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How to catch a ‘fat’ proton

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ABSTRACT

We argue that high-multiplicity events in proton–proton or proton–nucleus collisions originate from large-size fluctuations of the nucleon shape. We discuss a pair of simple models of such proton shape fluctuations. A “fat” proton with a size of 3 fm occurs with observable frequency. In light of this result, collective flow behavior in the ensuing nuclear interaction seems feasible. We discuss the influence of these models on the parton structure of the proton.

1. Introductory remarks

Few scientists have emphasized the need to study proton–nucleus ($p + A$) collisions more persistently than Wit Busza. For many decades Wit has argued that much can be learned about the process of energy deposition in nucleus–nucleus ($A + A$) collisions from studying and understanding what happens in $p + A$ collisions (see Fig. 1). In line with Wit’s arguments, $p + A$ collisions have been viewed as excellent probes of “initial state” effects in $A + A$ collisions. This is easy to understand. As an energetic proton penetrates a large nucleus, each subsequent nucleon it encounters has no information about the processes along the prior trajectory of the proton, because the proton travels nearly at the speed of light and thus no, or very little, information propagates ahead of it. In other terms, as the proton plows through the nucleus, it continues to interact with cold nuclear matter. On the other hand, for the speeding proton the approaching nucleus looks very highly Lorentz contracted, and the time between subsequent collisions with nucleons is exceedingly short. The proton wave function thus has no time to evolve between different interactions. The individual p + nucleon collisions thus act coherently on the wave function of the colliding proton.

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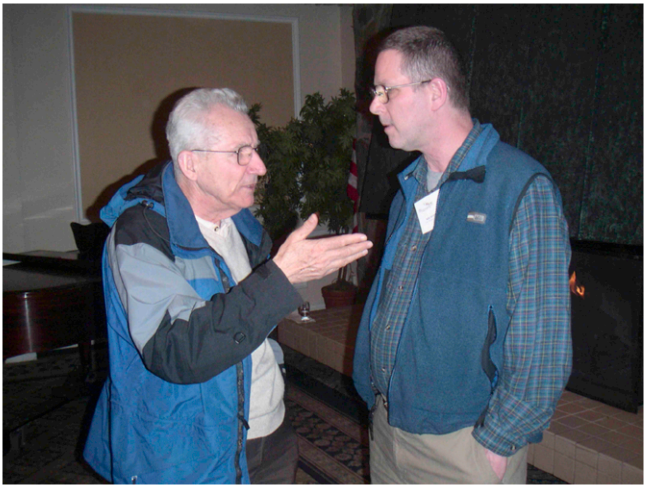

Fig. 1. Wit Busza arguing about the value of p + A collisions at the SQM2006 conference.
Source: Photo courtesy of J. Rafelski.

The proton in a p + A collision is thus thought to probe the structure of the nucleus in its ground state and all the final state interactions occur when the proton has emerged on the other side of the nucleus, i.e. in vacuum. In particular, no collective effects were expected to occur, because the size of the emerging highly excited object – the former proton – cannot be larger than the incident proton itself by virtue of causality.

How can we then understand high multiplicity events in p + Pb collisions at the LHC where flow like properties have recently been observed [1,2]? The properties of events in the large N_{part} tails of these multiplicity distributions resemble in many respects those of Pb + Pb events at the same multiplicity. I propose that the tail of the p + Pb multiplicity distribution arises from long-lived (on the collision time scale) quantum fluctuations in the colliding proton's wave function, as opposed to fluctuations in the Pb nucleus or fluctuations in the final state particle production process.

The wave function of the nucleon includes configurations that are so spatially extended that their inelastic cross section is much larger than the average. These fluctuations correspond to relatively low energy excitations of the proton in the co-moving frame, which are vastly time dilated in the reference frame of the Pb nucleus. As such they can be considered as approximately frozen during the entire p + Pb collision, except for perturbations caused by the interactions with nucleons in the Pb nucleus.

How can one catch these fat protons? You need a net: A heavy nucleus.

Having a larger geometric size, it is natural to expect that the incident proton will have a much larger cross section with the nucleus when it finds itself in one of these configurations. As a result, more energy will be deposited and more particles will be produced. Such cross section fluctuations in hadron collisions have a relatively long history of study [3–7]. What is most important for the interpretation of the observed collective flow-like properties of the high multiplicity events, however, is that the energy will be deposited over a much larger transverse area, which makes the validity of a hydrodynamical description [8–12] of the following expansion more credible.

In the following, we will outline two alternative models for the spatial structure of the large-size configurations of a highly boosted nucleon. The first model is based on the flux-tube model of quark confinement (the "stringy" nucleon). The second is a pion-cloud model, in which the nucleon is surrounded by one or several soft virtual pions (the "cloudy" nucleon). I argue on the basis of existing data for the antiquark distribution in the nucleon that the probability of finding the nucleon surrounded by a cloud of four pions is of the order of $P(4\pi) \sim 10^{-6}$ and thus should be abundantly sampled in the CMS experiment, which recorded an event sample corresponding to 6×10^{10} minimum bias events.