Registration form

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1b. Title of research proposal

Exotic forms of matter

1c. Scientific summary of research proposal

We know that we are all made of atoms. But let's zoom in further: 99.9% of their mass is in a nucleus consisting protons and neutrons. These in turn contain *three quarks*, which have a very small mass given to them by the Higgs mechanism. However, the Higgs is not to blame for most of our body weight. Most of it is due to the strong force holding the quarks together.

But how does this force work? Are there other combinations of quarks which are allowed, rather than just triplets? Recently exotic particles composed of four or five quarks, dubbed tetraquarks and pentaquarks, have been unexpectedly observed by my experiment. I propose to study them at the Large Hadron Collider, LHC, and plan to find more. History has shown that searches for exotic hadrons yield positive — though often surprising — results. *This programme will very likely lead to new discoveries.*

Understanding the nature of tetraquarks and pentaquarks opens a window on understanding the strong interaction that holds all matter together. If the existence of pentaquarks is confirmed, it would change our understanding of particles.

In this proposal I will answer the following questions: What is the nature of these particles? Are they tightly bound like protons? Or are they much bigger "molecules" of known particles held together by the strong force?

This research will tell us how particles are bound together, which will teach us about the ordinary matter we are made of. To make this possible I will develop a new real-time data-processing technique which also has applications transferable to other Big Data research fields.

[Word count: 265 (max 300)]

1d. Keywords

Pentaquark, Exotic Hadron, Spectroscopy, Strong Interaction, Large Hadron Collider.

1e. Current institution of employment

NWO-institute Nikhef

1f. Prospective host institution

NWO-institute Nikhef

1g. NWO Domain

NWO Science Domain (ENW)

1h. Main field of research

12.10.00 (subatomic physics)

1i. Public summary of your research proposal

Title: Exotic forms of matter
Applicant: Dr. P. S. (Patrick) Koppenburg (m), Nikhef

Abstract:

Do we really understand how ordinary matter is bound? Tantalising observations of bound states of five quarks dubbed pentaquarks indicates we do not. Physicists will study these mysterious states and develop novel data-processing techniques to find even more exotic states, thus arbitrating between competing theories explaining their nature.

Samenvatting :

Begrijpen wij hoe gewone materie bijeen wordt gehouden? Blijkbaar niet, gegeven de recente, fascinerende ontdekking van deeltjes bestaande uit maar liefst vijf quarks: zogenaamde pentaquarks. Wij bestuderen deze mysterieuze materie en ontwikkelen nieuwe analyse technieken om andere exotische verschijningen van materie te vinden, en daarmee hun bestaan te verklaren.

[Word count: 48 and 49 (max 50)]

Research proposal

2a1. Overall aim and key objectives

Among the particles discovered during the last two decades, the long-anticipated Higgs boson has a special role as the last discovered building block of the Standard Model of particle physics. However, most of the particles discovered during this time were totally unexpected and seem to be connected: They are *exotic hadrons*, particles made of at least four quarks or anti-quarks. With the proposed research I will use data obtained with the LHCb detector at CERN to understand their nature.

Particle physics describes the building blocks of matter and their interactions. A century of research has produced the very successful Standard Model of Particle Physics (Fig. 1). Ordinary matter is composed of atoms made of electrons surrounding a nucleus of protons and neutrons. Protons and neutrons are examples of hadrons, particles made of quarks held together by gluons, the carrier of the strong nuclear force. No quark or gluon has ever been observed alone, due to a mechanism called colour *confinement*. If a quark tries to escape from the hadron, the strong force will pull it back. The exact mechanism of confinement is not fully understood [1] and it is implemented in models *ab initio* [2] describing how quarks organise themselves in hadrons. Finding out which groupings of quarks are allowed — and which are not — is a test these models and will pave the way to a correct description of the strong interaction.

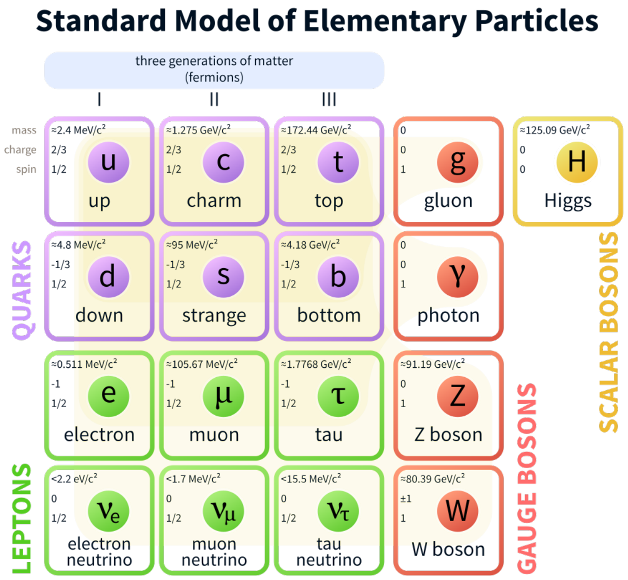

Figure 1: The known particles of the Standard Model. Most relevant to this proposal are the five lightest quarks u, d, s, c, b, and the gluon g.

The theory of strong interactions is called "QCD", for quantum chromo-dynamics [3]. It describes the interactions of spin-$\frac{1}{2}$ *quarks* and spin-1 *gluons*. It is conceptually similar to quantum electrodynamics, the theory of electromagnetism, describing the interactions of charged particles and photons. Yet there are major differences: quarks carry a charge (dubbed "colour") and so do gluons. Therefore, unlike the uncharged photons, gluons can interact with each other. Also, the value of the interaction constant is large (which is why the force is called *strong*) and depends on the energy of the problem. At large energies, quarks behave as free particles (the so called "asymptotic freedom" [4]). But at the low energies involved in a hadron, the theory is strongly coupled and quantitative predictions are very difficult to obtain from first principles. Perturbative calculations successfully used in other quantum field theories do not converge. There is thus still no rigorous way to determine the properties of hadrons from QCD.

Therefore, QCD-inspired models have been created to make predictions and experimental results are required to guide the model builders. While confinement prevents coloured particle to be free, there are many ways of combining quarks and gluons to form colourless hadrons. *Hadron spectroscopy* studies these questions: What are the properties of the allowed bound states such as mass, decay width[1] and decay products. Answering this question eventually leads to a better understanding of QCD.

The importance of "lattice" QCD simulations, that attempt to solve QCD equations by discretising space-time, should be stressed. Presently lattice QCD is the only well-developed systematically improvable method for calculating QCD observables [5]. These improvements requires experimental inputs to validate the calculations. Exotic hadron spectroscopy is an excellent playground for testing lattice calculations.

Here I propose to study the bound states that put these models most under stress: exotic hadrons made of more than three quarks. This study will determine which models match the data and eliminate those which do not. This is natural selection of theories, leading to the survival of the fittest.

The observation of tetra- and pentaquarks

Hundreds of composite particles are known. Until 2003 all of these were either pairs of a quark and an antiquark, $q\bar{q}$ (mesons), or triplets of quarks, qqq (baryons). This simple picture was upset by the observation of the so-called $X(3872)$ meson at the Belle experiment [6]. Since then several potential four-quark states have been observed, both neutral and charged. A good chronology can be found in Ref. [7].

Then, in 2015, two five-quark pentaquarks, dubbed P_c^+, have been reported [8] by my experiment (Fig. 2). Although pentaquarks were already predicted in 1964 [9] and the word coined in 1987 [10], nobody anticipated that such states would be seen at LHCb. The pentaquarks were first seen in 2012 by me and my CERN summer student while studying decays of Λ_b^0 baryons [11]. As physics coordinator of the LHCb experiment, I have been closely involved in the supervision of the subsequent analyses that led to the announcement of their existence [8, 12, 13].

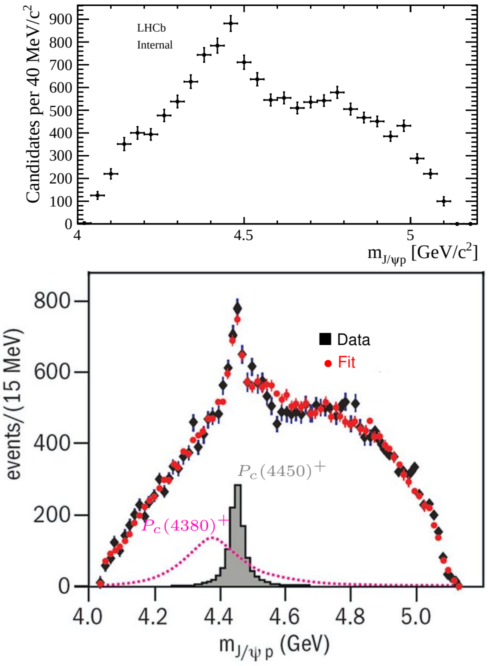

Figure 2: (top) Unpublished $J/\psi p$ mass distribution which I observed in 2012 [11] and (bottom) later published fit result [8]. The $P_c(4380)^+$ state has a lower mass but a larger decay width than the $P_c(4450)^+$ state.

The two P_c^+ pentaquarks are observed through a "bump" (Fig. 2) in the mass distribution of their decay products, a proton and a charm–anti-charm ($c\bar{c}$) state called J/ψ.[2] This observation has led to more than 400 theoretical publications discussing the nature of these states. It is striking that Refs. [8] and [6], are the most cited LHCb and Belle publications. They have many more citations than the CP-violation and rare-decays publications which were the original justifications for these experiments.

After fifteen years of discoveries, many exotic hadrons have been observed. Many models exist describing how quarks organise in these hadrons, as described below. They all predict additional, yet unobserved, hadrons. Verifying the predictions of these models will lead to falsifying some (or all) of the current allowed models.

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[1] The decay width Γ is related to the particle's lifetime τ by $\Gamma = \hbar/\tau$. Strongly decaying particles have lifetimes of order 10^{-23} s, which is not measurable while the decay width is.

[2] Throughout this proposal antiparticles are implied, so here also $\overline{P}_c^-$ decays to a J/ψ state and an anti-proton are considered.

We are in a situation similar to that of Mendeleev 150 years ago, or, closer to us, Gell-Mann in the sixties (Fig. 3): Exotic hadrons need to be organised by quantum numbers, and eventually by quark content and structure. Understanding their patterns will significantly improve our knowledge on the theory of interactions between quarks and gluons (QCD).

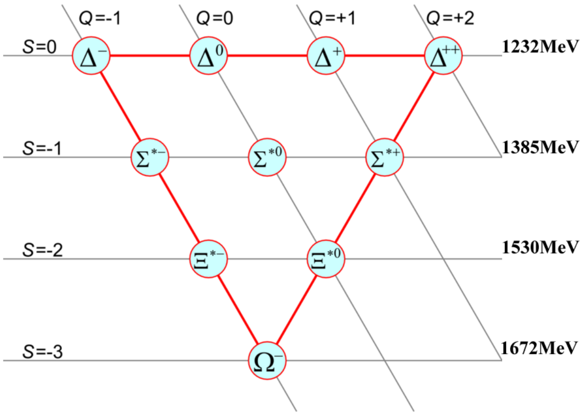


Figure 3: Gell-Mann's "eightfold way" baryon decuplet (1961) [14] predicted the then unobserved Ω^- baryon which was found later [15].

Understanding QCD at the energy scales of hadrons is not only important *per se* but also a necessary input in searches for physics beyond the Standard Model. The core programme of the flavour-physics experiments LHCb and Belle II is to disentangle Standard-Model phenomena from those that cannot be described with the present theory. However, a better understanding of QCD is needed to understand the flavour anomalies reported by these experiments. See for instance my reviews in Refs. [16, 17].

I will disentangle the exotic-hadron models by searching for new particles. I will measure their decay modes, quantum numbers and production rates. I will collaborate with theorists to interpret the results and propose new searches. I have demonstrated in the past that I know how to interpret results [18, 19] and set up collaborations with the theory community.

The context of exotic spectroscopy

Charmonium is known and studied since the "November revolution", the discovery of the J/ψ meson in 1974. Afterwards, more states have been found under the assumption that all charmonium mesons are $c\bar{c}$ states. Masses are predicted using the Born-Oppenheimer approximation, solving the Schrödinger equation and using effective potentials modelling the QCD interaction (notably asymptotic freedom and confinement) [20].

There is a one-to-one correspondence between the allowed charmonium states and those of the hydrogen atom: The predicted states differ by their mass, and are organised by quantum numbers J^{PC} with $J = L + S$, S the spin and L the angular momentum. Other quantum numbers are the parity $P = (-1)^{L+1}$ and charge-conjugation $C = (-1)^{L+S}$ eigenvalues. All allowed states are shown in Fig. 4 in black (if found) and blue (if not yet). Any observed state that does not fit this picture is "exotic", and marked in red.

How can such exotic states occur? Putting quarks and gluons together, any multiple of three quarks (number of quarks minus anti-quarks), plus any number of gluons can be put together to get a valid colourless hadron. All combinations are shown in Fig. 5. More details on the models describing these configurations can be found in Box 1.

Which of these configurations are realised in Nature is unknown. It is also not yet possible to unambiguously assign any of these exotic states to a given configuration. More measurements of the properties of exotica hadrons are required. There may even be several configurations at play simultaneously: The $X(3872)$ meson behaves like a $\overline{D}^0 D^{*0}$ molecule, but also like regular $c\bar{c}$ charmonium. It may be a quantum superposition of a molecule and the yet undiscovered $\chi_{c1}(2P)$ charmonium state.

All exotic hadrons observed so far either contain a pair of charm quarks $c\bar{c}$, or beauty

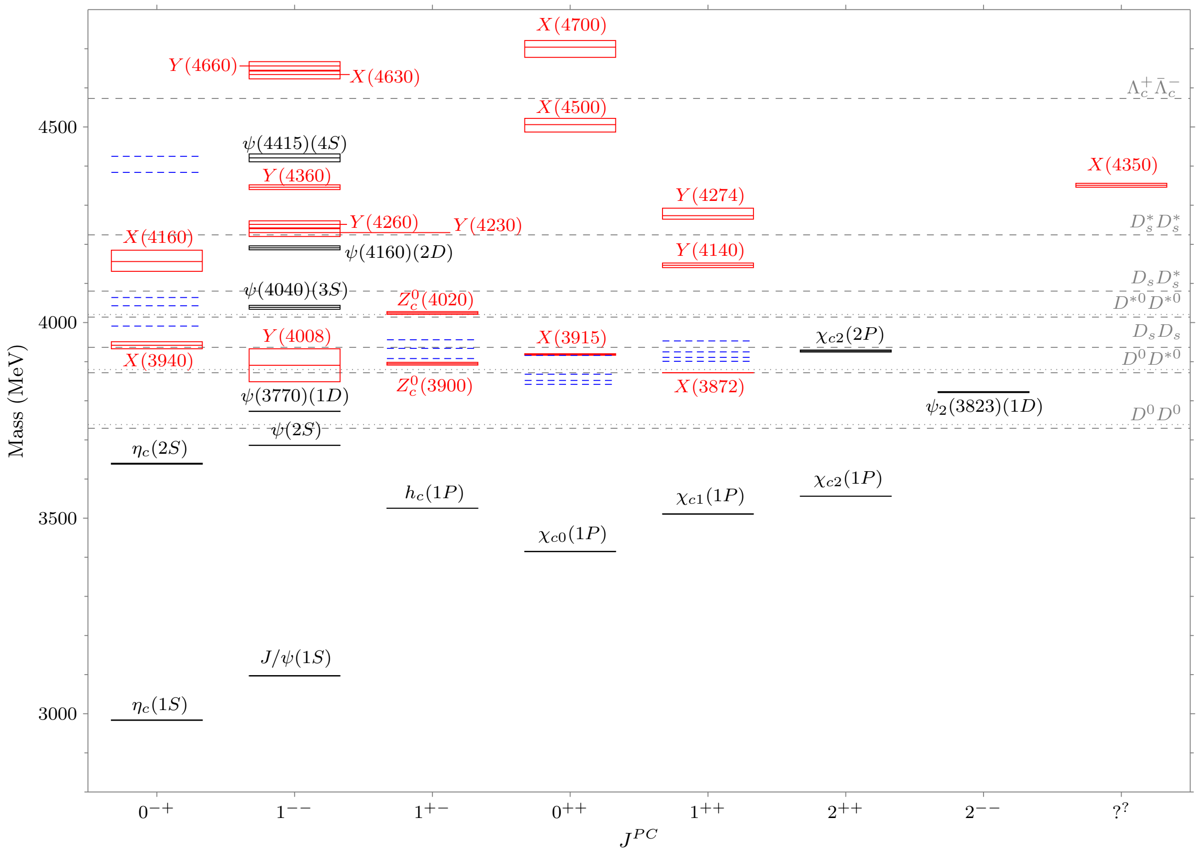


Figure 4: Mass spectrum of neutral charmonium states versus quantum numbers J^{PC}. Observed conventional states are indicated in black, yet unobserved conventional states in blue and observed exotic states in red. Boxes indicate wide states. The dashed lines indicate two-meson thresholds. Figure from Ref. [7], where the corresponding figure for charged states can also be found.

- Hadron
  - Conventional states
    - Meson : $q\bar{q},\ Q\bar{q},\ Q\overline{Q}$
    - Baryon : $qqq,\ Qqq,\ QQq,\ QQQ$
  - Exotic states
    - Molecular state: $(Q\bar{q})(\overline{Q}q), (q\bar{q})(\bar{q}q)\dots$
    - Hybrid meson: $Q\overline{Q}g, q\bar{q}g\dots$
    - Glueball: gg
    - Tetra- pentaquark
      - Compact: $Q\bar{q}\overline{Q}q, Q\overline{Q}\bar{q}qq\dots$
      - Diquark-antidiquark: $(Qq)(\overline{Q}\bar{q})\dots$
      - Triquark-antidiquark: $(Qqq)(\overline{Q}\bar{q})\dots$
      - $\dots$

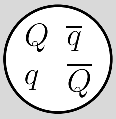
Figure 5: Possible configurations of quarks (Q for the heavy b or c quarks, q for lighter quarks), and gluons (g). The aim of this proposal is to determine which are realised in Nature. See Box 1 for more details.

quarks $b\bar{b}$. It is not clear why, and thus searches for exotic hadrons of a different kind are of high importance. There was a short hope that the D0 experiment at the Tevatron had found evidence of a hadron containing $\bar{b}s\bar{u}d$ quarks [37], but this state was rapidly debunked by an LHCb analysis to which I contributed [38].

Box 1: Models of Exotic Hadrons

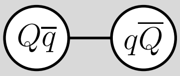
Tetraquarks and pentaquarks could be of several types depending on how the constituent quarks are organised. The models are grouped below in main categories. Here Q denotes the heavy (c,b) and q the light (u,d,s) quarks. In the diagrams below, white objects have no net colour charge. See Refs. [7, 21, 22] for reviews at introductory level.

Compact tetraquarks have constituent quarks in overlapping orbitals [23]. They are tightly bound with a radius less than 1 fm. Although conceptually the simplest, this is the least developed model.



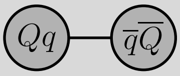
Compact tetraquark

"Molecules": It is known since 1965 that the deuteron is a kind of proton-neutron molecule, loosely bound by a virtual pion exchange [24]. As most exotic hadrons have masses close to a two-hadron threshold it is natural to think of them as molecules formed by these two hadrons. Such models were immediately inspired in 2003 by the observation of the $X(3872)$ meson with a mass at the $\overline{D}^0 D^{*0}$ threshold. See Ref. [25] for a review. Exotic hadrons would be loosely bound molecules of radius between 2 and 10 fm, held together by a strong-force analogue of the van der Waals force [26], mediated by a π meson. A drawback is that the binding energy is weak and thus the radius large, posing the question of how such states could form in the decay of a compact hadron [27]. These models naturally explain why exotic hadrons seem not to form charge multiplets.



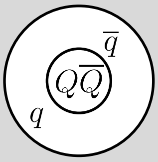
Molecule

Diquark-antidiquark mesons, dubbed "diquarks", are inspired from baryons, where one quark pair usually forms a diquark system. In this model, exotic hadrons are new hadron species with two colour non-singlet diquarks as bosonic building block [28]. Typical diquark sizes are about 1 fm [29]. 't Hooft suggested that some light mesons also fit in this picture [30]. This model predicts many more states than have been found so far: A priori, for every $c\overline{c}$ state a corresponding $b\overline{b}$ state should exist, but only few have been observed. "Selection rules" must be identified to explain which states occur in Nature and which do not. See Ref. [31] for a review.



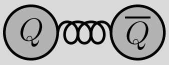
Diquark-onium

Hadro-quarkonium models are inspired by atoms. A hard heavy core is formed by the heavy quarks $Q\overline{Q}$ surrounded by the light quarks [32, 33]. These models predicted the existence of P_c^+ pentaquarks [33]. The binding is expected to be weak and it is thus disputed whether such states could form [34].



Hadro-quarkonium

Hybrids: Exotic mesons could be $Q\overline{Q}g$ hybrid states, where the quarks are not a colour singlet, compensated by a gluon [35]. In principle even gg glueballs could exist.



Hybrid

Kinematic effects: The fact that some tetraquarks have masses slightly *above* the closest threshold is a puzzle for the molecular model. "Bumps" with mass close to a di-hadron threshold appear via the interaction of these two hadrons scattering on each other [36, 29]. For instance the $P_c(4450)^+$ pentaquark could be due to the decay $\Lambda_b^0 \to \Lambda_c(2595)^+\overline{D}K^-$ followed by $\Lambda_c(2595)^+\overline{D} \to J/\psi p$. In this case the P_c^+ states would be kinematic features and not actual particles. Real particles and cusps can be disentangled by using amplitude analysis (Work package **A**).

It is also striking that no doubly charged exotic hadron has been seen so far (nor triply charged baryons). Finding a state with two charm quarks, as $cc\overline{d}\overline{d}$, would tell whether the fact that only exotica containing a heavy quark and the corresponding heavy anti-quark, $c\bar{c}$ or $b\bar{b}$, have been found is a feature of QCD or an experimental accident: States with two heavy quarks are more difficult to produce as they require double the energy. The huge energy of the LHC will allow to overcome this difficulty.

Another puzzle is that, so far, most exotic hadrons have been observed in a single production mechanisms and a single decay mode. Finding known exotic hadrons in other decay modes, or produced in a different manner is an important test of models. For instance most exotic hadrons found to decay to the $\psi(2S)$ state do not decay to J/ψ and vice-versa. It is not clear why. It has been suggested that this is due to the J/ψ meson having a smaller radius than the $\psi(2S)$ meson. For a large object like a molecule or a diquark it is thus more likely to decay to the $\psi(2S)$. This would not be the case for the hadro-quarkonium model [7]. Finding J/ψ and $\psi(2S)$ partner decays for the same exotic hadron is thus of prime importance to disentangle models.

The $X(3872)$ state is atypical: it was found in six decay modes and both in b decays and hadron collisions. It thus plays a central role in exotic spectroscopy as it allows many studies to be performed. While its nature is still disputed, a lot is known about its mass, which is exactly that of a $\overline{D}^0 D^{*0}$ system $m_X(3872) - m_{D^0} - m_{D^{*0}} = 0.01 \pm 0.19\,\mathrm{MeV}/c^2$ [39], its decay width, which is unexpectedly narrow, its quantum numbers, $J^{PC} = 1^{++}$ [40], and its allowed decays, which indicate that it can neither be a classical charmonium nor a $c\bar{c}g$ hybrid.

Many predictions of quark configurations that could be stable are provided by such simulations [41, 42] and their number will increase in the future. Experimental observations are vital to validate and calibrate the mass scales of these predictions. The ability to quickly react to new ideas and predictions is important and requires some flexibility. This flexibility is built in the present proposal.

The interplay of the strong force and gravity forms neutron stars and black holes. If other pentaquarks, which are lighter than those observed by LHCb, are found, they will have an impact on our understanding of these stellar bodies [43]. Similarly, the description of hadrons and in particular charmonia is essential to understand quark-gluon-plasma [44].

The main deliverable of this proposal is a test of models, which will pave the way to a better understanding of QCD.

The models will be tested by asking Nature precise questions, listed in Box 2. The answers to will be fed back to the theory community, who will refine their models and improve the understanding of QCD. In particular, measurements of masses are important benchmarks for lattice QCD simulations, which will validate their calculations. With improved understanding and increased computing resources lattice QCD is likely to be able to provide the precise QCD predictions which are needed in searches for physics beyond the Standard Model.

History has shown that searches for exotic particles yield positive — though often surprising — results. This programme will very likely lead to new observations. Conversely, as all of the above questions address predictions, a non-observation leads to a limit being set on the rate of the predicted particle. Such limits are useful to determine which predictions are incorrect and thus which configurations of Fig. 5 can be observed at the LHC.

Box 2: Questions to be answered

In the following I list the questions addressed by this proposal.

1. **Are there other decays of P_c^+ baryons than $J/\psi\, p$?** If P_c^+ are kinematical effects they are unlikely to produce resonances in other decay modes. Also, in the molecular picture, the allowed decay modes depend on the hadrons entering the composition of the molecule [45]. I will be looking at decays of P_c^+ baryons to other $c\bar{c}$ states than J/ψ, as $P_c^+ \to \eta_c p$ states.
2. **Can the P_c^+ states be found in other baryons?** If P_c^+ are near-threshold kinematical features, they are unlikely to appear in other b baryons than the Λ_b^0. Decays of beauty-strange baryons, as $\Xi_b^0 \to J/\psi\, pK^-$ [46], will be investigated.
3. **Are there P_c^+ states decaying to $\psi(2S)p$?** Experience with tetraquarks show that they prefer decaying to $\psi(2S)$ than to J/ψ. The two observed P_c^+ pentaquarks have a mass just below the $\psi(2S)p$ threshold, but their large width could allow them to decay to this state. Are there other P_c^+ decaying to $\psi(2S)p$? A study of the decay $\Lambda_b^0 \to \psi(2S)pK^-$ is required.
4. **Are there neutral P_c^0 states?** While the decay $P_c^0 \to J/\psi\, n$ is not accessible at LHCb, the decay $P_c^0 \to J/\psi\, p\pi^-$ is visible [47]. This search requires a study of the yet unobserved decays $\Lambda_b^0 \to J/\psi\, p\pi^-\overline{K}^0$ and $\Xi_b^- \to J/\psi\, p\pi^-K^-$.
5. **Do pentaquark states with b quarks exist**, as predicted in some models? Heavy P_b pentaquarks with a $b\bar{b}$ pair could be found. They would naturally decay to Υp.
6. **Are there strange siblings of the P_c^+?** Do P_s^+ pentaquarks with an $s\bar{s}$ pair exist [48]? Belle reported a hint of a peak in the ϕp mass distribution in $\Lambda_c^+ \to \phi p\pi^0$ decays [49].
7. **Are there singly charmed pentaquarks?** Several authors [50] suggests that some of the excited narrow Ω_c^0 states observed by LHCb [51] are $cs\bar{s}ud$ pentaquarks. They could be found by looking for $\Xi_c^+K^-$ or $\Xi_c^0K^0$ resonances, as Ω_c^0 baryons do not decay to those.
8. **Which exotic hadrons can be found at the LHC?** Direct production is the ultimate test of the nature of P_c^+ states, as kinematic effects cannot occur in high-energy collisions. So far, only $X(3872)$ production has been observed at the LHC [52, 53, 54]. The flexible LHCb trigger (see page 13) allows searches for known, but also yet unknown states, in the modes $J/\psi\, p$, $J/\psi\,\pi^+$, $J/\psi\,\pi^+\pi^-$, $J/\psi\, K^+$, $J/\psi\,\phi$, $\Lambda_c^+\overline{\Lambda}_c^-$, *etc.*
9. **How are exotic hadrons produced at the LHC?** The study of the exotic hadron production is a strong test of models,[a] as diquark and hadro-quarkonium models predict larger production cross-sections and harder p_{T} spectra than molecular models.
10. **Are there doubly charged exotic hadrons?** Double charm production is observed at the LHC [55]. Searches for resonances in same-sign pairs of D^+, D_s^+ and Λ_c^+ hadrons will be performed, in particular searches for hexaquarks decaying to $\Lambda_c^+\Lambda_c^+$.
11. **How can spectroscopy be performed at a high-luminosity hadron collider?** A challenge posed by the questions 6 to 10 is how to select the data without knowing a priori what states exist. The `TURBO++` strategy addresses this problem in a novel way.

These questions are grouped in four work packages, described in page 9 and following.

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[a] Luciano Maiani, private communication

The Large Hadron Collider

The large hadron collider at CERN is a fantastic machine for hadron studies. Its proton-proton collisions at high energy (13 TeV presently) provides charm and beauty cross-sections of around 5 and 0.5 mb, respectively, which are several orders of magnitude larger than at e^+e^- colliders. Moreover about 15% of all b hadrons decay through the chain $b \to cW$ followed by $W \to \bar{c}s$, producing a $c\bar{c}$ pair. This situation is extremely valuable as the initial state is a fully reconstructed b hadron and is thus very well known. The drawbacks of hadron colliders are the large amount of background and the enormous collision rates. The LHCb experiment is ideally equipped to overcome these difficulties.

The LHCb detector

The LHCb detector (Fig. 6) is a forward spectrometer located at one of the interaction points of the LHC at CERN. It consists of a series of sub-detectors designed for the measurement of the trajectories of charged particles, followed by the identification of pions, kaons, protons, muons, electrons and photons. Its vertex detector (“VeLo”) detects charged particles as close as 7mm away from the LHCb proton beam. It is the detector that comes closest to the LHC beam of all LHC experiments. This features permits the precise determination of the decay point of short-lived particles and a precise measurement of their mass. These are the two distinctive features of charm and beauty hadrons, allowing LHCb to efficiently separate the signal from the background.

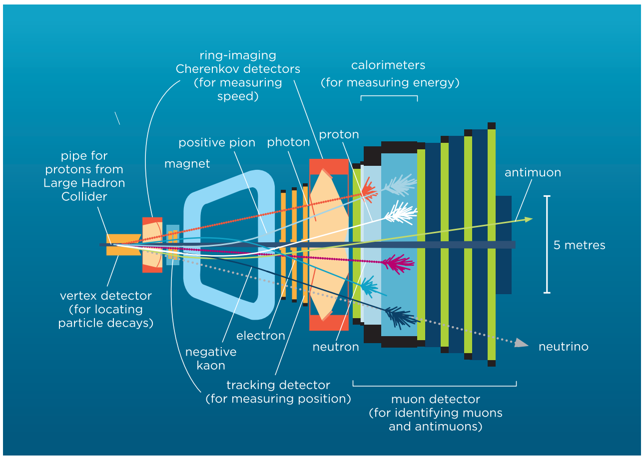

Figure 6: The LHCb detector, displaying how each sub-component is optimised to detect specific particles.

LHCb was designed to study rare decays of hadrons containing b and c quarks and asymmetries between quarks and anti-quarks. Yet, while spectroscopy was not in its initial funding plans [56], LHCb proved to be very good at finding new resonances. Examples are the observation of pentaquarks, or the very recent observations of charmed baryons [51, 57].

There are two reasons for this unanticipated success. First, LHCb is optimised for detecting particles at masses much lower than the heavy bosons searched for by other experiments. In particular its versatile online selection system, (“trigger”) permits the reconstruction in real time of beauty and charm hadrons. This feature will be exploited and extended in this proposal, see page 13. Second, hadrons containing charm quarks may be produced in decays of beauty hadrons, which are copiously produced at LHCb. These can be selected with very little background, giving a clean initial state which can be studied using amplitude analysis, as explained in Work Package **A** below.

In the present proposal I show how these techniques can be exploited to find and study exotic hadrons.

Complementary experiments

There are two other experiments at the LHC which perform studies of exotic hadrons: the two general purpose detectors ATLAS and CMS. They run at a higher luminosity than LHCb and thus collect even more data, but are not optimised for hadron physics. Their searches are limited to hadron with very large transverse momenta (p_{T}). The latter actually makes them complementary to LHCb in measurements of particle production: LHCb covers the low-p_{T} and ATLAS and CMS the high-p_{T} range. They both lack hadron identification and are thus less able to distinguish peaks in $J/\psi\, p$ and $J/\psi\, \pi^+$, for example.

The Belle experiment in Japan is presently finalising a major upgrade and will start collecting data. It is complementary to the LHC as it can search for new particles in e^+e^- collisions at $\sim 10\,\mathrm{GeV}/c^2$ centre-of-mass energy, or via initial-state radiation. The same applies to BES III in China, which runs at a lower energy.

On the other hand, the Belle II experiment competes with LHCb in the study of decays of B^0 and B^+ mesons. Its much lower backgrounds and better capabilities for neutral final states as π^0 mesons, compensates for the much lower cross-sections in some channels. Having worked there I know very well which decays are better suited for LHCb and which for Belle II. The present proposal reflects this.

Finally, there are running fixed-target experiments at CERN and Jefferson Laboratory which provide complementary measurements of charmonia production. An observation of P_c^+ baryons from J-Lab is eagerly awaited. In the longer term future the $\overline{\mathrm{P}}$ANDA experiment in Germany will be dedicated to exotic spectroscopy. There is a strong involvement of the Netherlands in this experiment, see page 16, leading to a synergy of expertise.

Work packages and publications

The following sections describe the work packages in more detail. The present proposal connects two different techniques of identifying new particles: observation in prompt production and determination of quantum probability amplitudes (“amplitudes” in the following) in b-hadron decays. The two techniques interact as a particle found in one way may best be studied in the other (Fig. 7).

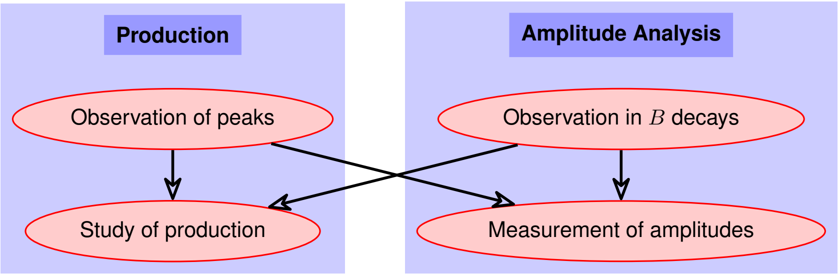

Figure 7: Schematic discovery diagram.

The project spans over the end of LHC Run 2 (2015–2018) and the beginning of Run 3 (2021–2023). Work Packages **A** and **B** will exploit all data taken up to 2018. Work Package **C** will be based on data collected in special LHCb runs at the end of 2018 and the early Run 3 data. It relies on the new `TURBO`++ scheme, developed in Work Package **D**.

Based on this programme, approximately fifteen publications can be achieved by a team of six people. This does not count any potential collaborations with theorists. While ambitious, this plan is realistic based on the number of publications a good student–post-doc team can achieve in LHCb.[3]

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[3] My student Kristof De Bruyn had four experimental and six theory publications during his PhD.

Work package A — Searches P_c^+ in decays of b baryons	
Addressed questions	Questions 1, 2, 3, 4 (Box 2)
Personnel	Post-doc 1 and PhD student 1 (≈2 FTE)
Activity and Data	2018–2022, using all data collected up to 2018
Planned publications	*Observation of the decays* $\Xi_b^0 \to J/\psi pK^-$ *and* $\Xi_b^0 \to \psi(2S)pK^-$ *Observation of* $\Lambda_b^0 \to J/\psi p\pi^-\overline{K}^0$ *and* $\Xi_b^- \to J/\psi p\pi^-K^-$ *Observation of pentaquarks in the decay* $\Lambda_b^0 \to \eta_c pK^-$ *Observation of pentaquarks in the decay* $\Xi_b^0 \to J/\psi pK^-$ *Observation of pentaquarks in the decay* $\Lambda_b^0 \to \psi(2S)pK^-$

This work package focuses on the study of decays of beauty baryons. The most prominent are the Λ_b^0 (quark content: bud) and the beauty-strange Ξ_b^0 (bsu) and Ξ_b^- (bsd) baryons.

The first step will be the observation of the decays listed above using the LHCb data collected up to 2018. This work builds on my previous experience with rare decays to charmonia, where I led the analyses of the decays $B_s^0 \to J/\psi K_S^0$ [58] and $\Lambda_b^0 \to J/\psi p\pi^-$ [11]. In all cases the two-body mass distributions (as in Fig. 2) will be published, as well as the Dalitz plane, a representation of the decay structure in terms of squared masses. Fig. 8 shows the Dalitz plane of the $\Lambda_b^0 \to J/\psi pK^-$ decay, where the contributions of the P_c^+ and $\Lambda(1520)$ baryons are emphasised.

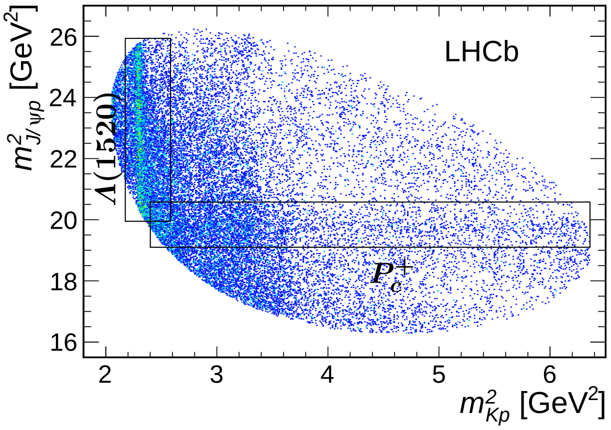

Figure 8: Dalitz plane of the $\Lambda_b^0 \to J/\psi pK^-$ decay, with the prominent P_c^+ and $\Lambda(1520)$ resonances indicated in boxes [8].

For the decay modes that provide enough data, an *amplitude analysis* of the decay structure will be performed, as in Ref. [8]. Amplitude analyses use the description of the decay in terms of angles and masses and fit a model describing a quantum superposition of decay amplitudes to the data. The output are the yields and phases (and, if appropriate, masses and widths) of all intermediate states contributing to the decay. In the case of $\Lambda_b^0 \to J/\psi pK^-$, they are the two pentaquarks but also 14 known Λ baryons decaying to pK^-. The measured pentaquark amplitude will be represented on an Argand diagram and compared with the expectation from resonances and kinematical effects [59].

Amplitude analysis will be performed for the decays $\Lambda_b^0 \to \eta_c pK^-$ (Question 1), $\Xi_b^0 \to J/\psi pK^-$ (Question 2) and $\Lambda_b^0 \to \psi(2S)pK^-$ (Question 3). An unpublished 2σ excess of $\Xi_b^0 \to J/\psi pK^-$ was found as a by-product of the analysis of Ref. [11]. In the corresponding paper titles given above I am planning for success. In case no pentaquarks are seen, the publications would be called *Amplitude analysis of the decay…* and still have an very important impact on QCD models.

Amplitude analyses require experience in understanding detector biases in the angular description, as I have done with my work on rare B meson decays [60] and CP-violation analyses [61]. Several open-source amplitude-analysis frameworks exist and are in use in LHCb. There is presently limited experience with those at Nikhef, a situation which this proposal aims to change. It will be ensured that Post-doc 1 has worked with one of these frameworks and will transfer her/his expertise to Nikhef.

Concerning the neutral P_c^0 states (Question 4), it does not seem realistic to collect enough data for the decay modes $\Lambda_b^0 \to J/\psi p\pi^- \overline{K}^0$ and $\Xi_b^- \to J/\psi p\pi^- K^-$ to perform an amplitude analysis. The full Run 3 data will be required, which is beyond the scope of the project. However, an observation of the decay modes and a first look at the two-body mass distributions, as I have done with $\Lambda_b^0 \to J/\psi p\pi^-$ would be an important step forward.

The deliverable of this package is an improved understanding of the P_c^+ pentaquarks and their production in b baryons. The goal is to establish them as actual resonances or to identify their nature as kinematical effects. The results of the $\psi(2S)$ and η_c fits will disentangle models describing the nature of the P_c^+ states.

Work package B — Study of exotic $b\bar{b}$ and $c\bar{c}$ states at the LHC	
Addressed questions	Questions 5, 8, 9 (Box 2)
Personnel	Post-docs 2 and PhD student 2 (≈1 FTE)
Activity and Data	2019–2023, using all data up to 2018
Planned publications	*Study of $X(3872) \to J/\psi\pi^+\pi^-$ production at the LHC* *Observation of exotic hadron production at the LHC in $J/\psi p$, $J/\psi K^+$ and $J/\psi\phi$* *Observation of pentaquarks decaying to Υp, $\Upsilon\pi^+$, ΥK^+* *Observation of pentaquarks decaying to $\Upsilon\phi$*

This work package exploits LHCb's high efficiency for final states containing muons, resulting in the mass distribution shown in Fig. 9. These data will serve as input to searches for promptly produced exotic hadrons decaying to J/ψ and Υ states.

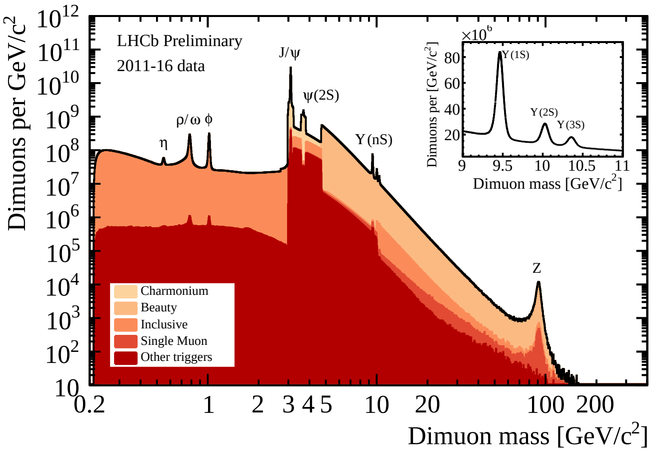

Figure 9: Unpublished dimuon mass distribution as reconstructed in the trigger, based on Ref. [62]. A zoom into the Υ region is shown.

There is a strong motivation to look for hidden-beauty partners of the P_c^+ states, as these are predicted by diquark models. These would be P_b^+ pentaquarks with quark content $b\bar{b}uud$ and would decay to Υp [63] (Question 5). All states from $\Upsilon(1S)$ to $\Upsilon(3S)$ are to be investigated. LHCb is in the ideal situation for such a study thanks to its large sample of Υ mesons and its proton-identification capabilities. In case no Υp state is found, the paper would be titled *Search for structure in the Υp mass spectrum* and would set limits of production cross-sections times branching fractions. These are important inputs to constrain models.

The study will be extended to $\Upsilon\pi^+$ (where the $Z_b(10610)^+$ and $Z_b(10650)^+$ states can be searched for), ΥK^+ and $\Upsilon\phi$ states. The latter would be hidden-beauty partners of the four $c\bar{c}s\bar{s}$ states observed by LHCb [64].

It is doubted that loosely bound objects such as molecules could be formed at the LHC, so a limit on, or a measurement of the production cross-section and the transverse-momentum p_T distribution allows discriminating between models. This was done for the $X(3872)$ state [52, 53, 54], indicating that it is a compact object. As it could be a quantum superposition of a molecule and a regular quarkonium, this measurement does not yet solve the puzzle. Measurements for other hadrons are required, starting with the states $J/\psi p$, $J/\psi K^+$ and $J/\psi\phi$ (Question 8). Known states will be studied and yet unknown states searched for.

I will use the same approach which I defined and led for the first cross-section measurements at 13 TeV [65] and perform high-precision production studies of the $X(3872)$ meson (Question 9). An ATLAS analysis indicates that an unexpectedly large fraction of $X(3872)$ may originate from decays of B_c^+ mesons [54]. This fraction will be more precisely measured at LHCb by reconstructing the lifetime distribution of $X(3872)$ mesons and determining the components coming from prompt collisions, B_c^+ decays and other b-hadron decays. I will employ the same techniques as those which I presently use to measure the $J/\psi \to e^+e^-$ cross-section.

The deliverables of this work package will be observations or exclusions of $b\bar{b}uud$ pentaquarks, which will test the predictions of diquark and molecular models. This is a high-risk high-gain project but with a win-win situation as no observation would be very interesting too. Furthermore, cross-sections measurements will be performed, which will disentangle between molecular and other models. They may even lead to the observation of new charmonium-like states.

Work package C — Study of exotic hadrons decaying to hadronic final states	
Addressed questions	Questions 6, 7, 8, 10 (Box 2)
Personnel	Post-doc 2 and PhD student 3 (≈1 FTE)
Activity and Data	2020–2023, using `TURBO++` data of 2018 and 2021
Planned publications	*Observation of pentaquarks decaying to $\Xi_c^+ K^-$ or $\Xi_c^0 K^0$* *Observation of hidden-strangeness pentaquarks in $\Lambda_c^+ \to \phi p \pi^0$* *Observation of doubly charged hadrons in $D_{(s)}^+ D_{(s)}^+$, and $\Lambda_c^+ \Lambda_c^+$* *Study of $Y(4630) \to \Lambda_c^+ \overline{\Lambda}_c^-$ production at the LHC*

The main aim of this work package is to study the production of exotic hadrons with hadronic final states. Its scientific goals are similar and complementary to those of Work Package **B**, but it requires changes to LHCb data collection strategy (Work Package **D**).

Hidden-strangeness pentaquarks P_s^+ with quark content $s\bar{s}uud$ could be found in decays of Λ_c^+ and Ξ_c baryons [48] (Question 6). Belle reported a hint of a peak in the ϕp mass distribution in $\Lambda_c^+ \to \phi p \pi^0$ decays [49]. These studies will require a new trigger selection to be run in dedicated data taking periods scheduled in 2018 and 2021. The Λ_c^+ baryon being very prominent, a small fraction of the 2018 or 2021 data would be enough to perform this study.

Searches for resonances in the mass spectra of $\Xi_c^+ K^-$ and $\Xi_c^+ K^0$ aim at finding unambiguous open-charm pentaquarks (Question 7). Among the five Ω_c^0 (css) resonances found by LHCb [51], two could be $cssu\bar{u}$ pentaquarks [50]. The decay $\Omega_c^0 \to \Xi_c K$ is forbidden by isospin conservation, but this would not apply to pentaquarks. The latter could be found by looking for $\Xi_c^+ K^-$ or $\Xi_c^0 K^0$ resonances.

LHCb has measured double-charm production (for instance two D^+ mesons) with a small data set collected at a centre-of-mass energy of 7 TeV [55]. Using a larger data sample at a higher collision energy and the more efficient `TURBO++` scheme, a search for doubly charged tetraquarks (Question 10), pentaquarks and even hexaquarks can be performed. All combinations of D^+, D_s^+, D^{*+} and Λ_c^+ should be tried and scanned for mass peaks. As a control, the right sign combinations, as $\Lambda_c^+ \overline{\Lambda}_c^-$, will also be investigated, permitting the study of $Y(4630) \to \Lambda_c^+ \overline{\Lambda}_c^-$ decays (Question 8). In all cases, a 13 TeV update on the double-charm cross-section will be performed.

All these studies will be based on `TURBO++` data and will require the design of selections at trigger level.

The deliverables of this work package will be observations or exclusion limits on exotic hadrons not containing a $Q\bar{Q}$ pair. These would be particles of a totally new kind, which would boost the understanding of exotic hadrons. No observations would also be an important input for theory models. Furthermore the claims that some Ω_c^0 resonances are pentaquarks will be investigated.

Work package D — `TURBO++` development and commissioning of the LHCb trigger	
Addressed question	Question 11 (Box 2)
Personnel	Post-doc 2 and PhD students 2 and 3 (≈1 FTE)
Activity and Data	2019–2022
Planned publications	*TURBO++: Fast and low-bandwidth spectroscopy at the LHC* *The upgraded LHCb trigger for the LHC Run 3*

The LHCb experiment will be upgraded in 2018–20 [66], with the goal to increase the data rate tenfold. To accommodate the data, not all information from the collision will be recorded but only the parts considered interesting by the data acquisition system [67]. This is made possible as the data is stored on disk for a short time, while calibrations are performed before the data is used in the trigger. This new system — which I invented in 2011 — was put in production in 2015. It makes high-quality data available immediately after data taking, without the need of a long post-processing.[4] As a side-effect, a reduction of systematic uncertainties is achieved as only one processing is performed, thus avoiding cumbersome computation of trigger selection efficiencies.

This scheme, dubbed `TURBO` as it allows fast access to data, is the future of collider physics data acquisition [69, 70]. With data sizes growing more rapidly than Moore's law, analysing the whole data is not affordable. The usual procedure for, say, a study of Λ_c^+ production, is to keep the whole collision event and restrict the kinematic range of the Λ_c^+ production to keep the rate affordable. However, in most analyses only a small fraction of the collision data is required. An alternative is thus to keep the trigger objects, so the Λ_c^+ baryon, and discard the rest of the collision event. This is the `TURBO` idea: keep what is needed and remove the rest. `TURBO` was first used in measurements which I proposed and delivered for the 2015 summer conferences only 18 days after the data was taken [65].

Following LHCb's first successes, other large LHC collaborations are also studying the implementation of similar schemes, which will undoubtedly be at the core of future projects like the International Linear Collider (ILC) or the Future Circular Collider (FCC) [70].

However, for spectroscopy, the particles which can be combined with the original Λ_c^+ candidate to search for new states are needed. This is what `TURBO++` delivers: keep the trigger candidate and a small selection of particles which are nearby (Question 11).

The `TURBO` scheme was upgraded by Nikhef scientists into `TURBO++`, which allows to store additional information. Recently the first publications using its prototype reported the observation of the Ξ_{cc}^{++} baryon [57]. `TURBO++` is thus already demonstrated to work in simple cases. The challenges are at the computing level: As the data rates will increase and CPU budget of the LHCb trigger farm is limited, a re-design of the trigger is required to keep the selections

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[4] A similar system has been designed by the CMS collaboration, under the name "data scouting" [68].

within the CPU and rate budgets without affecting the physics reach.

I will develop the trigger using real-time machine-learning techniques and demonstrate that `TURBO++` can be used for the production of exotica hadrons at high-luminosity [71]. While such techniques are standard in many fields of science, running them in real-time in a single-shot situation is novel.

I will teach the software to quickly recognise exotic hadrons by developing fast algorithms using parallel computing and machine learning. I will participate in the re-design of the LHCb trigger with a new framework presently being developed at Nikhef. I will take responsibility for the `TURBO++` part of the new framework. As an original designer of the LHCb software and former operations coordinator I am in the best position to take a leadership role in this software development.

Post-doc 2 and Students 2 and 3 will work on this project and be members of the development and commissioning teams. Myself and Post-doc 2 will take leadership roles in this project.

The `TURBO++` software has to provide data rapidly at the beginning of the LHC run 3. First tests of the selection algorithms (which do not require the new framework) will be put in production during dedicated data taking periods in 2018.

The deliverable will be ready-to-use open-source machine-learning `TURBO++` ***software which will provide data rapidly at the beginning of the LHC run 3.***

Risks and mitigation

The risks that this project faces are for two kind: scientific and technical.

The main scientific risk is Nature not being kind to us. Expected states may not exist, only decay in modes that are hard to detect, or have a very large natural width, which will make them look like background. All these possibilities would lead to non-observations, but also be interesting inputs for the theory community. Some states are indeed predicted to exist, be narrow and decay to a visible final state. If they are not found, the model needs revision, which is a positive outcome.

On the technical side, many of the measurements rely on a working `TURBO++` scheme in a functioning trigger. The idea of `TURBO++` has been validated already. However, there is a risk that the LHCb high-level trigger cannot cope with the anticipated input bandwidth. This would force a reduction of the running luminosity and require more work to improve the trigger during Run 3. It would affect the core physics programme more than this proposal, which does not require enormous data samples.

Finally, the LHC has a long history of delays, which are to be expected for such a large technological project. Run 3 was anticipated for 2020 and is now scheduled to start in 2021 (Fig. 10). In case additional delays are added, the part of Run 3 overlapping with this project would be reduced. This would not cause a problematic loss of data, as the project does not critically depend on the amount of data taken. However, the data collected during this latter period could arrive too late for the whole programme of (in particular) Work Package **C** to be performed. To mitigate this risk, I will put in place several prototype `TURBO++` selections at the start of the project funding period, in 2018.

2a2. Research plan

The team will consist of myself, two post-docs and three PhD students. The work-plan is outlined in Table 1. It is well tuned to the LHC operations schedule (Fig. 10).

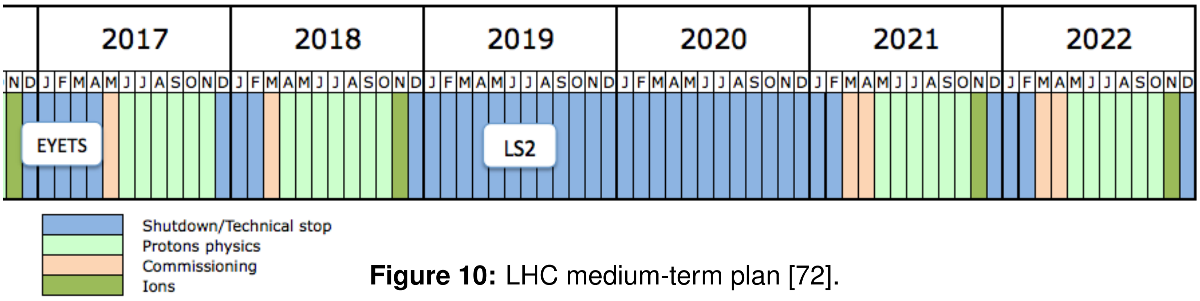

Figure 10: LHC medium-term plan [72].

PhD students are given a four year contract. Their curriculum is organised in the Dutch Research School for Subatomic Physics. In their first two years, PhD students participate in an annual two-week Belgium-Dutch-German graduate school. Three times per year they attend 3-day topical lectures, which take place at Nikhef in Amsterdam. In their third year PhD students participate in an international summer school, normally the CERN school. Students usually represent LHCb once or twice at an international conference on a topic related to their PhD thesis. Finally, students are expected to spend up to 10% of their time on teaching assistance.

The postdocs are given a three year contract. The postdocs participate in the analyses of the students, contributing to the daily supervision. They will have the operational responsibility of the work-packages.

The students and postdocs will become member of the LHCb collaboration. LHCb members are required to perform data taking shifts and contribute to detector operation and calibration. As some of these tasks can only be performed while being near to the experiment, students and postdocs are expected to spend a prolonged period at CERN. A stay at CERN benefits their future career as well, as it improves visibility in the collaboration. I will realise this project as part of the Nikhef group that participates in LHCb. This group has a strong record in detector construction, track reconstruction, trigger software and data analysis, providing an excellent environment to carry out this research.

Table 1: Time-line of the project. Years correspond approximately to the periods April–March.

	Grant period (April 2018 – March 2023)				
	2018	**2019**	**2020**	**2021**	**2022**
LHC	**Run 2**	Long shutdown		**Run 3**	
Work Packages	**A.** Searches in b baryons				
		B. $q\bar{q}$ states			
			C. Hadronic final states		
		D. TURBO++ development			
Applicant	Supervision, analysis and publications				
Post-doc 1	Work-package **A**				
PhD 1	Work-package **A**				
PhD 2		Work-packages **D** and **B**			
PhD 3		Work-packages **D** and **C**			
Post-doc 2		Work-packages **D**, **B** and **C**			
Physics Publications	1	2	3	4	3
Technical Publications			1	1	
PhD theses				1	2

National and international collaboration

This project is performed within the LHCb collaboration involving over 1000 physicists from 70 institutions in 16 countries. The Netherlands and Nikhef are the ideal place to take the leadership in this programme. I have strong ties with the KVI-PARC group in Groningen, involved in exotic spectroscopy in the BES-III (China) and P̄ANDA (Germany) experiments. While the former cannot produce pentaquarks, the latter will only come online in 10 years and has a limited sensitivity to P_c^+ states. I will develop synergies and transfer knowledge by presenting this work at relevant computing conferences. I was recently invited by the P̄ANDA collaboration to present LHCb pentaquark analyses.

2a3. Summary of innovative aspects

This proposal considerably expands the exotic hadron spectroscopy programme of LHCb, which was not part of the motivations for building the experiment. However, with the proposed change of the trigger, LHCb is the optimal detector for this research. The most innovative parts of the proposal are listed below

`TURBO++`: A scheme to select only the minimal amount of information to allow a physics analysis directly on the triggered candidates. As spectroscopy is looking for the unknown, not only the trigger object (typically a J/ψ or a Λ_c^+ hadron) but also the particles surrounding it are to be saved. This sets a future route for very high luminosity experiments, as at the high-luminosity upgrade of the LHC, where 99% of the event data will not be needed in the physics analysis. The data sizes are thus not only reduced by removing uninteresting collision events, but also the parts of these events that are not relevant.

Spectroscopy at the LHC: The above scheme will allow to scan the LHC collision data looking for new signatures which were not available at e^+e^- colliders or in b physics. The LHCb experiment with its precise displaced vertex and particle identification is ideal for this programme.

Agility: The field of exotic spectroscopy is less than 15 years old, and is very fast moving. In particular lattice QCD has recently become an essential provider of predictions. The present proposal will need to be revised as new discoveries are made and new interpretations are published. The `TURBO++` scheme allows to find in data particles that were not thought of initially.

Theory: A close link with the theory community will be arranged for. I have strong contacts with theorists involved in the developments of the models described in Box 1 and with the lattice QCD community. I will collaborate to theory publications and help turning these models in a better understanding of QCD.

As former operations coordinator, in charge of LHCb operations in Run 1, I am well placed to know how the experiment and its operations react to new ideas. I proposed the prompt calibration of the trigger and supervised its commissioning in 2012. In 2013 I was elected physics coordinator and promised two extremely fast publications on J/ψ and charm cross-sections at 13 TeV. They were delivered in 2015 within weeks of the data taking [65] and were the first use of the `TURBO` stream.

2b. Knowledge utilisation

The *wetenschapsagenda* asks if we know all constituents of matter [73]. This poses a philosophical question: what are we made of and where do we come from? There is a great interest for physics, as seen with the Higgs [74], pentaquark [8] and gravitational wave [75] discoveries. Science is part of culture.

I participate in **outreach** and **public engagement** activities coordinated by CERN and Nikhef to explain to the public what knowledge we have gained. In particular there is a demand for a narrative that connects fundamental physics and the Big Bang, as shown in a London Science Museum exhibition to which I contributed. I will use my experience with the press and outreach teams to communicate on our findings. I spoke to many dutch and international journalists about pentaquarks, including de Volkskrant, KIJK, the Daily express, Time, and the BBC.[5] I was involved in recent CERN and Nikhef **press releases** on the observations of rare decays [76], pentaquarks [8] and new baryons [51, 77]. Thanks to my contacts I will further develop this involvement, in particular in the dutch Press.


Figure 11: The applicant (right) demonstrating a spark chamber at the London Science Museum.

My experience is that news in the press create an excitement which can be exploited to increase awareness of and interest for science. High-school students are particularly receptive for science, the scientific method and critical thinking. The particle physics **Masterclass** programme[6] is giving students a hands-on experience wit the scientific method using actual data [78]. I have contributed to the development and running of masterclass exercises based on LHCb data. I plan to extend it to exotic spectroscopy, such that students in the Netherlands and elsewhere can get to see on their own computer screen the pentaquarks they have seen in their local newspaper.

Particle physics has always been at the forefront of developments in scientific computing, with the notable development of the world wide web [79]. The proposed work on the `TURBO++` implementation is an investment in the future of **Big Data science**. It combines real-time data processing and machine-learning to achieve a significant data reduction, which is one of the major challenges in high-energy physics and other fields [71]. Just considering the J/ψ mesons produced at LHCb during its lifetime, `TURBO++` allows saving 75% of data storage and processing, i.e. 2 million TB, or a stack of external disks 40 km high (or 10% of all Google storage). This corresponds to a cost reduction of up to **40 M€**. Intelligent data handling allows for more science at a lower cost.

Further reduction in data size while keeping a high signal efficiency will be achieved by using **machine learning** techniques. While such techniques are standard in many fields of science, running them in real-time in a single-shot situation is novel. Bringing the machine-learning and fundamental-research communities together to find common solutions to big-data problems is a necessity but also a major challenge [71]. I was among the organisers of the very successful LHCb "flavours of physics" machine learning challenge, organised on the Kaggle [80] platform, recently bought by Google. I invited the machine-learning community to use

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[5] A list is at http://www.nikhef.nl/~pkoppenb/outreach.html.

[6] http://physicsmasterclasses.org/

LHCb data and will organise other such events. The outcome will be a further development of data-mining algorithms usable in particle physics but also transferable to any big-data analysis.

When presenting these ideas in conferences, I face great interest but also scepticism about the risks of removing most of the data. Yet, such actions are necessary in all fields requiring *big data* and machine-learning techniques, as social sciences, astronomy or genomics. By 2025 these fields will be facing similar challenges as particle physics [81]. `TURBO`++ will serve as a demonstrator for other experiments and other fields. All software will be provided as **open-source** packages and made independent of the underlying LHCb software architecture. Potential industrial applications are difficult to foresee, but Nikhef and its business incubator[7] are the ideal place to find synergies spread knowledge.

I will present the technical implementation in conferences outside of my field and thus will help other research projects to move in this direction. I will demonstrate that science can be done at lower cost without any loss in precision.

2c. Number of words

2a	7139 (max 8000)
2b	688 (max 1000)

2d. Literature references

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2e. Data management

The data is the main output and most valuable asset of the gigantic Large Hadron Collider project. Past experience has shown that occasionally high-energy physics data collected decades ago has to be accessed again. The LHC experiments have consequently planned for the future. As for all LHC experiments, multiple copies of the raw ("unprocessed") LHCb data are stored at international computing centres, such as SARA in Amsterdam. These data are planned to be kept indefinitely at CERN.

LHCb has adopted an LHCb External Data Access Policy [1], which will make the LHCb data available to any interested party. CERN will provide the necessary infrastructure. The required analysis software will be maintained, thus allowing any researcher to replicate any LHCb analysis, to extend it, or to design new analyses. The first LHCb data-set will be made public in 2018.

The data relevant for this project is a subset of the LHCb data mentioned above. The procedures to analyse the data will be documented so that researchers can reproduce and extend my studies in the future. Following my initiative as Physics Coordinator, the LHCb collaboration is developing an analysis-preservation framework [2], which will permit to re-play physics analyses from the data to the final figures and numbers.

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Cost estimates

3a. Budget

	Description			Year 1	Year 2	Year 3	Year 4	Year 5	Total
Staff		**FTE**	**Months**						
WP	**Applicant**	0.8	60	110	110	110	110	110	550
WP	**Postdoc 1**	1	36	72	72	72			216
WP	**Postdoc 2**	1	36		72	72	72		216
WP	**PhD 1**	1	48	54	54	54	54		216
WP	**PhD 2**	1	48		54	54	54	54	216
WP	**PhD 3**	1	48		54	54	54	54	216
Total Staff		5.8	276	**236**	**416**	**416**	**344**	**218**	**1630**
Equipment									0
LHCb membership	10/postdoc/year			10	20	20	10	0	60
Total Investments				**10**	**20**	**20**	**10**	**0**	**60**
Total Materials				**0**	**0**	**0**	**0**	**0**	**0**
Stationing at CERN	15/year			15	60	45	15	0	135
Travel	7/year when at Nikhef			7	7	14	21	14	63
	3/year when at CERN			3	12	9	3	0	27
Total Travel				**25**	**79**	**68**	**39**	**14**	**225**
Other									
Grand Total				**271**	**515**	**504**	**393**	**232**	**1915**

All costs above are in k€. The salary costs for postdocs and PhD students follow the latest NWO guidelines. There is no need for special equipment, notably computers, as LHCb and Nikhef resources are being shared. The postdocs are stationed at CERN and the PhD students at Nikhef, except for their second year during which they are at CERN. People based at Nikhef need a larger travel budget so they can come to CERN when needed. The yearly travel budget is thus 7 k€ when at Nikhef and 3 k€ when at CERN.

3b. Cofinancing 'in kind'

Cofinancer/party	Description	Estimated value
NWO/Nikhef	75% of applicant's salary	415 k€

3c. Cofinancing 'in cash'

Cofinancer/party	**Description**	**Estimated value**

3d. Totals

Grand Total	1915 k€
Requested budget	1500 k€

3e. Have you requested any additional grants for this project either from NWO or from any other institution, and/or has the same idea been submitted elsewhere

No.