Constructing 'Doable' Dissertations in Collaborative Research:

Alignment Work and Distinction in Experimental High-Energy Physics Settings

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Abstract

Many young scientists are trained in research groups, yet little is known about how individual doctoral dissertations are carved out of collaborative research projects. This question is particularly pronounced in high-energy physics, where thousands of physicists share an experiment's apparatus, data, and the authorship of publications. Based on qualitative interviews with researchers working at CERN's Large Hadron Collider, this paper analyses what makes a PhD dissertation 'doable' in this context. Describing the levels of work organisation, the challenges, and the actors involved in constructing 'doable' dissertations in collaborative research, I argue that doctoral dissertations are the emergent product of alignment work performed throughout the PhD. Individualisation is achieved by temporally, qualitatively and formally distinguishing dissertations from work on collective publications. I discuss how these processes shape the roles of students and advisors, and the content and value of dissertations in collaborative research.

Keywords: alignment work, collaboration, doctoral students, dissertations, authorship, physics

Introduction

The observable increase in the number and size of research collaborations across the sciences (Milojević, 2014; Wuchty et al., 2007) seems to be in conflict with traditional academic career and reward systems focusing on individual achievements (Mangematin, 2001). This includes the work of PhD students, who contribute substantially to collaborative knowledge production (Larivière, 2012). Although Science and Technology Studies (STS) has long had an interest in the socialisation of students as members of research communities, there is no dedicated study on the practices that shape doctoral dissertations in collaborative environments. PhD dissertations based on collaborative research need to satisfy seemingly opposing requirements. As an academic qualification, the dissertation should constitute an independent and original research contribution, yet contributing to research in practice means supporting the ongoing work of a collective. Against the backdrop of this structural tension between collaborative research practices and individual attribution of results, this paper asks *how doctoral dissertations – as individually attributed research outcomes – are made doable in collaborative research.*

Contemporary experimental high-energy physics presents an extreme case of collaborative research, where thousands of physicists share an experiment's apparatus, data, and the authorship of publications. About one third of the researchers involved in the experiments at the European Laboratory for Particle Physics' (CERN) *Large Hadron Collider* are doctoral students. Based on an analysis of interviews with graduate students, post-docs, and PhD advisors in experimental high-energy physics, this paper describes the practices involved in constructing dissertations that contribute to collective research goals while being attributable to an individual student. I refer to dissertations satisfying both requirements as 'doable', drawing on Fujimura's (1987) concept of 'doable problems'. Constructing doable problems in collaborative research requires 'alignment work' (Jackson et al., 2011) between various levels of work organisation. Describing the levels of work organisation, the challenges, and the actors involved in constructing 'doable' dissertations in collaborative research, I argue that doctoral dissertations are the emergent product of alignment work performed throughout the PhD. Given that academic qualifications rest on the attribution of work to a single author, I also describe how dissertations are distinguished from collaborative work. These processes have implications for the respective roles of students and their advisors. Practices of distinction also shape the contents and value of dissertations vis-à-vis other products of collaborative research, particularly the collective publications of results. My work contributes to studies on knowledge production and doctoral training across epistemic cultures (Delamont et al., 2000; Knorr Cetina, 1999) and demonstrates that a focus on dissertations offers a magnifying lens on the internal dynamics of collaborative research.

Doctoral students in collaborative research

Existing work in social studies of science has conceptualised doctoral training as a process of socialisation into culturally specific forms of knowledge production. As such, the PhD involves transmitting tacit problem-solving skills (Delamont and Atkinson, 2001) and a field-specific habitus (Delamont et al., 1997; Traweek, 1988). Doctoral training and the format of students' contributions reflect a research community's specific epistemic practices and work organisation. Compared to the humanities and social sciences, PhD students in natural sciences work less independently (Laudel and Gläser, 2008), often as members of research groups with a clear division of labour (Delamont et al., 2000). Research groups in turn have multiple and sometimes conflicting functions, serving as sites of academic training and career building as well as of (collaborative) knowledge production (Hackett, 2005).

Studies focusing specifically on the contributions of doctoral students to collaborative research are few and far in between. The most comprehensive comparative study (Delamont et al., 2000) found that in laboratory-based research groups, research problems are typically passed on from one generation of doctoral students to the next. Students do not have much choice in their topics, theoretical frameworks, or research methods, as these are determined by the advisor and the group. Advisors take care to choose experiments that can be expected to deliver publishable results within the timeframe of the PhD, and assign back-up problems to students, in case an initial project does not work out (Campbell, 2003). Although publications based on a student's work will usually be co-authored by their advisor and other collaborators, existing authorship conventions ensure that the main contributor can be identified (Laudel, 2001).

More recently, STS research has focused on how external factors such as changes in research governance affect epistemic and social practices in research groups (e.g. Fochler et al., 2016; Müller, 2014), including the construction of 'interesting' research problems (Rushforth et al., 2019). It has been argued that tighter funding regimes entail a 'projectification' (Ylijoki, 2016) of research, based on third-party funding with clearly defined deliverables and timeframes (Whitley et al., 2018). Doctoral students are increasingly hired as members of project-specific research groups, where they may be required to 'tailor' their dissertations to the demands of research funders (Möllers, 2017). Depending on the supervisory styles of PhD advisors (Louvel, 2012) and the ability of research groups to create a 'protected space' for PhD students (Degn et al., 2018) students may be more or less required to align their research external productivity goals.

Given that these observations mainly concern smaller research groups based at a single laboratory, it is unclear how well they map onto large-scale collaborations. In experimental physics, where collaborative research is the norm and dissertations are best characterised as post-hoc collections of a student's contributions to a team effort, the trend towards 'projectification' of doctoral training may be resisted (Torka, 2018). Contemporary experimental high-energy physics is collaborative in quite a radical sense, as no single step in the research process – from planning and building the technical infrastructure to taking, reconstructing and analysing data – could be achieved by an individual, a team or even a large research institution (such as CERN) alone. Moreover, high-energy physics experiments are known for their egalitarian and consensus-oriented style of self-governance (Knorr Cetina, 1995; Shrum et al., 2007). Experimental results are always published in the name of the entire Collaboration[1] (listing up to 3000+ authors in alphabetical order) running the experiment. This convention of collective authorship (Biagioli, 2003; Galison, 2003) recognises the broad range of contributions and extensive internal review required for any publication (Graßhoff and Wüthrich, 2012), and establishes the Collaboration as a collective epistemic subject (Knorr Cetina, 1999). Although the collectivisation of results and reputation prevents internal struggles for authorship, it raises the question of how individual achievements are adequately recognised within and beyond the Collaborations (Birnholtz, 2006; European Committee for Future Accelerators, 2015). This question also concerns dissertations, which require individual authorship, implying that students' contributions need to be actively distinguished from collective research outcomes.

The process of constructing doctoral dissertations in high-energy physics Collaborations differs from the same process in laboratory-based research groups in at least three significant aspects. The first is the convention of collective authorship, which troubles the identification and attribution of individual contributions. Second, due to the wide range of tasks involved in experimental research, PhD students often contribute to the work of several different groups within their Collaboration. We may ask how the availability of many different potential projects and supervisors shapes students' contributions and affects the respective roles of students and PhD advisors, in comparison to the research groups described above. Third, the peculiar timelines of high-energy physics experiments present a potential challenge for constructing dissertations. A single cycle of data-taking and analysis may take several years. One such process also involves the work of several different groups, which means that its completion is beyond the control of any individual team or group leader. This raises the question of how dissertations, which need to produce individually attributable results within a given timeframe, are constructed despite the intrinsically collaborative nature and long timespans of research.

Doable problems and alignment work

To answer the questions raised above, I will use the sensitising concepts 'doable problems' and 'alignment' introduced in Fujimura's (1987, 1996) study on oncogene research. Given that a dissertation should produce a research contribution, we may conceptualise it as consisting of (one or several) 'doable' research problems. Fujimura argues that the 'doability' of research problems not only depends on their technical feasibility but is actively constructed as researchers align tasks at several levels of work:

> In fact, scientific work gets done and problems are solved when all the necessary parts at all levels of work organisation are collected and made to fit together. […] That is, articulation between levels is required to bring all the tasks at different levels of work organisation together into alignment to create a doable problem. Problems are more or less doable depending on how difficult it is to articulate among levels to create alignment. (Fujimura, 1987: 262).

In Fujimura's case study, the levels of work organisation in need of alignment are an experiment as a set of tasks, the laboratory where experiments are conducted, and the wider social world of cancer research and molecular biology. Fujimura mentions the case of a PhD student who had to give up his initial project one year before graduation, because the problem had been solved and published by a different research group. Instead of postponing his graduation, which future hiring committees might interpret as a personal failure, the student focused on a secondary problem to finish his dissertation on time (Fujimura, 1987: 262-264; Fujimura, 1996: 171-172). This example illustrates how constraints arising at a different level of work (the 'social world') instigate a researcher to re-organise their experimental work. The initial problem was not 'doable' as a dissertation project anymore, because it did not meet the requirements that a dissertation contain original research, and that graduate research should not exceed a certain period of time.

Jackson et al. (2011) extend Fujimura's notion of alignment to the temporal dimension and the challenges of multi-sited research in large-scale collaborations. The authors point out that to make collaborative research doable, researchers need to reconcile the different temporal structures or 'rhythms' emanating from organisations, infrastructures, phenomena, and researchers' own biographies:

> To resolve issues of temporal conflict and fit, participants build instruments and environments, reshape organisations and institutions, and recraft or reorient their personal lives. All of this constitutes what we refer to here as *alignment work*, understood as the complex set of actions and activities required to bring otherwise disparate rhythms into heterogeneous and locally workable forms of alliance. (Jackson et al., 2011: 251; emphasis added)

This concept of 'alignment work' draws attention to the material and biographical aspects of collaborative research, which are only implicit in Fujimura's conception. To stabilise levels of work organisation and enable the configuration of tasks and problems, the organisational, infrastructural, phenomenal and biographical dimensions of distributed scientific work need to be (at least temporarily) aligned. These dimensions provide temporally situated resources and constraints ('rhythms') for the construction of doable problems. Such resources and constraints include the availability of instruments and data at different sites (Bruyninckx, 2017); the life cycles of research objects (Dippel, 2019); the academic schedules of collaborators and their institutions; the recurring dates of major conferences (Ochs and Jacoby, 1997), and the individual time constraints of researchers' lives beyond the lab.

For the purpose of analysing doctoral students' research, I adapt Fujimura's concept of 'doable problems' and Jackson et al.'s concept of 'alignment work'. We may distinguish several levels of work organisation relevant to the construction of 'doable' dissertations in collaborative research, which are in turn structured by the infrastructural, phenomenal, organisational and biographical 'rhythms' described above, and subject to 'alignment work'. Work organisation takes place on and between these levels: the *level of individual tasks* done by the student (corresponding to Fujimura's 'experiment'), the *level of the group or team* working together on the same project (corresponding to the 'laboratory') and the *level of the epistemic community* (corresponding to the 'social world'). We may expect these levels of work organisation to be relevant to doctoral students' work in all disciplines where collaborative research is the norm.

Experimental high-energy physics presents a specific case, because research groups are joined into large research Collaborations. This means that beyond the individual and the group level, there are several formally distinguished levels of work organisation within the Collaboration that doctoral students' work is embedded in (cf. Fig. 1). Moreover, because the majority of active high-energy physicists are members of only a handful such collectives, the Collaboration is, in many ways, directly equivalent to the epistemic community or 'social world' for a student. Alignment with to the level of the epistemic community as described in this paper is thus specific to collaborative research where collaborators beyond the local research group may directly influence PhD researchers' work.

Materials and method

My analysis builds on 15 interviews conducted in the course of a research project on the social and epistemological conditions of knowledge production in high-energy physics experiments.[2] This sample contains two different types of semi-structured expert interviews. The first type are exploratory interviews with ATLAS Collaboration members at different career stages based at research institutions in Germany and the US. These interviews covered a wide range of topics concerning collaborative research. The second type are problem-centred interviews conducted with ATLAS and CMS Collaboration members who were selected for their familiarity with a specific research topic or organisational process.[3] Although initially corresponding to different research interests, both types of interviews provided insights on the construction of dissertations, as became evident during the first round of analysis.

For the 12 interviews of the first type (7 PhD students, 3 professors, 2 post-docs), I visited one US-American and two German university departments in 2018 and 2019.[4] These brief two-day research visits allowed for informal conversations with researchers during lunch and coffee breaks, which were helpful in contextualising my interviews. My sampling strategy was to gather a range of perspectives from within the same institution, which means that the researchers I interviewed were not necessarily working closely together (except for two professor/post-doc/student triangles: Philipp/Natalie/Judith and Toby/Cara/Sam, the professors in both cases being experienced group leaders and PhD advisors). The interviews focused on the development and organisation of a researcher's work within their department and their working group in the Collaboration, as well as the supervision and situation of doctoral students.

In the course of analysis of the research project's shared interview pool, I supplemented this sample with three more interviews of the second type, which my colleagues and I had conducted to learn about specific Collaboration-internal processes.[5] I selected these accounts from experienced senior researchers (10+ years of supervising students) because they illustrate important aspects of the integration of PhD students' work in their respective Collaborations. In these interviews, the supervision of PhD students was not initially addressed by the interviewer. That dissertations nevertheless became a topic indicates the significance of PhD students' work for collaborative research processes.

Most interviews were conducted in person, at researchers' workplaces or in one of the cafeterias at CERN. Two interviews were conducted via video call. Interviews lasted between 45

Table 1. Selected interviews

Interviews Type 1			
Group 1	Germany	Professor	Philipp
		Post-Doc	Nathalie
		Student	Judith
		Student	Anton
		Student	Brian
Group 2	Germany	Professor	Tim
		Student	Matilda
		Student	Gabriel
Group 3	USA	Professor	Toby
		Post-Doc	Cara
		Student	Sam
		Student	James
Interviews Type 2			
	France	Professor	Simon
	France	Professor	Paul
	UK/Germany	Professor	Karen

minutes and 2 hours. Upon obtaining the explicit consent of the interviewees, they were recorded and transcribed verbatim.[6] I analysed interviews using the Atlas.ti software, following the principles of Grounded Theory (Charmaz, 2006; Corbin and Strauss, 2008) in the manner of the 'flexible coding' approach (Deterding and Waters, 2021). After an initial round of close reading and thematic coding, I identified the negotiations involved in constructing dissertations to be an emerging topic and focused selectively on references to such processes. The analytic category of 'alignment work' emerged from iterative open coding and comparative analysis of these passages. Starting from the observation that interviewees often indicated 'misalignments' between individual and collective projects or the necessity for 're-aligning' a student's work to that of a group, I noticed that also seemingly unproblematic cases of 'deciding on a topic' or 'being assigned a task' may be understood as instances of alignment work, as I will describe below.

The organisation of research in the ATLAS Collaboration

My case study focuses on PhD students in the ATLAS Collaboration, a research organisation building, running and maintaining the eponymous particle detector at CERN. The ATLAS Collaboration currently comprises research groups based at 181 research institutions from 41 countries. Of the more than 3000 researchers actively involved in ATLAS, about 1200 are doctoral students.[7] ATLAS is the largest of the four experiments recording and analysing the decay products of proton-proton collisions produced by the Large Hadron Collider (LHC). Its main scientific goals, shared with the CMS experiment, are to confirm and study the Higgs boson, and to discover hitherto unknown phenomena ('novel physics'). As protons collide and produce energy, new particles (such as the Higgs boson) are created and decay into other particles (such as electrons, photons or muons). From the traces of decay products registered by the detector, the original particle produced in the collision can be statistically inferred. To do so, the relevant data need to be selected, processed and calibrated, and the objects of interest need to be reconstructed and distinguished from noise and background processes. A 'physics analysis', the research process that leads to potentially new and publishable results, is only the last step in a long line of technical and analytic tasks. Physics analyses may be 'measurements' of properties of known particles or 'searches' for new particles and phenomena.

The main branches of the ATLAS Collaboration's internal organisation represent the activities necessary to run the experiment (including data preparation, software and computing, and 'hardware' work on the detector), with 'physics analysis' being one such activity. The branch of 'physics analysis' is organisationally divided into 'combined performance groups', which calibrate analysis methods and study their efficiency, and 'working groups' focusing on specific searches and measurements (Fig. 1). A prominent working group in ATLAS, such as the Higgs boson group, may have several hundred members and is further divided into subgroups investigating specific 'decay channels' of the Higgs. One subgroup, for example focusing on Higgs bosons decaying into two b-quarks, is made up of several analysis teams.

Students become involved in the ATLAS Collaboration through their affiliation with an institution that hosts an ATLAS group. The student's advisor and a few other researchers and students at the same department constitute the student's 'local group'. PhD students are typically based at their home institutions, working from their local offices and collaborating with other ATLAS members remotely. If their home institution has enough funding, PhD students may also spend between a few months to a year at CERN.

For all the students I interviewed, original contributions to at least one physics analysis – ideally resulting in a publication – were required to obtain a PhD in experimental particle physics. This means that the PhD student will be a member of an analysis team embedded in a subgroup of a working group in ATLAS. The student's main analysis project would usually be related to the research foci of their advisor's local group, and their analysis team and working group would often (but not necessarily) include local colleagues. A local post-doc would then supervise

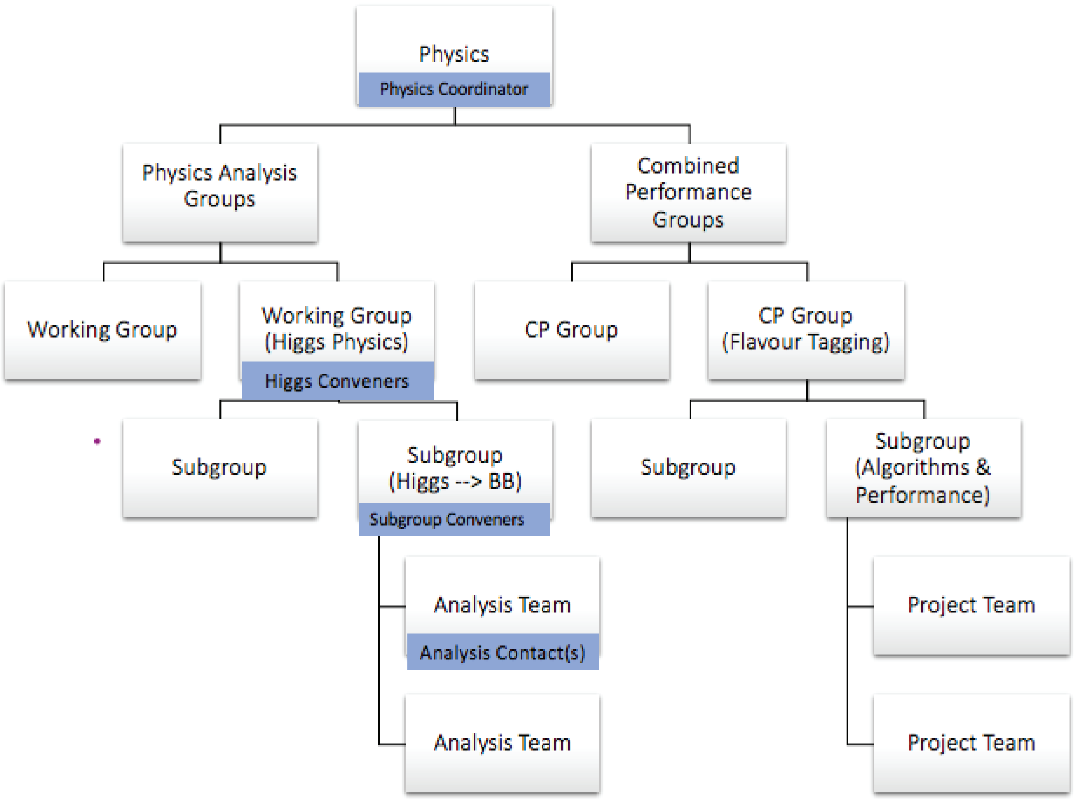

Figure1. Levels of Work Organisation in ATLAS

the student on the job, with the advisor receiving regular updates. As in other natural science disciplines (Delamont et al., 2000), PhD advisors steer the research of their students on a strategic level and are not involved in its hands-on aspects.

A PhD student is also expected to contribute to other activities of the experiment besides physics analysis. To be included on the list of ATLAS authors, every new Collaboration member must complete a 'qualification task'. The qualification task is defined as a purely 'technical' contribution, for example, to detector hardware (upgrading and testing a specific detector component), data preparation, or to 'combined performance'. Its completion should take the student about half a year of full-time work. Depending on the commitments of their local group and their personal interests, students may continue to contribute to technical activities beyond their qualification task. For this reason, PhD students in ATLAS often simultaneously work on several projects within the Collaboration, each coming with its own group and supervisors.

Constructing dissertations in the ATLAS Collaboration

The brief introduction to ATLAS research indicates that doctoral students perform several tasks within the Collaboration, and that besides their local advisors, group conveners and analysis contacts are involved in articulating those tasks. To illustrate how a student's tasks over time evolve into a dissertation, the following section describes this process from the perspective of two ATLAS PhD students. Both students were close to finishing their dissertation when I interviewed them and have graduated since. Their accounts allow a more comprehensive description of the several-year long process of constructing a dissertation in comparison to those of the advisors and coordinators discussed in the sections below, which zoom in on specific challenges within that process. The two cases are similar in that both dissertations were significantly based on 'technical' contributions. They differ in terms of how easily the requirement for the 'main project', i.e. a contribution to physics analysis, was fulfilled.

Natural choices and being lucky

Judith[8], an advanced PhD student at a German university, described the construction of her 'main analysis' as a somewhat organic process. She had developed an interest in particle physics during high school and proceeded to do a bachelor's and master's degree under the supervision of ATLAS physicists at her local university. Halfway through her master's programme, she was offered a PhD position with the same ATLAS group. In retrospect, her personal interests were perfectly aligned with those of the group at the local department, as well as the research agenda of ATLAS:

> So, I already did a very basic analysis in my master's thesis looking for exactly such a heavy particle […]. And then somehow it became a thing in ATLAS that they also wanted to do that analysis and then this was basically the natural choice, to say that we want to participate there. […] This has also grown historically, these [specific analyses] are something that the local group has been doing for a while. And then we just kind of went along with the course of events in ATLAS.

Judith refers to the project that she first started working on as a "natural choice" for her group, since there was an interest on the side of the Collaboration to do searches for such (unknown) heavy particles. The "historic" development of research at her local department coincided with the research priorities of the Collaboration following the confirmation of the Higgs boson. This created favourable conditions to further pursue an analysis project that she had started, in a rudimentary form, in her master's thesis.

The second part of Judith's dissertation belongs to the category of 'combined performance work', i.e., the study and optimisation of analysis methods used in ATLAS. Originally conceived as a qualification task to obtain ATLAS authorship, Judith worked on a method for identifying b-quarks (so-called 'b-tagging', a process in the category of 'flavour tagging') resulting from a specific decay throughout her PhD. Because of its novelty within the Collaboration, this work would eventually also result in a publication and turned into a major part of her dissertation:

> That was a real luxury. During the qualification task, we also published a [conference note] about it. So, it wasn't just a qualification task where you do something technical that maybe is integrated later on, but then you don't really contribute. For me, it really became a part of the dissertation, that was really cool, I was also lucky in a way.

According to Judith, it is not very common that qualification tasks result in contributions to ATLAS publications, or that students can base a solid part of their dissertation on these contributions. Judith was also "lucky" because the qualification task had resulted from a compromise. Initially, Judith had wanted to do a different project for her qualification task, which the group convenors rejected as being "too close to analysis" (interview Judith). Judith's dissertation eventually consisted of a general introduction to the theory and practice of high-energy physics at the ATLAS experiment, with a specific focus on the identification of Higgs-boson and b-quark decays; a description of the search for an unknown heavy particle, focusing on her contributions to the (already published) analysis; and a description of her work on b-tagging, some of which was documented for the first time in her thesis. Judith took longer than her initial project-based work contract to finish the dissertation, with a studentship funding the final year of her PhD. Shortly before graduation, she successfully applied for a post-doc fellowship at another German research institution.

Compromising to graduate

The story of another PhD student, based at a prestigious US-American research university, reveals that constructing a doable dissertation is not always a straightforward process. Sam had done some work on the CMS experiment as an undergraduate student and been recommended to a professor in the ATLAS Collaboration who later became her PhD advisor. For personal reasons, she decided to focus on projects that could be done remotely and stayed in the US throughout her PhD. Her qualification task was similar to Judith's in that it also studied the efficiency of a 'b-tagging' algorithm. Although only intended to earn her the status of an ATLAS author, this task developed into a project taking over the greater part of her PhD. It involved the production of particular data samples, which Sam started taking responsibility for, serving as a 'software contact' for all groups requiring these samples. Approaching the final year of her PhD, Sam had contributed substantially to software maintenance and 'combined performance' work in ATLAS, but still needed an analysis to form the centrepiece of her dissertation. Like Judith, she chose a search that aligned with the research at her department and the knowledge she had gained from working on 'b-tagging'. A few months into working on a task that had been suggested by one of the conveners, she had to find out that this task had already been accomplished by another student: "They were nearly done and [the conveners] just hadn't kept track of who was doing what." To salvage her dissertation, Sam then joined a new search led by a post-doc from her local group:

> The reason I picked the supersymmetry search I'm working on isn't because it's the most compelling physics beyond the standard model search. It's because I want to graduate and it's a final state involving [b-quarks]. […] I originally picked one just based on the physics I knew and that search was too full. So, then I picked one that wasn't quite what I wanted but there was room for me.

Sam's story illustrates that although there is more than enough data and work for everyone in ATLAS, this work is not easily distributed. Despite the formal hierarchy of coordinator roles, group coordinators cannot simply assign tasks to individual researchers, only suggest. Moreover, the more exciting analyses may attract more researchers than there are tasks required for preparing a publication, and group conveners may sometimes "lose track" of who is doing what. This experience of a search being "too full" made Sam chose a smaller group doing a novel analysis, minimising the risk of redundancy, but at the loss of her own enthusiasm for the project.

At the time I interviewed her, Sam did not yet know whether the results of this analysis would be available in time for her graduation:

> I'm not 100 percent certain if the data will make it into my thesis, because I think we're going to unblind our results right around when I do my defence. But I already discussed with [my advisor] and some of the faculty from my committee and they decided that would be OK. Because I do have data in my other projects […].

Sam did not want to postpone her graduation because she had been accepted to a job placement program for the tech industry. Her dissertation eventually consisted of an introduction to LHC physics with the ATLAS experiment, a description of her work on b-tagging, a description of her software support work and a description of her contributions to the supersymmetry search and its expected results, based on simulated data.

The cases of Sam and Judith exemplify several elements of constructing doable dissertations in ATLAS. Students are asked to become members of local research groups as potential contributors, based on the skills they have demonstrated in earlier work. Even when students have an initial research interest, the project they end up working on emerges from (re-)aligning their interests to the tasks available in analysis groups and the current research priorities of the Collaboration. Constraints for constructing doable problems may arise on the level of the group (finding a task that contributes to collective projects but has not been done), on the level of the Collaboration (e.g., the internal distinction between analysis and qualification tasks, current research priorities), but also on the individual level (personal competences and preferences, graduating at a certain time or securing additional funding). There are certain expectations concerning the contents of a dissertation, but advisors and advisory committees do have some leeway in deciding whether a student's contributions to collaborative work meet those expectations. The two accounts also indicate the alignment work performed by students, advisors and other coordinators to construct doable problems at different stages of the dissertation. In the following two sections, I will zoom in on these practices and describe instances of alignment work between the individual, group and Collaboration-wide levels of work organisation in ATLAS. The first section illustrates how the alignment of collective and individual rhythms and resources creates opportunities for doable dissertations. The second section describes the alignment work shaping a student's contribution within an analysis team.

Arranging alignment with collective priorities

As mentioned above, the timelines of most research processes in ATLAS exceed the duration of a single dissertation. A major challenge thus consists in fitting students' individual contributions into Collaboration-wide schedules. Particular measurements and searches for new particles are planned years in advance, based on the anticipated data output, which so far has exceeded expectations. Some of these anticipated results have been defined as 'milestones' for the experiment, because they represent significant advances in particle physics. The need for a result to "go out" to secure the scientific credibility of the Collaboration, and the need of individual students to make substantial contributions and graduate, may conflict in these cases. Paul, a senior researcher based in France, mentioned this conflict while describing his own role as a coordinator of a high-profile analysis in the CMS Collaboration:

> Clearly the big analyses like ttH observation [the observation of the production of a Higgs boson and a top quark-antiquark pair], it's an analysis of a Collaboration of 4000 people, so it's a measure that you have to do for the outside world. But we can do this measure thanks to the work of the Collaboration, but mainly thanks to the work of the PhD students. This kind of big analysis, the analysis has to go out, independently of the timeline or the graduation for a PhD.

Paul addresses a tension that is inherent to the work in the Collaboration. Although research projects depend on the labour of many individual PhD students (and post-docs), collective research processes do not respect individual timelines such as work contracts or graduation dates. The more prestigious an analysis and the more researchers are involved in it, the more likely it is that it will take longer than the expected duration of a PhD to be completed. Conversely, when students join such an effort too late, their chances to make significant contributions before the results need to be 'out' are diminished.

Constructing doable dissertation projects thus requires advisors to plan carefully on behalf of their students. PhD advisors need to anticipate the opportunities when enough data have been collected and students may still be expected to make a significant contribution. Simon, a professor at a French research institute, described his strategic considerations when hiring a new PhD student in the following way:

> You have to see how much it will match with the expected publications. So, for example, I will take a PhD student in HH [studying collision events where a pair of Higgs bosons is produced] for Run 2. Because we finished to take data end of this year. So, he will start in 2018 and he will finish 2021. So, to justify the funding we say, next year he will improve the bbgammagamma [Higgs bosons decaying to two b-quarks and two photons] analysis and the year after I will do a combination with the other channel with CMS, do the interpretation with theorists. And I think one year later it [would] be problematic. So, one year before it's too early to start, to be really involved in the publication. One year later we have only a bit more data here but not significantly more than before, so, it's not sure there will be a publication.

The opportunity for a doable dissertation is created through aligning several organisational and infrastructural rhythms (Jackson et al., 2011). Simon was looking for a student to join his group right at the end of 'Run 2', the LHC's second data-taking period (2015 to 2018). During this time, the accelerator produced collisions at the unprecedented centre-of-mass energy of 13 TeV and ATLAS recorded an even higher number of collision events than anticipated. This provided ample data to be analysed over the second 'long shutdown' of the LHC, before data-taking would expectedly resume in 2021.[9] From the Collaboration's point of view, it is beneficial to prepare a publication only when the full dataset has been analysed. For this reason, starting much earlier than at the end of Run 2, when data-taking is still underway, would disadvantage a student. A doable dissertation furthermore needs to fit into the three-year-funding cycle for research projects structuring academic work across disciplines in European countries. In France, this three-year cycle also applies to the individual funding of PhD students (Louvel, 2012). The topic and the start of a PhD project need to be chosen in such a way that contributions to ATLAS publications can be expected within three years. Simon also explained that whether such a pre-aligned dissertation succeeds will eventually depend on finding the right PhD candidate, who is capable and interested in completing the assigned tasks within the three-year timeframe.

Collective priorities may also require a student to align their work at a later stage, when they have already begun their analysis work. This, however, need not be detrimental to the student's interests. Corresponding to the cycles of data taking, there are times when fewer results can be expected, as researchers are asked to wait with publications until the full intake of data has been accomplished. As the following account from a PhD student at a German university illustrates, the Collaboration manages such droughts by "slipping in" smaller projects to maintain a steady flow of results and publications:

> We will have this [centre-of-mass energy of] 13 TeV for another year, and that's why [the ATLAS management] didn't want us to publish a whole lot of papers with last year's data, because then nobody would have time to add this year's data and publish based on those. [...] But of course we didn't want to say that we don't publish at all, so they said that there will be a few exceptions […]. And my analysis just somehow slipped in there, because [the working group conveners] also trusted that my local supervisors, my professor and my post-docs, they'd make sure that this won't take too long. (Gabriel)

Gabriel at the time was working mainly by himself, repeating an analysis that had already been done during Run 1 of the experiment. The promise of a timely result allowed Gabriel to begin working towards publication, even though his analysis was based on incomplete Run 2 data. The conveners of his working group chose it as one of the analyses that would fill the gap in the publishing cycle when most of the results based on the previous dataset (from Run 1) were already out, and data production for Run 2 was still underway. Gabriel's advisor negotiated a slightly later deadline than the group conveners had envisaged, but it was clear that the analysis should be out within the year. In this case, aligning the student's work to collective priorities was also beneficial to Gabriel, who could complete his main analysis earlier and start writing up the dissertation during the third year of his PhD.

Improvising alignment with group-level work

Once projects have been assigned and deadlines have been agreed on, the coordination of individual tasks among the group working towards a publication presents another challenge. Within the area of physics analysis, working group and sub-group conveners are expected to "keep track of who is doing what" (Interview, Sam) across analysis teams, while 'analysis contacts' oversee the coordination of tasks involved in a single analysis or publication project. These coordinators are responsible for integrating the work of individuals in collective research projects and thus play a vital role in constructing doable dissertations.

Cara was a post-doc at a US-American university at the time I interviewed her and served as an analysis contact in a search for a supersymmetric partner particle of the Higgs boson. She mentioned the example of a PhD student who came up with an ambitious, but only potentially doable idea:

> So, we knew exactly what we wanted to do with the paper, and I think everyone was on board with that. And then this student came out with his advisor and said, 'Oh, this is an improvement that we could add'. And we said, 'Great idea. But it's gonna be very challenging to have this in. You know, in the timescale that we need to have this in.' At this point we had a bunch of students that had to graduate on this analysis. We couldn't just have two more months to have a nice improvement on top. […] And the student worked for a very long time. He's a very good student. But it came to a point where it wasn't done yet. And we couldn't keep waiting for it.

Cara explains that constructing a doable research problem requires taking the group's interests into account. The analysis group as a whole had agreed to work towards a specific publication, and the tasks had been defined and distributed among the group members accordingly. The envisaged deadline reflected that other doctoral students on the team soon needed results to be able to graduate. Although this particular student's proposal for an improvement seemed promising to the analysis contacts, it turned out to be too time-consuming. Resolving the dissonance between the group's schedule and the student's individual contribution required alignment work:

> What happened at the time is we came up with another thing for him to work on, that we kind of had decided to have in the paper. […] And the advisor wasn't totally convinced at first, he said 'but this seems like too much of a small thing for him to have ownership of'. So, we then put another twist in that project. […] So it was something that, you know, I had to sit down with the other analysis contact and we had to be like, 'OK, we need to come up with something that he can claim ownership of and it can't just be a small task'. (Cara)

In this case, alignment work involved identifying another contribution that could be added to the paper within the remaining time, and then negotiating the specific contents of that contribution with the student's advisor. Cara's account also highlights that doctoral students' contributions to collective papers should not only consist of "small tasks". Cara defined such "small tasks" in terms of their duration: "You can have to find a little project that is like, a week long, where they do a little study, but it ends up being like a sentence in the paper." A contribution intended to form part of a student's dissertation would have to be more substantial than such a "little study". This is because the dissertation, unlike a collective paper, will be attributed to the student as an individual. In this case, the analysis contacts achieved sufficient substance to satisfy the student's advisor by "adding another twist" to the task. Between these two constraints — the publication deadline and the expectation that the student's contribution should be worth having "ownership of"— the analysis contacts managed to construct a doable problem.

Disentangling alignment

Existing academic norms require a PhD dissertation to be an independent research contribution that can be attributed to a single author. This requirement seems to contradict the realities of collaborative research in high-energy physics, where students' work must be aligned with collaborative work and results are attributed to a collective. How are these contradictory requirements reconciled? In this final section describing my findings, I identify three strategies of individualising students' work, which are partly embedded in the practices described above. By way of these disentanglements, PhD students' work is temporally, qualitatively and formally distinguished from collaborative work and collective publications.

The *first disentanglement* is *temporal*. There is a time when a student does collaborative work within the group, and there is a time when a student is working on their dissertation. Typically, these phases are consecutive, as the "writing up"–phase takes place once the student's contributions to collaborative work are considered substantial enough to be converted into a dissertation.

> Actually, you're part of the Collaboration until — well, until you start writing up. ATLAS does not set that date, that's something for you and your advisor to agree on. […] Usually, when you're at the point of finishing a paper or an analysis, that's a good time, of course. […] There's a few rules in ATLAS, they think that they can dictate the students more, but in the end it's the professor who is responsible for what's in the dissertation. (Brian)

As this German PhD student explains, transitioning into the "writing up"–phase' may feel like leaving the Collaboration and (re-)entering a mode of work under the auspices of one's advisor. The main work context shifts back from the Collaboration to the local group. For students who spent some of their PhD on site at CERN, this transition would also involve a re-location to their home university.

Brian's account also highlights the persistent authority of PhD advisors. Several of my German interview partners indicated that students who run out of funding sometimes abandon an analysis before publication, or hand over to a younger colleague. This seems only possible if advisors may decide when a student's contribution qualifies for a dissertation, and if the contents of a dissertation are to some extent detached from the collective publication. Although originating in collaborative work, a dissertation is the only publication in high-energy physics that is always attributed to a single author, and normally also the only publication that a student will obtain single authorship of. According to one PhD advisor, it is their responsibility to ensure that a student's dissertation satisfies the criteria of independence and originality "despite" its origin in a collaborative effort:

> The publication normally isn't the same as the dissertation. […] Here's the issue: [The dissertation] is defined as an independent scientific achievement that has not been done by anyone else. This means that you need to ensure that despite the collaboration in the working group, the contribution of the PhD student is scientifically independent, and that it will pass as a doctoral dissertation. That is my job […], in the end, it is my responsibility to say, 'this is a doctoral dissertation'. (Philipp)

The *second disentanglement* between dissertations and collaborative work thus proceeds via a *qualitative* distinction between routine work and original or independent work, or between *small* and *big* tasks. As exemplified by Cara's story above, advisors and coordinators consider the requirement of scientific independence when negotiating a student's contribution to a collective paper. In Cara's story, the student's advisor actively ensured that the student's contribution would be worth "having ownership of". This indicates that the need for distinction is anticipated and criteria of independence and originality are already applied when constructing doable problems for students. Just *how* substantial, original, and independent a student's work will be seems to be a matter of negotiation. It also depends on the advisor's expectations and local conventions at the student's home institution. Although the advisors I interviewed gave some examples of actual and hypothetical contributions that students may 'write up' in their theses (such as developing a new algorithm or applying a new statistical method), the criteria remain situational. What tasks are worth doing for a student is decided individually, as part of the alignment work between research goals on the level of the Collaboration, group-level projects and the student's individual interests, skills and constraints.

A *third disentanglement* from collaborative work takes place on a *formal* level. ATLAS has a strict policy allowing only results that have passed the Collaboration's internal review process to be published or presented in public, but an exception is made for PhD dissertations (Charlton et al., 2009). For example, PhD dissertations may contain figures of results that have not been approved (yet), but these figures must not show the label reserved for official ATLAS results. In practice, this means that students need to re-do the plots they have produced for a publication and mark them as preliminary results or 'work in progress'. The writing up–phase allows students to pursue ideas and approaches that could not be realised within the working group or included in a paper. Here, students have the opportunity to create contributions that are genuinely their own, as long as their results do not contradict those of official ATLAS publications. Students are also allowed to present their work at smaller workshops and national conventions. However, since these contributions are not subject to the collective review process, they will not be considered to be official ATLAS results and typically not be referred to in other ATLAS publications. A formal and qualitative distinction is made between the work that students create as part of the collaborative process, and the work that is their own, but merely validated as part of a dissertation.

The formal distinction between collective publications and dissertations suggests that dissertations only have value on the individual level, as a means of obtaining an academic title. However, in some of my interviews, another function of dissertations was described, namely the documentation of the technical and methodological state of the art: "Usually (the PhD) was the best knowledge of the thing at this time. And at least in my lab, the part of the PhD which is a technical part is documented. […] So, it's a document which is always useful" (Interview Simon). This value of the dissertation as documentation originates in the process of disentanglement just described, which implies that the technical contributions and innovations of doctoral students are often not included in collective publications, or not described in detail. The "independent scientific achievements" (Interview Philipp) that are only documented in dissertations may, however, be taken up in collaborative research projects later on.

Alignment work thus shapes dissertations in two distinct ways. Fulfilling the requirement that a dissertation consist of contributions to research in high-energy physics, dissertations result from aligning students' work with collective processes. The specific problem a student works on is a result of what can be made doable within an ATLAS group at this particular point in time. To fulfil the requirement that this contribution is an independent achievement, students and their advisors can take advantage of the overflows and excess produced through alignment work. The necessity of creating alignment with group-level and Collaboration-level processes excludes some ideas, contributions and approaches as outside the (momentary) scope of collective publications. This work can then be performed by students in a more independent manner as part of their dissertation. In this way, the content of a dissertation is created directly and indirectly through alignment work: Directly through the efforts of constructing doable problems, and indirectly through excluding some contributions from collective publications, such that they can be claimed individually.

Discussion – how are dissertations made doable?

My paper set out to investigate the tension between the notion of a scientific doctorate as an individual achievement, and the practical and organisational realities of collaborative research.

Based on an analysis of interviews with experimental particle physicists, my answer to the question *how doctoral dissertations are made doable in collaborative research* is two-fold: Dissertations are made doable by aligning students' work to collaborative research processes, as well as reflexively disentangling and proactively distinguishing students' contributions from collective research outcomes. Constructing dissertations in collaborative high-energy physics neither resembles the execution of a pre-conceived research project nor the post-hoc assembly of contributions into a written document but is best described as an emergent process of articulating and performing tasks that will result in distinguishable outcomes.

This process requires *alignment work* across levels of work organisation, performed by several different actors. Due to the long timespan of experimental research in high-energy physics, potentially doable contributions need to be identified in advance, considering the rhythms of instrumentation, data-taking, and planned publications, such that students' work is aligned with collective research goals on the level of the entire Collaboration. This type of alignment work is mainly performed by advisors, sometimes in coordination with group conveners. Constructing doable problems also requires an ongoing and flexible articulation of tasks that fit into group-level work. This type of alignment work is performed by group coordinators, together with students and their advisors. It requires flexibility and a capacity for improvisation when new ideas come up and individual tasks take longer than expected. On the part of students, it requires resilience when promising ideas are given up in favour of problems that are more consistency within the group's collective schedule.

To satisfy the requirement that dissertations showcase students' ability to do independent and original work, students' work is *temporally, qualitatively and formally distinguished* from the collaborative projects they have contributed to. "Writing up" dissertations is temporally separated from work on publications. What students "write up" are typically details and contributions that did not make it into collective publications due to constraints on time and space. Alignment work therefore shapes dissertations both directly, by constructing doable contributions for students, and indirectly, through defining some problems as outside the scope of collective publications, which can then be explored by students independently. The status of single authorship for dissertations formally distinguishes students work from collective publications. That dissertations are not listed as official ATLAS publications might signal that they are less epistemically significant or mere add-ons to collectively validated work. However, as described above, dissertations also provide a detailed documentation of analysis techniques and other technical contributions that is not otherwise publicly available. In this sense, the need for distinction of dissertations from collective work that seems to devalue dissertations might also result in making them more valuable to the collective, as technical documentations and repositories for new approaches.

Concerning the role of advisors in large-scale collaborations, my findings indicate that PhD advisors continue to play a significant role in the construction of doable dissertations despite the formally hierarchical management of research processes. When hiring PhD students, advisors need to identify potentially doable problems, considering collective research priorities and expected publications. Advisors may take on an active role in creating tasks for their students within collaborative research processes, negotiating with coordinators, and advocating for their advisee's work. They may also support students with additional funding, so a student need not abandon an analysis prematurely. It is the advisor's and advisory committee's prerogative to decide that a student's research contributions are sufficient for graduation. Despite the broader range of potentially doable problems within a Collaboration and the availability of supervisors beyond the student's local group, the advisor's influence on dissertations is thus comparable to that of group leaders in laboratory-based research groups (cf. Delamont et al., 2000; Campbell, 2003). One plausible explanation is that advisors mediate between the organisational dimension of dissertation work (i.e., the local institution's requirements for the PhD) and the Collaboration. Since the requirements for an academic qualification are locally defined, local advisors remain the final authority on its contents.

Concerning the role of students, the personal and biographical dimension of constructing doable dissertations becomes most evident. Students may have personal preferences, such as where to live and how much time to spend on their PhD, which influence the process of constructing a dissertation, for example through a selection of tasks that allow remote work or earlier graduation. Students who pursue careers outside academia may opt for a more pragmatic approach and an earlier separation from collaborative research. Here, the wide range of research processes and potential contributions available in a Collaboration seems to allow students in high-energy physics more flexibility concerning the content and duration of their dissertations than their colleagues in laboratory-based research groups have, and a more active role in alignment work, particularly at the later stages of the PhD.

The effects of external constraints on dissertations, in particular project-based funding, may be mitigated through alignment work, depending on how flexible local funding arrangements are and whether additional sources of funding are potentially available. Students who enjoy greater personal and institutional resources might, in turn, find it easier to write dissertations that are both well-aligned with collaborative research goals and considered to be original contributions.[10] However, to answer the question of whether changes and differences in PhD programme structures or funding arrangements also impact the construction of dissertations in high-energy physics, a more systematic comparison of these practices (either across time or across research groups subject to different arrangements) would be required.

Experimental high-energy physics certainly presents a boundary case of collaborative research. Some of the alignment processes described above will only exist in large-scale research collaborations, where collaborators and constraints beyond a student's immediate group directly influence the doability of individual research problems. Furthermore, alignment work between group-level and individual-level work is virtually absent in most of the humanities and many social science disciplines, where solitary work and single-authored publications are the norm. However, in humanities and social sciences, changing expectations such as an increased demand for journal publications are also transforming the formal requirements on PhD students' work, with cumulative dissertations and co-authored articles becoming more acceptable. Investigating how alignment work shapes dissertations, such that they fulfil the requirements of academic institutions as well as those of the respective epistemic community, would thus be insightful for STS research interested in the dynamics of contemporary research more generally. In particular, the specific mechanisms of distinguishing doctoral students' work and ensuring its independence and originality deserve closer scrutiny, given the observable trend towards more and larger research collaborations across disciplines. My analysis shows that dissertations emerge over time as a product of alignment work, based on the resources and constraints provided by the infrastructural, organisational and biographical dimensions of scientific work. They also show that a dissertation's content, format and epistemic value are shaped by formal and qualitative criteria of distinction, which are proactively applied in alignment work. This second observation indicates that beyond establishing a coherent collective (Boisot, 2011; Galison, 2003; Knorr Cetina, 1995), large-scale research collaborations also need to develop mechanisms for distinguishing individual contributions, which might be just as significant in shaping epistemic practices.

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Notes

1 To distinguish the organisations running high-energy physics experiments from research collaborations in a general sense, the former will be referred to as "Collaborations" with a capital C.

2 This research has been conducted in the context of the interdisciplinary Research Unit *The Epistemology of the Large Hadron Collider* and its sub-project 'Producing Novelty and Securing Credibility: LHC Experiments from the Perspective of Social Studies of Science'.

3 For a more detailed description of our approach to interviews, see (Merz and Sorgner, 2020).

4 While the experiences of PhD students reflect different models of graduate education in Germany and the US (Jones et al., 2018), these differences become less significant as soon as US students have passed their course requirements, become members of research groups and start working on their dissertations. At this point, doctoral students orient their work towards the Collaboration, and the various groups in which their projects are embedded become the main work contexts for US-American and German students alike. My interviews and analysis have focused on this phase of the PhD for the US-American students.

5 I thank Sophie Ritson, who conducted two of these interviews, for pointing out their relevance to me.

6 Participants were approached via email, informed about the research interests of the project, and provided with a copy of the consent form in advance (asking for the permission to record the interview, describing the use and storage of data, and the rights of the interviewee to remove consent and end the interview at any time).

7 https://atlas.cern/discover/collaboration, accessed November 30, 2021. For a detailed description of the (early) ATLAS collaboration from a management studies perspective, including the design of the detector and the scientific aims of the experiment, see (Boisot et al., 2011).

8 All names have been changed to preserve interview respondents' anonymity. Quotes from interviews originally conducted in German have been translated by the author.

9 Due to the delays incurred during the COVID-19 pandemic, the start of Run 3 eventually had to be postponed to 2022.

10 Regarding this observation, a limitation of my study is that most of my interview respondents are members of relatively influential 'local groups'. PhD students who are members of groups with fewer resources and connections might be less integrated in their Collaboration and experience less support for their work overall, resulting in very different challenges for constructing doable dissertations.