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研究課題名（和文）Digging deeper into effective field theory

研究課題名（英文）Digging deeper into effective field theory

研究代表者

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研究成果の概要（和文）：本研究により、与えられた対称性のもとでの相対論的有効理論における、相互作用の具体的な構築に関する問題、について最終的な回答が得られた。本成果は、これまでの有効作用研究に存在した空白を埋めるものであり、LHC実験やPre-Lab構築に向け進展しているILC実験における新物理探査にも寄与する。また有効作用研究自身に対し、ハーモニック解析やパワースペクトルの導入を促す等、これまでにない見地も与えた。更に、モンテカルロ積分や暗黒物質の直接探査と非自明な数学的にリンクを持つことも明らかにした。本成果は、高インパクトな査読付き雑誌や、国内外の研究会における招待講演を通じ周知徹底された。

研究成果の学術的意義や社会的意義
本研究は、有効理論の系統的な構築手法を提供するものであり、加速器実験における新物理探査や暗黒物質の直接探査等、多数の高エネルギー物理学における将来研究に寄与する。また同時に、高エネルギー物理において既に確立し広く使用されるパラダイムに新しい視点（ハーモニック解析）を導入するものでもある。本研究の社会的意義に関しては、宇宙に関する根本的な問題に関して更なる深い理解を与えるとともに、新しい加速器実験等の大型プロジェクトの科学的意義の議論に重要なインプットを与えるものでもある。

研究成果の概要（英文）：This project conclusively and systematically solved the problem of constructing operator bases in effective field theories. Namely, it provided a concrete recipe to construct the operator basis of a relativistic effective field theory, given its symmetries. It has filled a significant gap in the literature, and has application in theoretical aspects of the search for new physics at the Large Hadron Collider, and at future colliders, such as the International Linear Collider that is currently in Pre-Lab stage. The project also provided an unanticipated new viewpoint on effective field theory itself, introducing the language of harmonics and power spectra to the paradigm. Unanticipated mathematical links to Monte Carlo integration techniques, and to dark matter direct detection were also uncovered. The research was disseminated in publications in high-impact, peer reviewed international journals, and through invited talks at international and domestic conferences.

研究分野：Theoretical particle physics

キーワード：Effective field theory

１．研究開始当初の背景

Effective field theory (EFT) is a powerful and universal framework in which physics beyond the standard model of particle physics can be searched for. It has an ability to 'parameterize the unknown', and this makes its use mandatory at the Large Hadron Collider, where not only direct (production of new particles) but indirect signs (quantum 'whispers' of new particles) of new physics must be searched for. EFT is relevant for the latter approach, and has become an approach of paramount importance given the absence of direct signs of new physics.

Historically, the electroweak force of nature was discovered in this indirect EFT way, via its effect in beta decay. The physics is captured by an operator in the EFT of nucleons, electrons and neutrinos, and decades passed before the W and Z bosons that mediate the force were directly produced at a collider.

At the LHC, the list of particles in the EFT is simply the list of all known standard model particles. This 'standard model EFT' is of crucial important for the indirect search for new physics, as per the W, Z boson example given above. However, EFT is also invaluable in direct searches for dark matter, supersymmetric particles etc. at the LHC. Such particles are simply added to the input particle list to the EFT, and the catch-all nature of EFT gives predictions for all experimental avenues in which such particles might be observed, as is necessary to test the new theoretical model at hand.

However, the EFTs relevant for the LHC are much more complicated than the EFT relevant for beta decay, often involving hundreds of phenomenological relevant operators. The route from a given theoretical model to its EFT, and its experimental consequences, has been obscured by a lack of systematic understanding of what is essentially a coordinate system— a basis — for an EFT.

The reasons for this is that not all operators are independent—giving rise to overlapping physical effects—due to redundancies between operators called equation of motion (EOM) and integration by parts (IBP) relations. These relations have been notoriously tricky to deal with; simply counting the number of independent operators in e.g. the standard model EFT had a tumultuous history stretching for 1986 to 2016.

The key motivation for applying for this research proposal was to introduce and develop new techniques to systematically account for these relations between operators when constructing an EFT. That is, to conclusively solve the EFT construction problem in high energy physics, enabling e.g. better interpretations and understanding of LHC data, in the search for new physics.

２．研究の目的

The objective of the research project was to obtain a step-by-step recipe for constructing a phenomenologically relevant basis of independent operations in an EFT Lagrangian for theoretical models where particle internal symmetries (e.g. colour, isospin, etc) are linearly realised in the Lagrangian. The standard model is in this class, as are many extensions that include dark matter, etc.; their EFTs all share features that rendered the broad treatment appropriate.

This objective was aimed at removing an existing obstacle in relating a beyond-the-standard model theory of nature to experiment. The automatic construction of an EFT, together with a clear understanding of the EFT basis, was lacking the literature.

The research was also aimed at facilitating explorations away from the very lowest-lying operators in the minimal 'standard model only' EFT, where some such operators have been shown to be important at the LHC.

The proposal also had an original aspect in that in order to achieve the above objective, the underlying mathematical structure of EFT would be studied, particularly with an eye to clarifying how EOM and IBP act on the full operator basis (collection of all operators) in the EFT.

３．研究の方法

The method was to focus on a large class of relativistic theories with linearly realised internal symmetries. This is because in this case, a special operator basis could be chosen: a basis of what are called conformal primary operators. The method taken was to study the operator basis through the lens of the action of the conformal group.

In particular, it was proposed to construct the special basis of conformal primaries in a systematic manner using the annihilation properties of the special conformal generator. A simple numerical algorithm was planned to be developed. Regarding internal symmetries (colour, weak charge, etc), the method was to note that these considerations factorize from the conformal aspects of the problem; the internal symmetries can then be studied via standard group theory techniques.

Another key methodology that was proposed was to utilize objects called Hilbert series. These are all-order generating functions that enumerate (not construct) the operator basis of an EFT. The study of all-order properties of these objects can reveal structure about the basic building blocks of an EFT, i.e. generators, and how relations between generators are encoded.

As well as utilizing known properties of Hilbert series, another key method to achieve the object was to develop this mathematical technology for use in EFT construction. This would look for recursive properties and analytic (pole) structure of Hilbert series corresponding to 'toy' EFTs.

The method was to study all of the above in the simplest toy EFT cases, that do not correspond to real-world theories, but where the structure and technical aspects can be developed most transparently. Then, the method was to extend this to real-world theories involving multiple types of particle, including those with spin.

４．研究成果

The goal of the project was achieved, namely the problem of constructing operators in general relativistic EFTs (with linearly realised internal symmetry) was successfully elucidated. A concrete recipe to construct the operator basis of a relativistic EFT, given its symmetries as input, was provided. This filled the gap in the literature that existed at the outset of the project.

The method of studying EFTs thorough their underlying structure proved to be very successful. Indeed, more mathematical structure was uncovered than was anticipated. Specifically, it identified a new application of a mathematical duality - Howe duality - in physics. This relied on the identification of a 'physical manifold' upon which all observables in a quantum field theory have to live. This manifold is termed a Stiefel manifold.

The method of using the annihilation properties of the special conformal generator to construct primary operators for an EFT basis is given a new perspective through this underlying mathematical structure. The generator can be identified with a generalized Laplacian on the Stiefel manifold, such that the primary operators can be identified as harmonics of the manifold. In other words, constructing an EFT is a form of harmonic analysis, and one can talk of 'the power spectrum of the standard model' in a precise mathematical sense. This new way of looking at EFT is completely novel, and arose out of the particular methodology that was taken in this research project.

Unexpected results arose in the course of this research project, in the form of previously unidentified connections to Monte Carlo phase space generation. In fact, the Stiefel manifold is closely related to the Grassmann manifold. Using coordinates of a particular chart on the Grassmannian led to a particularly simple and unconstrained parameterisation of particle momenta on Lorentz invariant phase space. This is a particularly useful parameterisation when integrating over this phase space using Monte Carlo methods to obtain high precision predictions for LHC collisions. Technically, the singular (infra-red divergent) pieces of the calculation take a very simple form in the Grassmannian parameterisation.

While a connection to the study of dark matter at colliders was anticipated (via its inclusion into an EFT), another unexpected connection was discovered in the course of the research project. This was the realisation that the use of EFT is crucial in the description of the interaction of light dark matter (with mass well below that of a proton) with a dark matter detector material (e.g. a crystal). The point here is that the detector itself must be described by an EFT, because the de Broglie wavelength of the dark matter becomes larger than interatomic spacing, and thus individual atoms are not resolved. Thus one needs to construct a EFT to obtain reliable theoretical predictions of scattering rates. The techniques and methodology used in this project can be developed for application here too.

The above insights and results were disseminated in peer reviewed, high-impact international journals, and through invited talks at international and domestic conferences.

Particularly promising future research prospects include the application of the methods of EFT construction to the light dark matter detection, and to Monte Carlo calculations of high precision predictions of Large Hadron Collider events, described above. Other directions are to deepen the understanding of the Howe duality structure that was uncovered, and to further connections to the conformal field theory literature that were uncovered, especially with an eye to moving beyond the construction of a basis of an EFT towards the study of the dynamics of the theory.

5．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　4件／うち国際共著　3件／うちオープンアクセス　0件）

1．著者名	4．巻
Henning Brian、Melia Tom	100
2．論文標題	5．発行年
Constructing effective field theories via their harmonics	2019年
3．雑誌名	6．最初と最後の頁
Physical Review D	16015
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1103/PhysRevD.100.016015	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

1．著者名	4．巻
Cox Peter、Melia Tom、Rajendran Surjeet	100
2．論文標題	5．発行年
Dark matter phonon coupling	2019年
3．雑誌名	6．最初と最後の頁
Physical Review D	55011
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1103/PhysRevD.100.055011	有
オープンアクセス	国際共著
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1．著者名	4．巻
Campbell-Deem Brian、Cox Peter、Knapen Simon、Lin Tongyan、Melia Tom	101
2．論文標題	5．発行年
Multiphonon excitations from dark matter scattering in crystals	2020年
3．雑誌名	6．最初と最後の頁
Physical Review D	36006
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1103/PhysRevD.101.036006	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	該当する

1．著者名	4．巻
Cox Peter、Melia Tom	2018
2．論文標題	5．発行年
Independently parameterised momenta variables and Monte Carlo IR subtraction	2018年
3．雑誌名	6．最初と最後の頁
Journal of High Energy Physics	1
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.1007/JHEP12(2018)038	有
オープンアクセス	国際共著
オープンアクセスではない、又はオープンアクセスが困難	－

〔学会発表〕　計5件（うち招待講演　5件／うち国際学会　2件）

1．発表者名 Tom Melia
2．発表標題 Axion searches in heavy-ion collisions
3．学会等名 KAIST-KIAX workshop for future particle accelerators（招待講演）
4．発表年 2019年

1．発表者名 Tom Melia
2．発表標題 Probing the sub-MeV window in dark matter direct detection
3．学会等名 TAUP 2019（招待講演）
4．発表年 2019年

1．発表者名 Tom Melia
2．発表標題 The role of the conformal group in the SM EFT
3．学会等名 In search of new physics using SMEFT, Argonne National Lab, USA（招待講演）
4．発表年 2019年

1．発表者名 Tom Melia
2．発表標題 Pretty phase space for Monte Carlo IR subtraction
3．学会等名 High time for higher orders, at MITP Mainz, Germany（招待講演）（国際学会）
4．発表年 2018年

１．発表者名 Tom Melia
２．発表標題 Lovely phase space for good vibrations
３．学会等名 PRL 60th Anniversary（招待講演）（国際学会）
４．発表年 2018年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
米国	UC Berkeley	Johns Hopkins	Yale University	
スイス	University of Geneva			