Particle physics

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Three's the charm

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In proton–proton collisions, the CMS Collaboration measures the simultaneous production of three particles, each consisting of a charm quark and a charm antiquark, which yields insights into how the proton's constituents interact.

The proton is one of the key components of matter, and is a building block of all atoms together with the neutron and electron. At school one learns that the proton is not fundamental, but is composed of two up quarks and one down quark, called valence quarks. At university, we learn that this picture is too simple, and in fact these valence quarks are 'glued' together by further particles called gluons, which may themselves fluctuate into further virtual gluons or quark–antiquark pairs, known as sea quarks. The strength of interactions between these valence quarks, sea quarks and gluon constituents, collectively referred to as partons, decreases with energy scale. In high-energy collisions, protons resemble a bag of almost-free point-like partons. At the Large Hadron Collider, multiple collisions of these partons can occur in a single proton–proton collision. Now, writing in *Nature Physics*, the CMS Collaboration has reported the observation of triple J/ψ (a bound charm quark–antiquark pair) production, which receives a significant contribution from a process involving three-parton collisions[1].

How well do we understand the dance of partons within the protons? One way to attack this question — and how the existence of partons was experimentally confirmed in the first place — is to fire high-energy electrons at the proton, which smash into one of its partons. By examining the deflected electron as well as the other products of the collision, one can deduce various properties of the probed parton. Through such experiments, the first important quantities to be mapped out were the so-called parton distribution functions, which in a fast-moving proton determine the number density of partons carrying a fraction of the total proton momentum (Fig. 1a).

More recently, efforts towards three-dimensional imaging of the proton have started by measuring additional properties of the probed parton, as illustrated in Fig. 1b, c. Understanding these three-dimensional distributions is crucial to reveal how the proton's spin is distributed amongst its constituent partons. Solving this proton spin puzzle will be a key goal of the planned Electron-Ion Collider in the United States[2].

Our picture of the proton substructure appears to be fairly sophisticated. However, what these single-particle distributions do not tell us is how the partons interact with each other, and the quantum mechanical correlations between them. In order to probe such effects, we need a process in which two or more partons in the proton are struck at once. This can happen in proton–proton collisions at the Large Hadron Collider, where the two bags of partons collide with one another. In such collisions, it is most likely to have a single high-energy parton–parton collision, which probes the same single-particle distributions measured in electron–proton collisions. But multiple high-energy parton–parton collisions in a single proton–proton collision are also possible. These are known as multiple parton interactions.

The probability to have multiple parton interactions generically decreases with the number of interacting partons, and prior to the study by the CMS Collaboration[1], only measurements of double parton scattering had been performed. From these earlier measurements, intriguing hints of correlations already started to appear. For example, each measurement extracts a quantity known as σ_{eff}, which (loosely speaking) is linked to the average transverse separation (squared) of partons in that interaction. Previous measurements suggested that the average partonic separation may depend on parton species and/or their momentum fractions.

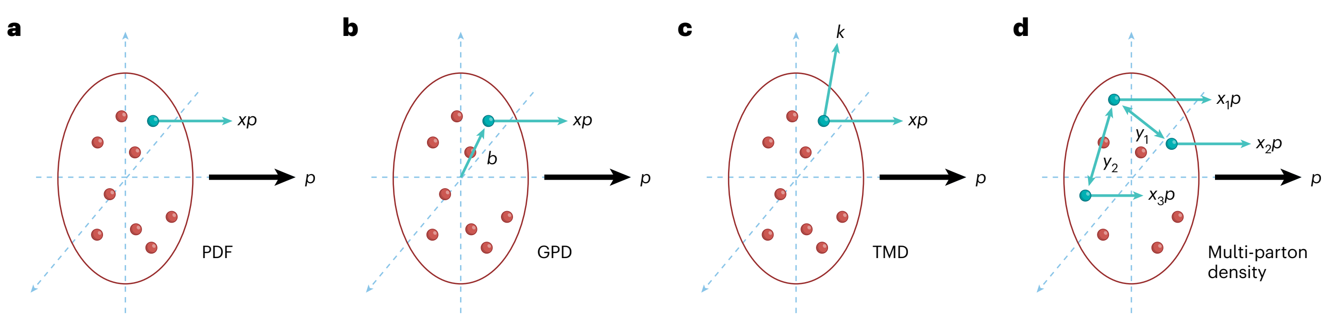

Fig. 1 | Different possible measurements on partons in the proton. a–d, The proton (red contour) with a momentum indicated by the thick black arrow, consists of partons, indicated by the dots. Single parton scattering processes probe the fraction of the proton momentum $\boldsymbol{p}$ carried by the probed parton (cyan) $\boldsymbol{x}$ (**a**). In addition, they may also probe the transverse distance of the parton from the centre of the proton, $\boldsymbol{b}$ (**b**), and/or the momentum of the parton transverse to the proton direction, $\boldsymbol{k}$ (**c**). The associated parton densities are referred to as the parton distribution functions (PDFs) (**a**), generalized parton distributions (GPDs) (**b**), and transverse momentum-dependent PDFs (TMDs) (**c**), respectively. Multiple parton scattering processes probe the properties of multiple partons at once, as illustrated in **d**, with momentum fractions $\boldsymbol{x}_i$ ($\boldsymbol{i}$ = 1,2,3) and transverse separations between partons $\boldsymbol{y}_i$ ($\boldsymbol{i}$ = 1,2).

As the energy of the collision increases, so does the probability of multiple parton interactions occurring. Therefore, it is possible to probe processes sensitive to triple parton scattering at the Large Hadron Collider. The CMS Collaboration studied triple J/ψ production – a process expected to be dominated by double and triple parton scattering[3].

Because a J/ψ can decay into a $\mu^+\mu^-$ pair, events with six muons were selected and additional criteria were imposed to ensure these events matched three reconstructed J/ψ mesons. With this selection, five events are consistent with triple J/ψ production, which translates into a significance of above five standard deviations. The cross section for triple J/ψ production is roughly 200 times rarer than the production of a Higgs boson.

Under certain assumptions, one can write the double and triple parton scattering cross sections in terms of products of single scattering cross sections and the average transverse partonic separation encoded in σ_{eff} (ref. [4]). Interpreting the measured σ_{eff} in terms of a transverse separation[5], the partons involved in triple J/ψ production are separated by around 0.1–0.4 femtometres, which is smaller than the proton radius of around 1 femtometre. The reason for this is not yet understood.

The measurement by the CMS Collaboration represents an important step in our journey to understanding the multi-partonic structure of the proton, but there remains much to be done. The result is indicative of a triple parton scattering contribution, but is not conclusive: one event out of a total of the five measured is attributable to this process, and one cannot rule out the possibility that all the events measured were due to single and double parton scattering. Therefore, an analysis with much higher statistics is desirable, in which the kinematics of the muons are studied to separate double from triple parton scattering contributions. Given that the experiments at the Large Hadron Collider will ultimately accumulate data samples that are 20 times larger than that analysed by the CMS Collaboration[1], this is hopefully just a matter of time.

In general, experimental analyses of double and triple parton scattering need to go beyond extraction of the single parameter σ_{eff} and achieve more detailed and differential measurements of processes sensitive to double/triple scattering. The higher statistics expected from the Large Hadron Collider will enable such measurements, that will probe the nature of correlations between partons in the proton in more detail. Finally, there is a need to go beyond the simple theoretical model discussed above and obtain proper field-theory-based predictions incorporating known correlation effects; much progress has been made in this direction in recent years[6].

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Competing interests

The author declares no competing interests.