(a name that means 'opposite birds', in reference to their atypical shoulder-joint articulations), which occupy a branch of the dinosaur family tree that is much closer to that of modern birds than the branches occupied by either *Archaeopteryx* or *Sapeornis*. The presence of an ectopterygoid in Enantiornithes has been suggested previously[9], but this identification has been questioned[10]. Thus, the detection of an ectopterygoid in *Falcatakely* either shows that this ancestral component of the palate was indeed retained in Enantiornithes (at a relatively late stage in avian evolutionary history), or challenges the identification of *Falcatakely* as a member of Enantiornithes, suggesting instead that it belongs on a deeper branch of the family tree of Mesozoic birds.

Although it is impossible to decide definitively between these two options without access to further fossil material, O'Connor *et al*. grapple with this uncertainty to an impressively thorough degree, showing that *Falcatakely* nests with Enantiornithes in evolutionary trees constructed under a range of alternative analytical approaches. Moreover, the identification of *Falcatakely* as a member of Enantiornithes makes sense in light of the previous identification of fragmentary bones assigned to Enantiornithes from the same Madagascan fossil locality[11]. Nonetheless, some research has indicated that family-tree reconstructions of dinosaurs can return conflicting results when skulls, instead of complete skeletons, are analysed[12]. This lack of certainty is all the more reason for the team to continue its productive fieldwork in the hope of discovering more-complete material.

Modern birds originated in the Late Cretaceous[13], and it has become increasingly apparent that the final 20 million years of the age of the dinosaurs (86 million to 66 million years ago) was a pivotal time in avian evolutionary history. The discovery of *Falcatakely* shows us that the importance of this window in time for bird evolution extends well beyond the origin of modern birds. Apparently, 'pre-modern' bird lineages such as Enantiornithes were still experimenting with bold new forms — and possibly previously unfilled ecological niches — well into the terminal stages of the Cretaceous.

The pre-modern birds were wiped out in the end-Cretaceous mass extinction event, along with all other dinosaurs, apart from modern birds[14]. Considering the impressive diversity and global distribution of Enantiornithes in the Late Cretaceous, determining why they disappeared in that mass extinction, whereas the earliest modern-bird lineages survived, remains one of the greatest mysteries in avian evolutionary history. The answers to such questions, much like the unexpected anatomy of creatures such as *Falcatakely*, can be revealed only by evidence from the fossil record. So, let's keep digging.

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Particle physics

How protons interact with their exotic siblings

Manuel Lorenz

The nuclear forces that act on short-lived subatomic particles have been hard to study. This problem has now been solved by smashing high-energy protons together and measuring the momenta of the unstable particles produced. **See p.232**

On page 232, the ALICE Collaboration[1] reports that data from high-energy collisions between protons can be used to investigate the little-understood nuclear forces between protons and subatomic particles called hyperons. The measurements have comparable precision to state-of-the-art numerical calculations of the forces, thereby allowing conclusive quantitative comparisons of experimental data with theory. Accurate knowledge of these forces is needed for various aspects of physics research, for example in efforts to understand the stability of neutron stars.

The nuclear force between neutrons and protons (which are known collectively as nucleons) is a residual effect of the strong interaction that acts between their elementary constituents (quarks and gluons). First-principles calculations of the nuclear force have been challenging because of the peculiarities of the strong interaction. Our knowledge of this force is, therefore, based largely on simplified models and theories[2], guided by experimental data[3]. The strong interaction between hadrons (subatomic particles, such as nucleons, that consist of two or more quarks bound together by the strong interaction) at low energies is therefore often referred to as the final frontier of the standard model of particle physics.

The interaction between nucleons has been measured with high accuracy[3], but the interaction of nucleons with their heavier siblings, the hyperons, is less well assessed. Hyperons consist of three quarks, at least one of which must be a type (flavour) known as a strange quark; the other quarks can be up or down, the two lightest quark flavours. Hyperons are not present in the everyday matter that surrounds us on Earth, but — depending on their interactions with nucleons — might affect the compressibility of nuclear matter at high densities. This means they could be relevant to the stability of neutron stars[4]. Precise knowledge of hyperon–nucleon interactions is therefore of great importance not only for nuclear physics, but also for astrophysics. However, measurements of these interactions are difficult to make in conventional experiments involving direct particle collisions in accelerators, because hyperons are short-lived (their lifetimes are about 10^{-10} s; ref. 5) and fly only a few centimetres, on average, before they decay.

The ALICE Collaboration now reports that proton–hyperon interactions can be investigated using high-energy collisions between protons carried out at the Large Hadron Collider (LHC) at CERN, Europe's particle physics laboratory near Geneva, Switzerland. The technique depends on measurements of correlations between the momenta of protons and hyperons produced in the collisions.

The process studied in the experiments involves three steps (Fig. 1). First, protons are collided at extremely high energies, taking advantage of the fact that the LHC produces higher collision energies than any other accelerator. Second, hadrons are emitted

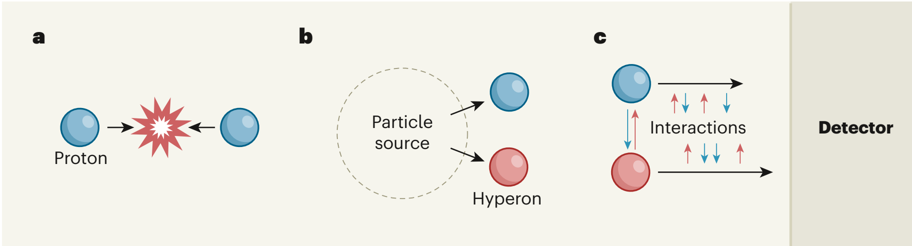

Figure 1 | Investigating the proton–hyperon interaction. **a**, The ALICE Collaboration[1] smashed together high-energy protons in CERN's Large Hadron Collider. **b**, The collisions generate a 'particle source' — a volume of space in which components of the colliding protons interact and become confined within new particles. These new particles are emitted from the source, and include protons that pair up with heavier particles known as hyperons. **c**, The paired-up protons and hyperons interact with each other in a way that alters the relative momentum of the system, which is then measured by a detector. These measurements are then used to determine the nuclear force between the proton–hyperon pair.

by a 'source' produced by the collision — a volume of space in which quarks and gluons that originally came from the protons interact and become confined within new hadrons. The source emits various types of hadron, including protons and hyperons, some of which form proton–hyperon pairs. Finally, the proton and hyperon in each of these pairs interact with each other in ways that alter the momentum of the paired system. This momentum is measured by a detector and used to determine the momentum correlations.

The momentum correlations reflect the size of the hadron source and the properties of the interaction between the produced proton–hyperon pairs. Such correlation analyses were originally used to determine the source size in collisions of heavy ions[6], but in the new work, they are instead used to investigate the interaction between the particles of interest. This approach to studying particle interactions was pioneered by the HADES Collaboration[7] at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, and was further developed by the ALICE collaboration[8] at the LHC. The current work depends on the fact that the extremely high-energy proton–proton collisions carried out at the LHC produce a high abundance of hyperons from small-volume hadron sources. The authors used this method to measure the strong force between protons and Ω^- hyperons (which consist of three strange quarks) and between protons and Ξ hyperons (which consist of two strange quarks and one up or down quark).

The ALICE Collaboration's findings open up a new 'laboratory' for investigating other nucleon–hyperon interactions, including the little-explored interactions with hyperons that contain two or three strange quarks. This will aid our understanding of metastable states of hyperon pairs or of the compressibility of nuclear matter at high densities. The latter is relevant not only for the stability of neutron stars, but also for neutron-star mergers and heavy-ion collisions.

In a lucky coincidence, recent developments in theoretical physics[9,10] allow nuclear forces to be calculated from first principles so that the results can be compared with experimental findings. The precision with which nucleon–nucleon interactions can be determined from experimental data is still superior to that obtained from these calculations, but the ALICE Collaboration's measurements of the proton–hyperon interactions almost exactly match those obtained from theory.

A wealth of high-precision measurements of proton–hyperon interactions is expected from the LHC in the next decade, following on from its recent upgrade. Moreover, various other facilities that will study particle collisions at lower energies than those produced at the LHC are expected to go into full operation in the coming years, including NICA in Russia, J-PARC in Japan and FAIR in Germany. Although fewer proton–hyperon pairs are generated per collision in lower-energy collisions, a greater proportion of those pairs will be emitted at low momenta — which might turn out to be advantageous, because more data are needed to reduce the statistical errors in measurements of low-momentum systems. Increases in computing power should also substantially reduce the uncertainties of first-principles calculations of nuclear forces. Taken together, these developments bode well for future research into the final frontier of the standard model of particle physics.

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Virology

Cracking the cell access code for a deadly virus

James Zengel & Jan E. Carette

The discovery that the receptor protein LDLRAD3 is essential for infection of human cells by Venezuelan equine encephalitis virus could inform strategies to combat this potentially lethal infection. **See p.308**

When viruses jump from animals to humans, disease outbreaks can follow. A striking example is Venezuelan equine encephalitis virus (VEEV). This virus causes sporadic disease outbreaks in horses in Latin America that frequently spill over into humans, resulting in often-deadly neurological disease[1]. Because of its pathogenicity in livestock and humans, VEEV has been studied as a biological weapon by several countries, including the United States[2]. Treatments for the disease are therefore highly desirable. It has been unknown how VEEV co-opts cellular pathways to establish infection in people — in particular, which host receptor protein allows VEEV to cross the cell membrane and initiate its replication cycle. On page 308, Ma *et al.*[3] describe the long-sought receptor for VEEV, and show that it is essential for viral replication in both human cells and mouse models.

Interactions between a virus and its host receptor protein can control which tissue types in the body support viral growth, thus influencing the type of disease that results. Furthermore, these interactions can determine how well the virus spreads through a host population. During the continuing SARS-CoV-2 pandemic, for instance, viral strains that had a specific mutation in the virus's spike protein became predominant soon after the virus