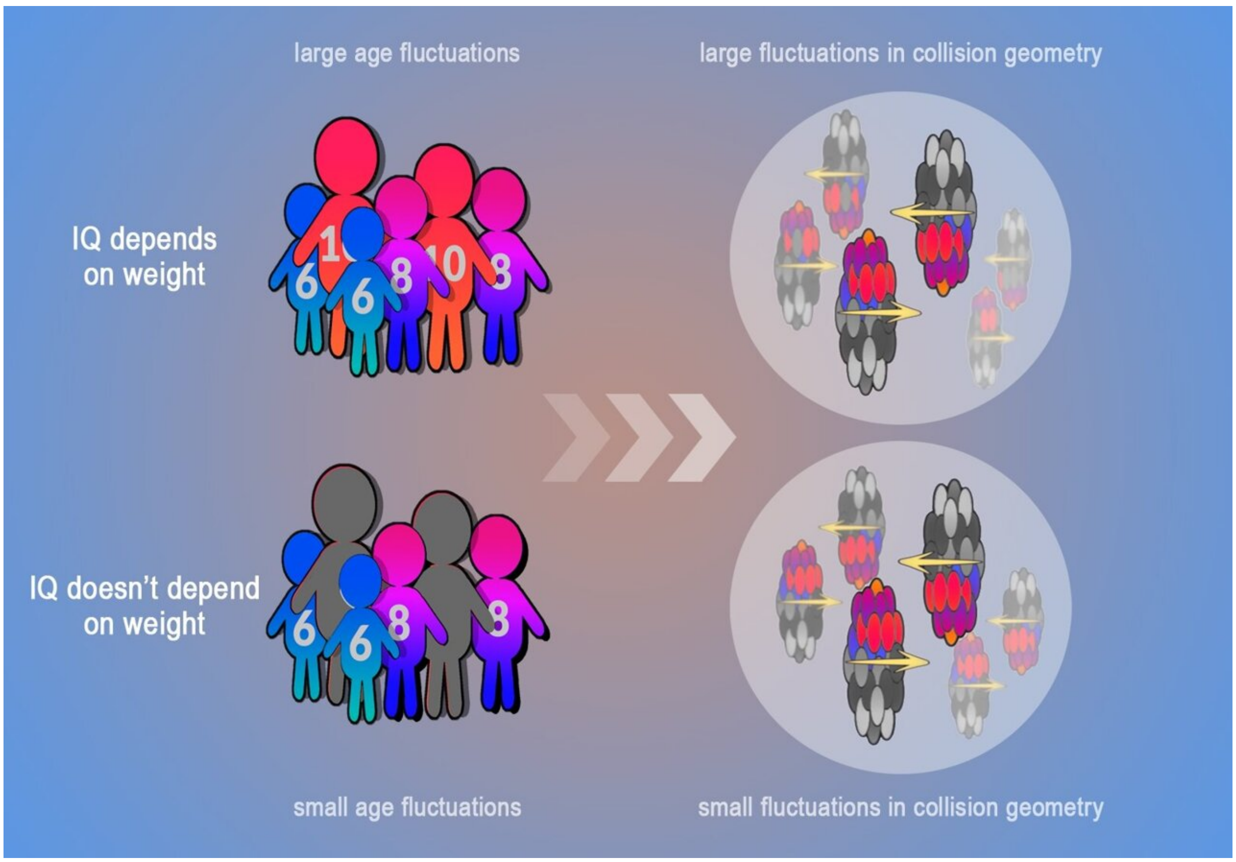
Examining the intriguing details of collisions at extreme energies

September 14 2023



Children's intelligence may appear to be statistically related to their weight because the relationship is sensitive to age fluctuations within the study group. A similar phenomenon occurs in the case of the correlation variable sigma and the centrality of heavy ion collisions in the LHC accelerator. Credit: IFJ PAN

The initial phases of heavy-ion collisions occurring at the maximum energies available at the CERN Large Hadron Collider continue to remain an enigma of modern nuclear physics. New theoretical tools improved by physicists from the Institute of Nuclear Physics of the Polish Academy of Sciences in Cracow will help to unlock this mystery.

The phenomena occurring during nuclear collisions are so fast and involve particles so small that they cannot be observed directly. Guessing the course of these sorts of processes resembles the work of a detective. Just as he is unable to observe the crime being committed and has to reconstruct an image of it based on witness statements, physicists try to reconstruct the course of nuclear phenomena on the basis of "accounts" given by the secondary particles born in collisions and recorded by detectors.

Sherlock Holmes's task, however, was much easier—he could talk freely to his witnesses, whereas physicists can only observe the particles' behavior. In order to reconstruct the actual course of the "crime" (the collisions of atomic nuclei), they have to create a suitable language for describing events (mathematical tools) and use it to recount what took place (with the help of a theoretical model of the phenomenon), and then compare whether the "testimony" thus obtained agrees with what the recorded particles appear to "say".

Particularly difficult processes to study include phenomena occurring in the early stages of heavy-ion collisions in the LHC accelerator, when a quark-gluon plasma may be formed. This is a state of matter in which quarks and gluons behave like free particles (in the world around us, quarks and gluons are always bound by the strong interactions and remain inside hadrons, i.e. protons or neutrons).

The quark-gluon plasma ends extremely quickly because it cools as it expands. Quarks and gluons are then trapped again in hadrons, creating secondary particles that are registered in detectors. It can be concluded whether a quark-gluon plasma was created by analyzing the so-called forward-backward correlations between particles produced in collisions.

"Forward-backward correlations measure the relationship between the number of particles produced forward and backward when beams of heavy ions collide. Although these correlations concern particles very far apart, they carry information about the early stage of the collision. This is because the correlations between the particles emitted forward and backward could only have formed before the particles moved away from each other, i.e. at the beginning of the collision," says Dr. Iwona Sputowska of the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Cracow, a physicist who is a member of the ALICE scientific collaboration at the LHC.

The problem with correlations, however, is that, used incompetently, they can lead to false conclusions. Suppose, for example, we conduct a study of children's intelligence in all the forms of a primary school. A correlation might then be found whereby the more intelligent a child is, the more they... weigh.

However, we know that in reality intelligence and weight are correlated to another variable: the age of the child. So if we narrow down our study to children of the same age, the correlation between their intelligence and weight drops dramatically. The correlation between intelligence and weight is therefore sensitive to age fluctuations in the group of children—there are a lot of children of different ages in the whole school, but within the same form the age differences are small.

We encounter an analogous challenge when examining correlations in heavy ion collisions. The relationship between the number of particles produced forward and backward is sensitive to fluctuations in the way the two atomic nuclei collided with each other, such as whether they collided centrally or just brushed against each other.

To deal with this problem, the concept of strongly intensive variables was introduced. These quantities are defined so that they depend neither on how the two ions collided with each other nor on how much the geometry of the collision fluctuated in the group of studied events.

A strongly intensive correlation variable is sigma. It was intended to provide information about the way in which the average source produces secondary particles. However, while analyzing data collected in the collisions of lead-lead and xenon-xenon nuclei as part of the ALICE experiment, Dr. Sputowska noticed that none of the most popular models used to describe these phenomena corresponds to the behavior of the sigma variable.

"There could only be one conclusion. Since our models do not correctly describe the experimental data for the highest-energy collisions available at the LHC, it means that we are incorrectly modeling how the average source produces secondary particles," says Dr. Sputowska.

Unexpectedly, collision models proposed over 45 years ago by theoreticians from Cracow turned out to be helpful in understanding the behavior of sigma. They treated collisions of heavy atomic nuclei as multiple collisions of single nucleons of one nucleus with single nucleons of the other nucleus (in the wounded nucleon model) or as collisions not of protons and neutrons, but of quarks (in the wounded quark model).

In these models, it is assumed that single, independent sources are responsible for the production of secondary particles, which are either nucleons or quarks, respectively.

Previous models have assumed that the average source generates secondary particles with the same forward and backward probabilities.

Sigma, by definition, should then be equal to one. It turns out that its actual dependance on the geometry of collision can be reproduced if one allows for the possibility that the average source emits particles forward with a slightly different probability than backward.

In the wounded nucleon model, an extra term then appears in the sigma formula, depending on the collision geometry, and sigma ceases to be a strongly intensive variable.

However, this situation gives rise to an intriguing contradiction, for sigma loses its status as a strongly intensive variable and yet correctly describes experimental data that do not depend on changes in collision geometry.

Why? The solution to the problem turned out to be in the fact that in the wounded source model sigma always gives the values of the forward-backward correlation for the average number of wounded nucleons/quarks, i.e. for the average collision geometry in a given collision group. This situation can be compared to measuring the correlation between intelligence and weight of children in a group where the average age of the child is fixed.

"A detailed understanding of the nature of sigma allowed us to determine the fragmentation function, linking the number of particles produced by nucleons in the model with the number of particles measured in the detectors. For the first time, for the highest collision energies at the LHC, we have been able to construct tools that allow us to reliably falsify this highly intriguing sigma behavior," Dr. Sputowska concludes.

The research is published in the journal *Physical Review C*.

More information: Iwona Sputowska, Forward-backward correlations

with the Σ quantity in the wounded-constituent framework at energies available at the CERN Large Hadron Collider, *Physical Review C* (2023).
DOI: 10.1103/PhysRevC.108.014903

Provided by The Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences