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Ultra-relativistic heavy ion experiments : a perspective

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1. Introduction

A great interest has arisen over the last few years in the study of ultra relativistic heavy ion collisions due to the possibility of producing Quark-Gluon Plasma (QGP) if the energy density reached in those collisions is sufficiently high. Although theoretical predictions based on Quantum Chromodynamics (QCD) about the possibility of producing and studying QGP in laboratory is more than a decade old, experimental attempts at understanding the reaction mechanism of ultra-relativistic heavy ion collisions started only just six years ago with the availability of 200A GeV oxygen beams at the CERN SPS and a year later with 14.5A GeV oxygen and silicon beams at the Brookhaven AGS. Since then experiments have been progressively updated in order to fully understand the background processes so that exotic events , if any, could be filtered out with greater degree of reliability. Table 1 gives a summary of the present and future facilities.

Table 1 (a). Time frame of Relativistic Heavy Ion Collision studies

Time	Machine	Beam	CM Energy (A GeV)	ΔE GeV/fm^3
1986–93	BNL-AGS	< ^{28}Si	5	
	CERN-SPS	< ^{32}S	20	
1993–98	AGS + Booster	All A	4 (Pb)	
	SPS + Injector	All A	17 (Pb)	~ 2.5
1998–...	RHIC	All A	200 (Pb)	~ 4.5
	LHC	All A	6300 (Pb)	~ 6–8

The subject has expanded considerably and a number of review articles have been published in addition to the regular proceedings of the Quark Matter series of conferences. Refs. [1–5] give a comprehensive list of introductory as well as up-to-date literature in this field.

Experimental searches for QGP are based on a number of theoretically predicted signals. As the plasma is expected to have a very short lifetime (10^{-24} sec.) and the final products are a result of hadronization processes, it is extremely important to understand the nature and extent of all the background processes that might

Table 1 (b). Comparison of particle density at various energies

	SPS		LHC
	S + Au	Pb + Pb	Pb + Pb
CM Energy	20	17	6300
$\left(\frac{dN_{ch}}{dy}\right)_{cms}$	160	~ 500	~ 2000
$(y_{lab})_{cms}$	2.5	2.9	0
$\left(\frac{dN_{ch}}{d\Omega}\right)_{cms}$	1000	~ 7000	~ 300

either mock up the signal or submerge it. Also, it is to be understood that the formation of QGP is a collective process and should stand out as compared to the superposition of nucleon-nucleon ($N - N$) and nucleon-nucleus ($N - A$) collision processes. Hence it also becomes the duty of the experimenters to investigate and understand the nature of $N - N$ and $N - A$ collisions.

A pre-requisite to searches for QGP in experiments is a good trigger for impact parameter selection. Peripheral collisions are not expected to produce sufficient energy density to lead to QGP formation. A good central collision trigger helps produce cleaner data samples with minimum confusion.

In what follows, we describe a representative experiment to illustrate what observables are required to be measured and what types of detector systems are being used. For want of space it is not possible to present many experimental setups and their results. The importance of photons as signals for QGP is stressed and our own efforts to study photon emission in ultra-relativistic heavy ion collisions is described in detail. The future of these experiments with the availability of lead beams at the CERN SPS and later at the LHC is briefly described in section 4 and a summary given in the last section.

2. Experiments at CERN SPS : a case study of the WA93 experiment

The experimental setup in general consists of a minimum of two components - a detector system to measure the physical variable of interest and another to provide suitable trigger for the beam interaction and events of interest. (In special cases e.g, emulsion experiments, the two can be merged). It is important to have a good trigger setup to record only useful data so as to keep the data volumes within manageable limits. Although there are wide variations in the experimental hardwares of different groups, there are always basic common features. As a representative case we describe below the setup of the WA93 collaboration [6] to which our group is also associated.

The goals of the WA93 experiment are as follows -

1. to measure, event-by-event, the momentum of a large number of charged particles in a large phase space region with a resolution sufficient to determine Bose-Einstein correlations of negatively charged particles, the relevant detectors being the Multi-Step Avalanche Counters (MSAC's),

2. to carry out high precision measurements of the production of π^0's and η's

(with transverse momentum p_T of about 200 MeV/c to 4 GeV/c for π^0's),

3. to measure the photon multiplicity in the forward hemisphere in the centre-of-mass system using a highly segmented preshower Photon Multiplicity Detector (PMD).

In addition the events are to be characterized globally by

(a) their impact parameter (as provided by the energy measurement in the Zero Degree calorimeter (ZDC)),

(b) their transverse energy flow, and

(c) their charged particle multiplicity.

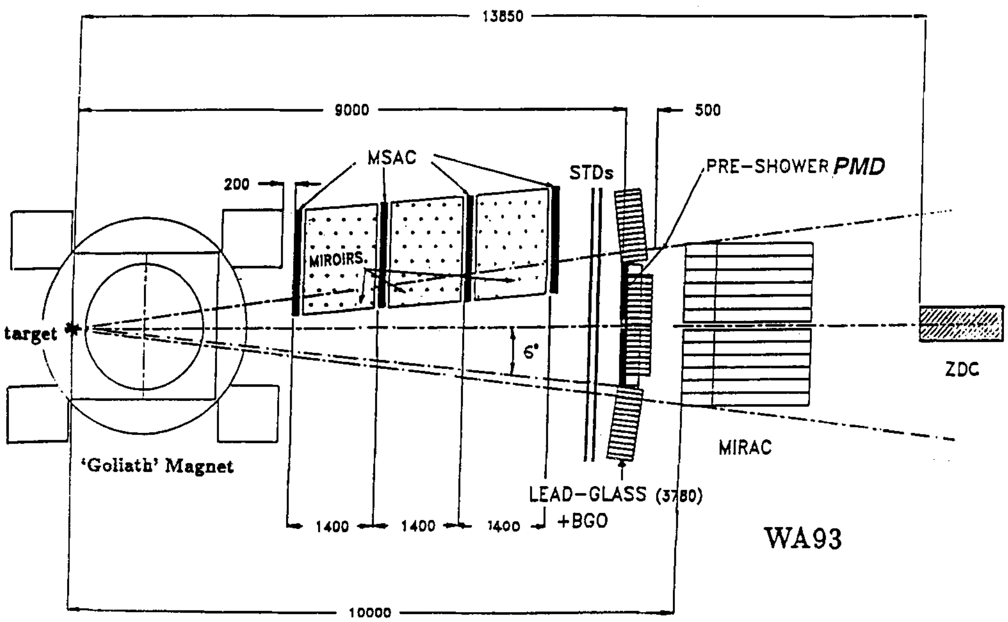

Figure 1. The WA93 experimental setup at CERN SPS

Measurements of the transverse flow of e.m. energy in comparison with the total transverse energy E_T, as well as with the one deduced from the multiplicity of the charged particles and from their mean p_T will also be used to focus on events that might involve large production of direct photons.

The experimental hardware of this experiment is schematically shown in Fig. 1. A summary of the various detectors used to measure the relevant observables is given in Table 2. It is clearly reflected that WA93 is a well balanced experiment covering a large solid angle.

The WA93 experiment has taken two runs of data during October-November 1991 and April-May 1992. Apart from the MSAC and PMD the setup is essentially the same as the old WA80 experiment. Details of the photon measurement in this experiment are given in the next section.

Table 2. List of observables and related detectors in WA93 experiment

Variable	Detector
$d\sigma/dE_T$	MIRAC
$d\sigma/dN_{ch}$, dN_{ch}/dy	Streamer tube detectors
Hadron identification	MSAC + Magnet
$\left(\frac{d\sigma}{dp_T}\right)_{\pi,K,...}$	MSAC + Magnet
HBT	MSAC + Magnet
Cont. γ's (everything)	Lead glass calorimeter
N_γ, N_γ/N_{ch}	PMD (+ STD)
b	ZDC + MIRAC
N_{proj}, N_{targ}	ZDC + TRC
γ/π^0	LGC

3. Photons in relativistic heavy ion collision

3.1. Photons as a QGP signal

Photons as a useful signature of QGP have been predicted for a long time [7] . Their usefulness arises from the fact that they interact only electromagnetically and hence have a negligible chance of getting contaminated in the intervening hadronic matter once they are produced. This enables them to probe the entire volume of the plasma of the size likely to be produced in such collisions. Also, the copious production of photons takes place in the early stage of the life of a plasma when it is very hot and very dense. In contrast, signals associated with hadrons are likely to be strongly affected by the final state interaction as they suffer their last interaction on the cool surface of the plasma or they are emitted in bulk at the time of freeze-out.

Of all the photons produced in relativistic heavy ion collisions that one measures experimentally, a large part comes from background sources e.g. hadronic decays like

$$\pi^0 \rightarrow 2\gamma, \ \eta \rightarrow 2\gamma \qquad \text{etc.}$$

By measuring the total energy and emission angle (E, θ) of the γ's, one can also reconstruct an invariant mass spectrum corresponding to π^0, η etc. These π^0's can then be used in much the same way as π^- for the interferometry analysis giving pion source radii.One can also calculate the ratio γ/π^0 from the experiment as a function of transverse momentum and compare with theoretically predicted values. Excess photons expected to come from QGP are likely to be reflected in the p_T window about 1-2 GeV/c. At much larger p_T, contributions from the direct QCD photons become important and at very low p_T hadronic bremsstrahlung makes large contributions.

Such a measurement of γ/π^0 ratio using the fine granularity lead glass calorimeter has been done by the WA80 group . For the *O+Au* reaction at 200 GeV analyzed in detail, it is found that direct thermal photons, if any, are less than 15% of the total at 90% confidence level [8].

An alternative and elegant way of studying photon production in QGP is to measure the multiplicity N_γ. For non-QGP processes it is expected that $N_{ch} \sim N_\gamma$

(N_{ch} consists of mostly π^+ and N_γ consists of mostly $\pi^0 \to 2\gamma$ and, if $N_{\pi^+} \sim N_{\pi^-} \sim N_{\pi^0}$, then $N_{ch} \sim N_\gamma$) and considering the slight photon excess in the incoming channel we have $N_\gamma/N_{ch} < 1$. For Pb+Pb collision we are dealing with about 2000 particles and hence the fluctuation in N_γ/N_{ch} is very small. Fig. 2 shows a VENUS simulation for the case.

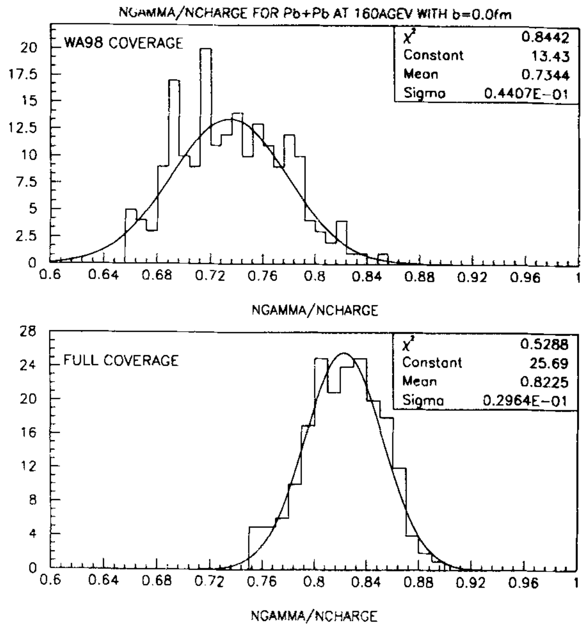

Figure 2. VENUS simulation of N_γ/N_{ch} for Pb + Pb collision at 160*A* GeV: (bottom) full acceptance in 4π, (top) WA98 PMD acceptance.

If we now consider excess photons to be produced in events leading to QGP formation, they should be reflected in the measured N_γ/N_{ch} values on event by event basis. In the ideal case that all the central trigger events lead to QGP formation, the peak in the Fig. 2 should shift towards right. In case only a fraction of the events leads to QGP formation, the shape of the distribution should change producing either a shoulder or a right asymmetry.This can be defected by careful statistical analysis. What we require is a high granularity detector for measuring N_γ over a large solid angle.

3.2. Photon multiplicity detector

3.2.1. Description of the detector

The present Photon Multiplicity Detector (PMD) consists of a matrix of 7600 plastic scintilator pads of size 20 mm x 20 mm x 3 mm arranged in 76 rows having 100 pads each placed behind 3 radiation length thick lead converter plate. The light from the scintillator pads is collected and transported using 1 mm dia 2 meter long wavelength shifting optical fibres glued into the diagonal holes in the pads.

The WLS fibre is inserted into light tight black PVC sleeves for protection from absorption of any stray light. The pad is then wrapped in double sided aluminised mylar foil (see Fig. 3 for details).

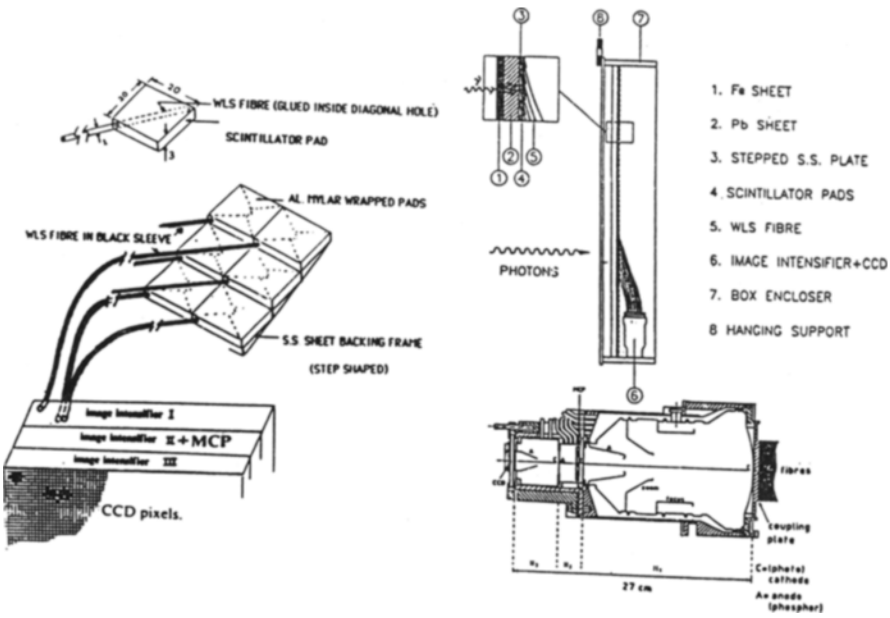

Figure 3. Physical layout of PMD : the box and II + CCD system.

The whole detector is arranged in the form of four quadrants each having 1900 pads. The other end of the 1900 WLS fibres is inserted into a perforated coupling plate having 1.1 mm dia holes with centre to centre separation of 1.3 mm . The set of 50 × 38 holes are contained within a diameter of 80 mm to match the diameter of the photo cathode of the first stage of the read out system. The fibre bundles as a whole is glued to the grid plate and then ends are machined and polished to mirror finish. The assembled detector is housed in a light tight box.

The bundle is coupled to a 3-stage image intensifier and CCD camera system for readout as used in the scintillating fibre detector of UA2 experiment at CERN (see Fig. 3 for details). Each quadrant of the PMD having 1900 fibres used one set of II+CCD system. The image of the grid plate is demagnified from 80 mm dia to about 7 mm dia in the three stages. Light amplification of the order of 800 is achieved using a microchannel plate in the second stage.

CCD pixel charge is digitized using a purpose built fastbus module employing an 8-bit 20 MHz FADC obtained from UA2 group.The pixel-to-fibre map can be loaded into the digitizer and a compact data format containing the fibre number,the sum of contributions from all pixels assigned to that fibre and their number can be generated by the fastbus module. Data can be recorded both in the form of full CCD frame image (pixel numbers with their ADC values)and in the compressed form using only pad signal obtained after data compaction.

3.2.2. Data analysis and results

The analysis of data obtained with the photon multiplicity detector consists of two stages :

(i) understanding the behaviour of minimum ionizing particle signlas on the PMD, so that an efficient algorithm can be developed for thier rejection on an event-by-event basis, and

(ii) developement of clustering algorithm forgammas and mips and then to use these with (i) for counting gammas and to study its distributions.

Early simulation results showed that because of the large number of particles falling on the detector, the total energy deposited on the PMD and also the total transverse component of this energy are rather well determined quantity. It is thus hoped that a measure of E_t complemetary to that of MIRAC can be obtained from PMD data.

The behaviour of minimum ionizing particles on PMD have been deduced using the sulphur beam data by taking isolated clusters having essentially single-pad energy deposition (minor details arising due to imperfections in pixel-to-fibre map of the CCD read out is being omitted here). Fig. 4 shows the resulting shape of mip signal at the top while that from geant simulation is shown on the bottom of the picture. For filtering mips and counting gammas, we have used a cluster-level ADC threshold of 3 mips. At the present situation it is estimated that about 20% of hadrons and their reaction products get mixed up with the gamma cluster at this threshold level. Fine-tuning of these is still in progress.

For the priliminary analysis presented here, the innermost part of the detector where cluster overlap is rather high has been omitted, leaving the η-coverage to only 2.8-4.0. The number of gamma clusters identified on the PMD is plotted in Fig. 5 against the energy deposited on the zero degree calorimter (ZDC). The nice anti-correlation is clearly seen suggesting that at least for off-line analysis purposes the PMD itself can be used as the trigger for the centrality of the events.

Using the "central" trigger based on ZDC-LOW logic, a sample of events have been analysed. The pseudo-rapidity distribution of γ's thus obtained is shown in top part of Fig. 6 along with the result from VENUS event genetaor for the case of impact parameter ≤ 1 fm. Although the hight of the curves are not yet properly matched and the systematic uncertainties on $dn_\gamma/d\eta$ are still under investigation, the first results are very encouraging in that the shape of the distributions nicely match. The psuedo-rapidity distribition values for gammas are similar to those for charged particles measured earlier in the WA80 experiment for the same projectile-target combination [9].

The bottom part of Fig. 6 shows the $dE_t/d\eta$ distribution in the accepted η-range of PMD. These values compare well with the published results of WA80 experiment for the same target projectile combinations. These results also are very encouraging.

4. The future of photon multiplicity measurements

The above discussions and the preliminary results obtained with the prototype photon multiplicity detector have given us very good insight into the behaviour of

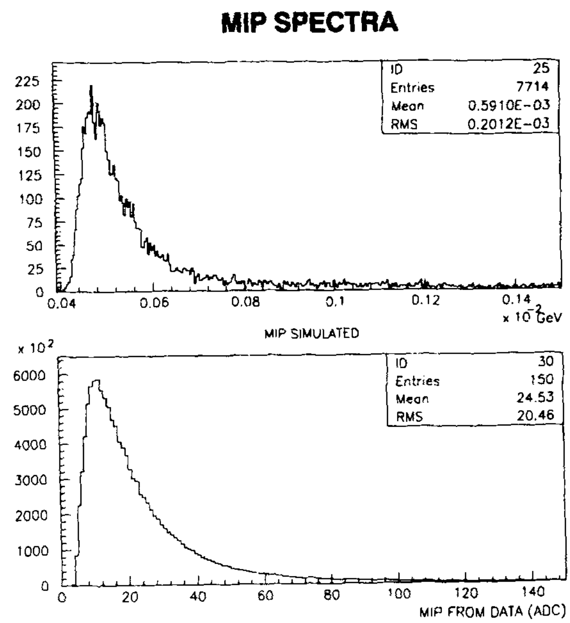

Figure 4. (top) ADC Distribution of minimum ionizing particle signal on the PMD, (bottom) GEANT simulation for the energy deposition by mips on PMD.

such a preshower detector for photon counting applications. An improved design has already been worked out for the lead beam experiment cheduled for fall 1994. This detector will cover the region $\eta = 2.5$ to 4.5 and will have varying granularity at different angular regions to contain the pad multiple hits to within acceptable limits. The detector will have about 55,000 scintillator pads and will be covering about 21 sq.m. area. This detector is already under fabriaction and tests are scheduled for July 1993. Top part of Fig. 2 shown the number of Venus γ's falling on the detector and it has a sigma of about 6.5%. This should be the limit to the accuracy with which photon multiplicity can be determined in the next experiment.

The task of photon multiplicity measurement at the Large Hadron Collider (LHC) of CERN is rather difficult because of two reasons : (a) in the mid-rapidity region where the space density of particles is manageable, the photon energies are rather too low for a meaningful conversion efficiency at the preshower stage, (b) at larger rapidities the particle density becomes prohibitive. However if a suitable technology is chosen in which transverse segmentation is comparatively easier and the material is radiation resitant, it may be worthwhile to investigate the possiblities of photon counting using a preshower detector at larger rapidites.

The liquid Argon based sampling calorimieter offers such a technology where both photon counting in the preshower region and total electromagnetic energy measurement might be possible. Very preliminary simulation results using HIJING event generator and EGS programs indicate the possibilities of such measuremets if the detector is placed at suitable distances from the interaction point ($6m$ to $20m$) at least in the η-region upto 3.5 [10]. Detiled simulation is in progress.

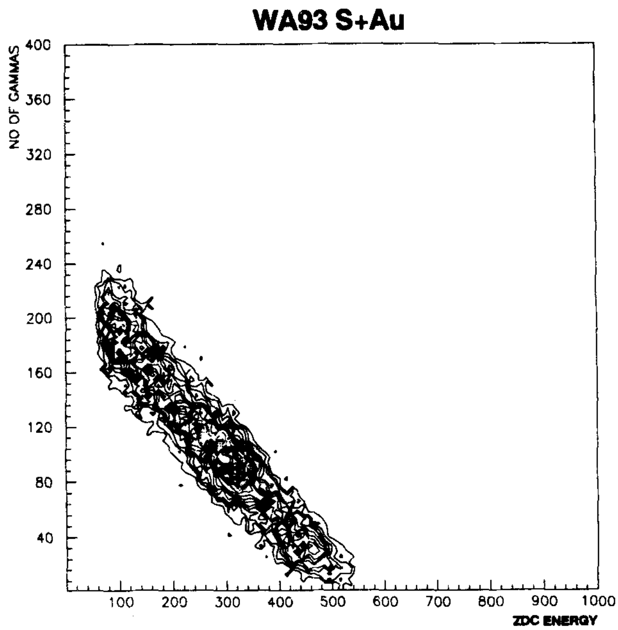

Figure 5. Anti-correlation between the energy deposited in the Zero Degree Calorimter (ZDC) and the number of gammas on the PMD.

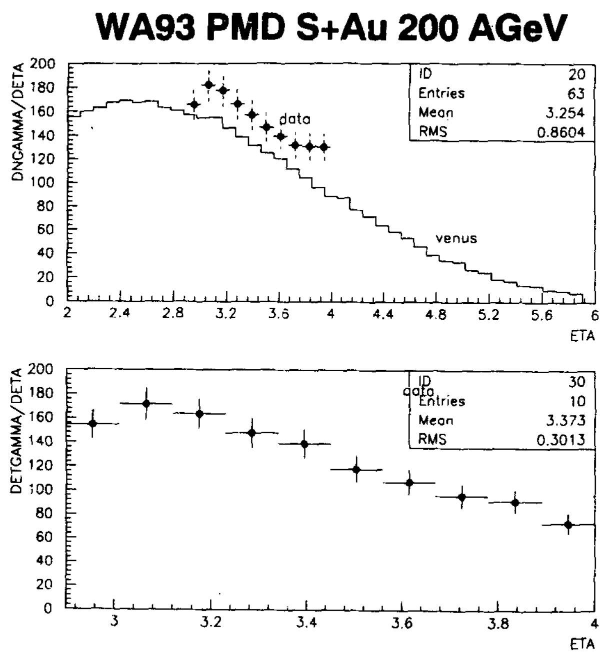

Figure 6. (Top) Pseudo-rapidity distribution of gammas in the $S+Au$ reaction at $200A$ GeV (solid points are experimental data) along with the results of VENUS event generator (both histograms and fitted continuous curve). (Bottom) Pseudo-rapidity distribution of electromagnetic transverse energy as measure by PMD.

5. Summary and future outlook

The present generation of experiments have certainly shown great promise in the measurement of relevant observables for QGP signals. The photon multiplicity measurement emerges as a good new possibility to study the excess production of thermal direct photons. In conjunction with observables in the same experiment, this should provide unambiguous signatures of phase transition.

The just concluded experiments with light heavy ions at the CERN SPS will be complemented with beams of heaviest elements within the next two years.Fixed target experiments at SPS using $160A$ GeV lead ions are being preapred and WA98 experiment [11] is expected to be much more versatile and exhuastive in measurement of several physical observables. As shown in Table 1, one should expect to achieve an energy density at least about 3 GeV/fm^3 in collisions of Pb on Pb. With spatial particle density increasing almost seven-fold, one will have to move the detectors much farther from the target than at present to measure anything with sufficient granularity, avoiding large multi-hit probabilities. For the WA98 setup it is proposed to move the detectors like PMD to 22m. The detector sizes will have to be correspondingly increased to cover the same amount of phase space as in reactions with $200A$ GeV sulphur ions.

Colliding beam facilities like the Relativistic Heavy Ion Collider (RHIC) at Brookhaven and the Large Hadron Collider (LHC) at CERN are expected to be operational just before the close of the century. For the physics in the mid-rapidity region a lot of discussions have already taken place [12] and the detectors to be used for tracking, charged particle multiplicity measurement and particle identification are in an advanced R & D stage.

The emerging new physics to be studied in the large η regions, like jet quenching, minijet productions, photon-depleted "Centauro"-like events etc. demand a large coverage of the phase space with capability to measure at least the electromagnetic transverse energy. By choosing a suitable technology, it is hoped that photon multiplicity measurements will also be possible in this region without much difficulty and using reasonable pad sizes in the preshower regions.

The collider experiments should see the final drama in the study of QGP phase transition as the expected energy density is 6-8 GeV /fm^3. As theoretical study progress and mature, the relative significance of signals as compared to backgrounds will be more clearly understood. On the whole the coming years will see many more exciting results.

Acknowledgements

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Discussion

R.V. Gavai : You quoted a large dN/dy of 8000. What is its theoretical basis/origin?

Y.P. Viyogi : Ranft's code gives $\frac{dN}{dy}|_{y=0} \sim 8000$. However this should be considered a pessimistic upper limit.