Luminosity calibration and beam-beam interactions at hadron colliders with Q-Gaussian beams

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Precise luminosity measurements is a crucial aspect of collider physics. Luminosity calibration at hadron colliders relies on the van-der-Meer scan method, where colliding particle beams are swept across each other and the reaction rates are recorded based on the separation distance between them. Initially, Gaussian distributions adequately described particle densities for luminosity calibration. However, with advancements in collider facilities, the deviations of the particle densities from Gaussian ones become more pronounced.

The electromagnetic interaction between colliding beams exerts both coherent and incoherent effects, impacting the overall motion of the beam and individual particle distribution within the beams, respectively. This interaction directly influences the number of collisions and introduces biases in luminosity calibration. To achieve higher precision, such as target precision 1% for LHC and 0.5% in HL-LHC, it is necessary to consider models that account for the non-Gaussian nature of the beam shapes to achieve enhanced precision in luminosity calibration.

Currently, models based on double Gaussian and/or multi-Gaussian beam densities are used to describe beams with heavy tails, where Gaussian of small width are used to describe the core while Gaussian function with a wider width are used to describe the tails. The Q-Gaussian distribution was found to be a more natural approach to the beam density for the LHC and HL-LHC upgrades, as it provides a more realistic description of the beam profile.

In this study, we explore the influence of the non-Gaussianity of the colliding beams on luminosity calibration and beam-beam interactions using beams with Q-Gaussian transverse profile. The deviation of the luminosity of Q-Gaussian beams from that of Gaussian is investigated, and an analytical formula is derived. To facilitate practical applications, a van-der-Meer scan-fit model based on the Q-Gaussian function was proposed. The van-der-Meer scans using the Q-Gaussian beams are simulated, and the proposed fit model is applied and compared to the traditional Gaussian fit models. The fit models are applied to the actual van-der-Meer scan dataset from CMS at Run 2. To consider the effect of the non-Gaussianity of the colliding beams on their beam-beam interaction, we introduce the model for coherent and incoherent interactions of Q-Gaussian colliding beams. The comparison of this model with the regular Gaussian model is performed for LHC conditions. Also, the evolution of the effect during the van-der-Meer scan is demonstrated.

By investigating the impact of non-Gaussian deviations on both luminosity calibration and beam-beam interactions, our research provides valuable insights for optimizing collider performance and achieving more accurate measurements in future high-energy experiments.