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Heavy Ion Physics with CMS Detector

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Abstract

The CMS detector is well suited to study heavy ion physics. Hermetic calorimetry, a precise inner tracking and a background free muon system make possible to study a wide range of phenomena, including quark-gluon plasma (QGP) formation. Trigger and data acquisition systems are flexible enough to cope with a large range of rates and particle densities.

In this paper we describe those features of the CMS detector which are important for heavy ion physics. We also discuss its physics potential with the emphasis on hard QGP probes, like jet quenching and resonance suppression.

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1 Heavy ion collisions in CMS

The Large Hadron Collider can accelerate various ion species ranging from oxygen to lead. Unprecedented energies per nucleon-nucleon pair of $\sqrt{s_{NN}} = 5.5\text{--}7\text{ TeV}$ and very high luminosity are especially suitable to study dense hadronic matter. A dedicated detector — ALICE — is being build to study heavy ion physics at LHC [1]. However, two general purpose LHC detectors, ATLAS and CMS, are also capable of studying this physics. The ATLAS Collaboration expressed an interest in heavy ion physics only recently and the work on evaluation of its physics potential has just started. Therefore, we concentrate in this paper on the CMS detector and its heavy ion physics programme.

1.1 Cross-sections and rates

Nominal running conditions for all ion species to be collided at LHC are given in Table 1. Luminosities and rates averaged over run period will be roughly two times lower than the maximum values given in Table 1. Collision rates are calculated for the CMS experiment assuming that another experiment is also collecting data at the same time.

Table 1: Heavy ion collisions in CMS. Nominal luminosities and rates calculated assuming two running experiments and 125 ns bunch spacing.

	p-p	O-O	Ar-Ar	Kr-Kr	Sn-Sn	Pb-Pb
A	1	16	40	84	120	208
Z	1	8	18	36	50	82
$\sigma[\text{barn}]$	0.55	1.5	3.1	4.5	5.5	8.0
luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	10^{34}	$3.1 \cdot 10^{31}$	10^{30}	$6.6 \cdot 10^{28}$	$1.7 \cdot 10^{28}$	10^{27}
collision rate [kHz]	500 000	46 500	3100	300	94	8

It is worth noting that probably one cannot use the maximal luminosity available for the LHC in the case of O-O collisions. In this case the average collision rate is 6 times higher then the bunch crossing frequency and one should expect a pile-up of several O-O collisions in every bunch crossing. This makes it impossible to measure the centrality of each collision which is crucial for most of the studies. Therefore, it is recommended to reduce the luminosity to the level of $10^{30}\text{cm}^{-2}\text{s}^{-1}$.

2 Physics goals

The physics programme to be studied by the CMS experiment with heavy ions is very rich. Proton-nucleus collisions can be used to measure nuclear structure functions and to study parton propagation in cold hadronic matter. They are very useful in attempts to understand heavy ion interaction models. They also provide basic normalization for nucleus-nucleus collisions.

Peripheral nucleus-nucleus collisions can turn the LHC into a $\gamma\gamma$ or γN collider. They are useful for hadron spectroscopy. They might also be used to search for higgs and SUSY particles. The large charges of colliding nuclei result in high $\gamma\gamma$ effective luminosity which could make such a study competitive with the standard proton-proton approach, although details need to be worked out yet.

In this paper, we concentrate mainly on central nucleus-nucleus collisions and hard probes of quark gluon plasma, namely jet quenching and resonance suppression. For the rest of the CMS physics programme we refer the reader to a comprehensive review given in Ref. [2]. All simulation results presented in this paper are based on HIJING Monte Carlo.

3 CMS as a detector for heavy ion physics

A schematic layout of the CMS detector is shown in Fig. 1. Going from the beam pipe outward, the detector consists of a pixel detector, silicon tracker, electromagnetic calorimeter (ECAL), the hadronic calorimeter (HCAL), the superconductive coil and the muon system. All subdetectors are described in detail in Ref. [3]. Here we concentrate only on those features which are crucial for heavy ion physics.

Figure 1: The CMS detector.

Both electromagnetic and hadronic calorimetry is important for jet detection and centrality measurement. ECAL is made of PbWO_4 crystals. HCAL barrel and endcap detectors are built as a copper and scintillator sandwich. Combined together, they provide a good energy resolution $\sigma/E_T = (0.8-1.2)/\sqrt{E_T} + 0.05$. Forward calorimeters made of quartz fibers cover up to $|\eta| = 5$ and ensure good hermeticity. A very useful feature in the environment with high particle density is the good granularity of the calorimetry equal to $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for the HCAL and 0.017×0.017 for the ECAL.

The measurement of muons from Υ and Z^0 decays is performed by the inner tracker and the muon system. These systems cover a wide pseudorapidity range of $-2.4 < \eta < 2.4$. Especially important is the central rapidity region which is expected to be relatively free of baryons.

The muon system consists of Drift Tubes in the barrel, Cathode Strip Chambers in the endcap and Resistive Plate Chambers in both regions. The muon chambers are arranged in four stations interleaved by the return yoke iron. Thickness of the absorber in front of muon stations is sufficient to keep them almost free from other particles while preserving relatively low value of the p_T cut-off for muons. It is equal to 3.5 GeV in the barrel and decreases down to 1.5 GeV in the endcap. This is adequate to provide good statistics for $\Upsilon \rightarrow \mu\mu$.

Analysis of $\Upsilon \rightarrow \mu\mu$ requires efficient suppression of the $\pi, K \rightarrow \mu$ background. The compact design of the CMS detector, with the ECAL of only 1.3 m from the beam leaves a rather short possible decay length for pions and kaons. Stringent vertex constraints given by a pixel detector are crucial for prompt muon recognition. Precise track measurements in the silicon tracker planes make it possible to observe a kink caused by a $\pi, K \rightarrow \mu$ decay; this makes tracking efficiency for prompt muons ≈ 6 times better than for those from hadron decays. Last but not least, the 4 T magnetic field in the tracker makes it possible to measure the upsilon mass with an excellent precision of ≈ 50 MeV.

It is important to note that all these features are in the baseline CMS design which thus does not require any change for heavy ion physics studies.

4 Centrality measurement

Phenomena occurring during the collisions of nuclei depend crucially on how central the collision is. Quark gluon plasma is more likely to be produced in central collisions where a higher energy density is expected. Therefore it is important to be able to measure the impact parameter b of colliding nuclei. The most promising way to make such measurement with the CMS detector is to look at the total transverse energy ΣE_T defined as a scalar sum of energies deposited in each calorimeter cell (ECAL+HCAL) multiplied by $\sin \theta$ of this cell.

Fig. 2 shows the strong correlation between ΣE_T and b , which makes possible a relatively precise measurement of b . One can see from Fig. 3 that the precision is better than 1 fm.

Figure 2: Correlation between the total transverse energy ΣE_T and the impact parameter b .

Figure 3: Accuracy of the impact parameter measured with E_T flow in the Hadron Forward (HF) calorimeter ($3 < |\eta| < 5$) for Ar-Ar collisions. Triangles — particle level HIJING Monte Carlo expectations, circles — taking into account the HF response.

5 Jet quenching

One of the most promising hard probes of quark gluon plasma is the so called "jet quenching" [4]-[6]. Partons traversing dense matter should be losing energy by radiating gluons. Therefore jets created by such partons should be softer if QGP were formed. For this reason it is important to measure jet energy quite precisely. In the following sections we describe calorimetric measurements of the jet transverse energy E_T . It is planned, however, to study transverse and possibly longitudinal energy flows using both calorimetric and tracker methods.

5.1 Background subtraction

Jet recognition in heavy ion collisions is difficult because of the underlying background of large number of particles. In the case of central Pb-Pb collisions one can expect up to 8000 soft charged particles per rapidity unit. This means that every calorimeter cell is hit by a number of particles. The rapidity distribution of the deposited energy is shown in Fig. 4. One can see that most of the energy of the soft underlying event is deposited in the ECAL. The average energy deposit $\langle E_T^{\text{tower}} \rangle$ in ECAL towers (5×5 crystals), and its fluctuation $\sigma(E_T^{\text{tower}})$ are given in the table below.

	$\langle E_T^{\text{tower}} \rangle$	$\sigma(E_T^{\text{tower}})$
barrel	4.4 GeV	1.3 GeV
endcap	9.6 GeV	3.9 GeV

Figure 4: Average energy deposit in calorimeter cells.

This underlying background must be subtracted before any attempt at jet finding. An example of such a procedure is shown in Fig. 5. A single jet (upper plot) is superimposed on a central Ar-Ar collision (middle plot) assuming 800 charged particles per rapidity unit. After background subtraction (lower plot) the jet is again well visible.

Ar+Ar, 1 event, $\sqrt{s}=6.3A$ TeV, $b=0$ fm, $E_T^{\text{jet}}=40$ GeV

Figure 5: Single 40 GeV jet (upper plot) superimposed on Ar-Ar central collision (middle plot), after background subtraction (lower plot).

5.2 Jet reconstruction

Jets are reconstructed with a usual sliding window algorithm, assuming a jet radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ of 0.6-0.7. The best results can be obtained with the following iterative procedure.

1. An average background is calculated for each ring of $\Delta\eta \times \Delta\phi = 0.087 \times 2\pi$ and subtracted from the event. At this step the background is overestimated, because jets are not excluded.
2. The jet finding sliding window algorithm is applied.
3. For each jet found a cone is built around the tower with the maximum energy deposit.
4. The average background is recalculated excluding the jet cones.
5. The jet energy is recalculated.

Efficiency of this algorithm is shown in Fig. 6. It is better than 90 % for jets with $E_T > 50$ GeV in the case of Ar-Ar central collisions and $E_T > 100$ GeV in the Pb-Pb case. The obtained energy resolution $\sigma(E_T)/E_T$ is about 19 % (at $E_T = 100$ GeV, $|\eta| < 1.5$), which is 30-40 % worse than in the pp case. The rate of fake dijets is $\approx 1\%$ of the real di-jet rate after cutting on jet radius and for $E_T > 100$ GeV [7].

Figure 6: Jet reconstruction efficiency as a function of generated jet E_T in central Ar-Ar and Pb-Pb collisions ($|\eta| < 1.5$).

5.3 Energy loss for gluons

The energy loss by gluons traversing dense matter can be studied measuring the ratio of monojet to dijet events [7]. Pairs of jets are produced in processes like $gg \rightarrow gg$. If we look for jets with transverse energy above certain threshold E_T it might happen that one of the jets from a given pair will not cross the threshold because of energy loss fluctuation. As a result, a certain number of dijet events will be identified as monojet ones. Therefore, a larger monojet/dijet ratio is expected if QGP was formed. This is illustrated in Fig. 7, where the collisional energy loss of leading gluon (outside the jet cone) ΔE of 9 and 18 GeV was assumed. The jet radius of $R=0.6$ was used.

Some effect is also present for $\Delta E = 0$ because of finite energy resolution of the detector, but it is significantly smaller than the one for $\Delta E = 9$ GeV.

5.4 Energy loss for quarks

The energy loss for quarks can be studied with $Z^0/\gamma + \text{jet}$ events [8]. The Z^0 and γ are produced mainly in the process $q_1 + g \rightarrow q_2 + Z^0/\gamma$. On average, the transverse energy of the recoil jet q_2 should be equal to that of Z^0 or γ . However, due to initial state gluon radiation and finite energy resolution of the calorimeters, they are exactly equal only on average, but not for each particular event. If the hard collision process took place in a dense matter the quark q_2 will lose some energy traversing the medium (QGP), which is not the case for electroweakly interacting Z^0 or γ . Thus, the difference $E_T^\gamma - E_T^{\text{jet}}$ can be used as a measure of the quark energy loss. This is illustrated in Fig. 8 showing the distributions of $E_T^\gamma - E_T^{\text{jet}}$ for the assumed collisional energy loss of leading quark (outside the jet cone) ΔE of 0, 4 and 8 GeV. The distributions are quite broad, but the shift due to the energy loss is well visible. Statistics shown in Fig. 8 corresponds to 1600 events in the $\gamma + \text{jet}$ channel collected in 2 weeks of Pb-Pb running with $\mathcal{L} = 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$. For the $Z^0 (\rightarrow \mu\mu) + \text{jet}$ channel one expects about 180 events in the same conditions. This was estimated assuming no shadowing, but it was checked with EKS parametrisation [9] that in such relatively high x and Q^2 domain the influence of shadowing corrections is very small. An alternative method to study b-quark energy losses with dimuons is proposed in [10].

Figure 7: Monojet/dijet ratio for an energy loss of 0, 9 and 18 GeV. The lowest curve shows the generator level simulation, others take into account the detector response.

Figure 8: Distribution of $E_T^\gamma - E_T^{\text{jet}}$ for an assumed energy loss ΔE of 0, 4 and 8 GeV in Pb-Pb collisions. Background from isolated $\pi^0 + \text{jet}$ is shown as a hatched area.

6 Resonance suppression

In heavy ion collisions many quarkonia resonances are produced. If they are formed within a quark gluon plasma it may screen the colour field and break some of them. Therefore, it is believed that the presence of QGP should reduce the number of observed resonances. Stronger reduction is expected for the states with lower binding energy. Suppression of the J/ψ and ψ' has been already observed at the CERN SPS and it is being studied extensively at RHIC. At LHC this role of the QGP probe will be taken by the Υ family [11].

In the following sections we describe the expected performance of the CMS experiment for the $\Upsilon, \Upsilon', \Upsilon'' \rightarrow \mu\mu$ channels. We consider the most demanding case of central Pb-Pb collisions with 8000 charged particles per rapidity unit. Recent results from RHIC indicate that this number is rather overestimated, which provides us with a desirable safety margin.

6.1 Reconstruction of muon pairs

A special algorithm has been developed for efficient muon reconstruction in the high particle density environment of up to $dN_{ch}/dy = 8000$ [12]. It makes use of muon chambers, pixel detector and five outermost silicon tracker layers as these are the only detectors with occupancy $< 20\%$ at this track density (see Fig. 9).

It might be surprising that the algorithm starts from the pixel detector where the track density is the highest. However, in these extreme conditions, pixels have occupancy below 1% due to the very high granularity ($100 \times 150 \mu\text{m}^2$). High precision 3D points make possible to find a longitudinal vertex position z with accuracy of $\sigma_z = 140 \mu\text{m}$ (see Fig. 10). This is a very powerful constraint against the combinatorial background.

Figure 9: Occupancy in 5 outermost silicon tracker layers in the case of central Pb-Pb collisions with $dN_{ch}/dy = 8000$.

Figure 10: Vertex position z in cm reconstructed with pixel detector in an event with $dN_{ch}/dy = 2500$ (a) and 8000 (b).

The full algorithm consists of the following steps.

1. Primary vertex determination

- select pairs of pixel hits (in layers at $R = 7$ and 11 cm) compatible with a track of $p_T > 0.5$ GeV
- extrapolate each pair in the non-bending RZ plane to the beam line

2. Track finding

- select tracks in the first muon station ($p_T > 3.5$ GeV)
- extrapolate inwards from the muon chambers to the tracker and then, from plane to plane using both transverse and longitudinal vertex constraints

3. Track selection by cuts on

- fit quality (χ^2)
- kink sensitive variable $\Sigma(\phi_{\text{pred}} - \phi_{\text{meas}})^2 / \sigma_\phi^2$ to kill $\pi, K \rightarrow \mu$
- vertex constraint

Performance of the algorithm for $\Upsilon \rightarrow \mu\mu$ events in the CMS barrel is summarized in Table 2. The obtained mass resolution for Υ is 46 MeV which enables clear separation of Υ , Υ' and Υ'' states.

Table 2: $\Upsilon \rightarrow \mu\mu$ reconstruction performance in Pb-Pb collisions.

	min. bias	central
dN_{ch}/dy	2500	8000
$\Upsilon \rightarrow \mu\mu$ signal efficiency	90 %	75 %
$\pi, K \rightarrow \mu$ background efficiency	15 %	12 %
purity	99 %	97 %

6.2 Υ detection

The expected number of reconstructed upsilons is given by the expression $N = \mathcal{L} \cdot \sigma \cdot \Delta t \cdot \epsilon$ where ϵ is a product of all efficiencies listed in Table 3.

Table 3: Estimated efficiencies for $\Upsilon \rightarrow \mu\mu$ detection in central Pb-Pb collisions.

machine efficiency	50 %
acceptance in the barrel	22 %
trigger efficiency	40 %
reconstruction efficiency	75 %

The expected statistics of $\Upsilon \rightarrow \mu\mu$ events is given in Table 4. Fig. 11 shows the resulting invariant mass spectra for the opposite sign dimuons in the case of Pb-Pb collisions. Further background reduction can be achieved subtracting the combinatorial contribution to the opposite sign muon pairs assuming that it is equal to the number of events with muons of the same sign: $N_{\text{signal}} = N_{+-} - 2\sqrt{N_{++} \cdot N_{--}}$. The result is shown in Fig. 12. The Υ , Υ' and Υ'' peaks are clearly visible.

Figure 11: Opposite sign dimuon invariant mass spectra assuming no suppression within Υ family.

Table 4: $\Upsilon \rightarrow \mu\mu$ statistics for $\Delta t = 1 \text{ month} = 2.6 \cdot 10^6 \text{ s}$.

	Ar-Ar	Kr-Kr	Pb-Pb
$L [\text{cm}^{-2}\text{s}^{-1}]$	$5 \cdot 10^{29}$	$3 \cdot 10^{28}$	$4 \cdot 10^{26}$
$\sigma [\mu\text{b}]$	20	70	410
events	860 000	180 000	14 000

Figure 12: Dimuon invariant mass spectra after background subtraction, assuming no suppression within Υ family.

6.3 $Z^0 \rightarrow \mu\mu$ channel

In previous experiments at the CERN SPS, J/ψ production was compared to the dilepton continuum, produced mainly via the Drell-Yan process of γ^*/Z^{0*} exchange. At the LHC, the continuum will be more difficult to understand because of an important contribution from semileptonic $c\bar{c}$ and $b\bar{b}$ decays, nuclear shadowing effects, etc. An alternative normalization can be provided by Z^0 production which should not be influenced by the presence of the quark-gluon plasma. However, one should keep in mind that the production mechanism is different ($q\bar{q}$ and $qg + \bar{q}g$ instead of gg) and nuclear effects might depend on mass, i.e. on x_{Bjorken} of parton.

Fig. 13 shows $\mu\mu$ invariant mass spectra for Z^0 production and other processes. One can expect 10000 $Z^0 \rightarrow \mu\mu$ events during 1 month of Pb-Pb running. It is worth noting that the Z^0 mass can be reconstructed with precision better than 5 GeV with muon chambers only, thus avoiding the difficult environment inside the inner tracker. This feature can be used for an experimental determination of track reconstruction quality within the tracker.

7 Trigger and data acquisition (DAQ)

Let us now discuss how to trigger on channels described in previous sections and what are the data volumes to be read-out and stored by the Data Acquisition System (DAQ). Once more we assume the most demanding case of central Pb-Pb collisions with $dN_{ch}/dy = 8000$ at $\mathcal{L} = 10^{27} \text{ cm}^{-2}\text{s}^{-1}$.

7.1 Trigger rates

Jet quenching phenomena described in section 5 can be selected with a two-jet trigger [13]. Transverse energy threshold of 40-50 GeV at the first level (LV1) leads to an LV1 output rate of 400-200 Hz. At higher levels (HLT) a sharper cut at 100 GeV reduces this rate down to 10 Hz. Centrality trigger based on ΣE_T is also very important and it deserves a dedicated study.

Figure 13: Dimuon invariant mass distributions obtained with muon chambers only for $|\eta| < 2.4$. The Z^0 peak is well reconstructed.

A single photon trigger is very effective for the $\gamma + \text{jet}$ channel (Sec. 5.4). $E_T > 50 \text{ GeV}$ cut at HLT gives an output rate below 1 Hz [13].

For the $\Upsilon \rightarrow \mu\mu$ channel (Sec. 6) the following strategy is proposed. All events with at least one muon recognized by the muon trigger are accepted at level 1. This puts an effective threshold in the barrel of $p_T > 3.5$ and 80 % efficiency. The efficiency is increasing with p_T and exceeds 90 % at $p_T \geq 4 \text{ GeV}$. The resulting rate is 500 Hz, dominated by background. At higher levels the second muon is searched for and the rate is reduced down to about 60 Hz.

Adding all channels together less than 1 kHz is expected at the LV1 trigger output and about 70 Hz of events should be written to the mass storage.

7.2 Data volumes

Data volumes needed to study jet events in the full detector and muon events in the barrel are listed in Table 5. The dominant contributions come from the pixel detector and silicon tracker. The muon system is relatively empty. Calorimeters are 100 % occupied, but one can save on data volume compared to the pp case by taking only one time slice of the ECAL data. In the pp case one has to store ECAL data for about 10 consecutive bunch crossings in order to resolve pile-up from different crossings. In the Pb-Pb case the distance between interactions is of the order of 10 ms, hence there is no bunch-to-bunch pile-up.

Table 5: Data volumes per event assuming $dN_{ch}/dy = 8000$

Detector	k Bytes
Pixel barrel	300
Tracker barrel (5 planes)	1000
ECAL - 1 time slice	170
HCAL full	30
Muon chambers	50

The total event size is thus about 1.5 megabytes which is only 1.5 time more than for a typical pp event. Assuming a mass storage capability of 100 MB/s, one can record about 70 events/s which is just what we have calculated as the expected trigger rate in the previous section. If larger mass storage is available it can be used to include the tracker endcap.

A safety margin is provided by the pessimistic assumption of $dN_{ch}/dy = 8000$. This number is conservative even

for central Pb-Pb collisions and of course not all recorded collisions will be central. Thus, one can conclude with confidence that the CMS Trigger and Data Acquisition Systems are powerful and flexible enough to cope with heavy ion runs without any modifications.

8 Conclusions

CMS is a good detector for heavy ion physics without any modifications. A wide range of phenomena can be studied including detailed investigation of QGP formation. Jet quenching can be measured thanks to fine grain calorimeters covering $-5 < \eta < 5$. The $\Upsilon, \Upsilon', \Upsilon'' \rightarrow \mu\mu$ channels can be used to study the suppression of resonance production thanks to

- a background free muon system covering $-2.4 < \eta < 2.4$ (adjacent to the ALICE coverage of $2.4 < \eta < 4.0$), with a low p_T threshold of 3.5 GeV
- a precise Si tracker providing a mass resolution of ≈ 50 MeV in the Υ range
- a low occupancy ($< 1\%$ for Pb-Pb) pixel detector, crucial for background rejection.

The trigger and DAQ systems can handle the expected rates and data volumes. Almost 4π coverage ensures high statistics and makes possible energy flow centrality measurement. All these features make CMS competitive and complementary to ALICE — a detector dedicated to heavy ion physics. The two detectors observe the same phenomena in different ways which is very useful for cross-checking and understanding the results.

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References

- [1] Y. Foka: *Hadronic measurements in ALICE*, this volume;
P. Crochet: *Heavy quark measurements in ALICE*, this volume
- [2] G. Baur et al.: CERN CMS NOTE 2000/060, to be published in Eur.Phys.J. C
- [3] M. Della Negra: *CMS*, this volume
- [4] M. Bedjidian et al.: *Jet physics in CMS heavy ion programme*, CMS NOTE 1999/016
- [5] I.P.Lokhtin, A.M.Snigirev: *Angular structure of energy losses of hard jet in dense QCD-matter*, Phys. Lett. B 440 (1998) 163
- [6] I.P.Lokhtin, A.M.Snigirev: *Nuclear geometry of jet quenching*, Eur.Phys.J. C16 (2000) 527
- [7] I.Lokhtin et al.: *Studies of dijet and monojet rates in heavy ion collisions with CMS*, CERN CMS NOTE 1998/025
- [8] A.Nikitenko et al.: *Study of gamma+Jet channel in heavy ion collisions with CMS*, CERN CMS NOTE 1998/063
- [9] K.J. Eskola, V.J. Kolhinen and C.A. Salgado, Eur.Phys.J. C9 (1999) 61
- [10] I.P. Lokhtin, A.M. Snigirev: *High-Mass Dimuon and Secondary J/ψ Production at CMS as Probes of Medium-Induced Energy Losses of Bottom Quarks in Heavy Ion Collisions*, CERN CMS NOTE-2001/008
- [11] M.Bedjidian and O.Drapier: *Detection of Heavy Quark Resonances with Heavy Ion Beams in CMS*, CERN CMS NOTE-1999/052
- [12] M. Bedjidian, O. Kodolova, S. Petrouchanko: *Dimuon Reconstruction in Heavy Ion Collisions Using a Detailed Description of CMS Geometry*, CMS NOTE-1999/004
- [13] A. Nikitenko et al.: *Estimations of L1 calo trigger rates in heavy ion collisions at CMS*, CERN CMS Note 1998/078