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Heavy Ion Physics with the CMS Detector

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Abstract

The status of the CMS Heavy Ion Program is presented. The methodical aspects of jet and quarkonium reconstruction and charge particle tracking using the trackers and calorimeters of the CMS apparatus are discussed, focusing on high multiplicity environment in heavy ion collisions at the LHC.

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1 CMS Detector and Heavy Ion Program

The Compact Muon Solenoid (CMS) is a general purpose detector designed primarily to search for Higgs boson in proton-proton collisions at LHC [1]. This is a large acceptance detector optimized for accurate measurements of the characteristics of high energy leptons, photons and hadronic jets, which provides unique possibility to make “hard probes” in both pp and AA collisions [2]. The detailed description of the CMS apparatus can be found in the corresponding Technical Design Reports [3, 4, 5, 6]. The basic element of CMS is a 13 m long, high-field (4 T) solenoid with internal radius of ~ 3 m. The tracker and the muon chambers cover the pseudorapidity region $|\eta| < 2.4$, while the electromagnetic (ECAL) and hadron (HCAL) calorimeters reach the values $\eta = \pm 3$ and $\eta = \pm 5.2$ respectively. A pair of quartz-fibre “very forward” (HF) calorimeters, ± 11 m distant from the interaction point, cover the region $3 < |\eta| < 5.2$. In addition, a quartz-fibre calorimeter named CASTOR covers the region $5.2 < |\eta| < 6.6$, and yet another “zero degree” calorimeter ZDC located as far as 140 m from the interaction point — the region $|\eta| \geq 8.3$. The high precision tracker of CMS apparatus, composed of silicon pixel and strip detectors, allows track reconstruction and its momentum estimation with a resolution better than 2% in the region p_T between 0.5 GeV/c and few tens GeV/c (fig. 1).

Figure 1: CMS detector.

The CMS experiment is an excellent tool for implementation of Heavy Ion (HI) Program. High rates and hence large cross-sections for specific reactions, combined with the large acceptance tracking and calorimetry, allow access to hard probes of quark-gluon plasma, quarkonia (J/ψ , Υ), heavy quarks ($b\bar{b}$) and Z^0 , high p_T jets, as well as jet-jet, jet- γ , jet- γ^*/Z^0 correlations.

Also of interest are global event characteristics — centrality, energy flow in the very forward direction, charged particle multiplicity, azimuthal anisotropy.

CASTOR and ZDC are the important supplements extending the area of observations to so called forward physics and ultra-peripheral interactions: limiting fragmentation, saturation, color glass condensate, exotics.

2 Quarkonia and Heavy Quarks

Quark-gluon plasma gets hotter and lives longer as energy increases from $\sqrt{s} = 200$ GeV/n-n (RHIC) to 5500 GeV/n-n (LHC). Quarkonia (J/ψ , ψ' , Υ , Υ' , Υ'') and Z^0 should be observed with high statistics under the conditions of LHC. Large cross-section for heavy quark (b , c) production allows evaluation of medium-induced energy loss of partons from the spectra of large mass $\mu\mu$ pairs and secondary J/ψ . For more detail on dimuon and quarkonia reconstruction in Pb-Pb interactions see the talk of Olga Kodolova to this conference.

3 Jets and Jet Quenching

The algorithm of jet reconstruction in HI collisions is based on event-by-event η -dependent background subtraction. This work started in 1994 [7] and has been in progress up to now [8, 9, 10].

The possibility of hard QCD jet reconstruction with initial parton energies in the range $50 \div 300$ GeV was investigated in central Pb-Pb collisions (HIJING model). In application to the CMS calorimeter system, the subtraction procedure was found to allow the identification and measurements of jets from heavy ion collisions with very high efficiency and purity basing on calorimeter data only. On average, the measured jet energy in Pb-Pb collisions is the same as that in jet events without background. For jets above 75 GeV, the energy resolution for a jet reconstructed in heavy ion environment appears to be by a factor ~ 1.3 worse as compared to jet events without background. The direction of hard jet axis in heavy ion environment can be determined with high accuracy: the uncertainty in the values η and φ is smaller than the size of single calorimeter tower.

One of the important tools for studying the properties of quark-gluon plasma (QGP) in ultrarelativistic heavy ion collisions is the analysis of QCD jet production: medium-induced energy loss of energetic partons (jet quenching) is very different in cold nuclear matter and in QGP, resulting in many specific observable phenomena. The energy lost by partons in the nuclear matter appears to be 10^2 times larger than that in a hadron gas (HG).

The jet quenching should manifest itself in p_T distribution, elliptic flow, jet fragmentation function, distribution of azimuthal angles in non-central HI collisions, and other characteristics. More detailed discussion on this subject is presented in the talk of I.P.Lokhtin to this conference.

4 Global Event Characteristics

The global event characteristics that may be studied at the initial stage of the experiment are the centrality of collision, multiplicity, various correlations and the energy flow down to very low p_T .

The determination of collision centrality is based on its correlation with the energy deposition in calorimeters [11]. The CMS calorimeters, HF and CASTOR would reveal this correlation most distinctly (maximum energy deposition and minimum relative energy fluctuations) (fig. 2).

Figure 2: Correlation between transverse energy deposition E_T in HF acceptance and collision impact parameter b .

Average resolution of impact parameter determination for Pb-Pb and Ar-Ar collisions ranges from 0.5 fm (central events) to 1 fm (peripheral events).

Non-central HI collisions ($b \neq 0$) imply the elliptic volume of interacting nuclear matter. The energy flow is the effect of azimuthally anisotropic elliptic volume. CMS calorimeter data allow determination of the event plane [12], although the azimuthal anisotropy can be estimated without the determination of this plane. The correlation between the energy flow and the azimuthal angle φ for Pb-Pb collision with the impact parameter $b = 6$ fm is presented in fig. 3.

Determination of the primary charged particle multiplicity is based on the relation between the pseudorapidity

Figure 3: Energy flow for azimuthal angle φ .

Figure 4: Distribution of charged particle multiplicity for pseudorapidity η .

distribution of reconstructed clusters in the innermost layer of the CMS pixel tracker and that of charged particle tracks originating from the primary vertex (fig. 4). The event-by-event analysis shows that the reconstructed multiplicity is within 1-2% of its true value in the region $|\eta| < 2$.

5 Monte-Carlo Simulation Tools

In the majority of existing HI event generators such important effects as jet quenching and elliptic flow are not duly considered or ignored. Special Monte-Carlo tools were developed for fast and adequate simulation of physics phenomena. These are [13]: PYQUEN — simulation of jet quenching, HYDRO — simulation of transverse and elliptic flow in central and semi-central $A + A$ collisions, HYDJET — combination of HYDRO (flow effects), PYTHIA (hard jet production) and PYQUEN (jet quenching) (see the talk of I.P.Lokhtin for more detail).

6 Summary

At LHC energies, a new regime of heavy ion physics will be reached: the hard particle production prevailing over the soft processes and the initial gluon density being much higher than at RHIC energies. This implies that strong parton energy loss would likely become observable in certain new reaction channels.

CMS is an excellent device for the study of quark-gluon plasma using hard probes:

- quarkonia and heavy quarks;
- jets, “jet quenching” in various reaction channels.

CMS will also yield information on global event characteristics at high energies:

- centrality, multiplicity;
- correlation and energy flow down to very low p_T .

CMS is assumed to take advantage of its unique capabilities:

- excellent rapidity and azimuthal coverage, high resolution;
- large acceptance, nearly hermetic geometry, fine granularity of hadronic and electromagnetic calorimeters;
- precision muon and tracking systems;
- new high level trigger algorithms designed specially for $A + A$ collisions;
- ZDC and CASTOR as the important supplements extending the range of observables to the forward physics.

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