Proton's internal structure and ridge-like correlations in proton-proton collisions

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Introduction

Analysis of multi-particle angular correlations in *pp* collisions provides detailed information on the properties of particle production and allows one to reconstruct events structure in phase space. Unpredicted by theoretical models novel phenomena in two-particle correlations called "ridge effect" is still not fully understood.

Two-particle correlation

Each particle produced in a collision point (primary vertex) is characterized by its azimuthal angle ϕ, pseudorapidity $\eta = -\ln[\tan(\theta/2)]$ and transverse to the beam direction (z) momentum p_T.

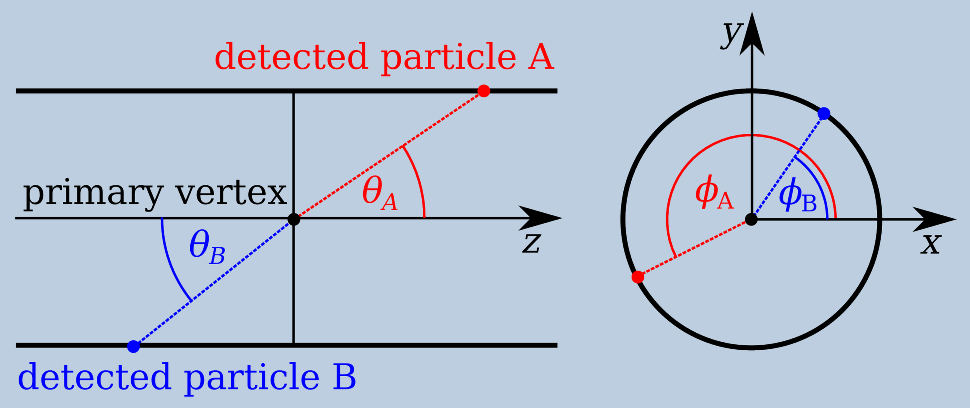

Figure 1: Side and frontview of a beampipe

The normalized pair density function S_N of relative azimuthal angle $\Delta\phi = |\phi_A - \phi_B|$ and pseudorapidity difference $\Delta\eta = |\eta_A - \eta_B|$ is constructed by combining all the pairs from one particular event. The background pair density function B_N pairs particles from different events of the same produced particles' multiplicity N.

$$S_N(\Delta\eta, \Delta\phi) = \frac{1}{N(N-1)} \frac{d^2N^{\text{pairs}}}{d\Delta\eta\, d\Delta\phi} \qquad B_N(\Delta\eta, \Delta\phi) = \frac{1}{N^2} \frac{d^2N^{\text{mixed pairs}}}{d\Delta\eta\, d\Delta\phi}$$

Two-particle correlation R is defined as follows:

$$R(\Delta\eta, \Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

Ridge effect

The correlation function extracted from the *pp* collisions at $\sqrt{s} = 7\,\text{TeV}$ by CMS Collaboration (Fig. 2) exhibits several interesting features. The peak at $(\Delta\eta, \Delta\phi) = (0, 0)$ is caused by jets of collimated hadrons. The elongated structure at $\Delta\phi = 2\pi$ is a signature of momentum conservation in particle production processes. The new and most interesting feature, seen in high multiplicity events, is the ridge-like structure along $\Delta\phi = 0$. There is no obvious reason why such a long-range in pseudorapidity correlation should occur.

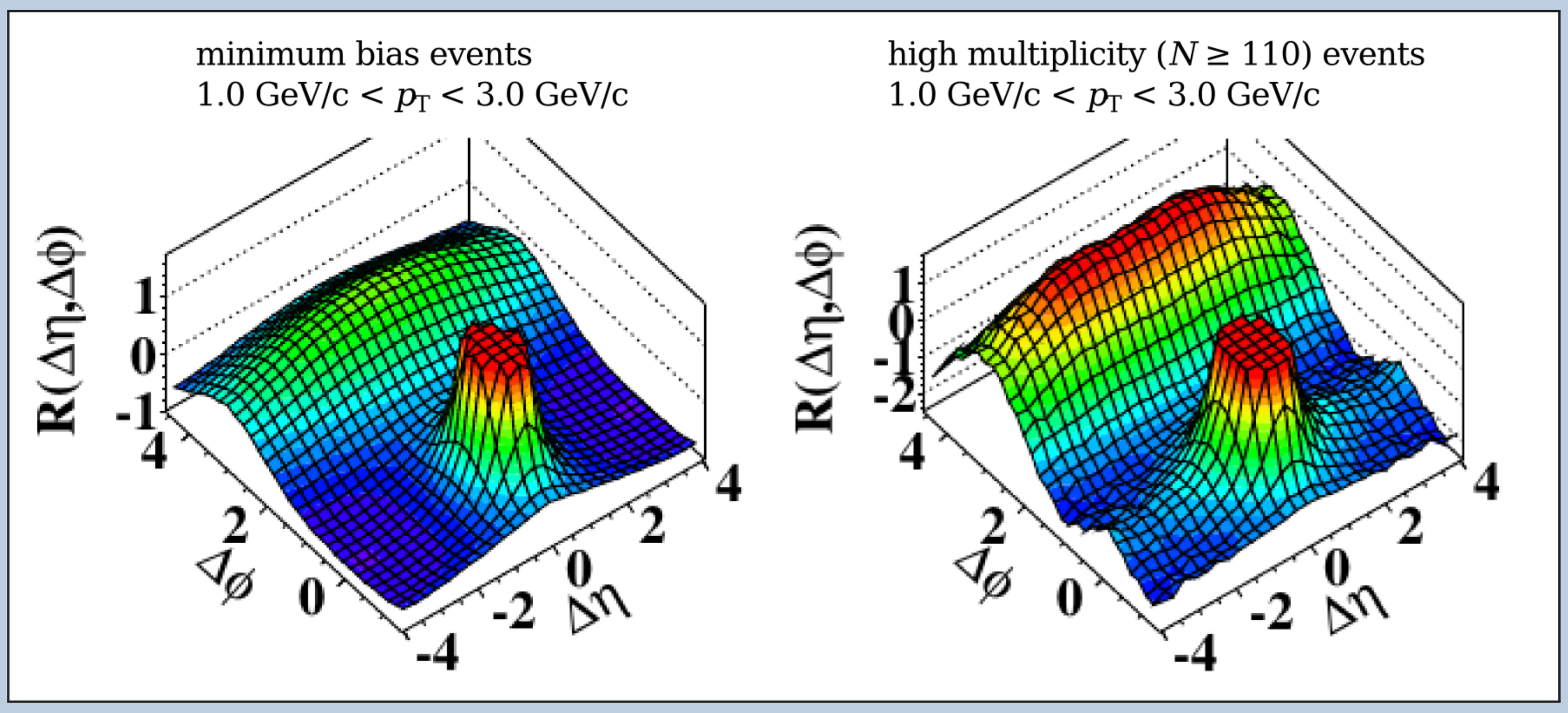

Figure 2: Two-particle charged hadron correlations in the intermediate transverse momentum range at $\sqrt{s} = 7\,\text{TeV}$ for minimum bias (typical) and high multiplicity events measured by the CMS experiment [1]

References

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Hydrodynamic approach

Ridge effect has been previously observed in relativistic heavy-ion collision. The plausible explanation was the collective elliptic flow of hot and dense medium (quark-gluon plasma) created during the collision. An interacting volume of two ions colliding with non-zero impact parameter b is anisotropic in plane xy (Fig. 3). The anisotropy in single-particle momentum yield driven by pressure gradient can be decomposed into Fourier series

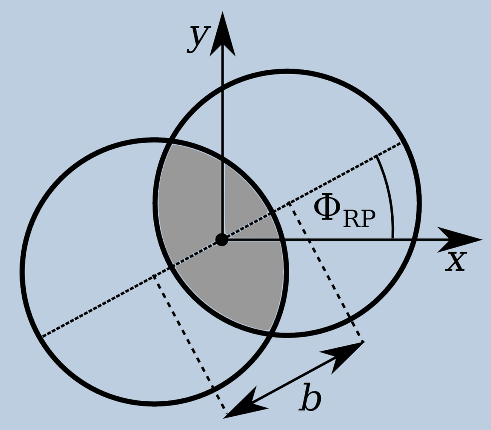

Figure 3: Elliptic shape of interacting matter

$$\frac{d^3N}{d^2\mathbf{p}_T d\eta} = \frac{d^2N}{2\pi p_T dp_T d\eta}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos\left[n(\phi - \Phi_{RP})\right]\right)$$

where $v_n(p_T,\eta) = \langle\cos[n(\phi - \Phi_{RP})]\rangle$.There is a crucial relation between v_n and two-particle azimuthal correlation:

$$\left\langle e^{in(\phi_A - \phi_B)}\right\rangle = \left\langle e^{in(\phi_A - \Phi_{RP})}e^{-in(\phi_B - \Phi_{RP})}\right\rangle = v_n^2 + \delta_n$$

where δ_n is a non-flow correlation. The elliptic flow coefficient v_2 is the largest contribution to ridges in $\Delta\phi = 0$ and $\Delta\phi = \pi$ similar to these in Fig. 2. The v_2 dependence on initial eccentricity $\epsilon = \langle y'^2 - x'^2\rangle / \langle x'^2 + y'^2\rangle$ (x', y' are x, y rotated by angle Φ_{RP}) may be roughly approximated by the formula:

$$\frac{v_2}{\epsilon} = \left(\frac{v_2}{\epsilon}\right)^{\text{hydro}} \frac{1}{1 + K/K_0}$$

where $(v_2/\epsilon)^{\text{hydro}} \approx 0.3$ is the ideal hydrodynamics limit value, Knudsen number $K = \lambda/R$ is a ratio of mean free path λ of partons constituting the medium to the transverse size R of the medium and $K_0 \approx 0.7$ [2].

Possible origin of ridge effect in *pp* collisions

It is not known whether quark-gluon plasma can be produced in *pp* collisions or whether hydrodynamics is applicable in such small systems. Nevertheless, assuming the existence of elliptic flow it is possible to extract v_2 coefficients from the CMS data (Fig. 4). Now one can build a theoretical model for the eccentricity ϵ and compare it with extracted v_2 The eccentricity can be generated not only by a non-zero impact parameter b but also by initial proton density anisotropy.

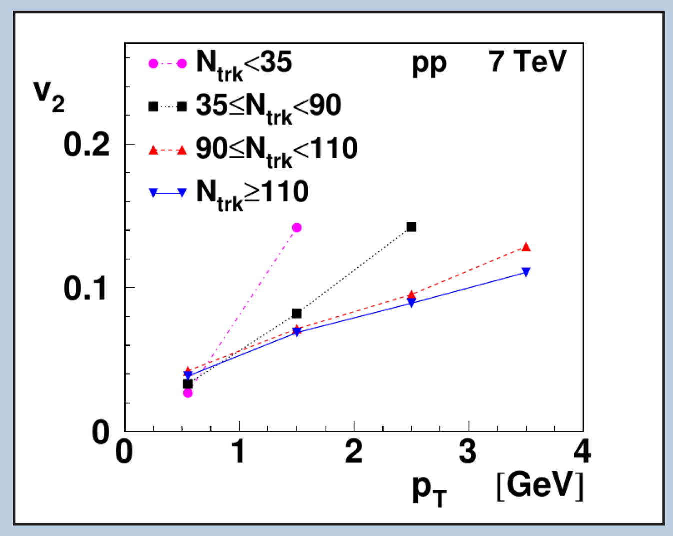

Figure 4: Elliptic flow $v_2(p_T)$ for the four multiplicity classes extracted from the CMS data [3]

Big quarks model

There are two distinct pictures of proton's internal structure: 1) proton built from three "constituent" quarks and 2) proton containing a sea of point-like partons: "current" quarks and gluons. The first picture arises from its ability to account for hadronic spectra, while the second explains well the results of hard scattering experiments. Renormalization group procedure for effective particles (RGPEP) offers a bridge between these points of view suggesting that the effective size of constituent quark can strongly depend on the energy scale used to probe it [4]. The larger the momentum transfer Q in partonic collisions, the smaller particles are observed. For $Q = \Lambda_{QCD}$ quarks can even be as big as whole proton (Fig. 5).

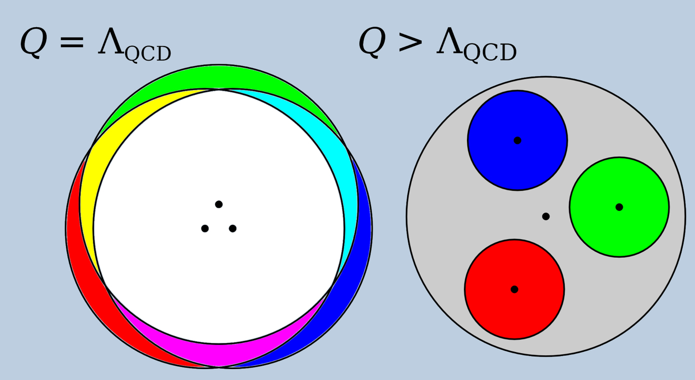

Figure 5: RGPEP picture of proton at energy scale $Q = \Lambda_{QCD}$ and $Q > \Lambda_{QCD}$. Note that the overlap of big quarks makes proton white and in case of smaller quarks locally white gluon medium fills proton in.

The wavefunction of quarks in position space is a Gaussian. Knowledge of this fact allows one to calculate probabilities of certain internal configurations and to estimate the average ϵ in *pp* collisions (choosing some ansatz for parton density of constituent quarks and gluon medium). The ϵ dependence on Q will manifest itself in the v_2 dependence on p_T as there is a relation between the average p_T and Q. Such an analysis may lead to the development of big quarks model.

Concluding remarks

The assessment of elliptic flow coefficient v_2 based on initial eccentricity ϵ may seem to be naive, however several authors have followed this way (e.g. [5-7]). The data from CMS is not precise enough to distinguish between proposed hydrodynamic and non-hydrodynamic (e.g. Color Glass Condensate [8]) models as most of them are able to explain the ridge effect. Nonetheless, research in this area is worth pursuing as in future it may shed more light on hadrons' internal structure.