Disoriented Chiral Condensate Effects on Soft Pion Spectra in Heavy Ion Collisions

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An important approximate symmetry of QCD with light quark flavours is chiral symmetry, the symmetry under phase rotations of left- and right handed spinor components, combined with isospin symmetry under rotations of up- and down quark components. This chiral symmetry is believed to be spontaneously partially broken by the vacuum, resulting in a non-vanishing vacuum expectation value (VEV) of the scalar component $\langle \overline{q}q \rangle \approx f_\pi \approx 93\,\mathrm{MeV}$ of the chiral condensate (CC), traditionally called the σ-field. The CC is not directly observable. The Nambu-Goldstone theorem explains the existence of three almost massless pion fields π^0, $\pi^\pm$ as the (pseudo) Nambu-Goldstone bosons of the spontaneously broken chiral symmetry. We study possible observable effects of this symmetry breaking and its restoration in the context of Heavy Ion Collisions.

Hot and Dense Nuclear Matter in Heavy Ion Collisions Spontaneous chiral symmetry breaking is a non-perturbative phenomenon of QCD, frequently studied by means of lattice QCD. It is expected that chiral symmetry should be restored at high temperatures, as achieved during high energy hadronic collisions – so called heavy ion collisions (HICs) – for example at the LHC or RHIC. The study of HICs provides insights into the dynamics of nuclear matter at extreme temperatures and densities, similar to those in the early universe, where an exotic state of matter is realized in which quarks and gluons are no longer confined into hadrons but can move through the hot and dense medium: the quark gluon plasma (QGP). This seemingly complex state of such a collision, involving way more particles than could be described by perturbative methods, can successfully be modelled as an almost ideal relativistic fluid by locally employing thermodynamic concepts and conservation laws of energy-momentum, particle number, electric charge, etc. in the fireball of QCD matter. Thus, given the thermodynamic equations of state, the dynamics during a HIC can be obtained by integrating an initial value problem of only a handful of spacetime dependent fields like temperature T, fluid four-velocity u^μ, viscosity coefficients etc. on some discretization of spacetime. Hydrodynamics are only valid if the medium is dense and hot enough such that collisions between particles in the fluid can maintain local equilibrium. The so-called freezeout separates the hydrodynamic stage from a stage of freely propagating, non-interacting particles emerging from the fireball that can subsequently decay via their various decay channels and ultimately be counted and classified in surrounding detectors.

Predictions using hydrodynamic models are largely successful in describing particle abundancies over an intermediate range in transverse particle momentum p_T. A large discrepancy between experiments and theory predictions is found in the regime of soft or low-p_T pions, where the data exceeds model predictions of particle yield by $\lesssim 50\%$, complicating systematic model-to-data-fits and therefore also a rigorous extraction of fluid dynamic properties of the QGP.

Condensate Contribution via Classical Field Theory This project attempts to improve upon the established hydrodynamic models by proposing an additional contribution to the particle spectra which explictly captures the effects of chiral symmetry breaking and restoration. For the highest energy collisions it can be expected that the effect of the symmetry restoration at high temperatures is quite large and the CC inside the fireball deviates significantly from the CC outside. Specifically in such an extreme quench scenario the deviation must not necessarily be oriented along the σ-direction of the true VEV, but could be disoriented and have excitations in the π-fields as well, coining the term disoriented chiral condensate (DCC). This scenario has been proposed in the 90s already for example by Anselm, Rajagopal & Wilczek or Amelino-Camelia, Bjorken & Larsson but has not been brought in contact with the presently available spacetime resolved fireball evolution in terms of relativistic hydrodynamics. Describing the DCC as a classical relativistic scalar field, we find not only a conceptional analogy but also formal equivalence to the description of non-relativistic Bose-Einstein condensates (BECs), which were originally observed experimentally as low-momentum peaks on top of thermal distributions in the spectra of particles released from ultracold atom traps. In both scenarios (DCC and BEC) classicality is achieved due to the large number of particles in the condensate and is formally described by the assumption of coherent quantum states. According to our model, a large number of soft pions can be produced from a reasonably large deviation of order $\lesssim \mathcal{O}(f_\pi)$ either in the pion fields, or the σ-field followed by the decay process $\sigma \to \pi^+ + \pi^-$.

If successful, our model allows to interprete the soft pion excess in HICs as direct evidence for the dynamical restoration of chiral symmetry and can give an estimate for the extend to which the symmetry is restored. This phenomenon would complement the presently existing searches for experimental signals of chiral symmetry restoration for example in dileption spectra or ratios of particle yields of chiral partners or strange- to non-strange particles.