The limits of a quark’s freedom

Bose-Einstein correlations in one and two dimensions in deep inelastic scattering

In this paper a peculiar quantum mechanical property of particles is used to get information on the region where quarks bind together to produce hadrons.

According to quantum mechanics, the wavefunction of a particle contains all the information about the particle, including its energy and momentum. Particles come in two types. For those known as fermions, no two particles are allowed to have the same wavefunction. However, those known as bosons like to have identical wavefunctions. This means that two bosons which have similar momenta will attempt to make their momenta equal, and so effectively attract one another. This effect is known as Bose-Einstein Correlation.

The size of this effect is determined by how close the particles are when they are produced. So measuring the size of the effect tells us about the size and shape of the source of particles. Since photons, the carriers of light, are bosons, Bose-Einstein Correlations have been used in astronomy to determine the angular diameter of stars and other astronomical objects.

Pions, which are produced in collisions between electrons and protons in the ZEUS experiment at HERA, at DESY in Hamburg, are also bosons. Pions are produced when quarks, which behave like free particles over short distances, reach the limits of their freedom and bind up together under the influence of the strong nuclear force. At HERA, quarks inside the proton are studied in collisions with electrons. The resolution, or distance scale, at which the quark scattering takes place is given by the variable $Q^2$ - high $Q^2$ means a short distance. At some point the scattered quarks, speeding away from the collision, are trapped by the strong force and form pions. Though the quark scattering at high $Q^2$ is well understood in the theory of strong nuclear force (QCD), the pion-formation stage is not. One important question is - Does size of the region over which pions are formed depend upon the size of the quark interaction - in other words on $Q^2$?

In this paper, the size of the pion formation region was measured, using the Bose-Einstein effect, as a function of $Q^2$ (see Fig. 1). In addition, the size was measured in two very different production regions. The size of the production volume does not depend on $Q^2$, over the widest range ever measured. This shows that the size of the pion production region does not depend upon the size of the quark scattering region.
Figure 1: The radius, $r$, of the pion production regions, and the incoherence parameter, $\lambda$ which also describes the strength of the Bose-Einstein effect, as functions of $Q^2$ (left-hand figures). In the right-hand figures the same parameters are shown, now measured in the target region and the current region of the Breit frame, two regions where the properties of the initial quarks are very different. The inner error bars are statistical uncertainties; the outer are statistical and systematic uncertainties added in quadrature.