

## Quantum chromodynamics: Working group report

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**Abstract.** This is the report of the QCD working group at WHEPP-6. Discussions and work on heavy ion collisions, polarized scattering, and collider phenomenology are reported.

**Keywords.** QCD; polarized scattering; light front field theory; heavy ion physics; non-equilibrium field theory; parton distributions at LHC; fragmentation functions; event shapes.

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### 1. Introduction

Sunanda Banerjee, Rahul Basu, Rajeev Bhalerao, M Dittmar, Rajiv Gavai, François Gelis, Dilip Ghosh, Sourendu Gupta, A Harindranath, D Indumathi, Rajen Kundu, Kajori Majumdar, Asmita Mukherjee, Krishnendu Mukherjee, R Ratabole, V Ravindran, H S Sharatchandra, Ajit Mohan Srivastava, W L van Neerven and Raju Venugopalan participated in the QCD working group.

The working group activity was structured around talks followed by discussions. The emphasis in this working group was on these discussions, which were usually moderated by the speaker.

In view of the forthcoming runs of RHIC, there is currently much interest in the experimental programs of heavy-ion physics and spin-physics. There are groups in the country which are actively interested in both kinds of physics. As a result, a major group of talks focussed on heavy-ion physics and polarized hard scattering. There were also discussions on QCD at colliders, light front QCD, non-equilibrium field theory and the confinement mechanism in QCD. Some of these discussions have already led to detailed work and publications, and some more work will come out of this meeting.

A list of the discussion talks is given in table 1. The talk by Harindranath is part of this proceedings, and the content of the talks by Venugopalan and Srivastava have been

**Table 1.** List of discussion talks and speakers in the QCD working group.

Confinement in QCD	H S Sharatchandra
Light front QCD	A Harindranath
Polarized gluon density	S Gupta
LHC as a parton collider	M Dittmar
Heavy-ion collisions	R V Gavai
Low-X gluons in nuclei	R Venugopalan
Non-equilibrium field theory	F Gelis
Disoriented chiral condensates	A M Srivastava
Thermalization in heavy-ion collisions	R Venugopalan
QCD in polarized scattering	W L van Neerven
Low-X fragmentation	D Indumathi
Light front QCD	A Mukherjee

included in their contributions to this proceedings. This report summarizes the rest of the talks and work by participants in this working group.

## 2. Determining polarized parton densities

D Ghosh, Sourendu Gupta and D Indumathi

It is widely known that the polarized gluon density is not determined well by current data on polarized deep inelastic scattering. This is surprising. After all  $\alpha_s$  is known to good accuracy after LEP. Then knowledge of the variation with  $Q^2$  of the structure function  $g_1(x, Q^2)$  should be enough to give us a good handle on the polarized gluon density.

The argument is correct, but measurement errors are large in the region where the slope of  $g_1$  determines the polarized gluon density. At present an NLO analysis can only determine the sign of the first moment of the polarized gluon density (it is negative in the  $\overline{MS}$  scheme).

Another surprise is that the world data on  $g_1$  can be fitted equally well by flavour SU(2) symmetric sea as by one in which this symmetry is maximally violated. Again this is due to errors in  $g_1$  at moderately low values of  $x$ .

It turns out that improved polarized DIS measurements at  $x < 0.1$  would be sufficient to remove a large part of the uncertainty in polarized sea and gluon densities. Details have now been published in [1].

## 3. Transverse spin and polarized DIS

Asmita Mukherjee

The complexities of spin of a composite system in the equal time formulation of relativistic quantum field theory is well known [2]. The Pauli–Lubansky operators qualify for the spin operators only in the rest frame of the particle. In an arbitrary frame the situation is complex because of the complicated interaction dependence arising from the dynamical

boost generators in both longitudinal and transverse spin operators and the difficulty of the separation of the center of mass motion from the internal motion [3].

Light front theory gives a unique opportunity to address the issue of the relativistic spin operators in an arbitrary reference frame since boost is kinematical in this formulation [6]. The longitudinal spin operator (light front helicity) is interaction independent and the interaction dependence of the transverse spin operators arise solely due to the transverse rotation operators [4]. We have derived the transverse spin operators for QCD starting from the manifestly symmetric, gauge invariant energy-momentum tensor in the light-front gauge. These can be separated into three parts; the first part depends on the coordinates explicitly, the other two parts ('intrinsic') come from the fermionic and gluonic parts of the energy-momentum tensor respectively. The fermionic part is directly related to the integral of  $g_T$  [7]. In analogy with the helicity sum rule [8], we propose a transverse spin sum rule.

#### **4. Enhancement of intermediate mass range dimuons in $A - A'$ collisions**

R V Gvai

$J/\psi$ -suppression has been regarded as a clean probe of quark-gluon plasma formation in heavy ion ( $A - A'$ ) collisions. A lot of excitement has been created recently by the announcement [9] of the CERN NA50 experiment, reporting anomalous suppression in Pb-Pb collisions.  $J/\psi$  is detected in NA50 (and in its predecessor NA38) as a peak in dimuon spectrum at its known mass of 3.1 GeV. One needs to understand well the continuum  $\mu^+ \mu^-$ -spectrum in the mass range around the  $J/\psi$  mass in order to extract the  $J/\psi$  cross-section and then check for suppression or otherwise. The continuum spectrum is in itself interesting as possible thermal effects may show up in it, giving another window on the hot QGP or thermal matter.

NA50 reported an enhancement [10] in the dimuon spectrum in the intermediate mass range, defined as that between 1.6 and 2.5 GeV, for S-U and Pb-Pb collisions. Using PYTHIA 6.1 to get shapes of Drell-Yan and open charm contribution (with different intrinsic  $k_T$  for the two) and  $m_c = 1.5$  GeV, open charm cross section is obtained by fitting the normalizations of these and  $J/\psi$  and  $\psi'$  terms to the data. While this exercise gave open charm cross section for  $p - A$  which was in agreement with other measurements, its extrapolation to the S-U and Pb-Pb cases are lower than the data, with the enhancement in data increasing as a function of  $E_T$ .

The working group discussed the possibilities that the excess may be due to (1) the absorbed or broken  $J/\psi$  in nuclear environment or (2) thermal dileptons [11] or (3) due to the extrapolation procedure in comparing the  $pA$  with  $AA'$ . It is hoped that they will be taken up for detailed studies in near future.

#### **5. Out-of-equilibrium field theory**

F Gelis

A naive way to generalize thermal field theory to out-of-equilibrium situations is to replace the Bose-Einstein and Fermi-Dirac distributions by arbitrary functions describing the state

of the system. The new statistical functions are kept constant in time. This simplification seems reasonable for systems that return very slowly to their equilibrium state, in which one is interested by a very fast microscopic process.

However, it was noticed in [12] that infinities known as ‘pinch singularities’ (and appear as products of  $\delta$  functions with the same argument) do not cancel if one uses this procedure, even for arbitrary small departures from equilibrium, contradicting the heuristic argument used to justify the procedure.

In [13], it was shown that giving a decay width to the particles would regularize this problem. Reference [14] showed that these singularities do not appear if one takes into account the relaxation of the system towards equilibrium.

Recently, [15] unified these two different solutions by showing that the pinch singularities cancel if one let the statistical weights evolve in time according to a Boltzmann equation (the relation with [13] is that the collision term of the Boltzmann equation is responsible for the decay width of the particles). In this improved procedure, the would-be singular terms are finite and of order  $\tau_{\text{micro}}/\tau_{\text{relax}}$  where  $\tau_{\text{relax}}$  is the relaxation time of the system, and  $\tau_{\text{micro}}$  is the timescale of the microscopic process one is studying, in agreement with the intuitive argument stated before.

## 6. LHC as a parton collider

M Dittmar

A new approach to the luminosity, parton distribution functions and cross-section measurements at the LHC is proposed [16]. The proposal considers the LHC directly as parton–parton collider. The combination of parton distribution functions and the proton–proton luminosities has thus to be replaced with parton–parton luminosities, which can be measured precisely from theoretically well understood reactions [17]. Candidates for reactions which constrain the quark and antiquark luminosities are the resonance production of  $W$  and  $Z$  bosons with their leptonic decays. Gluon luminosities can be constrained from events with high transverse momentum photons,  $W$  and  $Z$  bosons which are dominated by the scattering of quarks and gluons [18,19].

Studies indicate that the above reactions can be measured with negligible statistical errors and that experimental systematic uncertainties of perhaps  $\pm 1\%$  can probably be obtained up to rapidities of 2.5. The analysis of the rapidity distributions for the above reactions provides very accurate parton–parton luminosities for parton  $x$  ranges between 0.0001 and 0.2 at  $Q^2 \approx 10^4 \text{ GeV}^2$  and higher.

Following these optimistic experimental possibilities, and if future theoretical calculations can achieve similar accuracies for other processes relative to the control reactions, the LHC experiments can give precision cross sections for various final states.

## 7. Fragmentation functions at low- $x$

D Indumathi

Consider coherent time-like branching. If an external line emits a gluon, this introduces a propagator factor that not only leads to collinear enhancement, but also soft enhancement

as the gluon energy  $\omega \rightarrow 0$ . This factor leads to angular ordering of successive branches and hence to jet formation. In short, when soft enhancements are summed, they interfere destructively to reduce the phase space. The jet production cross-section can be expressed in terms of the fragmentation functions  $D_i^h(x, Q^2)$  where  $x = p \cdot q/Q^2$  is also the momentum fraction of the fragmentating parton,  $i$ , carried by the hadron  $h$ , in the parton model. The scaling violations of the fragmentation functions can be expressed in terms of the DGLAP evolution equations [20], analogous to the case of parton density distributions. We have

$$\frac{\partial}{\partial \log t} D_i(x, t) = \sum_j \int_x^1 \frac{d\alpha_s}{z 2\pi} P_{ji}(z, \alpha_s) D_j(x/z, t), \quad (1)$$

where the splitting functions are perturbatively calculable as  $P_{ji} = P_{ji}^0 + (\alpha_s/(2\pi))P_{ji}^1 + \dots$ . The effect of azimuthal ordering can be incorporated by replacing  $t$  by  $z^2 t$  in the argument for  $D_j$  on the RHS of the above equation [21,22]. This modified leading log approximation (MLLA) leads to a gaussian form of the fragmentation function at low- $x$  [21,23]:

$$xD(x, Q) = \frac{N(Q)}{\sqrt{2\pi}\sigma(Q)} \exp \left[ - [\log(x) - \log(x_0)]^2 / [2\sigma^2(Q)] \right], \quad (2)$$

where  $N(Q)$  is the total multiplicity,  $\sigma$  is the width of the gaussian and  $x_0$  is the position of the peak of the gaussian. The  $Q^2$  dependence of  $N$ ,  $\sigma$  and  $x_0$  are computable for total inclusive hadrons as an expansion in terms of the scale parameter,  $Y = \log(Q/\Lambda)$ ,  $\Lambda = 200$  MeV [21].

Comparison with data at  $e^+ e^-$  colliders [24] as well as at the HERA  $ep$  collider [25] shows good agreement with predictions for the scale dependence of the multiplicity as well as the peak position of the Gaussian. Semi-inclusive data on octet baryon and meson production at  $e^+ e^-$  colliders are also well-described [26] in this MLLA approximation. The main motivation was to discuss the approximations involved and validity of application of the theory to collider data.

## 8. Event shapes and power corrections in QCD

R Basu and S Banerjee

Power corrections to the leading twist results of perturbative QCD are being studied, specifically in the context of event shape variables like the thrust. The work of the Milan group gives a systematic methodology of analytically continuing the strong coupling constant to low values of  $Q^2$  using a spectral representation for  $\alpha_s(Q^2)$  [27]. They use it to calculate the leading power corrections to various measurables like hadronic decay widths, structure functions, event shapes in jet cross sections etc. They fit it to data to estimate one of the free parameters in their analysis (called the Milan factor). However calculation of the power corrections, particularly in event shapes like the thrust by including the effect of quark masses was carried out in [28].

Rahul Basu and Sunanda Banerjee used recent measurements of the thrust, coupled with the earlier data and include quark mass corrections from the above paper (particularly for the  $c$  and  $b$  quarks), to reanalyse and get a fresh estimate of the Milan factor. It appears from preliminary analysis that there is a substantial shift in the value of the Milan factor.

Some preliminary details can be presented. The average value of  $1 - T$  for the massless and massive case differ by about 18% at the lowest value of  $E_{cm}$ . The defect between this and the data is presumed to be made up by power correction as given by the Milan group. A fit to the power corrections has been done both for the Milan factor and for  $\alpha_s$ .

The following 2 fits were done — in the first  $\alpha_s$  and  $\alpha_0$  were floated for massless and massive formula. For massless formula the following results were obtained with Milan factor of 1.795:

$\chi^2$	100.532	for 35 points
$\alpha_s$	0.14757	$0.16916 \times 10^{-2}$
$\alpha_0$	0.72956	$0.56922 \times 10^{-2}$

For the massive formula the results were:

$\chi^2$	101.138	for 35 points
$\alpha_s$	0.15035	$0.16034 \times 10^{-2}$
$\alpha_0$	0.72057	$0.63981 \times 10^{-2}$

In the second case  $\alpha_s$ ,  $\alpha_0$  were not floated in the massive formula but the Milan factor was. Then the result is:

$\chi^2$	107.285	for 35 points
Milan	1.7116	$0.21051 \times 10^{-1}$

A more detailed analysis is being carried out and has now been reported in hep-ph/0006008.

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