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How research programs come apart: the example of supersymmetry and the disunity of physics

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Abstract According to Galison, the coordination of different "subcultures" within a scientific field happens through local exchanges within "trading zones". In his view, the workability of such trading zones is not guaranteed, and science is not necessarily driven towards further integration. In this paper, we develop and apply quantitative methods (using semantic, authorship, and citation data from scientific literature), inspired by Galison's framework, to the case of supersymmetry research in high-energy physics. In the past fifty years, supersymmetry has given rise to several major but distinct research programs, such as the formulation of a consistent theory of quantum gravity or the search for new particles in particle colliders. We show that "theory" and 'phenomenology" in high-energy physics should be regarded as distinct theoretical subcultures, between which supersymmetry has helped sustain scientific "trades". However, as we demonstrate using a topic model, supersymmetry research is very diverse and its phenomenological component has lost traction; therefore, the ability of supersymmetry to tie these subcultures together is now compromised. Our work supports that even fields with an initially strong commitment to unity may eventually generate diverging research programs and demonstrates the fruitfulness of the notion of trading zone for informing quantitative approaches to scientific pluralism.

Keywords scientific pluralism; trading zones; topic models; citation networks; high-energy physics

1 Introduction

This paper focuses on High-Energy Physics (HEP), the field of physics concerned with the fundamental entities of nature, and "supersymmetry", a symmetry between the two basic types of particles in nature. The idea of supersymmetry has brought together many of the most significant developments in the field thoughout the past 50 years, all the way from the highly abstract world of string theorists deep down to the machinery of under-ground particle colliders. However, none of the formidable discoveries promised by supersymmetry ever materialized as expected; as much as supersymmetry may be necessary to theorists seeking to unify the forces of nature in a coherent picture, it is increasingly plausible that it will not be of much use to the experimentalists looking to find new particles. Throughout this case study, our work exhibits the disunity of science, by demonstrating that even scientific fields that are strongly committed to unity can eventually fail to coordinate research efforts. Our paper is guided by the idea that empirical case-studies, although seemingly narrower in scope, do enrich our understanding of the nature of scientific enterprise (in this case, the nature of the coordination of diverse scientific cultures); and that quantitative studies of science should provide conceptually informed tools for carrying out such case-studies, preferably in ways that can be generalized for a variety of contexts. It is towards these two goals that we hope to progress in the present work.

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We start by presenting Galison's notions of subcultures and trading zones which is the framework for addressing the plurality of science and the dynamics of interactions between scientific fields that underlies our study (1.1). We will then provide the background knowledge necessary for understanding the context of our case-study, and proceed to laying out our hypotheses: i) that theory and phenomenology are to be regarded as two distinct theoretical subcultures within high-energy physics, ii) between which supersymmetry generated diverse research programs, iii) which sustained successful trades until it was challenged by experimental data (1.2). We will close our introduction by elaborating on our motivation for addressing these hypotheses through quantitative methods (1.3), at which point we will present the data, method, and results of our project.

1.1 Subcultures and trading zones: Galison's approach to the plurality of science

The fact that science is highly diverse is a challenge to those who, for various reasons[1], have sought to defend its unity. If indeed science is a unified enterprise, what is the nature of the relationship between fields as diverse as physics, chemistry, biology, psychology, or economics? Can we translate all the concepts of these disciplines into a basic (say, physical) scientific language, as Carnap proposed? Or is it that all these fields are so incommensurable and autonomous that it is impossible to translate their respective entities, laws, and explanations from one's language to another's, as proponents of a pluralistic view such as Suppes (1978); Dupré (1983); Cartwright (1999)? Disciplines themselves can be so diverse, too, that the nature of what makes their own unity is not necessarily obvious. For instance, the nature of the unity of physics has been the matter of much debate, with sometimes serious political implications: reductionist views (which imply that high-energy physics are the most fundamental, since they supposedly entail any higher-level theory) were mobilized to justify the funding of large particle physics facilities (Cat, 1998), potentially to the detriment of more "useful" projects, as certain condensed-matter physicists argued (Martin, 2018). As a result the latter were most often proponents of "methodological unity", i.e. the idea that what bounds the field together is a shared commitment to a common set of norms rather than relations of logical deduction from the most fundamental to the least fundamental theories.

Even within one subfield such as particle physics, it remains unclear what is the nature of the relationship between the objects manipulated by, say, experimentalists (for instance, tracks within a cloud-chamber, or electric signals from a sensor) and the more abstract entities manipulated by theorists (e.g. "quarks", "gluons", "strings", etc.). It is in order to address this challenge that Galison's concepts of subcultures and trading zones were developed (Galison, 1987, 1997), although these notions may generally apply whenever different scientific communities attempt to overcome difficulties to communicate and achieve coordination (Collins et al., 2010, p. 8). Consequently it is useful in a much broader range of contexts than the narrow case of physics; for instance, it is generally useful for studying the dynamics of interactions between disciplines in science[2]. Below, we propose a brief summary of the concepts of subcultures and trading zones and the rationale for their introduction.

The notion of subcultures was introduced by Galison (1987, 1988) in order to account for two aspects of high-energy physics: first, that it is subject to a strong division of labor, such that "theory", "experiment" and "instrumentation" are carried out by different groups of people (Galison, 1987, p. 138), with very distinct skill sets, manipulating quite distinct bodies of knowledge; and second, that each of these "subcultures" are partially autonomous, i.e., none of them are completely subordinate to the others. We can highlight two tangible components of such subcultures: a social component–their community of practitioners–and a linguistic component–the language specific to each community.

For Galison, the question is then what makes these subcultures part of a "larger culture" (physics), while retaining that their successful coordination is a "contingent matter" (Galison, 1997, p. 18); and his answer is "trading zones". Trading zones allow knowledge to be exchanged across different subcultures as practitioners of distinct communities locally agree on the usefulness of certain constructs in spite of the distinctness of their respective languages, commitments, aims, and methodologies. That trading occurs within "zones" captures the fact the exchange procedure is "local" rather than "global", such that subcultures working out trades with each other can retain much of their autonomy in the process.

What kinds of goods may be subject to these "trades"? One example of trade-able goods are "boundary objects", i.e. "objects that are both plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites" (Star

[1] See Hacking 1996; Bechtel and Hamilton 2007 for an overview of the various commitments underlying the Unity of Science "ideology" and of the attempts to unify the sciences.

[2] For instance, Digital History can be regarded as a trading zone (Kemman, 2021).

and Griesemer, 1989, p. 393)[3]. Trading zones may give rise to a purposely crafted inter-language that allows for further communication and coordination (a "pidgin"). If the inter-language grows, it may turn into a full-blown language (a "creole"); this signals the emergence and stabilization of a new scientific discipline of its own.

Arguably, this is the process through which "phenomenology" – a subfield of HEP at the boundary between theory and experiment – has developed (Galison, 1997, p. 837). However, we may wonder whether phenomenology is still merely dedicated to bridging the theoretical and experimental cultures together or whether it acquired enough autonomy to depart from the supremacy of abstract theory. In the following subsection we will suggest treating "theory" and "phenomenology" in high-energy physics as two distinct subcultures, such that they may both enjoy considerable autonomy and eventually fail to coordinate their developments.

1.2 Supersymmetry across theory and phenomenology

1.2.1 Theory and phenomenology as distinct subcultures within high-energy physics

High-energy physics involves a complex web of mathematical and technical knowledge, whether it concerns the details of the often abstract underlying theories, the behavior of the instruments that are assembled within sophisticated experiments, statistical notions for the analysis of the data derived from these experiments, etc. As a result of this complexity, labor is strongly divided within high-energy physics, and we can distinguish two different groups within the theorists themselves. While "pure" theorists (we will call them "theorists", in accordance with the terminology within the field) are driven by "the abstract elaboration of respectable theories", phenomenologists (the second kind of theorists) are often more concerned with "the application of less dignified models to the analysis of data and as a guide to further experiment" (Pickering, 1984), or at least more concerned with experimental consequences rather than high theory. This division is itself strong enough that these two kinds of physicists can generally receive different training and diverge early in their careers, although some physicists – usually prominent ones – have expertise in both these domains and are able to sustain exchanges between the two. Therefore, in the present paper, we will make the following claim:

> **Claim 1**: The categories "theory" and "phenomenology" in high-energy physics should be regarded as distinct subcultures with their own body of knowledge, ontology and methodology, and which are carried out by different people.

It is not controversial in itself that "theory" and "phenomenology" are different matters in HEP; these are distinct categories within the literature and it is not uncommon for physicists to label themselves as "theorists" or "phenomenologists" depending on their specialization. However, our claim goes further by stating that the nature of their work is *so* distinct that it should not be postulated *a priori* that they can sustain fruitful connections; per Galison, we should not assume *a priori* that these subcultures are bound to cooperate flawlessly under any circumstance; we should instead remain open to the possibility that they may fail to produce constructs that they can mutually value in the context of their respective enterprise. It may indeed be that there is not one single overarching goal that is equally shared and served by these theorists and phenomenologists; and it is not obvious that they should believe that their respective methods equally contribute to achieving their goals at any time[4]. In the following subsection, we will propose that supersymmetry exemplifies the contingency of the ability of high-energy physicists to coordinate their respective methods and goals in a successful way. It does so because the story of supersymmetry is that of a partial failure, rather than that of a total success. Although successful cases of cross-fertilization across fields are valuable to illustrate the notion of trading zones, the disunity of science is better exemplified by instances of failures to successfully establish coordination between scientific cultures, even when such coordination is believed to be possible and is actively sought for. Below, we will argue that the dramatic story of supersymmetry provides such an instance.

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[3] In the context of physics, Darrigol's theoretical modules may constitute another kind of trade-able good (Darrigol, 2007, p. 214). One could consider multi-purpose scientific instruments (Shinn and Ragouet, 2005, pp. 179–182) as another example.

[4] Galison 1995 provides a distinction between two kinds of theorists similar to the one we propose to make here, resting on the recognition that these two groups rely on very different sets of constraints as guides towards theoretical progress.

1.2.2 Supersymmetry as a trade-able good between theory and phenomenology

Supersymmetry is a symmetry that relates the two fundamental kinds of particles that arise in nature: fermions and bosons. It was postulated simultaneously and independently by several physicists in the early 1970s, who were each motivated by very different aims[5]. Supersymmetry rapidly gathered substantial attention from the theoretical community. The reasons were manifold, but clearly theoretical rather than empirical, as early reviews of the topic show[6]. First, symmetry principles play a fundamental role in High-Energy physics, and supersymmetry was an especially attractive symmetry because of its peculiar properties. Second, supersymmetry can naturally give rise to gravity, as was observed by Volkov and Akulov (1973), which suggested that it could lead to a consistent theory of quantum gravity. This feature of supersymmetry gave birth to an entire research program, "supergravity", which then spanned over decades[7]. Third, while quantum field theory is prone to mathematical difficulties due to divergences appearing in the perturbative calculations of certain quantities, in many instances such infinities were suppressed in supersymmetric theories.

However, as appealing as it was to theorists, supersymmetry posed a number of empirical difficulties. First, supersymmetry establishes a symmetry between bosons and fermions; and yet, at first it was not at all clear which of the bosons and fermions should have been related to each other by this symmetry. Moreover, if supersymmetry was perfectly realized in nature, the particles it relates should have had identical masses, which was also in contradiction with the data. This contrasted situation was well summarised by Witten (1982) in his *Introduction to supersymmetry*:

> [Supersymmetry] is a fascinating mathematical structure, and a reasonable extension of current ideas, but plagued with phenomenological difficulties. [...] Supersymmetry is a very beautiful idea, but I think it is fair to say that no one knows what mysteries of nature (if any) it should explain.

Still, efforts to incorporate supersymmetry into a theory consistent with the data were undertaken over several years, and they culminated to what is now called the Minimal Supersymmetric Standard Model (MSSM) (Fayet and Ferrara, 1977; Dimopoulos and Georgi, 1981). The MSSM is the result of reconciling the achievements of the Standard Model of Particle Physics (SM) (the best theoretical account available at the time and still today) with the requirement of supersymmetry. This, however, has very undesirable consequences. Compared to the SM, the MSSM introduces 105 additional unspecified parameters, such that supersymmetry can accommodate a large range of observations and has little predictive power in general. In particular, although supersymmetry predicts the existence of many new particles (the "superpartners"), there is *a priori* little chance that these particles will have just the right properties to be discoverable in experiments. If not, supersymmetry may be of high value to theorists (because of its mathematical properties, and its promise to achieve a coherent account of quantum gravity), while being of low value to phenomenologists who are interested in building predictive models that can lead to the discovery of new particles or phenomena[8].

Still, for a long time, supersymmetry was seen across the field as the theory beyond the SM that was most likely to manifest itself in experiments (Mättig and Stöltzner, 2019, 2020). The reason why it became highly credible and valuable to the phenomenologists as well, was that it could solve the so-called "naturalness" problem of the standard model on the condition that it was discoverable. In parallel to these developments around supersymmetry, there was indeed increasing recognition that an explanation was required as to why the the mass of the Higgs boson (an important piece of the Standard Model) could be many orders of magnitude below the mass scale at which the unification of forces is assumed to take place. It was also realized that supersymmetry could provide an answer to this "naturalness" problem (Weinberg 1979; Veltman 1981; Witten 1982), *but* only as long as the masses of the superpartners (the particles predicted by supersymmetry) are not too high, so that they should be discoverable in

[5] For a history of early supersymmetry, see Kane and Shifman 2000.

[6] Fayet and Ferrara 1977; Freedman 1979; Taylor 1984 provide a good overview of the main arguments for supersymmetry in its early days, all of which are highly theoretical.

[7] Later on, supersymmetry proved even more interesting to theorists, by improving the consistency of string theory, and by supporting the conjectured AdS/CFT correspondence, yet another major development in quantum gravity research.

[8] Supersymmetry suffers from other disadvantages. For instance, many parameters of the theory imply certain phenomena to extents that have not been observed, e.g., baryon and lepton number violation, or flavor changing neutral currents (Weinberg, 1995), which requires *ad-hoc* explanations as to why, although allowed by the model, these mechanisms do not occur in nature.

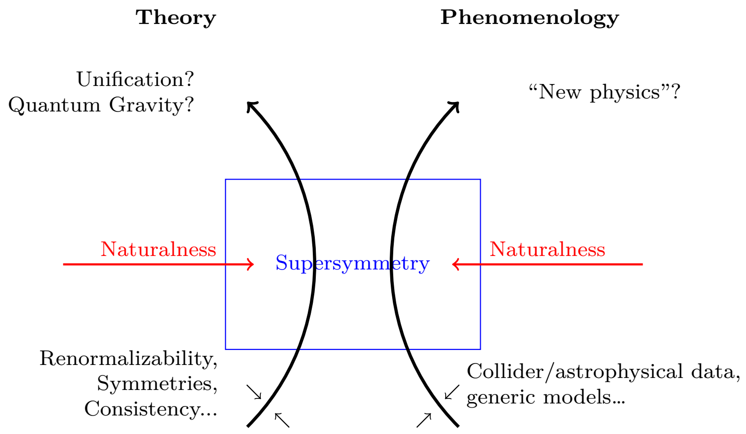

Fig. 1 Supersymmetry in the trading zone between theory and phenomenology. Theorists and phenomenologists have different aims and methodologies, and whether they can positively appraise a same construct is not guaranteed. In the case of supersymmetry, it is the naturalness requirement that ensures that the MSSM is so valuable to both subcultures. As a result supersymmetry enhances a trading zone between these two cultures.

future experiments[9]. In light of this, supersymmetry became of very high value to phenomenologists and experimentalists as well, rather than just a mathematical toy for the theorists to play with[10].

This situation is summarised in Figure 1. As theorists work out a path towards their goals (e.g., the unification of forces, or the formulation of a consistent theory of quantum gravity), they rely on theoretical heuristics such as renormalizability, symmetry principles, consistency requirements, etc. (Galison, 1995). In that context, supersymmetry emerges as a very valuable concept. Phenomenologists, on the other hand, try to work out a path towards the discovery of "new physics" (evidence for new phenomena unaccounted for by the SM) by relying instead on more generic models and constraints derived from experimental data (e.g. from particle colliders or astrophysical observations). It is the naturalness requirement that makes supersymmetry valuable to phenomenologists as well, by strengthening the belief that the superpartners should have masses that are low enough to be discoverable. In this way, supersymmetry effectively enhances the "trading zone" between theorists and phenomenologists: both communities can acknowledge its value in spite of the vast differences in their aims, methods, and objects of inquiry.

It is now time to introduce the last (but not the least) player in our drama: the Large Hadron Collider (LHC). The LHC is the largest physics experiment ever built, and its operation began in 2010. By performing particle collisions at the highest energies ever achieved, it promised to discover supersymmetric particles provided that they had the properties prescribed by the naturalness problem that supersymmetry should solve. However, no such discovery has been made, which suggests that the "naturalness problem" was unwarranted (Giudice, 2017). If there is no naturalness problem, then, supersymmetry is left unconstrained again; there is no guarantee that supersymmetric particles will ever be discovered; and its phenomenological value plunges back to the depths from which it surfaced. Therefore we will put forward the following claim, which will also be evaluated in the present paper:

> **Claim 2**: Supersymmetry occurs in a variety of partially independent contexts within high-energy physics, some of which belong to "theory" and some of which belong to "phenomenology", and these applications of supersymmetry have responded differently to the LHC's failure to find supersymmetric particles.

Consequently supersymmetry should be losing its ability to sustain trades between theory and phenomenology. Therefore, we will evaluate the following claim:

[9] One can put other constraints on the MSSM, by requiring that supersymmetry explains dark matter, or that it ensures the convergence of the "couplings" that measure the strength of the fundamental forces at different length scales, which suggests it should play a role in the unification of these forces. However, as Giudice and Romanino 2004 put it, "the unification and dark-matter arguments [for supersymmetry] are not in general sufficient to insure that new physics be within the LHC discovery reach, contrary to the naturalness criterion".

[10] The naturalness argument also provides a "narrative" that connects what theorists are concerned with (the details of the theories at energy scales unattainable in the experiment) to what experimentalists can probe. As Borrelli (2015, p. 76) puts it, "the strength of the naturalness narrative is largely due to its flexibility, which allows it to become a unifying factor in the high-energy community and to bridge the gap between theorists and experimenters"

Claim 3: Supersymmetry sustained trades between theory and phenomenology in high-energy physics, until it was challenged by the LHC's failure to observe the particles predicted by supersymmetry.

If theorists and phenomenologists fail to share a similar appraisal of supersymmetry, then this may pose a serious problem for the field: this would imply that the theorists' research programs no longer provides useful guidance to the phenomenologists, and conversely that experimental input has little impact onto the theorists; if that is the case than the unity of high-energy physics would indeed be fragilized. Therefore, addressing claims 1-3 (that theory and phenomenology are partially autonomous subcultures of high-energy physics; that supersymmetry arises in distinct, autonomous contexts, which responded differently to the absence of supersymmetric particles at the LHC; and that the value of supersymmetry for bridging together subcultures of physics has decreased as a result) should contribute to answering the questions of what makes and unmakes unity in HEP. In the following section, we will defend the use of quantitative methods for addressing these claims.

1.3 Towards a quantitative assessment of subcultures and trades

In the following, we propose an array of methods implementing several dimensions of Galison's framework for addressing the plurality of science, which evaluate the claims put forward above. To this end, we will rely on authorship data (for investigating the social entrenchment of theory and phenomenology as distinct subcultures), semantic analyses (for investigating the linguistic divide between these subcultures as well as the plurality of supersymmetry research), and citation data (in order to locate "trading zones" within the field). To our knowledge, this is the first attempt to implement Galison's framework into a quantitative analysis of the scientific literature. Of course, the plurality of science and the coordination between scientific fields have already been addressed quantitatively in numerous publications. In the context of physics research, for instance, Battiston et al. (2019) have evaluated the ability of physicists to publish in various subfields. In particular, they demonstrate that HEP physicists are among the most specialized physicists (i.e., they have a high probability of publishing only in their primary subfield), although their work does not distinguish between the various kinds of high-energy physicists, which will be done in the present paper. There remains to address the linguistic component of the divide between these subcultures, in particular theory and phenomenology, and to this end we will propose a novel strategy based on semantic data (titles and abstracts of the literature).

In order to investigate the plurality of supersymmetry-related research in HEP, we will use semantic analyses as well. To this end, we will develop a topic model approach in order to identify heterogeneous clusters of concepts that are most likely to be associated with supersymmetry in the literature, and we will explore their dynamics throughout time.

Finally, we will assess the intensity of trades between theoretical subcultures and to locate the concepts that facilitate these trades. Yan et al. (2013) proposed a quantitative assessment of dependency relations between scientific disciplines based around a metaphor with international trade, by measuring quantities such as "exports", "imports", or "self-dependence" of various fields throughout time based on citation data. However, this work does not investigate what exactly allows these trades to happen, e.g., which concepts sustain them. This requires combining citation data with semantic information about the contents of the papers, as achieved by Raimbault (2019) who proposed measures of interdisciplinarity built upon such data. However, in our case, we are more interested in measuring the ability of certain concepts to sustain trades between established categories of the literature throughout time. Similarly to Yan et al. 2013, we will examine the self-dependence of experiment, phenomenology, and theory in HEP based on the citation network. However we will also assess the ability of different concepts (such as supersymmetry) to sustain trades across subcultures throughout time, by combining semantic and citation data.

More broadly, this works aims to participate in the quantitative studies of science literature, by helping to fill a gap that has come to the attention of the community. As stressed by Kang and Evans (2020); Leydesdorff et al. (2020); Bowker (2020), quantitative and qualitative studies of science have mostly diverged in their goals and worldviews, urging the need to "bridge the gap" between the two. The current paper aims to propose perspectives for bridging this gap. First, we demonstrate that such methods can address question raised by the philosophy, history, and sociology of physics. Moreover, we show that concepts from this literature can give structure to quantitative methods in a way that could be generalized for much more diverse cases than the case-study proposed in this paper, in line with the call by Heinze and Jappe 2020 to inform quantitative analyses with "middle-range theories" (of which Galison's trading zones are an example). For that, we deploy a range of methods informed by our conceptual framework, that can be applied to the scientific literature at large. Consistently with our aim to provide tools useful to colleagues interested in quantitative methods, we share parts of our code that may be of interest to a broad scientific audience.

The remaining of the paper is organized as follows. Section 2 describes the data on which our analysis rests and how it was collected. Section 3 details the quantitative methods that were deployed in order to address each of the three claims put forward in the introduction. The first subsection (3.1) elaborates quantitative methods for assessing the level of semantic and social autonomy of certain categories (subcultures), and applies these methods to the two theoretical subcultures in HEP. The second subsection (3.2) elaborates a methodology based on topic models in order to address the "plasticity" and "plurality" of supersymmetry, which can in principle be applied to all "boundary objects", i.e. those objects that can be traded between distinct subcultures while preserving and sustaining their distinctness. The third subsection (3.3) provides a quantitative model for locating "trading zones" or more broadly concepts that enhance trades between subcultures (or scientific disciplines in general), and applies the model to the exchanges between the theoretical subcultures of HEP. Section 4 reveals and interprets the results of these analyses. Finally, Section 5 explores the consequences of this work, both for our case study (supersymmetry within HEP) and for the more general question of the plurality of science from a quantitative perspective.

2 Data

Our data consists in the high-energy physics scientific literature, which semantic, authorship, and citation data are expected to capture the information of interest for our questions.

The data was retrieved from the Inspire HEP database (Moskovic, 2021). Inspire HEP is a platform dedicated to the HEP community and is maintained by people from CERN, DESY, Fermilab and SLAC. It aggregates publications from the HEP literature, and maintains a list of institutions and collaborations involved in the community, while also publishing job offers. It has replaced SPIRES in 2012[11].

The database is fed by an automatic aggregator that retrieves articles from multiple sources[12] including a number of databases (including the Astrophysics Data System, arXiv, etc.), data shared by research institutions (CERN, DESY, Fermilab, IHEP, IN2P3, SLAC), and data provided by scientific editors such as the American Physics Society or Springer.

Inspire aggregates data on the literature, the researchers, their institutions, as well as high-energy physics experiments with automated crawlers and performs manual curation for completion or error-correction[13], including author name disambiguation. Considering its high quality, this database has a strong and yet untapped potential for quantitative analyses. However, only contents related to HEP are subject to a systematic effort of collection and curation, and the data should preferably be used in analyses which scope is limited to HEP, thereby making it unsuitable for, e.g., studying interactions between HEP and other fields of physics (e.g. condensed matter physics).

The database includes data about the contents of the literature (title, summary, sometimes keywords), the authors (name, unique identifier, affiliations), dates corresponding to different events related to each paper, associated experiments, references of the articles. The only data that are both informative about the contents of the articles and very consistently available are titles and abstracts. Most articles are categorized according to a classification scheme mostly built upon that of arXiv. This scheme includes categories such as `Theory-HEP`, `Experiment-HEP`, `Phenomenology-HEP`, `Astrophysics`, etc. This classification rests upon arXiv's categories for articles that are available on that platform, or manual curation otherwise. A fraction of the articles between the years 1990 to 1995 were not categorized and this led to some issues with the data collection process, as described in Appendix A.1. For this reason, we have not conducted longitudinal analyses that included this date range, which did not prevent us from addressing our research questions.

[11] "Physicists, start your searches: INSPIRE database now online", *Symmetry*, May 24th 2012, https://www.symmetrymagazine.org/breaking/2012/05/24/physicists-start-your-searches-inspire-database-now-online
[12] Melissa Clegg, "INSPIRE Content Sources ", May 30th 2020 (https://help.inspirehep.net/knowledge-base/inspire-content-sources/)
[13] Stella Christodoulaki, "Content Policy", March 4th 2020, https://help.inspirehep.net/knowledge-base/content-policy/

3 Method

3.1 Social and semantic analysis of subcultures of high-energy physics

The first claim that we seek to establish is that "theory" and "phenomenology" should both be regarded as distinct subcultures within physics. There are two components to subcultures: a linguistic one (they should have vocabularies that are distinct enough to signal complementary bodies of knowledge) and a social one (they should correspond to distinct groups of people). Therefore we will proceed twofold: first, we will demonstrate that theory and phenomenology manipulate vocabularies that are distinct enough that we can predict whether a paper belongs to one of these categories based on the words present in its abstract with reasonable accuracy, and use our predictive model to unveil the ontological differences between these subcultures. Second, we will show that these categories from the literature are associated with different communities.

3.1.1 The semantic divide between Theory and Phenomenology

If it is possible to tell whether a paper is theoretical or phenomenological based on the vocabulary it contains, then this implies that these categories use partially distinct "languages". In order to establish whether we can predict which articles d belong to any of the categories $c \in \{\text{Experiment, Phenomenology, Theory}\}$, we will build a simple linear logistic regression using a bag-of-words as the predictive features. In this approach, the corpus is represented by a matrix $B = (b_{d,i}) \in \mathbb{R}^{D \times V}$ where D is the amount of documents, V is the size of the vocabulary, and $b_{d,i}$ the amounts of occurrences of the word (or expression[14]) i in the document d. This representation excludes a lot of semantic information that results from the knowledge of the ordering of the words and the structure of sentences within the documents; it is in line with our goal to find out whether the vocabularies of each category are so distinct that the mere presence or absence of certain words can be used to infer the category of a document. We perform a normalization of the bag-of-words prior to the regression, by applying the tf-idf transformation[15] to $(b_{d,i})$, resulting in a normalized bag-of-words which we will name $(b'_{d,i})$. Then resulting predictive model is then given by:

$$P(d \in c) = \text{logit}^{-1}\left(\sum_{i=1}^{V} \beta_{ci} b'_{di}\right) \tag{1}$$

This model is then trained on $N = 50,000$ articles of our database that belong to any of the following categories: `Experiment-HEP`, `Phenomenology-HEP`, and `Theory-HEP`[16]. The vocabulary used in the regression is the V expressions (n-grams) among those that belong to predefined syntactic patterns (up to three word long), that have the highest "unithood" as measured in Omodei 2014[17]. The size of the vocabulary V is chosen to be a round number that is just high enough to reach about the maximum accuracy of the model, as evaluated on the test set (which consists in 10,000 articles not present in the training set). Then, the accuracy of the predictions of the model are evaluated using the same test set. The coefficients β_{ci} are then analyzed in order to extract the words that are the most discriminatory between "theory" and "phenomenology", thus revealing the most salient differences. For that, we retrieve those expressions i that maximize $\beta_{\text{th},i} - \beta_{\text{ph},i}$ and $\beta_{\text{ph},i} - \beta_{\text{th},i}$. Because of the inverse document frequency transformation applied prior to the regression, expressions that are more common are favored by this selection process.

3.1.2 The social divide between Theory and Phenomenology

What does it mean to say that theory and phenomenology have a "demographic component", as Galison (1987, p. 138) puts it regarding theory and experiment in HEP? It means that these categories of the

[14] We also include some n-grams in the model, i.e. expressions of several words, provided they follow certain pre-defind syntactic patterns (e.g. "adjective +noun")

[15] For a definition of the tf-idf transformation, and information theoretic justifications of its relevance, see Beel et al. 2015; Robertson 2004. We use scikit-learn's implementation of the inverse-document frequency transformation which is $\text{idf} = 1 + \log(1/f)$ where f is the fraction of documents in which a word occurs. It differs from the "textbook" definition $\log(1/f)$ because of the regularization term $(+1)$.

[16] The fit is performed with the scikit-learn python library (Pedregosa et al., 2011).

[17] The "unithood" measures "the degree of strength or stability of syntagmatic combinations or collocations" (Kageura and Umino, 1996)

literature are supplied by distinct groups of people, "theorists" and "phenomenologists". Therefore, we will investigate whether it is the case that experimental, phenomenological and theoretical papers are published by three distinct groups of physicists, such that these physicists usually contribute mostly to just one of these categories. We also include "experiment" in our analysis, since it will be useful to assess whether the distinction between phenomenology and theory is as strong as the distinction between theory and experiment (the one initially stressed by Galison).

Let N_{ij} be the amount of articles co-authored by a physicist i that belong to the category $j \in \{\text{theory, phenomenology, experiment}\}$, and N_i the total amount of articles co-authored by i. Let us assume $N_{ij} \sim \text{Binomial}(N_i, p_{ij})$, where p_{ij} is the latent probability that a paper from physicist i belongs to the category j[18]. Since the researchers co-authored widely varying amount publications (from a few papers to hundreds for some), we assumed that the latent probabilities p_{ij} were described by the following model:

$$\begin{aligned} N_{ij} &\sim \text{Binomial}(N_i, p_{ij}) \\ p_{ij} &\sim \text{Beta}(\alpha_j, \beta_j) \\ \alpha_j, \beta_j &\sim \text{Exponential}(1) \end{aligned}$$

Indeed, this model allows to combine information from researchers with many papers and researchers with very papers; for those with few papers, the estimation of the latent probabilities is then more influenced by the shape of the Beta distribution. The model was fitted to 2500 researchers randomly sampled among those with more than 3 publications in HEP for 1980-2020. In order to evaluate the social entrenchment of these categories, we verify that most physicists contribute mostly to just one of these categories.

3.2 Assessing the plurality of supersymmetry research with topic models

Our second claims pertains to the plurality of supersymmetry research. In this section, we present our methodology for assessing the plurality of supersymmetry related research, by recovering the contexts, i.e., the topics in which supersymmetry occurs, and by evaluating the extent of their independence, and how they responded to the results of the LHC. More broadly we provide a methodology for investigating scientific "objects" akin to "boundary objects" in that they are "plastic enough to adapt to local needs and constraints of the several parties employing them" (Star and Griesemer, 1989, p. 393), by unveiling the plurality and autonomy of the contexts in which such objects may arise.

3.2.1 Model

In order to evaluate in which contexts supersymmetry arises in the high-energy physics literature, we have chosen to subdivide the literature in sub-topics using an unsupervised probabilistic topic model, namely the Correlated Topic Model (CTM, Blei and Lafferty 2007). We have not used conventional classifications such as the Physics and Astronomy Classification Scheme® (PACS) codes from theAmerican Institute of Physics (AIP) since those were not available for the whole dataset – PACS codes were only available from 1995 onwards, and for a subset of the papers, which may not be representative of the whole. Besides, PACS codes are too numerous (more than 5000 categories)[19] for our purposes. Therefore, we extracted the topics in the literature using unsupervised topic models instead.

Probabilistic topic models generally assume that each document of a corpus is a mixture of variable proportions of a certain amount of topics, each of these topics having their own vocabulary distribution. When trained on a corpus, such models simultaneously learn the "topics" in the corpus (and their vocabulary), as well as the relative contribution of each topic to each document of the corpus. These models have demonstrated their ability to capture the semantic information contained within the scientific and academic literature, as shown in previous work[20], even from the sole abstracts (Syed and Spruit, 2017); as a result this technique has seemingly taken precedence over network-based semantic maps (Leydesdorff and Nerghes, 2016, Figure 1). Topic models models provide a straightforward derivation of

[18] Since these categories are not mutually exclusive in our database (an article may belong two more than one of them), a multinomial process would not be a good fit.

[19] "Full list of PACS numbers", *Physics-Uspekhi*, `https://ufn.ru/en/pacs/all/`

[20] Notable examples are Nichols 2014; Hall et al. 2008; Griffiths and Steyvers 2004; see Malaterre et al. 2022 for a more recent application in the context of History and Philosophy of Science, and Allen and Murdock 2022 for an assessment of the potential and limitations of these methods in the field.

the information that is of interest to us: the vocabulary associated to each "topic", and the contribution of each "topic" to each document of a corpus. Although co-occurrence networks may have more bearing in the STS tradition, we have preferred topic models for their intrinsic ability to capture the polysemy of certain words (e.g., "supersymmetry"), in terms of the probabilities that such words can arise in different contexts (i.e. topics).

In particular, we have chosen the Correlated Topic Model for its ability to capture correlations between topics. According to the Correlated Topic Model, the contribution of a topic z to a document d, $P(z|d)$, is drawn from a hierarchical model involving a correlated multivariate distribution (Blei and Lafferty, 2007):

$$\vec{\beta}_d \sim \mathcal{N}(\vec{\mu}, \Sigma) \tag{2}$$

$$P(z|d) = \frac{\exp \beta_{d,z}}{\sum_{i=1}^{k} \exp \beta_{d,i}} \tag{3}$$

Through the covariance matrix Σ, the CTM model is therefore able to learn correlation between topics, and therefore to account for the fact that some topics are more likely to occur together within a same document. Moreover, our intuition is that using CTM allows the derivation of more realistic topic-distribution for short texts such as abstracts, for which the small amounts of words only moderately inform the prior topic distribution. Most importantly, this model allows us to assess directly the level of independence between the topics derived by the model, which is important for assessing the autonomy of the contexts in which supersymmetry arises.

The model is trained on $N = 120,000$ articles randomly sampled from those in the 1980-2020 period that belong to any of the categories `Theory-HEP`, `Phenomenology-HEP`, `Experiment-HEP`, and `Lattice`. The vocabulary selection procedure and the procedure for choosing the hyper-parameters are described in details in appendices A.2.1 and A.2.2 respectively. Two methodological contributions can be highlighted. First, we included informative n-grams matching pre-defined syntactic patterns in the vocabulary in order to preserve more semantic information. Second, we made a prudent and balanced use of perplexity and topic coherence measures in order to recognize the advantages and limitations of both these kinds of measures for assessing the quality of topic models and choosing the best hyper-parameters.

3.2.2 Interpretation and validation

Once the model was trained, we manually assigned a label to each topic, by inspecting and interpreting their top-words and the categories from the PACS classification of the physics literature that were most correlated to each topic[21]. Informing our interpretation of each topic with these correlations rather than the sole top-words help overcome issues associated with the interpretation of fat-tailed topic-word distributions based on a handful of top-words (Chang et al., 2009; Allen and Murdock, 2022). We failed to provide a meaningful label for some topics, but this had no impact on the rest of the analysis. Finally, in order to assess the meaningfulness of the metrics produced by the model (the document-topic distributions and the topic-word distributions), we performed an additional validation procedure using the PACS classification of the literature and the input of independent experts (see appendix A.2.3).

In section 4.2, the model is applied to a number of tasks: the evaluation the contexts (i.e. topics) in which supersymmetry occurs in the literature, the extent of the correlation between theses contexts and finally the trends in research involving supersymmetry since the start of the LHC.

3.3 Locating trades across scientific cultures

In this section, we elaborate a longitudinal methodology for locating trades between scientific cultures, which we use to assess the ability of supersymmetry to enhance trades between the theoretical and phenomenological cultures of HEP throughout time. Trading zones can manifest themselves in a myriad of ways, some of which are readily prone to a quantitative analysis. For instance, citing the example of quantum chromodynamics, a theory of the strong interaction, Galison notes that "the contact between the experimenters and the phenomenological theorists had grown to the point where Andersson [a theorist] and Hofmann [an experimentalist] could coauthor a *Physics Letter* (Galison, 1997, p. 655). In that sense, a paper co-authored by scientists from different cultures is indicative of a trading zone, such that

[21] We used pointwise mutual information (see equation 7, appendix A.2.3) as the measure of correlation.

co-authorship data can in principle be used to probe trades across scientific cultures. Another manifestation of trading zones can be found in the citation network. That, for instance, a phenomenological paper cites a theoretical paper indicates that phenomenologists can acknowledge the value and significance of certain theoretical constructs in their enterprise. Although both the citation networks and the collaboration networks could be used for our purpose, the presentation analysis will rely on the former. Indeed, the citation graph preserves more information about the directionality of the exchanges involved and better sustains the trade metaphor (Yan et al., 2013). Intuitively, it is also vulnerable to non-epistemic factors associated with authorship (e.g. senior physicists co-authoring papers they mostly supervised; or physicists authoring papers they did not contribute to as is frequent in large collaborations in the field). Appendix A.3 demonstrates that the citation network can indeed reveal the relative autonomy (self-reliance) of HEP subcultures, but also the special role of phenomenology in sustaining the unity of HEP by channeling trades across subcultures.

In order to assess the ability of supersymmetry to facilitate trades between theorists and phenomenologists, we develop a method that combines two important aspects of Galison's trading zone: their locality and their linguistic component (the "inter-language"). In particular, we look for scientific concepts that are most likely to be involved in trades between these subcultures throughout time. We perform the analysis on a subset of the citation graph, such that the nodes are limited to theoretical and phenomenological papers, excluding hybrid papers (that belong to both these categories). We then extract informative keywords from the abstracts of these papers by extracting n-grams ($n > 2$) matching certain syntactic patterns and selecting the 500 with the highest "unit-hood" (see A.2.1). We obtain a bag of words b_{ik} for each publication such that $b_{ik} = 1$ if keyword k is present in abstract i, and $b_{ik} = 0$ otherwise. We then evaluate the probability $P(b_k = 1|\text{trade})$, i.e. the probability that the keyword occurs in an abstract given the paper is involved in a trade between a theoretical and a phenomenological paper. To which extent supersymmetry helps sustain the trading zone between these theoretical cultures is roughly measured by $P(b_k = 1|\text{trade})$ for those keywords k related to supersymmetry.

4 Results

4.1 Theory and phenomenology as distinct subcultures

Let us now examine our first claim that "theory" and "phenomenology" in should be regarded as distinct subcultures within high-energy physics. The claim requires that these categories mobilize distinct bodies of knowledge which manifest themselves through distinct vocabularies. As shown in Table 1, it is indeed possible to predict to a reasonable accuracy whether a paper belongs to either one of these categories based on the vocabulary of its abstract. The accuracy is higher than 90% for "theory" and reaches 86% for "phenomenology", far above one would obtain from assigning the most probable class irrespective of the contents. This supports the existence of a linguistic divide between these two theoretical cultures.

	Theory	Phenomenology	Experiment
Model accuracy	91%	85%	92%
Baseline	55%	51%	84%

Table 1 Accuracy of the model for predicting which categories HEP papers belong to. The precision of the model for each category is estimated based on the test corpus. For reference, the accuracy of a naive model that assigns the most likely class irrespective of any information about the papers is given (baseline). The size of the vocabulary used for the predictions is set to 500 words and expressions.

Our model also unveils the expressions that are most capable of discriminating between theory and phenomenology, as shown in Table 2. They reveal the vocabulary that is most responsible for the linguistic divide between theory and phenomenology. One striking difference between theory and phenomenology appears to be the importance of space-time related concepts in theory ("space-time", "geometry", "manifold", "dimension", "coordinate", etc.). The objects (entities) of interest also differ, which signals an ontological divergence: on the pure theory side, "black holes" and "strings" are prominent entities, while particles ("quark", "neutrino", "gluon", "hadron", "nucleon", etc.) belong to the realm of phenomenology. Among those terms most specific to phenomenology but absent in pure theory (bottom-right cell), we also find the notions of model ("mssm", "standard model"), and effective field theories ("effective theory", "effective field theory", "chiral perturbation theory") which are approximate theories emerging from more fundamental theories. Interestingly, one aspect of supersymmetry (the MSSM) appears as markedly phenomenological, while "supergravity" is specifically theoretical.

Table 2: Vocabulary specific to theory (left column) versus phenomenology (right column).

Vocabulary distinct from phenomenology	Vocabulary specific to phenomenology
algebra, spacetime, manifold, theory, gravity, branes, action, partition, chern-simons, string, geometry, supergravity, ad, deformation, space-time, horizon, quantum, central charge, duality, entropy, conformal field, coordinate, modulus space, construction, yang-mills, correspondence, surface, space, transformation, dimension	quark, qcd, neutrino, lhc, extra dimension, parton, dark matter, electroweak, phenomenology, experimental data, mssm, high energy, collider, nucleon, sensitivity, effective theory, hadron, standard model, gluon, color, chiral perturbation, new physic, chiral perturbation theory, neutron, contribution, neutrino mass, process, pion, effective field, effective field theory

What about the "demographic component" of the divide between theory and phenomenology? Do these categories have social counterparts? The results of our social analysis are shown in Figure 2. Figure 2 is a ternary diagram in which each red dot represents a physicist and is positioned according to the relative prevalence of each category (among experiment, phenomenology and theory) among the papers they authored or co-authored. The majority of the dots are clustered near vertices, which means that most physicists dedicate themselves to mostly one of these categories. In particular, the inner of the ternary diagram, which corresponds to physicists with balanced contributions to each category, is almost empty. We do find that some authors are scattered along the experiment-phenomenology edge and the phenomenology-theory edge; still, our results suggest that the category of phenomenology does feature a "demographic" counterpart as well, although it is more porous than experiment or pure theory. Therefore, phenomenologists do, to some extent, constitute a social group distinct from that of theorists; however, phenomenology seems to play a special role in sustaining some form of cooperation between experimentalists and theorists. Overall, we find that 81% of high-energy physicists publish more than 80% of their papers in just one of these categories, which is clear evidence of specialization.

Our quantitative analysis supports our claim that theory and phenomenology should be regarded as distinct subcultures with distinct languages. Consequently strategies ought to be devised for them to communicate and coordinate their efforts. It follows that their unity should not be assumed; instead, why a trading zone can be successfully worked out remains to be explained. Before we turn to the ability of supersymmetry to sustain the coordination between these subcultures, we will address the plurality of supersymmetry research itself.

4.2 The plurality of supersymmetry

In this section we apply our methods to address our second claim regarding the plurality of supersymmetry research and the recent decline in phenomenological supersymmetry research as a response to the LHC results.

Topic models are able to link one word to several topics, thus allowing us to unveil different aspects of supersymmetry, i.e. different contexts[22] in which this concept may occur. For three words w that explicitly refer to supersymmetry ("supersymmetry", "supersymmetric", "susy"[23]), we evaluated the probability $P(z|w)$ that these words occur in the context of a topic z:

$$P(z|w) = \frac{P(w|z)P(z)}{P(w)} \tag{4}$$

Where $P(w|z)$ is frequency of the term w within the topic z, $P(z)$ is the marginal probability of topic z, and $P(w)$ is the overall term-frequency of w. The five most probable topics for each of the

[22] Like Allen and Murdock (2022), we caution that these "topics" may not be as coherent as the common understanding of the word may suggest and that they should really be understood as different "contexts", although we use both terms interchangeably below.

[23] Short for "supersymmetry"

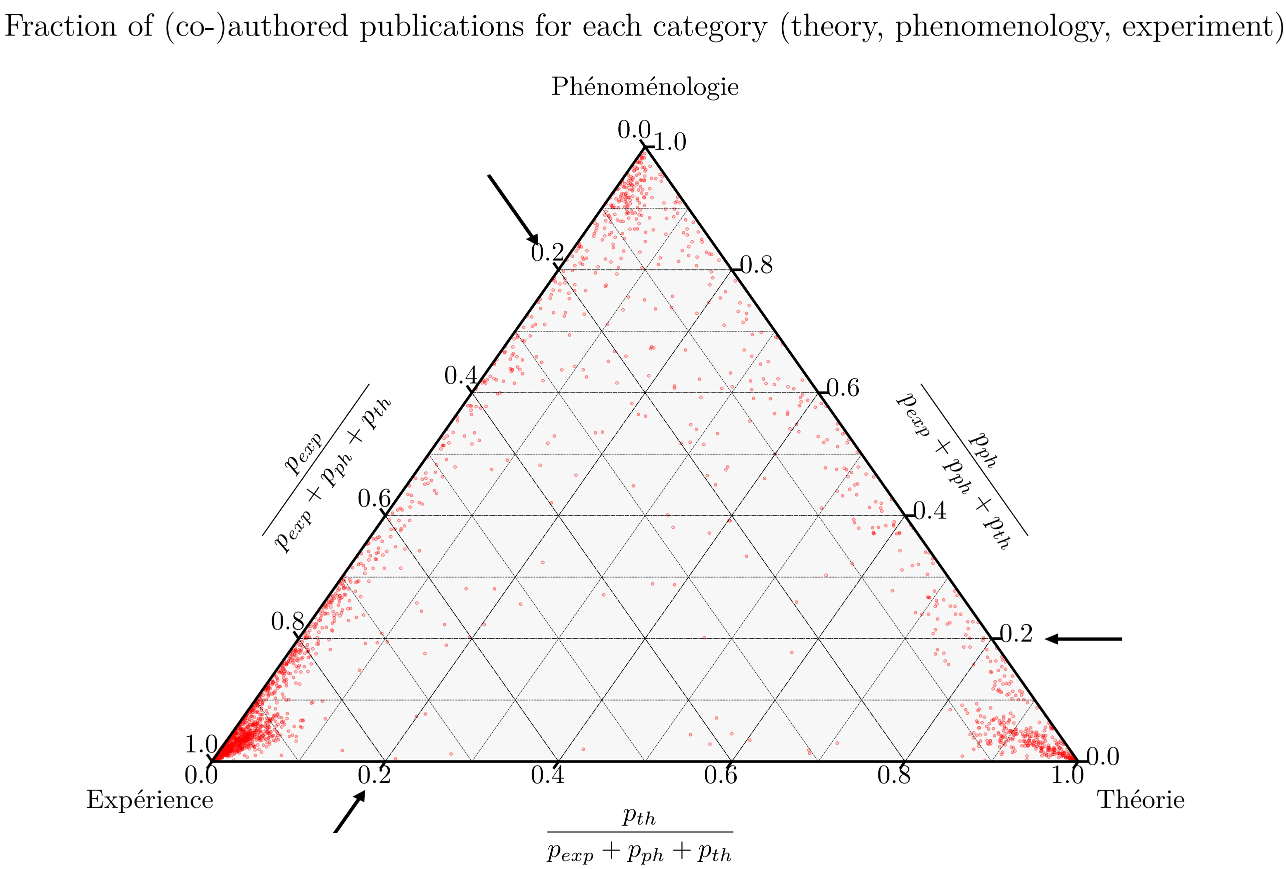

Fig. 2 Relative fraction of articles from any of the categories "Experiment", "Phenomenology" and "Theory", for 2,500 HEP physicists. Each physicist among those sampled is represented by a red dot on the diagram, positioned according to the estimate of $(p_{i,exp}, p_{i,ph}, p_{i,th})$, the probability that any of his articles belong to those three categories. The dashed lines, along the direction of the arrows, form a grid along which one can read the relative importance of each category for every physicist ($\frac{p_{ij}}{\sum_k p_{ik}}$). Physicists near the vertices of the triangle contribute almost exclusively to one category; those near an edge contribute quasi-exclusively to two categeories. Most physicists are located near a vertex, thus contributing to mostly one category.

words "supersymmetry", "supersymmetric", and "susy" are shown in Figure 3. We can see that each of these terms may indeed occur in relation to a variety of topics: "supersymmetric gauge theories", "superalgebras and super-fields", "Beyond the SM Higgs", "Supergravity", "Higgs sector", "Supersymmetry phenomenology and superpartners", "Leptons and flavor physics". It is notable that several of these are directly tied to supersymmetry ("'supersymmetric gauge theories", "supergravity" and "Supersymmetry phenomenology and superpartners", for instance). This stresses the importance of supersymmetry in the high-energy physics literature.

Moreover, although all these words ("supersymmetry", "supersymmetric" and "susy") should refer to the same concept, we find that they are in fact related to different topics: "supersymmetry" seems to encompass more theoretical aspects of supersymmmetry (e.g. notions of field and supergravity) while "susy" is more likely to occur in relation to supersymmetric particles (phenomenological supersymmetry). In fact, we find that 60% of papers mentioning "supersymmetry" belong to theory (versus ∼40% to phenomenology) while only 30% of papers mentioning "susy" in their abstract belong to "theory" (versus 70% to phenomenology).

That these topics are at least partially independent can be assessed by inspecting the covariance matrix Σ of the Correlated Topic Model from which they were derived. We therefore compute the Pearson correlation[24] between the seven topics most commonly associated with supersymmetry; the results can be found in Figure 4. Overall the correlations are close to 0, which suggests that these topics are rather independent, although there are a few exceptions. In particular, pairs of topics that belong to the same

[24] The Pearson correlation coefficients R_{ij} can be deduced directly from the covariance matrix Σ of the CTM model – cf. equation (2) – according to $R_{ij} = \frac{\Sigma_{ij}}{\sqrt{\Sigma_{ii}\Sigma_{jj}}}$

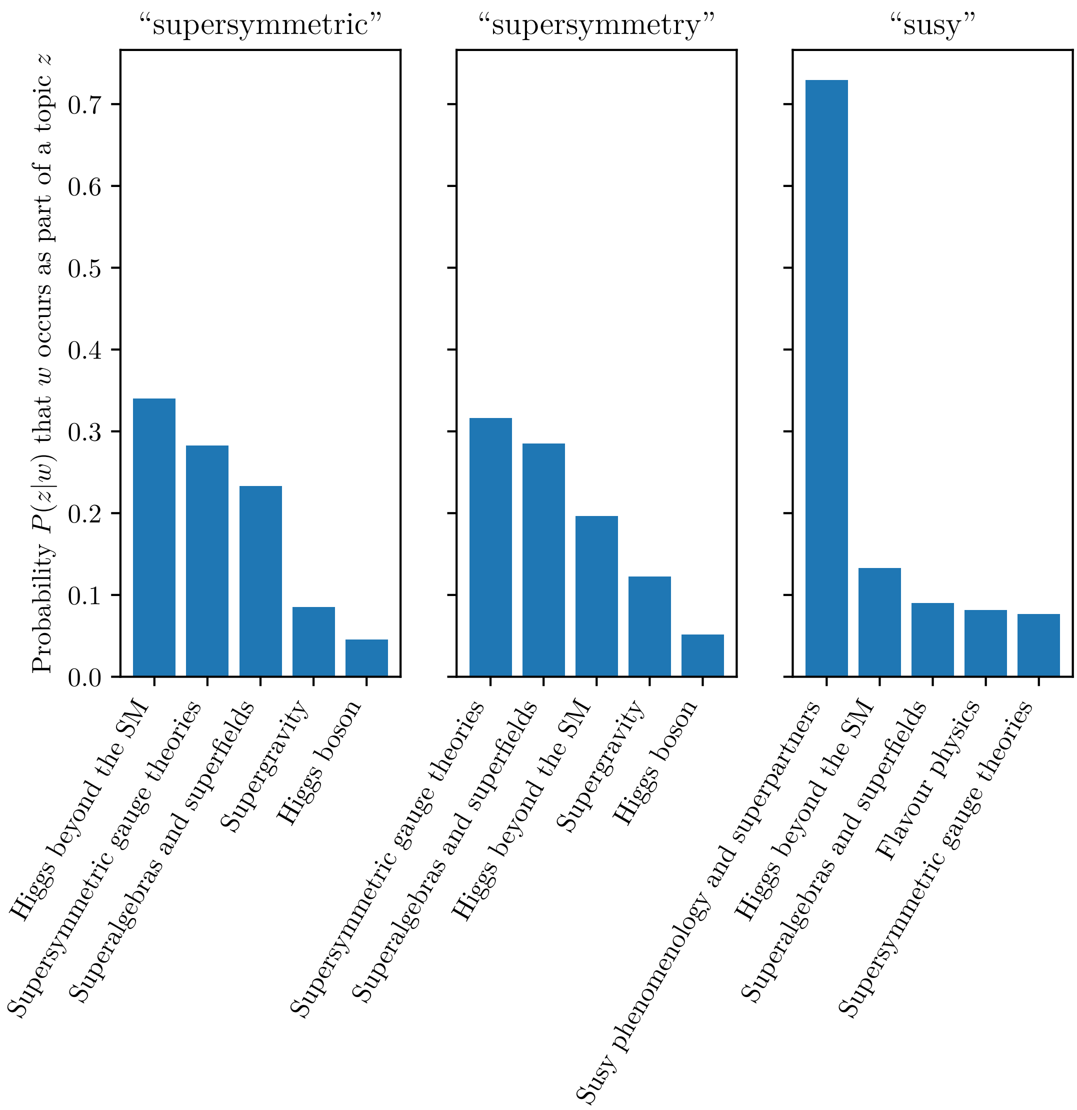

Fig. 3 The many uses of supersymmetry. For three terms w refering to supersymmetry ("supersymmetric", "supersymmetry", and "susy"), the five topics z that are most likely to have led to their occurrence and their respective conditional probability $P(z|w)$ are shown. "supersymetry" and "supersymmetric" have similar distributions, and mostly occur within theoretical topics. "susy"'s topic distribution is much more peaked, and most often occurs within phenomenological topics.

kind (theoretical or phenomenological) are moderately correlated; pairs of topics that are directly tied to supersymmetry (e.g., supergravity and phenomenological supersymmetry) but of different nature (in this case, theoretical and phenomenological, respectively) are less correlated.

From these results, one can see that supersymmetry is itself a diverse concept. It arises in a variety of partially independent contexts. In particular, theoretical and phenomenological aspects of supersymmetry are quite independent. How have these different aspects of supersymmetry responded to the negative results of the searches for supersymmetric particles at the LHC?

In order to address this question, we evaluate the evolution of supersymmetry research in HEP since the first results of the LHC (2011) until today. For that, similarly to Hall et al. (2008), we assess the relative importance $\hat{\theta}_{z,y}$ of each topic z for every year y from 2011 to 2019:

$$P(z|y) = \frac{1}{D_y} \sum_{d \in y} P(z|d) \tag{5}$$

Where D_y is the amount of articles first submitted in year y. We then selected the three topics with the highest increase (hot topics) and decrease (cold topics) in magnitude over this period. For that, $P(z|y)$ was fitted to a linear time trend ($P(z|y) = a_z y + b_z$), discarding topics for which the correlation was not significant (i.e. $R = 0$ is excluded from the 99% CI). Then, the topics were sorted according to

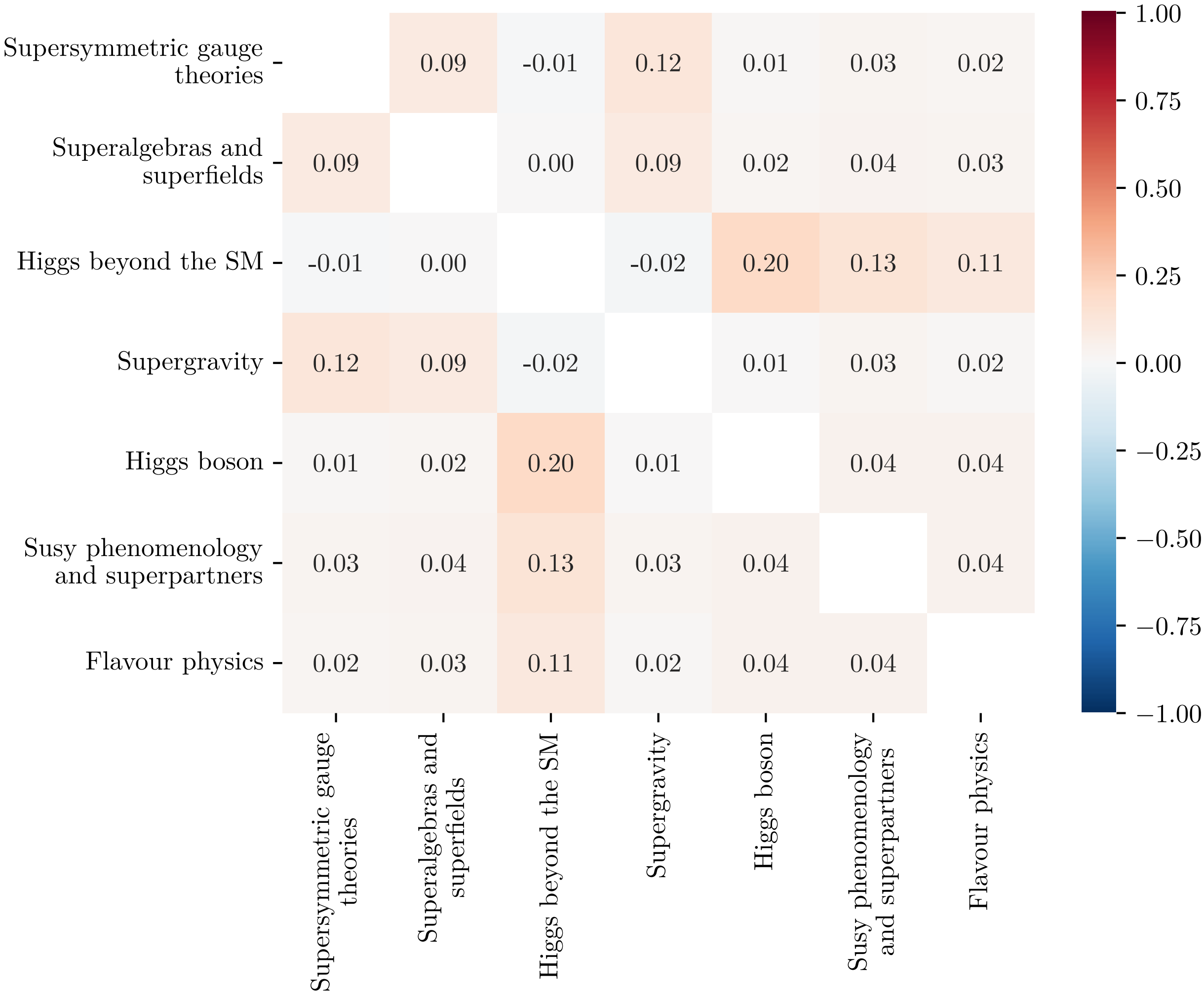

Fig. 4 Correlation between the topics most associated to supersymmetry. The Pearson correlation is comprised between -1 (perfect anti-correlation) and 1 (perfect correlation). A correlation close to 0 means that a pair of topic is partially independent, i.e. that they can arise or not in variable proportions in a paper.

the best fit value of a_z, the rate of increase of its magnitude per year (similarly to what was done by Griffiths and Steyvers 2004). We apply the procedure to all papers mentioning at least one of the words "supersymmetric", "supersymmetry" or "susy" in their title or abstract in the years following the start of the LHC. The results are shown in Figure 5.

According to these results, the most rapidly declining topics among articles that mention supersymmetry are Higgs-sector related topics and phenomenological supersymmetry, i.e. phenomenological aspects of supersymmetry. By contrast, two of the increasingly active topics (relatively) are very theoretical (in particular, Supergravity and Conformal Field Theory). In order to understand these dynamics, it is therefore useful to distinguish theoretical supersymmetry from phenomenological supersymmetry. As physicist Mikhail Shifman put it in an early assessment of the first results of the LHC in 2012,

> [Theoretical supersymmetry] is an example of a complete success story. I use the word 'theoretical' to differentiate from 'phenomenological' supersymmetry [...] which [...] at the moment has a rather murky status. Theoretical supersymmetry proved to be a powerful tool with which to deal with quantum field theory, especially at strong coupling, a regime which was considered intractable for decades[...]. Progress in this line of research [...] is absolutely steady (Shifman 2012, p. 6)

Shifman's assessment strikingly converges with the patterns that emerge from our analysis. Topic models reveal the plurality of supersymmetry in high-energy physics. They support that supersymmetry arises in different context, some of which being theoretical and others being phenomenological. They allowed us to demonstrate that these "faces" of supersymmetry have responded differently to the absence

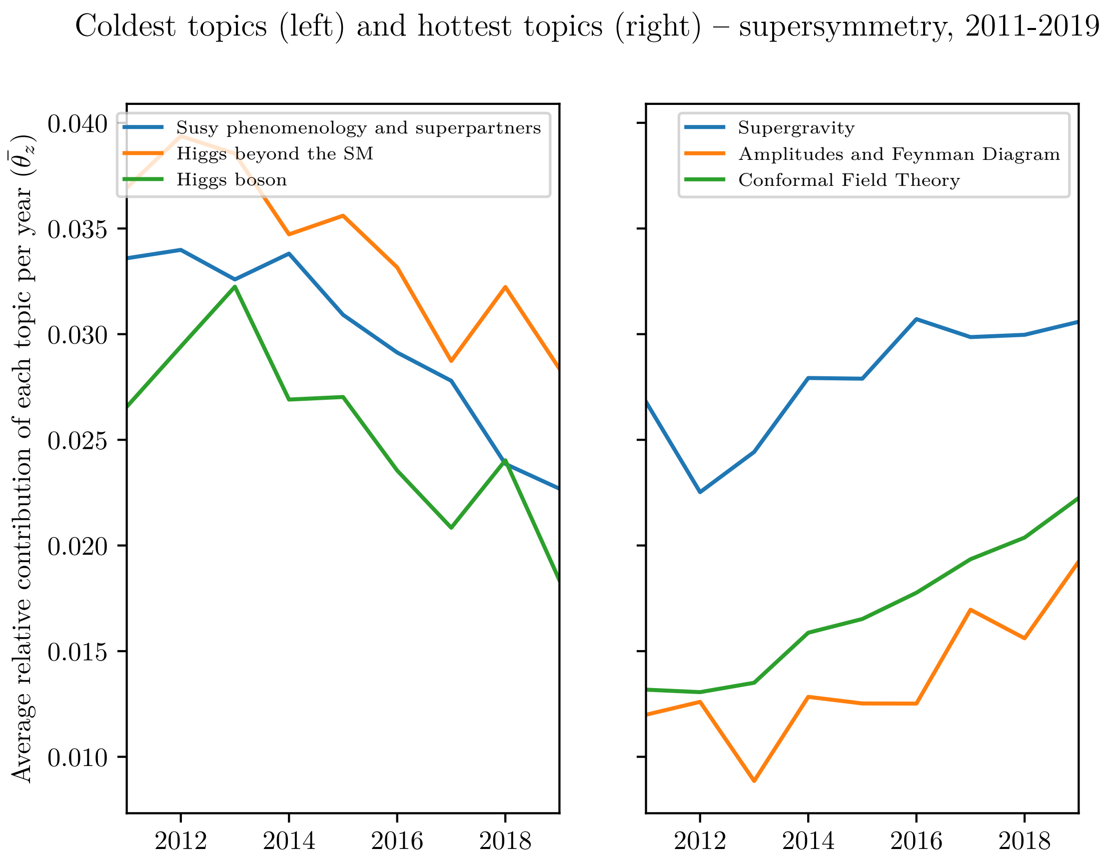

Fig. 5 Cold and hot topics among those that mention supersymmetry since the first results of the LHC (2011-2019). On the left, the three coldest topics are "Susy phenomenology and superpartners", "Higgs beyond the SM" and "Higgs boson". On the right, the three hottest topics are "Supergravity", "Amplitudes and Feynman Diagrams", "Conformal Field Theory".

of evidence for supersymmetric particles at the LHC. This supports that cultures can "trade" certain concepts (according to Galison's terminology) while retaining much of their autonomy[25].

In the next section, we investigate the contribution of supersymmetry to sustaining the trading zone between these theoretical traditions throughout time.

4.3 Supersymmetry in the trading zone

Where do trading zones occur within HEP? As discussed in the Method section, citations can signal trades between subcultures. We apply the methodology proposed in Section 3.3 for localizing trading zones. We measure the ability of certain concepts (keywords) to sustain trades through time – most specially, exports from the theoretical subculture to the phenomenological subculture – in terms of the probability that each of these concepts occurs in citations across these two categories of the literature. The results are shown in Figures 6 and 7.

Both these figures show the probability of occurrence of the five most common keywords (left side) and the five most common supersymmetry-related keywords (right side) involved in trades across these subcultures. Figure 6 shows those probabilities for trades where phenomenological papers draw from theoretical papers. Three main trends are revealed: the fall of trades involving extra dimensions; the increase in trades involving black-holes; the decline of trades involving supersymmetry, despite a short increase after the start of the LHC in 2010. Interestingly, in the early 2000s, "supersymmetric model[s]" had a trade-ability on *a par* with that of that of the keywords most involved in these trades. Turning to Figure 7 – trades involving theoretical references – , we get an even more striking picture of the demise of "extra dimensions", which were involved in about 30% of the trades in 2000 and went down to 5% only. Similarly, "weak-scale" (which refers to the domain of phenomena targeted by the LHC) and

[25] "trading partners can hammer out a local coordination, despite vast global differences." (Galison, 1997, p. 783)

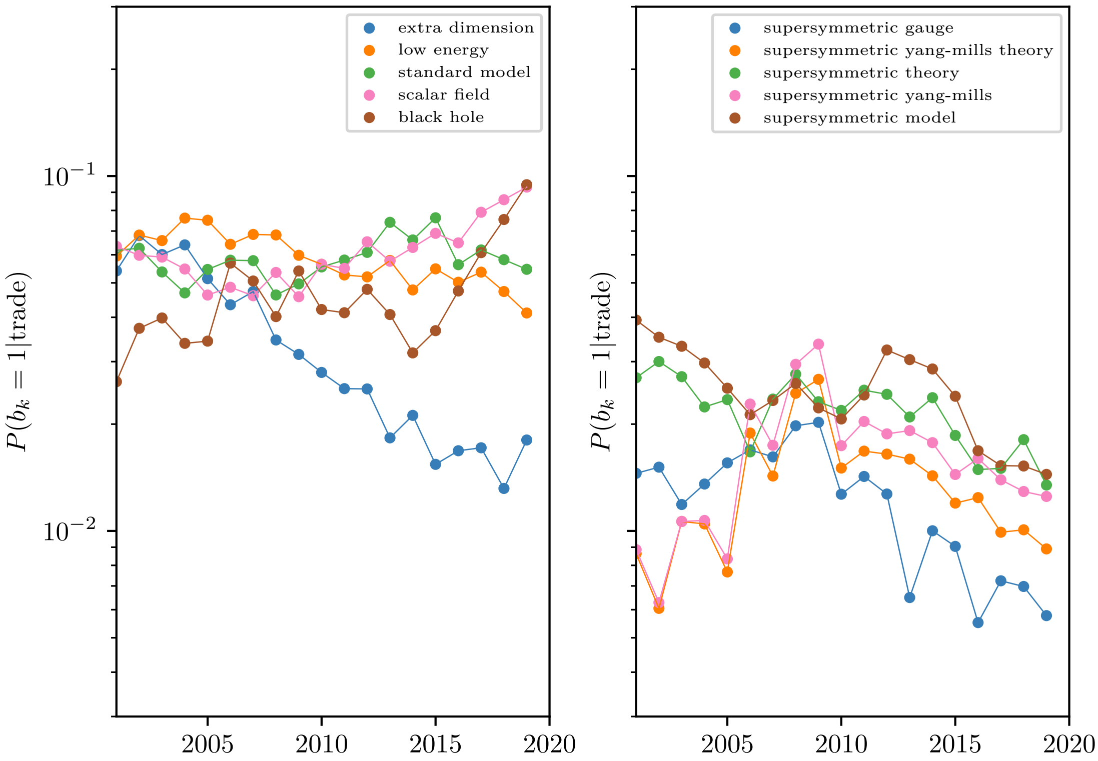

Fig. 6 Inside the trading zone: probability that certain keywords appear in the abstract of a theoretical paper involved in a trade (a phenomenological paper citing a theoretical paper). To the left, the five keywords are those with the highest peak probability of occurrence; to the right, are the five keywords with the highest probability of occurrence among supersymmetry related keywords.

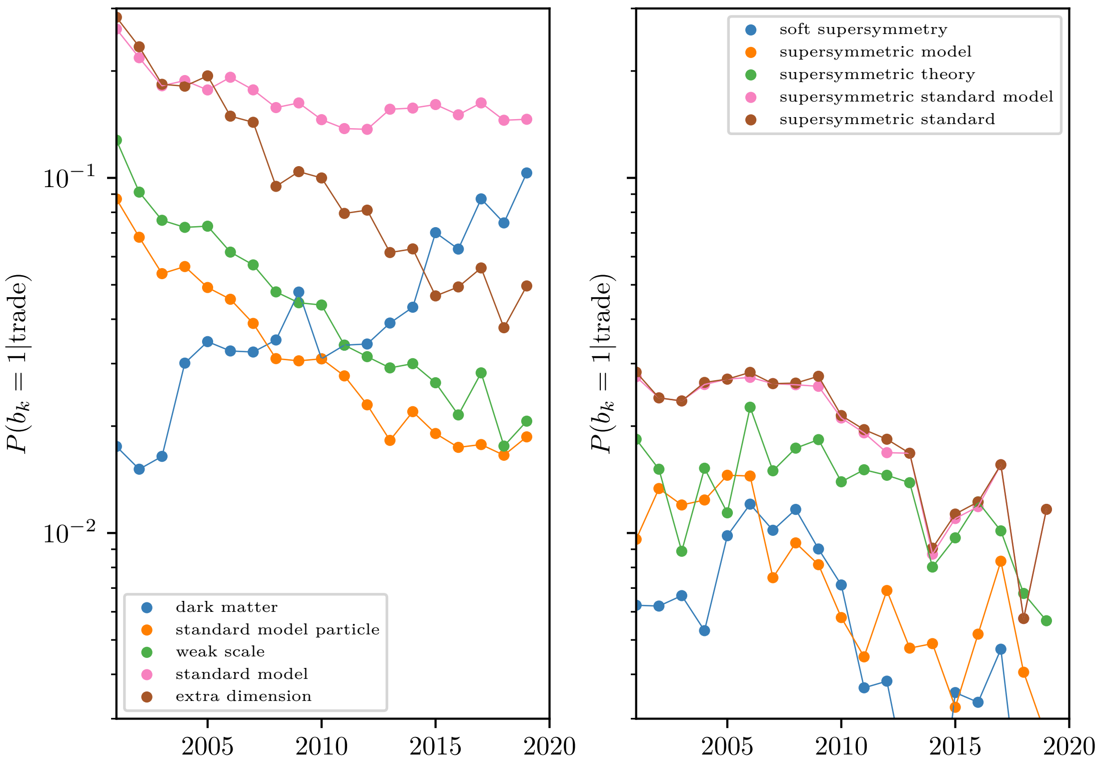

Fig. 7 Inside the trading zone: probability that certain keywords appear in the abstract of a phenomenological paper involved in a trade (a theoretical paper citing a phenomenological paper). To the left, the five keywords are those with the highest peak probability of occurrence; to the right, are the five keywords with the highest probability of occurrence among supersymmetry related keywords.

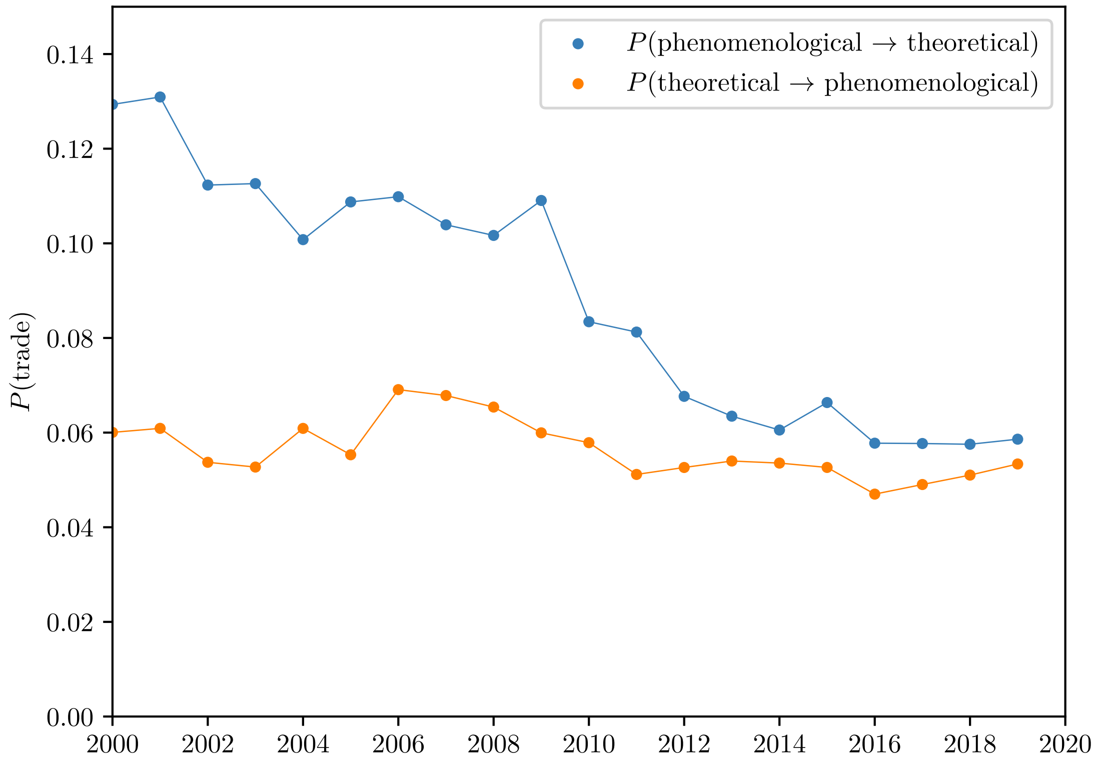

Fig. 8 Probability of trades between theoretical subcultures. $P(\text{trade})$ is evaluated as the fraction of citations involving certain trades (phenomenological papers citing theoretical papers in blue, theoretical papers citing phenomenological papers in orange) among all citations involving only theoretical or phenomenological papers.

"standard model particle[s]" (which are all observable at the LHC) have become much less frequent in the "trading zone" (from ∼10% of trades to ∼2%). This suggests that phenomenological models dedicated to this domain of phenomena have become much less useful to the "theoretical" subculture over time. On the other hand, "dark matter"[26] is increasingly common in the phenomenological papers theorists draw from. This suggests dark matter is deemed valuable for the theoretical enterprise as well. This figure also confirms the overall decline of supersymmetry in the trading zone.

The magnitude of the observed variations suggests that the frequency of trades may have itself significantly varied. In order to verify this, we compute the overall trade probability $P(\text{trade})$[27] as the fraction of trades among all these edges of the subset of the citation graph under considerationg (limited to theoretical/phenomenological papers). The results are shown in Figure 8. They demonstrate that phenomenology has become relatively much less reliant on theory since 2000, as $P(\text{trade})$ has decreased from 13% down to 7% — in other words, the trading zone has shrinked. A significant portion of the decrease seems to be imputable to the start of the LHC in 2010. Theory seems more self-reliant overall and rather unaffected by the effect of the LHC. This suggests the LHC has contributed to further decouple these two subcultures, even though "theory" was itself already rather autonomous prior to its start.

5 Discussion

5.1 Conceptually informed methods in quantitative science studies

Before exploring the implications of this case-study, we want to emphasize that Galison's conceptual framework has been a fruitful guide for our quantitative approach. The linguistic component of his

[26] Dark matter refers to the observation that a significant fraction of the mass of the universe is currently unexplained.

[27] For instance, the frequency of phenomenology→theory trades is defined as:

$$P(\text{trade})_{\text{ph}\to\text{th}} = \frac{\#\text{phenomenology} \to \text{theory citations}}{\#\text{phenomenology} \to \text{theory citations} + \#\text{theory} \to \text{theory citations}} \quad (6)$$

notion of subculture led us to build a bag-of-words model for measuring the extent of the divide between two theoretical cultures, and for unveiling the concepts that are specific to these cultures as well as their methodological and ontological differences. The social autonomy of these subcultures, too, can be readily quantified from authorship data. Furthermore, the notion of trading zone invited us to explore citations quantitatively (as a proxy of scientific "trades") while devising ways to determine their "location" in the semantic space. We also found that topic models can reveal the plurality of contexts in which a concept may arise, and how the dynamics of these contexts compare throughout time. Although we have applied our topic model approach to supersymmetry, in principle it can be applied to any kind of "boundary object", understood in the broad sense of a shared notion that allows some coordination to be achieved while preserving the distinctness of the scientific cultures at play. In the end, these methods illuminated our study of supersymmetry in high-energy physics, and provided further grounds for Galison's claim that unity is a contingent matter.

5.2 Unity challenged?

The two theoretical subcultures we have distinguished – pure "theory" and phenomenology – no longer appraise supersymmetry equally, as transpires in the dynamics of the various contexts in which supersymmetry arises. The reason is that supersymmetry fails to provide equally satisfying solutions to the heterogeneous commitments of HEP physicists, which poses a challenge to the unity of the field. Indeed, the example of supersymmetry shows that what drives theoretical progress may not drive phenomenological progress, and developments in these subcultures may become quite orthogonal.

Of course, supersymmetry is not the only channel of coordination between the theoretical and phenomenological cultures in their search for "new physics". Another channel, for instance, has been the notion of extra dimensions (see Figures 6 and 7), i.e. spatial dimensions beyond the 4 space-time dimensions that we have direct evidence for. Extra-dimensions are required by string theory, but they are also subject to trades with phenomenologists interested in their observable consequences. However, no evidence for extra-dimensions was found at the LHC. This further supports that the goals that drive string theory (like the search for a quantum description of gravity) may not provide as much ground for progress to phenomenologists as it was first perceived, and that abstract theoretical developments around, say, quantum gravity, are quite orthogonal to the phenomenologists' agenda.

Eventually, the LHC provided "a test of the unity of physics"[28], and its verdict was ruthless. In the future, what will prevail? Some shared belief that unity should be maintained, or the socially entrenched divergences between these "cultures" of high-energy physics? We may assume that the challenge is merely transitory, and that theorists will eventually move on to other theories which will turn out to be more successful from an empirical or phenomenological standpoint. However, the divergence between these theoretical cultures has become axiological (Ritson, 2021; Laudan, 1984), and it may persist as long as their differences in aims persist; as Galison puts it, "there is no teleological drive towards ever-greater cohesion", and "fields previously bound [may] fall apart" (Galison, 1997, p. 805). As illustrated in Figure 1, the aims of the theorists is to achieve the unification of the fundamental forces and a coherent theory of quantum gravity. By contrast, the aim of phenomenologists is to guide the experiment towards promising directions where evidence of "new physics" may be found. Both these aims may seem well-founded; however, there is no reason to expect that a simultaneous solution can necessarily be worked out. The apparent failure of supersymmetry to provide such a simultaneous solution does not undermine by itself the relevance of the "theorists"' aims, nor it undermines the methodology they deploy for addressing their goals (e.g. their trust in certain theoretical constraints, cf. Galison 1995). It does however challenge the belief that such methods can provide grounds for progress to the field *as a whole*; indeed, unification and quantum gravity might eventually not provide much reliable guidance to the experimental side; and conversely, it might be that the details of the theory "at high energy", where quantum effects matter to gravity, cannot be extrapolated from our knowledge of the low-energy theory, i.e. the one that we can probe in our experiments[29]. Disagreements in the aims of a scientific enterprise sometimes cannot

[28] Wilson (1986, p. 29) (cited in Cat 1998, p. 292) used this expression in reference to the now aborted Super-Conducting Supercollider.

[29] More drastically, Cao and Schweber (1993) expressed the view that the theories at different energy scales (i.e. corresponding to different ranges of phenomena) are irreducible, and argued for a "pluralist view of possible theoretical ontologies" while challenging the possibility of achieving a "ultimate stable theory of everything" (p. 69–71). According to this view, the plurality of ontologies in physics is not an accident but the result of partially disconnected "phenomenological domains" which knowledge cannot be deduced from one another. For a criticism of this view, see Rivat, Sébastien and Grinbaum, Alexei 2020.

be resolved on purely epistemic grounds and a resolution, provided it occurs, may involve some sort of negotiation instead. As long as theorists believe in the feasibility of their aims, they may pursue them even if this furthers isolate themselves from other cultures. Alternatively, they could decide that the schism should be resolved; as Galison puts it, distinct scientific cultures "can [...] understand that the continuation of exchange is a prerequisite to the survival of the larger culture of which they are part" (Galison, 1997, p. 803).

5.3 Trading zones as a mean to sustain diversity

More generally, the example of HEP and supersymmetry demonstrates how disunity can be endogenously produced in the fabric of science. Even initially tightly bound scientific cultures can diverge into quite distinct and autonomous programs, with different ontologies, methodologies and aims, as new domains of inquiry are opened up that require new modes of knowing(e.g. quantum gravity. The extent of the coordination between disciplines will in general depend on epistemic factors (depending on how fruitful certain "trades" turn out to be), but also on non-epistemic factors as well: for instance, it may depend on the institutional setting, or whether such exchanges are incentivized or "coerced" (Collins et al., 2010).

Paradoxically, it can be noted that trading zones can stabilize the heterogeneity of cultures within a field, by sustaining the practitioners' beliefs that in spite of the large differences in what they are doing, their respective efforts somehow support each other; if that is the case, there is no perceived need for a profound re-alignment of their respective practice. In that sense, trading zones can contribute to a mutual process of legitimization of heterogeneous scientific practices, which is hardly tantamount to further unity. In order to further emphasize that, it is useful to come back to the example of HEP, and most particularly that of string theory, a highly theoretical research program driven by the pursuit of a consistent theory of quantum gravity. String theorists such as Matt Strassler have argued that even if string theory did not directly provide testable predictions to phenomenologists and experimentalists, it generated mathematical tools that could be useful to their practice, e.g. for predicting the behavior of quark-gluon plasma (Ritson, 2021). Consequently phenomenologists may have a low appraisal of string theory in terms of its ability to generate models for testing its assumptions about nature, and still recognize the usefulness of what string theorists do for their own practice in the sense that some of their work is effectively "applicable". As Ritson and Camilleri (2015) put it, "if string theory has proved so useful for branches of physics whose scientific status is not in question, it can be argued it forms a legitimate part of physics". Supersymmetry itself may be experiencing the same fate, considering that "supersymmetry as a tool for exploring gauge dynamics at strong coupling [...] is taking precedence over phenomenology" (Shifman 2020, p. 7–8). Such trades do support the usefulness of the theoretical program to other endeavors, without necessarily implying further integration of the subcultures of HEP (ontological unity); just like successful interdisciplinary work does not necessarily amount to further integration of disciplines (Grüne-Yanoff, 2016).

5.4 Limitations and future work

Before concluding we would like to hint at several directions for future work that could overcome certain limitations of the present methodology and further inform the question of the disunity of science.

First, none of our semantic methods distinguished between different kinds of words, i.e. which words refer to, say, methods (such as computation techniques) rather than entities (e.g. strings, particles, etc.). Yet it would be interesting to evaluate to what extent the coordination between theoretical cultures involves ontological or mere methodological trades, depending on whether the constructs of high-theory are referred to as the proper description of nature or as mere mathematical tools, and how this may have changed throughout time. This might uncover evidence for a shift from an ontological to a more methodological coordination between the subcultures of high-energy physics, as the arguments for supersymmetry and string theory as "tools" rather than accurate accounts of the natural world suggest.

Another direction of future work involve the topic model approach. Although the topic model used in this work yielded seemingly acceptable results overall, some topics were difficult to interpret. In that respect, we made several improvements compared to previous works, by training the model on not just single words but also n-grams matching specific and presumably semantically informative syntactic patternsand by informing our interpretation of topics using correlations with a standard classification (rather than the top-words only). Yet, further improvements could be made. First, vocabulary selection could be enhanced by a better handling of mathematical expressions, for instance by parsing LaTeX formulas.

The NLTK library picked up some of these expressions, and since they captured some information about the documents, we did not exclude them from the vocabulary; however, this way of proceeding does not preserve the underlying mathematical structure, although it may be valuable to distinguish references to, say, specific particles, or certain symmetry groups, based on their mathematical notations. We may also want the model to learn to discard uninformative words such as “result”, “parameter”, “model”, etc.. In our case, we found such vague words to be clustered in three topics that we labeled as “jargon” which correlated very poorly with the standard classification (see Tables 3 and 4), but they should ideally not emerge as distinct topics on *par* with more meaningful topics. To this end, we may want to build on Griffiths et al. 2004, which provides a model that is able to distinguish between “semantic” and purely “syntactic” clusters of words without prior knowledge of the language. A more critical limitations of topic models pertains to the challenge of hyper-parameters’ tuning, considering it is unclear which performance metric should be maximized in the process. Although we proposed a procedure for choosing these parameters that accounts for known limitations to the reliability of perplexity or topic coherence metrics, non-parametric methods may provide a better answer to this fundamental issue (Gerlach et al., 2018).

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A Appendices

A.1 Data collection

Our goal was to collect the whole HEP literature from 1980 to 2020. Data were collected through the public Inspire HEP API (Moskovic, 2021). For that, we collected metadata for all articles through automated search requests, category per category, and year per year. This strategy was intended to abide with the limitations of the API, in terms of matching entries per search request. However, it appeared that many articles in years 1990 to 1995 were not categorized, and therefore our collection strategy missed many HEP articles from this period. In order to recover these articles, we gathered all articles that were referenced in publications collected through the first batch but which were missing. This methods fails to recover articles that were not cited in any article from the first batch. More importantly, the lack of categories means that selecting all HEP papers during the problematic time period will require unlabeled articles to be manually or automatically classified. Although there are ways to circumvent these issues and to assess their potential implications, we have decided to narrow down several analyses to years 2000 onwards in the present work.

A.2 Topic model

A.2.1 Data and vocabulary selection

The model is trained on $N = 120,000$ articles randomly sampled from those in the 1980-2020 period that belong to any of the categories `Theory-HEP`, `Phenomenology-HEP`, `Experiment-HEP`, and `Lattice`. Titles and abstracts of each papers are concatenated in order to maximize the textual content used for training. Very short texts (less than 100 characters) are removed.

Before applying the model, we performed a number of pre-processing steps on the abstracts with the goal of maximizing the amount of useful information in the training data. This procedure, largely inspired from Omodei 2014 and implemented with the use of the NLTK library (Bird et al., 2009), is as follows:

- Tokens (words separated by punctuation or spaces) are extracted from the text and transformed to lower-case.
- All single nouns and adjectives are retrieved from these tokens.
- We also retrieve all n-grams that match specific syntactic patterns (e.g. “adjective+noun+noun”, such as “supersymmetric standard model”, “effective field theory”).
- Single words are lemmatized, i.e. they are normalized to their root (e.g. “symmetries” becomes “symmetry”).
- Words and expressions that occur less than 20 times are removed.

First, these steps allow us to reduce noise by removing words that convey little to no information about the topics of the articles (such as stop words). Second, extracting n-grams that matching certain syntactic patterns allows us to preserve some information about the relative position of words within the abstracts – which CTM do not do otherwise – while taking advantage of our prior knowledge of the documents’ language. For instance, the word “dark” may convey different meanings depending on whether it occurs immediately before the word “matter”, or, alternatively, “energy”; similarly, the occurrence of the expression “dark matter” in a text conveys more information than the simultaneous occurrence of “dark” and “matter” without more knowledge about their relative position.

As a result of this procedure, the vocabulary contains $V = 18{,}658$ “words”, with 58 words per article on average.

A.2.2 Hyper-parameters

The implementation of CTM by Tomotopy has three hyper-parameters: the amount of topics k, an $\vec{\alpha}$ parameter that controls the sparsity of the document-topic distribution ($\theta_{d,i}$), and a $\vec{\eta}$ parameter that controls the sparsity of the topic-word distribution (the vocabulary associated to each topic). For choosing the amount of topics k, we considered three values that seemed acceptable in terms of interpretability and compliance with the values from the literature: 50, 75 and 100. We assumed $\vec{\alpha}$ and $\vec{\eta}$ to be symmetric, i.e. $\alpha_1 = \alpha_k = \alpha$ and $\eta_1 = ... = \eta_V = \eta$[30]. We considered $\alpha \in \{10^{-2}, 10^{-1}, 1\}$ and $\eta \in \{10^{-3}, 10^{-2}, 10^{-1}\}$, according to values encountered in the literature. We then trained the model for each triplet of k, α and η among the candidate values. We rejected all triplets that led to significant overfitting, by comparing the perplexity[31] obtained for the training corpus and that obtained by applying the trained model to a validation set of abstracts unseen during training. Although Chang et al. (2009) have shown that perplexity could be negatively correlated to human judgments about the interpretability of the topics recovered by topic models, we believe it is a suitable metric to discard models that fail to capture meaningful regularities in the data, which is the case of models that show overfitting. Among the remaining models, we then selected the two models with the highest normalized pointwise mutual information coherence, a coherence metric frequently used to assess the consistency of topic models (Hoyle et al., 2021). Topic coherence metrics in general, as stressed by Hoyle et al., are not very strongly correlated with human judgments about the quality of a model; however, we believe they may be useful to discard certain models in order to limit the amount of those that should be inspected manually (since manual inspection is time-consuming and quite subjective). We finally inspect manually the two models with the highest coherence measure, and choose the one with $k = 75$, $\alpha = 0.1$ and $\eta = 0.001$. Our preference for this model stemmed from the fact that it contained more topics than the other remaining model, and that these more numerous topics seemed reasonably consistent.

A.2.3 Validation

Since the model infers document-topic distributions and topic-word distributions, we would like to assess the validity of these metrics, i.e. "their ability to measure what they purportedly measure" (Bannigan and Watson, 2009, p. 3240). In order to simultaneously assess both measures, we designed the following protocol. First, we derived the PACS categories c that were the most correlated to each topic z (this approach is in a sense comparable to that employed in Griffiths and Steyvers 2004, who extracted the topics that were more strongly associated with PNAS categories). For that, we listed the categories c that maximize the pointwise mutual information with each topic z according to:

$$\text{pmi}(z, c) = \log \frac{p(z|c)}{p(z)} \tag{7}$$

Where $p(z)$ is the marginal probability of the topic z, and $p(z|c)$ the probability that a word in a document belongs to a topic z given that the document was assigned the PACS category c. Thefore, $\text{pmi}(z, c)$ measures the increase in probability of a given topic provided that a PACS category is present. The 5 categories most correlated to each topic are given in table 4, which helped inform our choice for each tpic label, in complement to their top-words.

Then, we submitted the lists of PACS categories thus constitued to a human task derived from the methodology of Bennett et al. (2021), as follows:

1. We draw at random a topic z_1 with a probability equal to its marginal probability
2. We draw at random 5 PACS categories $c_1, ..., c_5$ among the 10 most correlated to z_1, as described above.
3. Then, we do any of the following, with equal probability 1/2:
   (a) We draw at random another topic $z_2 \neq z_1$ with probability $\frac{p(z_2)}{1-p(z_1)}$, and we pick at random 5 PACS categories $c_6, ..., c_{10}$ among those most correlated with it.
   (b) Alternatively, we draw $c_6, ..., c_{10}$ from the 5 remaining PACS categories most associated to z_1
4. We submit $c_1, ..., c_5$ and $c_6, ..., c_{10}$ to an expert unaware of the model. The expert is asked to guess whether the two lists of 5 categories were drawn from one and same general topic, or whether they were drawn from two separate topics.
5. The procedure is repeated a certain amount of times. The final score is the fraction of correct responses.

The rationale for this method is that good scores should only be achievable provided the topics are rather coherent, and that the document-topic distributions $\theta_{d,i}$ are reasonably accurate. The final average score is 0.74 for 100 guesses from two HEP PhD students, which is significantly better than a random baseline (0.5). This shows that, to some extent, the topic distributions derived for each article correlate with PACS categories that are rather coherent with each other. Now equipped with these results, we can turn to applications..

A.2.4 Topics

Table 3: Most frequent terms for each topic.

Topic (context)	Most frequent expressions
Algorithms and calculation techniques	simulation, carlo, monte, lattice, method, correlation, distribution, cluster, generator, statistical, study, function, scaling, size, event
Amplitude of processes in colliders	amplitude, contribution, state, interaction, resonance, final, final state, process, exchange, reaction, tree, scattering, double, polarization, level

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[30] This is common in the literature, but this choice is disputable, cf. Wallach et al. 2009. One implication of symmetric priors is that topics must have comparable probabilities. This also has an impact of the meaning of topics.

[31] Perplexity is the exponential of the average log-likelihood per word, cf. Blei et al. 2003. It measures the improbability of a corpus according to a given model.

Table 3: Most frequent terms for each topic.

Topic (context)	Most frequent expressions
Amplitudes and Feynman Diagram	amplitude, function, loop, limit, pole, conformal, relation, integral, diagram, correlation, scattering, analytic, block, correlators, feynman
Analyses and measurements from colliders	data, measurement, event, result, detector, experiment, gev, algorithm, analysis, muon, experimental, energy, precision, fit, beam
Annihilation and scattering cross-sections	section, cross, annihilation, photon, energy, scattering, gev, production, total, elastic, process, pair, total cross section, total cross, elastic scattering
Astrophysics	star, wave, nuclear, matter, neutron, collision, gravitational waves, energy, nuclear matter, flow, density, gravitational, relativistic, heavy-ion, equation
Black holes	black, hole, black hole, black holes, horizon, entropy, extremal, radiation, schwarzschild, thermodynamics, black hole solutions, black hole entropy, hawking, charge, kerr
Boundary conditions/non-locality	boundary, condition, boundary conditions, state, tensor, entropy, entanglement, distance, case, surface, general, correlation, boundary condition, term, phys
CP violating processes	cp, asymmetry, violation, parameter, b^0, bound, direct cp, direct, mixing, penguin, decay, constraint, experimental, direct cp violation, effect
Chern–Simons	gauge, field, spin, topological, theory, chern-simons, higher spin, abelian, vortex, non-abelian, gauge field, dirac, term, hall, fermion
Conformal Field Theory	conformal, string, algebra, theory, conformal field, conformal field theory, central, central charge, conformal field theories, charge, operator, open, superconformal, virasoro, representation
Cosmological sources	cosmic, spectrum, scale, energy, ray, universe, radiation, gravitational, cosmological, power, observation, cmb, background, cosmic ray, cosmic rays
Cosmology and gravity	cosmological, gravity, constant, axion, scale, lorentz, universe, cosmological constant, violation, problem, quantum, vacuum, cosmology, time, planck
Cross-sections in colliders	production, section, cross, collision, energy, lhc, rapidity, process, pair, pp, inclusive, differential, fusion, nuclear, gev
Dark matter (particles and direct searches)	dark matter, matter, dark, dm, particle, detection, direct detection, direct, wimp, relic, relic density, density, annihilation, search, candidate
Dark matter in the universe	dark, matter, dark matter, dark energy, model, abundance, energy, sector, constraint, density, candidate, galaxy, universe, cold, scenario
Decay measurements	decay, state, d, meson, stat, syst, $+/-$, $+-$, fraction, final, final state, width, ratio, $pi+$, final states
Detectors	detector, experiment, physic, beam, high, crystal, nuclear, liquid, performance, precision, resolution, high energy, search, target, chamber
Double-beta decay	mass, baryon, decay, scalar, beta, double beta decay, double, double beta, scale, light, neutrinoless, effective, glueball, gev, hierarchy
Early-universe and other cosmological data	constraint, big bang, big, galactic, signal, cosmic microwave, background, axion, bound, galaxy, bang, microwave, halo, detection, dm
Effective Field Theory	field, effective, theory, effective field theory, effective field, noncommutative, action, effective action, scalar, scalar field, potential, effective theory, effective potential, eft, non-commutative
Electromagnetism	magnetic, field, particle, magnetic field, electric, relativistic, electromagnetic, effect, plasma, moment, energy, medium, magnetic fields, external, electromagnetic field
Events in colliders (kinematics)	production, collision, jet, tev, lhc, collider, event, transverse, large hadron collider, energy, large hadron, hadron, pair, pp, luminosity
Events in colliders (signatures)	jet, event, lhc, tev, production, cm, pair, atlas, final state, final, collision, data, luminosity, channel, large hadron collider
Experimental investigation of the leptonic sector	decay, search, data, limit, gamma, collider, muon, gev, measurement, signal, experiment, detector, magnetic moment, event, upper
Experimental jargon	result, mass, effect, large, parameter, energy, value, analysis, small, order, region, current, due, contribution, present
Experiments on light	photon, electron, particle, experiment, mi, laser, compton, optical, mo, beam, light, atom, year, math, pulse
Field theory and gravity	scalar, field, scalar field, mode, gravity, massive, scalar fields, gravitational, potential, massless, perturbation, geodesic, background, metric, spacetime
Flavor mixing	cp, violation, asymmetry, mixing, matrix, lepton, cp violation, flavor, standard model, model, quark, phase, standard, angle, mass
Flavour physics	mass, lepton, bound, flavour, flavor, decay, neutrino, heavy, scale, generation, violation, light, quark, coupling, number
Form factors	factor, form, nucleon, electromagnetic, pion, electromagnetic form, electromagnetic form factors, momentum, form factors, result, ratio, ^{2}, transfer, nn, form-factors
Gauge Theory	gauge, theory, action, invariance, field, lorentz, transformation, invariant, brst, yang-mills, symmetry, effective action, lattice gauge, massive, covariant

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Table 3: Most frequent terms for each topic.

	Most frequent expressions
Topic (context)	
Gauge symmetry breaking/GUTs	symmetry, gauge, su, model, group, theory, breaking, anomaly, fermion, spontaneous, unification, representation, discrete, symmetric, grand
Gravitons and extra-dimensions	gravity, dimension, scalar, extra, field, constant, brane, cosmological, massive, cosmological constant, extra dimensions, scalar field, bulk, graviton, derivative
Hadronic zoo	state, resonance, d, gev, mev, b, channel, e^+e^-, charmonium, narrow, b, molecule, s1, reaction, e^+
Heavy quarks and ions	quark, heavy, hadron, distribution, collision, production, gluon, hadronic, qcd, heavy quark, heavy ion, charm, correlation, ion, heavy ion collisions
Higgs beyond the SM	higgs, model, standard model, standard, boson, electroweak, supersymmetric, lhc, minimal, supersymmetric standard model, collider, tev, mass, scalar, supersymmetric standard
Higgs boson	higgs, boson, model, standard model, mass, standard, coupling, gauge, sector, sm, higgs mass, doublet, higgs boson, neutral, scalar
High-energy source fluxes	energy, flux, source, high energy, spectrum, high, event, signal, emission, time, radiation, solar, information, gravitational wave, such
Holographic Principle and dualities	conformal, dual, holographic, boundary, entropy, cft, entanglement, ad, bulk, defect, theory, conformal field, correspondence, conformal field theory, entanglement entropy
Inflation	inflation, perturbation, universe, inflationary, field, scalar, cosmological, inflaton, cosmology, potential, scalar field, initial, evolution, fluctuation, curvature
Lattice calculation techniques	operator, lattice, matrix, fermion, loop, wilson, theory, element, gauge, function, action, calculation, continuum, expansion, method
Lepton/Meson decay	decay, branching, ratio, semileptonic, meson, fraction, asymmetry, mode, measurement, rate, br, nu, semileptonic decays, inclusive, lifetime
Lie algebra	algebra, space, integral, representation, function, group, operator, invariant, form, path, transformation, lie, differential, product, partition
Loops and next order expansions in Feynman Diagrams	correction, order, one-loop, term, contribution, radiative corrections, approximation, qed, calculation, loop, radiative, logarithmic, effective, expansion, expression
M-theory and theories of everything	theory, gauge, duality, supergravity, string, dual, action, dimensional, type, background, m-theory, reduction, dimension, abelian, field
Measurements and analysis of colliders data	data, measurement, uncertainty, experiment, analysis, experimental, fit, determination, systematic, first, theoretical, error, parameter, detector, current
Meson phenomenology	meson, state, resonance, vector, decay, mass, width, mev, pseudoscalar, pion, amplitude, experimental, channel, quark, wave
Neutrino physics	neutrino, oscillation, mass, experiment, majorana, neutrino mass, right-handed, neutrino oscillations, neutrino oscillation, flavor, interaction, supernova, antineutrino, seesaw, sterile
Partons distributions	qcd, distribution, parton, next-to-leading order, order, function, nlo, gluon, jet, next-to-leading, correction, transverse, momentum, calculation, perturbative
Perturbative QCD	qcd, perturbative, factorization, anomalous, order, contribution, result, function, approach, perturbative qcd, calculation, anomalous dimension, coefficient, kernel, expansion
Phenomenological jargon	state, new, interaction, coupling, physic, strong, problem, particle, theory, recent, such, bound, model, approach, role
QCD	rule, sum, qcd, wall, domain, qcd sum rules, viscosity, qcd sum, quark, heavy, shear viscosity, shear, vacuum, condensate, bubble
QCD calculation techniques	propagator, expansion, lattice, gluon, effective, finite, loop, theory, potential, qcd, numerical, gauge, perturbative, method, regularization
Quantum Field Theory	theory, field, quantum, equation, solution, classical, dimension, quantum field, class, quantum field theory, problem, space-time, dimensional, two-dimensional, arbitrary
Quantum Systems and Equations of motion	equation, hamiltonian, constraint, system, term, formalism, charge, monopole, dirac, solution, first, second, kinetic, nonlinear, part
Renormalization	renormalization, group, flow, point, coupling, scale, fixed, uv, rg, ir, cutoff, infrared, fixed point, effective, ultraviolet
Scattering of composite particles	scattering, function, data, proton, structure, nucleon, inelastic, distribution, moment, deep, dipole, q^2, inelastic scattering, hera, target
Search for BSM physics	physic, new, new physics, standard model, experiment, standard, neutral, search, tau, measurement, current, decay, future, lepton, rare
Solar neutrinos	neutrino, oscillation, solar, mixing, solar neutrino, angle, atmospheric, neutrino mass, sterile, atmospheric neutrino, experiment, hierarchy, sterile neutrinos, matrix, sterile neutrino
Space-time geometry and gravity	solution, gravity, spacetime, metric, gravitational, ad, geometry, space, flat, curvature, sitter, singularity, general, dilaton, einstein
Spin/angular momentum/polarization	momentum, polarization, asymmetry, angular, spin, distribution, angular momentum, polarized, reaction, transverse, cross, section, beam, production, photon

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Table 3: Most frequent terms for each topic.

Topic (context)	Most frequent expressions
States of matter	phase, transition, critical, temperature, point, holographic, spectral, order, exponent, behavior, imaginary, critical point, finite temperature, finite, first order
String theory	string, solution, charge, soliton, branes, configuration, topological, type, monopoles, open, flux, bps, tachyon, background, vortex
Superalgebras and superfields	model, symmetry, supersymmetric, supersymmetry, sigma, term, integrable, lagrangian, algebra, su, group, chiral, deformation, fermionic, sl
Supergravity	supergravity, modulus, manifold, type, space, calabi-yau, supersymmetric, geometry, supersymmetry, moduli space, topological, bps, class, curve, iib
Supersymmetric gauge theories	theory, gauge, supersymmetric, yang-mills, supersymmetry, anomaly, supergravity, duality, chiral, $n = 4$, super, $n = 2$, super yang-mills, branch, su
Susy phenomenology and superpartners	mass, susy, parameter, soft, neutralino, space, scale, mssm, squark, region, scenario, constraint, gluino, gaugino, large
Symétrie chirale	chiral, quark, qcd, lattice, chiral symmetry, mass, chiral perturbation theory, chiral perturbation, pion, condensate, baryon, transition, perturbation, flavor, symmetry
Systems dynamics and thermodynamics	system, energy, time, quantum, state, fluctuation, density, gas, dynamic, thermal, temperature, phase, casimir, force, surface
Theoretical jargon	model, case, structure, limit, new, term, function, such, number, different, method, particular, property, spectrum, approach
Thermodynamics	phase, temperature, transition, potential, density, chemical, finite, finite temperature, matter, chemical potential, critical, high, thermal, order, first order
Top quark	quark, top, top quark, mass, decay, bound, standard model, top quark mass, coupling, new physics, lepton, top quarks, standard, chiral quark, physic
Topology	space, dimension, modulus, string, bundle, manifold, vacuum, extra, moduli space, heterotic, torus, instanton, singularity, compact, theory
Yang-Mills models of matter	su, symmetry, fermion, gauge, chiral, mass, model, breaking, coupling, boson, flavor, color, composite, quark, dirac

Table 4: PACS categories most correlated to the topics derived with the unsupervised model. Correlation is measured as the mutual pointwise information (pmi).

topic	PACS category	pmi
Algorithms and calculation techniques	Lattice theory and statistics	1.39
	Lattice gauge theory	1.17
	Lattice QCD calculations	1.12
	Particle correlations and fluctuations	0.99
	Inelastic scattering: many-particle final states	0.80
Amplitude of processes in colliders	Baryon resonances (S=C=B=0)	1.13
	Pion-baryon interactions	1.10
	Meson-meson interactions	1.03
	Nucleon-nucleon interactions	0.93
	Dispersion relations	0.92
Amplitudes and Feynman Diagram	Analytic properties of S matrix	1.66
	Properties of perturbation theory	1.57
	General properties of perturbation theory	1.39
	Dispersion relations	1.04
	Lattice theory and statistics	0.86
Analyses and measurements from colliders	Neutrino-induced reactions	0.96
	Muons	0.89
	Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors	0.81
	Pion-baryon interactions	0.79
	Meson production	0.77
Annihilation and scattering cross-sections	Total cross sections	1.60
	Hadron production in e−e+ interactions	1.23
	Meson production	1.11
	Elastic and Compton scattering	1.07
	Electromagnetic processes and properties	1.03
Astrophysics	Collective flow	1.91
	Hydrodynamic models	1.74
	Particle correlations and fluctuations	1.52
	Relativistic heavy-ion collisions	1.38
	Particle and resonance production	1.35
Black holes	Black holes	2.64

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Table 4: PACS categories most correlated to the topics derived with the unsupervised model. Correlation is measured as the mutual pointwise information (pmi).

topic	PACS category	pmi
	Quantum aspects of black holes, evaporation, thermodynamics	2.59
	Physics of black holes	2.57
	Classical black holes	2.55
	Higher-dimensional black holes, black strings, and related objects	2.38
Boundary conditions/non-locality	Entanglement and quantum nonlocality	1.18
	Theory of quantized fields	0.90
	Foundations of quantum mechanics; measurement theory	0.80
	Conformal field theory, algebraic structures	0.71
	Integrable systems	0.70
CP violating processes	Decays of bottom mesons	1.53
	Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements	1.48
	Bottom mesons (|B|>0)	1.34
	Charge conjugation, parity, time reversal, and other discrete symmetries	1.30
	Decays of bottom mesons	1.19
Chern–Simons	Gauge field theories	1.04
	Magnetic monopoles	1.03
	Canonical formalism, Lagrangians, and variational principles	0.97
	Lagrangian and Hamiltonian approach	0.88
	Noncommutative field theory	0.87
Conformal Field Theory	Conformal field theory, algebraic structures	1.72
	Algebraic methods	1.34
	Nonperturbative techniques; string field theory	1.19
	Lattice theory and statistics	1.15
	M theory	0.99
Cosmological sources	Background radiations	1.86
	Observational cosmology (including Hubble constant, distance scale, cosmological constant, early Universe, etc)	1.55
	Neutrino, muon, pion, and other elementary particles; cosmic rays	1.49
	Dark energy	1.29
	Cosmology	1.21
Cosmology and gravity	Lorentz and Poincaré invariance	1.34
	Loop quantum gravity, quantum geometry, spin foams	1.32
	Axions and other Nambu-Goldstone bosons (Majorons, familons, etc.)	1.30
	Dark energy	1.28
	Quantum cosmology	1.26
Cross-sections in colliders	Total cross sections	1.57
	Inclusive production with identified hadrons	1.43
	Particle and resonance production	1.42
	Production	1.40
	Inclusive production with identified leptons, photons, or other nonhadronic particles	1.36
Dark matter (particles and direct searches)	Dark matter	2.36
	Elementary particle processes	1.94
	Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors	1.40
	Neutrino, muon, pion, and other elementary particles; cosmic rays	1.18
	Supersymmetric partners of known particles	1.15
Dark matter in the universe	Dark matter	1.86
	Dark energy	1.69
	Elementary particle processes	1.44
	Observational cosmology (including Hubble constant, distance scale, cosmological constant, early Universe, etc)	1.36
	Cosmology	1.27
Decay measurements	Decays of charmed mesons	1.93
	Decays of bottom mesons	1.91
	Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements	1.83
	Decays of J/ , Υ, and other quarkonia	1.82
	Bottom mesons (|B|>0)	1.82
Detectors	Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors	1.48
	Muons	0.99
	Ordinary neutrinos	0.98
	Neutrino interactions	0.91
	Solar neutrinos	0.87
Double-beta decay	Baryons	1.20
	Charmed baryons (|C|>0, B=0)	1.08
	Glueball and nonstandard multi-quark/gluon states	1.03
	Bottom baryons (|B|>0)	0.99
	Hadron mass models and calculations	0.97
Early-universe and other cosmological data	Background radiations	1.57
	Dark matter	1.38
	Axions and other Nambu-Goldstone bosons (Majorons, familons, etc.)	1.28
	Neutrino, muon, pion, and other elementary particles; cosmic rays	1.27

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Table 4: PACS categories most correlated to the topics derived with the unsupervised model. Correlation is measured as the mutual pointwise information (pmi).

topic	PACS category	pmi
	Elementary particle processes	1.11
Effective Field Theory	Noncommutative field theory	1.89
	Noncommutative geometry	1.77
	Quantum mechanics	0.85
	Nonlinear or nonlocal theories and models	0.82
	Canonical quantization	0.81
Electromagnetism	Hydrodynamic models	1.45
	Collective flow	1.31
	Electric and magnetic moments	1.16
	Relativistic heavy-ion collisions	1.11
	Relativistic wave equations	1.11
Events in colliders (kinematics)	Limits on production of particles	1.71
	Production	1.60
	Inclusive production with identified leptons, photons, or other nonhadronic particles	1.57
	W bosons	1.53
	Jets in large-Q2 scattering	1.53
Events in colliders (signatures)	Limits on production of particles	1.69
	Jets in large-Q2 scattering	1.56
	Production	1.45
	Inclusive production with identified leptons, photons, or other nonhadronic particles	1.37
	W bosons	1.35
Experimental investigation of the leptonic sector	Limits on production of particles	1.38
	Electromagnetic decays	1.30
	Decays of J/ , Υ, and other quarkonia	1.26
	Decays of J/ , Υ, and other quarkonia	1.19
	Muons	1.18
Experimental jargon	Electromagnetic corrections to strong- and weak-interaction processes	0.35
	Solar neutrinos	0.30
	Electroweak radiative corrections	0.30
	Nucleon-nucleon interactions	0.29
	Neutrino-induced reactions	0.25
Experiments on light	Specific calculations	1.31
	Elastic and Compton scattering	1.26
	Electromagnetic processes and properties	1.09
	Axions and other Nambu-Goldstone bosons (Majorons, familons, etc.)	1.09
	Quantum electrodynamics	1.08
Field theory and gravity	Classical general relativity	1.10
	Modified theories of gravity	1.08
	Lower dimensional models; minisuperspace models	1.06
	Fundamental problems and general formalism	1.05
	Classical black holes	1.02
Flavor mixing	Quark and lepton masses and mixing	1.36
	Flavor symmetries	1.30
	Charge conjugation, parity, time reversal, and other discrete symmetries	1.28
	Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements	1.10
	Neutrino mass and mixing	1.06
Flavour physics	Global symmetries (e.g., baryon number, lepton number)	1.04
	Flavor symmetries	1.03
	Non-standard-model neutrinos, right-handed neutrinos, etc.	1.02
	Unification of couplings; mass relations	1.00
	Quark and lepton masses and mixing	0.99
Form factors	Electromagnetic form factors	1.97
	Relativistic quark model	1.34
	Protons and neutrons	1.33
	Hyperons	1.18
	Sum rules	1.18
Gauge Theory	Gauge field theories	1.20
	Lorentz and Poincaré invariance	1.16
	Canonical formalism, Lagrangians, and variational principles	1.10
	Lagrangian and Hamiltonian approach	1.09
	Noncommutative field theory	1.08
Gauge symmetry breaking/GUTs	Unified theories and models of strong and electroweak interactions	1.34
	Unification of couplings; mass relations	1.26
	Spontaneous breaking of gauge symmetries	1.15
	Unified field theories and models	1.14
	Spontaneous and radiative symmetry breaking	0.96
Gravitons and extra-dimensions	Higher-dimensional gravity and other theories of gravity	1.41
	Gravity in more than four dimensions, Kaluza-Klein theory, unified field theories; alternative theories of gravity	1.39
	Modified theories of gravity	1.34

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Table 4: PACS categories most correlated to the topics derived with the unsupervised model. Correlation is measured as the mutual pointwise information (pmi).

topic	PACS category	pmi
	Lower dimensional models; minisuperspace models	1.08
	String and brane phenomenology	1.04
Hadronic zoo	Decays of J/ , ϒ, and other quarkonia	1.92
	Heavy quarkonia	1.73
	Exotic mesons	1.71
	Decays of J/ , ϒ, and other quarkonia	1.65
	Mesons with S=C=B=0, mass > 2.5 GeV (including quarkonia)	1.58
Heavy quarks and ions	Particle and resonance production	1.40
	Particle correlations and fluctuations	1.39
	Collective flow	1.38
	Relativistic heavy-ion collisions	1.37
	Fragmentation into hadrons	1.29
Higgs beyond the SM	Other neutral Higgs bosons	1.65
	Supersymmetric Higgs bosons	1.64
	Non-standard-model Higgs bosons	1.60
	Extensions of electroweak Higgs sector	1.55
	Standard-model Higgs bosons	1.37
Higgs boson	Other neutral Higgs bosons	1.91
	Supersymmetric Higgs bosons	1.87
	Non-standard-model Higgs bosons	1.77
	Extensions of electroweak Higgs sector	1.73
	Standard-model Higgs bosons	1.69
High-energy source fluxes	Neutrino, muon, pion, and other elementary particles; cosmic rays	1.39
	Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors	1.33
	Solar neutrinos	1.28
	Background radiations	0.89
	Ordinary neutrinos	0.74
Holographic Principle and dualities	Entanglement and quantum nonlocality	1.89
	Gauge/string duality	1.53
	Conformal field theory, algebraic structures	1.43
	Higher-dimensional black holes, black strings, and related objects	1.06
	Quantum aspects of black holes, evaporation, thermodynamics	1.02
Inflation	Particle-theory and field-theory models of the early Universe (including cosmic pancakes, cosmic strings, chaotic phenomena, inflationary universe, etc.)	1.80
	Origin and formation of the Universe	1.78
	Observational cosmology (including Hubble constant, distance scale, cosmological constant, early Universe, etc)	1.76
	Background radiations	1.70
	Quantum cosmology	1.67
Lattice calculation techniques	Lattice QCD calculations	1.38
	Lattice gauge theory	1.36
	Lattice theory and statistics	0.80
	General properties of perturbation theory	0.76
	Renormalization	0.74
Lepton/Meson decay	Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements	1.97
	Decays of charmed mesons	1.94
	Decays of bottom mesons	1.89
	Decays of charmed mesons	1.86
	Bottom mesons (|B|>0)	1.81
Lie algebra	Algebraic methods	1.39
	Integrable systems	1.28
	Geometry, differential geometry, and topology	1.19
	Noncommutative geometry	1.03
	Quantum mechanics	0.94
Loops and next order expansions in Feynman Diagrams	Electromagnetic corrections to strong- and weak-interaction processes	1.32
	Electroweak radiative corrections	1.23
	Specific calculations	1.08
	Summation of perturbation theory	1.00
	General properties of perturbation theory	0.98
M-theory and theories of everything	M theory	1.63
	Supergravity	1.34
	Nonperturbative techniques; string field theory	1.27
	Compactification and four-dimensional models	1.22
	D branes	1.13
Measurements and analysis of colliders data	Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix elements	0.90
	Solar neutrinos	0.87
	Muons	0.84
	Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors	0.75
	Decays of charmed mesons	0.73
Meson phenomenology	Other mesons with S=C=0, mass < 2.5 GeV	1.53

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Table 4: PACS categories most correlated to the topics derived with the unsupervised model. Correlation is measured as the mutual pointwise information (pmi).

topic	PACS category	pmi
	Hadron mass models and calculations	1.48
	Meson-meson interactions	1.45
	Mesons	1.41
	Glueball and nonstandard multi-quark/gluon states	1.37
Neutrino physics	Ordinary neutrinos	2.04
	Solar neutrinos	1.98
	Non-standard-model neutrinos, right-handed neutrinos, etc.	1.97
	Neutrino mass and mixing	1.94
	Neutrino, muon, pion, and other elementary particles; cosmic rays	1.92
Partons distributions	Summation of perturbation theory	1.62
	Factorization	1.49
	Production	1.46
	Jets in large-Q2 scattering	1.44
	Perturbative calculations	1.43
Perturbative QCD	Factorization	1.17
	Summation of perturbation theory	1.10
	Perturbative calculations	1.03
	Production	0.66
	Heavy quark effective theory	0.65
Phenomenologica l jargon	Foundations of quantum mechanics; measurement theory	0.34
	Axions and other Nambu-Goldstone bosons (Majorons, familons, etc.)	0.31
	Loop quantum gravity, quantum geometry, spin foams	0.30
	Experimental tests of gravitational theories	0.29
	Potential models	0.27
QCD	Sum rules	2.24
	Other nonperturbative calculations	1.42
	Bottom baryons (|B|>0)	1.32
	Charmed baryons (|C|>0, B=0)	1.26
	Heavy quark effective theory	1.16
QCD calculation techniques	Gluons	1.29
	General properties of perturbation theory	1.02
	Renormalization	0.96
	General properties of QCD (dynamics, confinement, etc.)	0.94
	Lattice gauge theory	0.89
Quantum Field Theory	Foundations of quantum mechanics; measurement theory	1.32
	Quantum mechanics	1.15
	Algebraic methods	1.06
	Canonical quantization	0.97
	Theory of quantized fields	0.95
Quantum Systems and Equations of motion	Canonical formalism, Lagrangians, and variational principles	1.23
	Magnetic monopoles	1.15
	Lagrangian and Hamiltonian approach	1.11
	Relativistic wave equations	1.04
	Canonical quantization	1.00
Renormalization	Renormalization group evolution of parameters	1.77
	Renormalization	1.46
	General properties of perturbation theory	0.85
	Technicolor models	0.85
	Other nonperturbative techniques	0.81
Scattering of composite particles	Total and inclusive cross sections (including deep-inelastic processes)	1.78
	Photon and charged-lepton interactions with hadrons	1.65
	Elastic and Compton scattering	1.49
	Regge theory, duality, absorptive/optical models	1.35
	Polarization in interactions and scattering	1.32
Search for BSM physics	Muons	1.12
	Decays of K mesons	1.09
	Decays of taus	1.09
	Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors	1.07
	Neutral currents	1.05
Solar neutrinos	Solar neutrinos	2.64
	Ordinary neutrinos	2.30
	Neutrino mass and mixing	2.13
	Non-standard-model neutrinos, right-handed neutrinos, etc.	1.98
	Neutrino, muon, pion, and other elementary particles; cosmic rays	1.89
Space-time geometry and gravity	Exact solutions	1.75
	Classical general relativity	1.57
	Einstein-Maxwell spacetimes, spacetimes with fluids, radiation or classical fields	1.53
	Classical black holes	1.51
	Higher-dimensional black holes, black strings, and related objects	1.51
Spin/angular mo mentum/polariza tion	Polarization in interactions and scattering	1.80

Continued on next page

Table 4: PACS categories most correlated to the topics derived with the unsupervised model. Correlation is measured as the mutual pointwise information (pmi).

topic	PACS category	pmi
	Photon and charged-lepton interactions with hadrons	1.47
	Fragmentation into hadrons	1.41
	Inclusive production with identified hadrons	1.35
	Meson production	1.21
States of matter	Quark deconfinement, quark-gluon plasma production, and phase transitions	1.09
	Finite-temperature field theory	1.08
	Gauge/string duality	1.02
	Lattice theory and statistics	0.90
	Quark matter	0.84
String theory	D branes	1.86
	Magnetic monopoles	1.71
	Nonperturbative techniques; string field theory	1.67
	Extended classical solutions; cosmic strings, domain walls, texture	1.52
	Strings and branes	1.46
Superalgebras and superfields	Integrable systems	1.74
	Algebraic methods	1.23
	Supersymmetry	1.09
	Lattice theory and statistics	1.00
	Conformal field theory, algebraic structures	0.99
Supergravity	M theory	1.62
	Supergravity	1.58
	Compactification and four-dimensional models	1.51
	Nonperturbative techniques; string field theory	1.37
	Geometry, differential geometry, and topology	1.30
Supersymmetric gauge theories	Supersymmetry	1.37
	M theory	1.35
	Supergravity	1.20
	Nonperturbative techniques; string field theory	1.05
	Gauge field theories	1.05
Susy phenomenology and superpartners	Supersymmetric partners of known particles	1.68
	Supersymmetric models	1.35
	Supersymmetric Higgs bosons	1.27
	Unification of couplings; mass relations	0.85
	Non-standard-model Higgs bosons	0.82
Symétrie chirale	Chiral Lagrangians	1.55
	Chiral symmetries	1.54
	Lattice QCD calculations	1.48
	Light quarks	1.30
	Lattice gauge theory	1.21
Systems dynamics and thermodynamics	Hydrodynamic models	1.21
	Theory of quantized fields	0.96
	Foundations of quantum mechanics; measurement theory	0.93
	Entanglement and quantum nonlocality	0.90
	Quark-gluon plasma	0.75
Theoretical jargon	Integrable systems	0.36
	Quantum mechanics	0.36
	Foundations of quantum mechanics; measurement theory	0.33
	Algebraic methods	0.31
	Fundamental problems and general formalism	0.28
Thermodynamics	Quark deconfinement, quark-gluon plasma production, and phase transitions	1.62
	Quark matter	1.61
	Finite-temperature field theory	1.57
	Quark-gluon plasma	1.35
	Other models for strong interactions	1.11
Top quark	Top quarks	1.96
	Neutral currents	1.20
	Limits on production of particles	1.07
	Other neutral Higgs bosons	0.98
	Other gauge bosons	0.97
Topology	Compactification and four-dimensional models	1.40
	Geometry, differential geometry, and topology	1.31
	Nonperturbative techniques; string field theory	1.20
	M theory	1.11
	Strings and branes	1.04
Yang-Mills models of matter	Technicolor models	1.23
	Unified theories and models of strong and electroweak interactions	1.06
	Unification of couplings; mass relations	0.99
	Composite models	0.94
	Spontaneous breaking of gauge symmetries	0.88

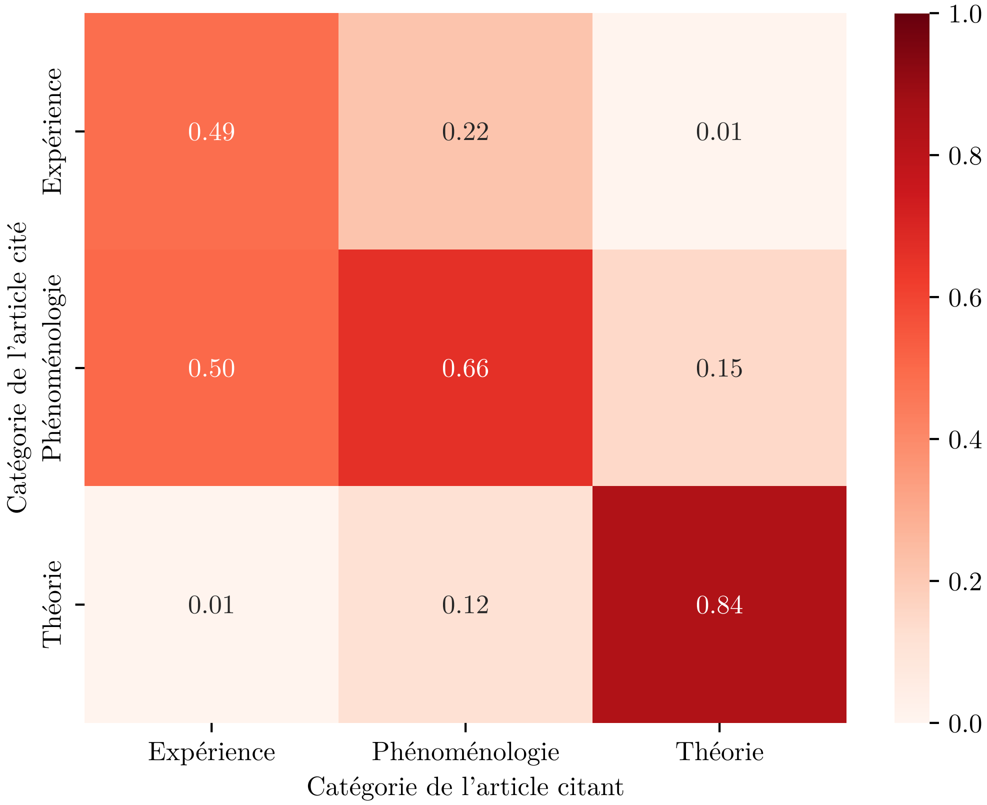

Fig. 9 Origin of the references (citations) in the HEP literature Each matrix element $\tilde{n}_{ij}$ represents the fraction of references from the x-axis category (columns) that target papers from the y-axis category (lines). For instance, 49% of references in experimental papers refer to experimental papers. 22% of citations from phenomenological papers refer to experimental papers. If these categories were completely hermetic, the matrix would equal the identity matrix, which is not the case.

A.3 The centrality of phenomenology in bonding HEP

We build a citation network where each node is one paper of the literature and the edge between nodes x and y is assigned a weight $w_{x,y} = 1$ if x cites y and 0 otherwise. From this we can define the amount of citations of papers from the category i to a paper from the category j as:

$$n_{ij} = \sum_{x \in i, y \in j} \frac{w_{xy}}{(\sum_c \mathbb{1}_c(x))(\sum_c \mathbb{1}_c(y))} \tag{8}$$

Where $\mathbb{1}_c(x) = 1$ if x belongs to $c \in \{\text{Experiment, Phenomenology, Theory}\}$, and 0 otherwise. We then normalize n_{ij} by the amount of citations *from* category i, thus yielding the normalized matrix $\tilde{n}_{ij}$. By construction, $0 \leq \tilde{n}_{ij} \leq 1$ is the effective fraction of references from papers of category i to papers of category j. The matrix is built from the citation network between 2011 and 2019. We then verify that $\tilde{n}_{ii}$ is high (papers mostly cite papers from the same category); and that for cross-culture citations ($i \neq j$), $\tilde{n}_{ij} \ll 1$ unless i or j is "phenomenology"; i.e., "trading zones" in the field occur around phenomenology. Evaluating the fraction of citations from papers of a category i that target papers from a category j yields the matrix in Figure 9. In this matrix, borrowing the trade metaphor from Yan et al. (2013), non-diagonal elements represent "imports" (references to publications from other subcultures) and diagonal elements measure the "self-dependence" of each subculture. The results confirm that most citations occur within categories, emphasizing the relative autonomy of each of these subcultures – except for experimental papers, which are much more scarce then the others, and cannot cite themselves as much. Moreover the results confirm that most trades involve phenomenology: cross-citations between purely theoretical and experimental papers are very rare (∼1% of their references). Overall, "theory" is highly self-reliant.