Quantum Chromodynamics at Work:

European Research Council Scientific Council

What is this ERC project all about?

The matter in our world and the visible matter in the universe is made up of atoms consisting of nuclei and electrons. The nuclei are built from nucleons, positively charged protons and neutrons. Nucleons are tiny, their radius being just under 1 femtometer (that is 10^{-15} meter or explicitly 0.000 000 000 000 001 meter). They are more or less closely packed in the nuclei (sizes of 1 - 10 fm) and in an atom the positively charged nucleus is neutralized by negatively charged electrons that occupy quantum orbits with sizes of 10^{-10} meter (0.1 nanometers). For instance a Hydrogen atom (H) consists of just one proton and one electron. A Helium atom (He) has a nucleus consisting of two protons and two neutrons (together also referred to as an alpha particle) and two electrons. Oxygen (O) has a nucleus with 8 protons and 8 neutrons and 8 electrons complete the atom. These atoms can in turn be combined into molecules such as H₂O (water) and an enormous number of other chemical substances.

The forces in atoms come from the attraction and repulsion between the electric charges in the atomic nucleus and those of the electrons. Even between neutral atoms these forces remain active because nature has found ways to cope with this, such as exchanging or sharing electrons between the atoms. An important ingredient in the structure of atoms is played by the spins of the particles. Protons, neutrons and electrons are like tiny tops that actually carry the smallest possible angular momentum. The only thing that can change in their rotational behaviour is that they can rotate one way or the other way (also referred to as left-handed or right-handed). This is a consequence of quantum mechanics. In this way spins can ideally act as the zero's and one's of a computer, which is the basis of ongoing work on quantum computers. For my purpose, the atomic world serves to illustrate how a few simple building blocks (with a charge and two spin states) can provide an enormous complexity.

The theory for this atomic world deals with electric and magnetic forces described within the beautiful theoretical framework known as Quantum Electrodynamics (QED). This is the quantum version of Maxwell's theory of electromagnetism. It describes the electric and magnetic forces via the exchange of photons (the quanta of light) between electric charges and it allows for stunningly accurate calculations and predictions, such as for the magnetic moment of the electron up to 14 digits, although it required many years of theoretical and calculational efforts.

Back to the proposal, which does not deal with electrodynamics but with another type of forces. These forces are the ones that work in the subatomic world inside and between nucleons, which turn out to be composite and are built from two types of quarks, up quarks with charge +2/3 e and down quarks with charge -1/3 e (compare with the charge -e of an electron and +e of an proton). Two up quarks and one down quark make up a proton, two down quarks and one up quark make up a neutron. The dominant forces between the quarks, however, are not electromagnetic in nature, but come from a new type of charge that has been named colour charge and comes in three varieties. Just like colours, it takes a combination of three quarks with different colours to produce a neutral (colourless) nucleon. The colourless nucleons feel each other via the exchange or sharing of quarks and their antiparticles.

There exists since the early seventies a framework, known as Quantum Chromodynamics (QCD), that rivals in beauty with Quantum Electrodynamics. It describes the forces via the exchange of gluons between coloured particles. These gluons transport colour but having three different colours and three oppositely charged anti-colours requires them to have colour charge themselves (which makes them very different from photons that do not carry electric charge). Gluons therefore can again exchange gluons, making the interactions into a big web, that acts to create a confining bubble from which colour cannot leak away, except in the form of particles like pions that contain a quark and an oppositely colour-charged antiquark. The exchange of pions then governs the force between nucleons in an atomic nucleus. The quarks within a proton and neutron turn out to be almost free-moving inside the bubble, but they cannot escape. They move practically at the speed of light. The masses of up and down quarks are only 1% of the mass of the proton, somewhat heavier but comparable to the mass of the electron. It is the kinetic energy of quarks and gluons that makes up the mass Mc² of nucleons. The free-moving quarks inside the protons not only have electric and colour charges, like electrons they also have spins, again the smallest possibility with just two (left-

handed and right-handed) options. Also the gluons carry spin which is, like in the case of photons, referred to as polarization. This maze of orbiting spinning quarks and polarized gluons makes up the proton.

The up and down quarks and the leptons, the electron and the up to now not mentioned electron-neutrino, constitute a family of elementary particles from which the known matter in the universe is built. The neutrino plays a role in the so-called weak decay of particles through the exchange of yet another set of force particles, which have large masses coming from the Higgs field. The recent likely discovery of the excitation of this field is an important step in our quest what is beyond the so-called Standard Model of particle physics describing all these forces. This question has come up earlier with the discovery that there are three families of quarks and leptons. These families are more massive, but have extremely short lifetimes. They were recreated in accelerators.

To understand what happens in accelerators in which one collides electrons on their antiparticles, the positrons, electrons on protons, or as in the Large Hadron Collider at CERN, protons on protons, one can do calculations using the Standard Model of particle physics, which incorporates also QED and QCD. Precise calculations can be done for electrons, photons, quarks and gluons, but the colliding particles are protons just as the particles produced in collisions are composites of three quarks or quarks and antiquarks. The calculations work in colliders at high energies, because interactions at high energies correspond to the exchange of force particles with small wavelengths, smaller than the size of the proton at which length scales quarks and gluons move freely.

Here we get to the central issue of the proposal. Although moving freely, the quarks and gluons have their internal degrees of freedom, in particular the motion transverse to the collision axis of two colliding fast protons and the correlation of this transverse motion with their spins or polarizations. Actually high energy experiments can be used to study these correlations (which is the specific field of expertise of the PI). The correlations are welcomed as input for physicist that want to understand the full quantum substructure of nucleons, after all the basic constituents of matter, by modelling the QCD confinement or studying it on a lattice of points. Detailed knowledge of the quark and gluon substructure enables the use of accelerators effectively as quark-quark, quark-gluon or gluon-gluon colliders. For instance, gluon-gluon collisions can excite the Higgs field through the intermediate step of production of a heavy quark-antiquark pair. For the discovery of the Higgs sector, the spins and polarizations of quarks and gluons are irrelevant. Just bang protons together hard enough. But imagine that we would be able to use the full set of degrees of freedom. This would provide a unique toolbox to work with. Like new medical imaging methods are developed to probe tissue or quantum optics is used at the atomic nano-scale, this project is driven by curiosity and wants to do theoretical physics research to come up with new ways to probe the atto-scale of 10⁻¹⁸ meters and find out about the basic tissue of the universe.



Figure: correlations between coloured quarks and gluons, their polarizations and their orbits in the protons can produce specific angular correlations in the produced jets, which in turn can give information on what happens in the collisions. Because the protons in the LHC are not polarized one must rely on specific correlations that involve not only spins but also orbital motion and the colour charges of the quarks and gluons.