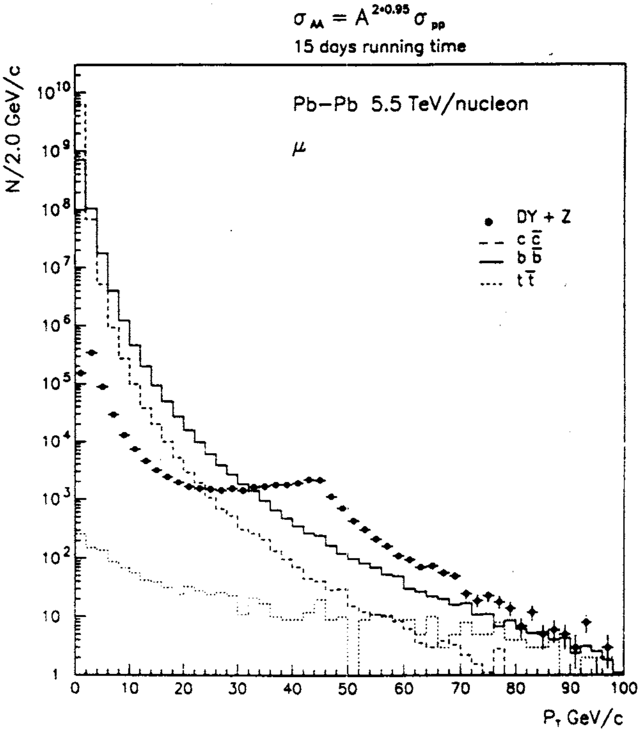

Fig.1. Transverse momentum distributions for muons of various processes in Pb-Pb collisions

Another approach was used to study the high P_T tails of transverse momentum distribution of muons from π and K decays. The high P_T distributions of these particles were estimated using QCD jet production from PYTHIA Monte-Carlo program for *pp* interactions. The cross section for the dijet production in Pb–Pb collisions was obtained in the same way as for other hard processes. However, due to the jet quenching, pion and kaon spectra will be softer in nuclear collisions than in *pp* interactions. So, our estimates should be considered as an upper limit for this type of background, as we have ignored jet quenching effects in our calculations.

The CMS muon detector has the geometric acceptance up to $|\eta| = 2.4$ and full coverage in ϕ, with minimal losses due to cracks. The muon reconstruction efficiency in heavy ion collisions using muon chambers and inner tracker strongly depends on the multiplicity of produced particles. For minimum bias Pb–Pb events, reconstruction efficiency of 0.9 was used for muons with $P_T > 5$ GeV/c. The μ trigger efficiency of 0.95 was assumed. In the CMS detector for heavy ion collisions the muon momentum resolution can be approximated by the function $\Delta P \approx 0.5\% \times P$ GeV/c.

In order to estimate the contribution from uncorrelated muon pairs coming from π and K decays, the acceptance tables generated by the GEANT Monte-Carlo simulation program have been used. Only hadronic interactions and decay processes of secondary particles in the detector were taken into account.

Figure 1 presents the simulated transverse momentum distributions of muons coming from Drell-Yan, Z and heavy flavour production processes in Pb–Pb collisions. In the range 5 GeV/c $< P_T <$ 30 GeV/c the main source of muons is open beauty production. For lower

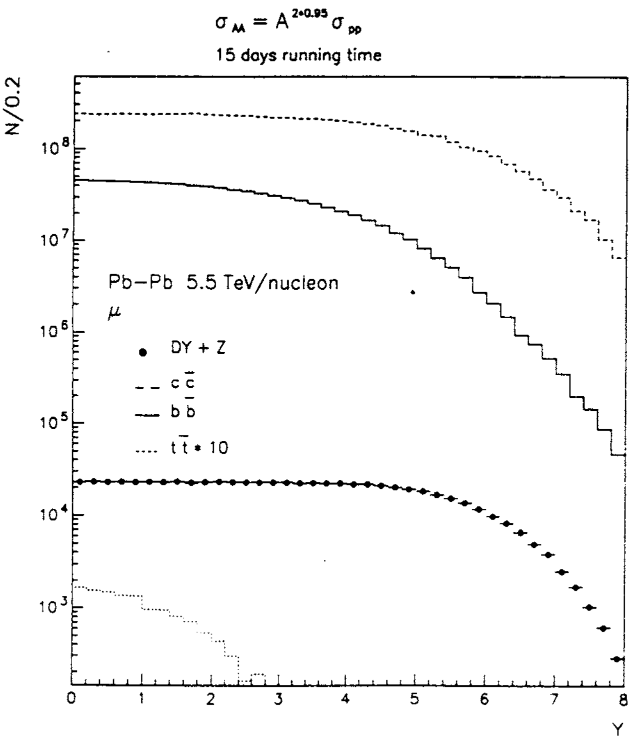

Fig.2. Rapidity distributions of muons in Pb-Pb collisions

P_T values, the contribution from open charm fragmentation is dominant. It should be noted that *W* production and its subsequent decay $W \rightarrow \mu\nu$ can also give a high transverse momentum muon, but this contribution becomes significant only for $P_T > 20$ GeV/c.

The rapidity distributions of muons from the same processes are presented in Fig.2. These distributions are nearly flat within the range of CMS muon detector acceptance $|\eta| \leq 2.4$ and significant part of produced μ will be detected.

4. Invariant Mass Distributions of $\mu^+\mu^-$ Pairs

Invariant mass spectra of dimuons coming from Drell-Yan, *Z* and heavy flavour production processes were studied for the different cuts on the transverse momentum of μ. We have assumed 15 days of running time for Pb–Pb collision with the above-mentioned design luminosity. Figure 3 presents $\mu^+\mu^-$ pair invariant mass distribution for muons with $P_T > 5$ GeV/c. A clear signal from $Z \rightarrow \mu^+\mu^-$ decays is seen. The expected number of detected *Z* decays in ± 10 GeV mass window is 6400 with very low background. In the mass range 20 GeV $< M_{\mu^+\mu^-} <$ 50 GeV dominant contribution comes from $b\bar{b}$ fragmentation (about 75%). The obtained number of dimuons in this mass interval, coming from $b\bar{b}$ decays, will be 15600. The Drell-Yan and $c\bar{c}$ processes are giving nearly equal number of $\mu^+\mu^-$ pairs in this range – 15% and 10%, respectively. The contribution from $t\bar{t}$ fragmentation is negligible at all dimuon masses.

For the transverse momentum cut on muons 10 GeV/c (Fig.4), contribution from the Drell-Yan process increases to about 34%, however $b\bar{b}$ fragmentation is still dominant – 57%, which corresponds to about 3000 detected $\mu^+\mu^-$ pairs. Taking into account the contributions from next-to-leading order processes discussed above, the expected number of detected dimuons from these processes might be higher by a factor of two.

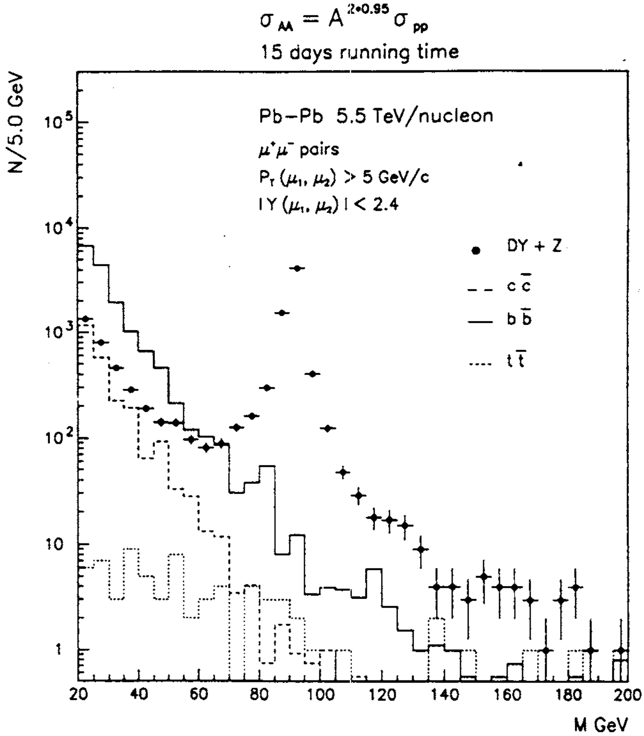

Fig.3. Invariant mass spectra of $\mu^+\mu^-$ pairs for muons with $P_T > 5$ GeV/c

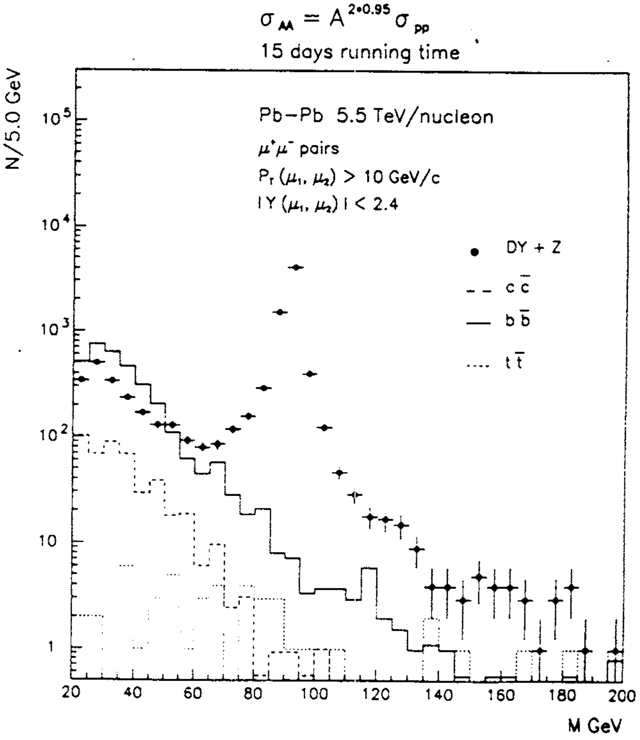

Fig.4. Invariant mass spectra of $\mu^+\mu^-$ pairs for muons with $P_T > 10$GeV/c

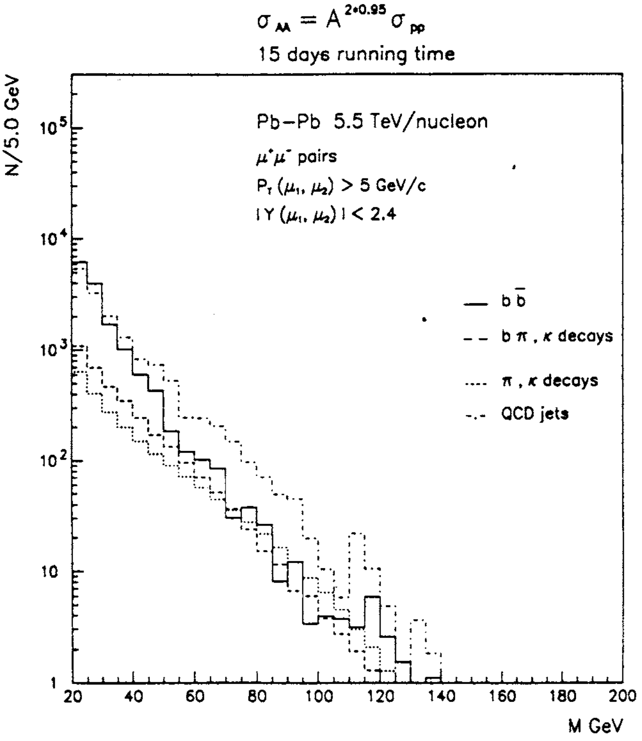

Fig.5. Invariant mass distributions of dimuons from $b\bar{b}$ fragmentation, π, K decays and QCD jets for muons with $P_T > 5$ GeV/c

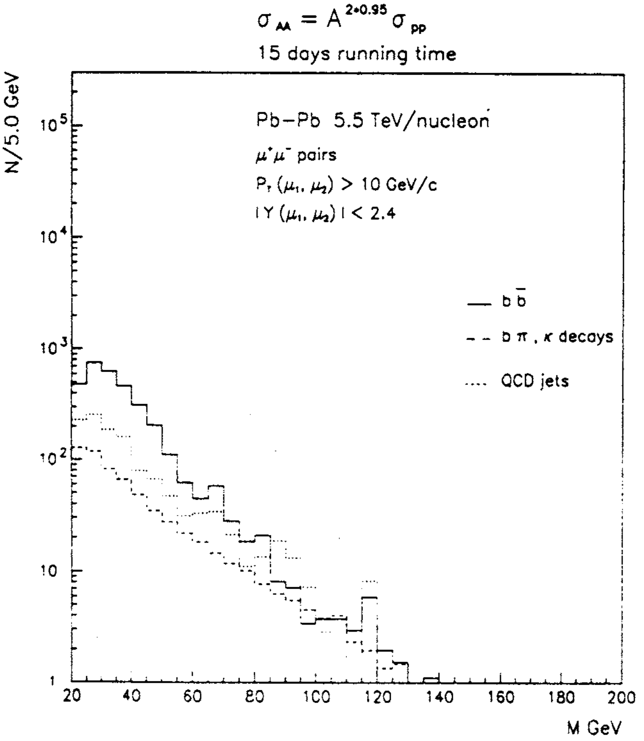

Fig.6. Invariant mass distributions of dimuons from $b\bar{b}$ fragmentation, π, K decays and QCD jets for muons with $P_T > 10$ GeV/c

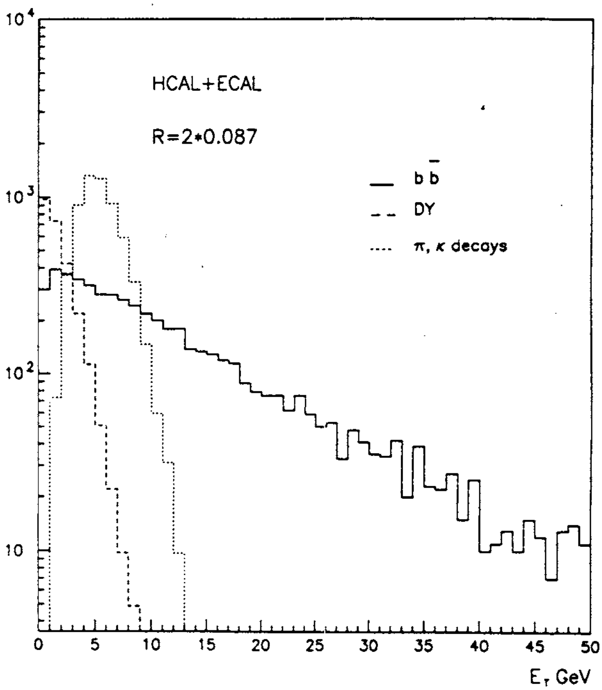

Fig.7. Transverse energy deposition in calorimeter cells for $b\bar{b}$, Drell–Yan processes and minimum bias Pb-Pb events

Figures 5 and 6 present the dimuon invariant mass spectra for muons with transverse momenta greater than 5 GeV/c and 10 GeV/c for $b\bar{b}$ production, π and K decays, for the case when one μ comes from b quark fragmentation and the other is the pion or kaon decay product and for QCD jet events. Backgrounds from pion and kaon decays and when one muon coming from b and another from π/K decays is small. The background from QCD jets is important and gives almost the same number of muon pairs in the mass interval 20 GeV $< M_{\mu^+\mu^-} <$ 50 GeV for the muon transverse momentum $P_T > 5$ GeV/c. However, the contribution from these backgrounds decreases quickly with increasing transverse momentum of muons, so that for $P_T > 10$ GeV/c dimuons from above mentioned background processes amount to less than 15% of muon pairs coming from $b\bar{b}$ fragmentation. Note once again, that contribution from QCD jet events in real heavy ion collisions should be smaller than our estimates, because of the energy losses of hard partons in rescattering on the constituents off the dense matter. Moreover, it should be possible to keep these sources of background under control by estimating the rate of same-sign dimuons, as far as the muons from pion/kaon decays are uncorrelated.

Therefore, for the muon transverse momentum greater than 10 GeV/c the main contributions to dimuon mass spectra in the range $20 \div 50$ GeV are $b\bar{b}$ fragmentation and Drell-Yan production. It is possible to distinguish these two processes because muons from b fragmentation are accompanied by hadrons within a narrow cone, while Drell-Yan μ pairs are isolated. For this purpose one can use the information from the calorimeters of the CMS detector.

The granularity for the hadronic (HCAL) and the electromagnetic (ECAL) calorimeters is expected to be quite different. We have assumed granularities to be $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for HCAL and 0.0145×0.0145 for ECAL. The energy resolution for the calorimeter response was parameterized by the following expression:

$$\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b. \qquad (4)$$

The values of parameters a and b are the following: 2.0%, 0.5% for the ECAL and 68.0%, 5.0% for the HCAL, respectively.

Figure 7 presents the transverse energy deposition in calorimeters within the narrow cone of the radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.176$, around a muon coming from $b\bar{b}$ and Drell-Yan production, as well as for minimum bias Pb–Pb events. This radius of the cone corresponds to the size of 2 HCAL cells, and was found to be optimal for our purposes. Accompanied transverse energy is much larger for b quark fragmentation, and this can be used to distinguish different processes of dimuon production. It is interesting to note that using the information from the hadronic calorimeter only gives better results: the strong magnetic field 4 T allows only charged particles with $P_T > 0.8$ GeV/c to reach the calorimeter, thus getting rid of the background of soft pions and kaons.

5. Results and Conclusion

We have performed the Monte-Carlo simulation of the processes contributing to the sample of high invariant mass dimuons in lead-lead collisions at LHC, with the CMS detector. For two weeks of running time at the design luminocity, CMS detector will be able to detect about 6400 events of $Z \to \mu^+\mu^-$ decays with the background less than 5%. The relative contribution of other processes into the overall sample of the $\mu^+\mu^-$ pairs are found to depend strongly on the applied cuts on the lepton transverse momenta and the invariant mass of the pair. For example, for $P_T > 5$ GeV/c and 20 GeV $< M_{\mu^+\mu^-} <$ 50 GeV the contribution from open beauty decays is quite large, yielding about 15600 events. However, for this transverse momentum cut the contribution from QCD jet events is very high. This background can be reduced by using a higher cut $P_T > 10$ GeV. For this cutoff, the Drell-Yan contribution becomes comparable in the above mass range. Using the information from the hadronic and electromagnetic calorimeters, it should be possible to distinguish the dimuons coming from open beauty decays from those of Drell-Yan type processes. It should be noted that next-to-leading order QCD processes have not been included in our simulation, so the real number of detected $\mu^+\mu^-$ pairs should be greater by a factor of 2.

Thus, after the above cuts, one expects about 6 thousands of measured dimuon events originating from b-hadron decays, with a relatively small background. This should be enough for using this process as a reference for studying Υ family suppression in Pb–Pb collisions. This is a reasonable choice, because both Υ and open beauty are produced mainly in gluon-gluon collisions, with similar values of the subprocess energies, so that any initial state corrections (e.g. structure function variation, etc.) are expected to cancel in the ratio. Moreover, both Υ and open beauty are detected as lepton pairs, thus reducing the systematic uncertainties of the measurement.

However, as our knowledge of the properties of the final state in the collisions of heavy nuclei is at present very limited, one should also use other reference processes as well. Another good choice is the Z boson production, which is completely free of final state interaction effects. However, in this case the production mechanism is mainly dominated by initial quarks and antiquarks, and the *Z* mass is somewhat too high. This latter process can be used as a reference for the dileptons originating from open beauty decays – in this case one could check the influence of the final state interactions on *b*-quark fragmentation.

In order to make definitive conclusions about the formation of quark-gluon plasma and study its properties, it is necessary to investigate the dependence of various measured parameters upon the energy density in the collision of two nuclei. This can be achieved by using nuclei with various atomic numbers, from bare protons to $A \sim 200$. Obviously, all the manifestations of QGP critically depend on its temperature and size, which are higher for heavier nuclei, but similar studies for lighter nuclei can successfully complement them because of higher luminosities and lower backgrounds. Indeed, the energy density achieved in central Nb–Nb collisions should not be much smaller than in Pb–Pb interactions [25], still above the expected phase transition value, and because of much higher luminosity $L_{\mathrm{Nb}}/L_{\mathrm{Nb}} = 90$, would result in a significantly greater statistics.

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