ERC Starting Grant 2014
Research proposal [Part B1]

Strategic Predictions for Quantum Field Theories

preQFT

Cover Page:
- John Joseph Carrasco
- CEA-Saclay
- 60 months

Ambitious Questions:

- How does the relatively calm macroscopic universe survive and emerge from the violent quantum fluctuations of its underlying microphysics?
- How do classical notions of space and time emerge from fundamental principles, and what governs their evolution?

These questions are difficult to answer—perhaps impossible given current ideas and frameworks—but I believe a strategic path forward is to thoroughly understand the quantum predictions of our Yang-Mills and Gravity theories, and unambiguously identify their non-perturbative completions. The first step forward, and the goal of this project, is to move towards the trivialization of perturbative calculations.

Consider the notion of *failure-point calculations* – calculations that push modern methods and world-class technologies to their breaking-point. Such calculations, for their very success, engender the chance of cultivating and exploiting previously unappreciated structure. In doing so, such calculations advance the state of the art forward to some degree, dependent on the class of the problems and nature of the solution. With amplitude calculations, we battle against (naive) combinatorial complexity as we go either higher in order of quantum correction (*loop order*), or higher in number of external particles scattering (*multiplicity*), so our advances must be revolutionary to lift us forward. Yet I and others have shown that the very complications of generalized gauge freedom promise a potential salvation at least as powerful as the complications that confront us. The potential reward is enormous, a rewriting of perturbative quantum field theory to make these principles manifest and calculation natural, an ambitious but now realistic goal. The path forward is optimized through strategic calculations.

Section a: *Extended Synopsis of the scientific proposal (max. 5 pages)*

The state of the art in Standard-Model scattering calculations involving the gluonic sector is at the first quantum correction to semi-classical predictions, and these calculations can be horrendously complicated. String theory has the promise to be a full (UV-complete) theory of quantum gravity, yet with traditional methods we can hardly calculate more than a handful of the first quantum corrections in the $\alpha' \to 0$ (point-like) limit for anything but the most (super)-symmetric non-trivial theories. Yet when we do manage to arrive at a prediction – pushing through the complex intermediary steps – we find simplicity. On-shell methods, some pioneered by me with collaborators (see e.g. [1] and refs. therein), have cracked open the higher-loop (higher-order in quantum corrections) barrier in the most supersymmetric theories, demonstrating a richer universal *algorithmic* structure than we ever expected – independent of supersymmetry – and tantalizing us with the possibility of rewriting QFT to make this structure manifest. So this is my goal: I aim to solve the prediction problem in Yang-Mills and Gravity theories, learning from explicit calculation how to tease out the structure we know they possess, and ultimately to identify the mathematical language most conducive to discovering — through analytic derivation — the implications of their underlying principles. This program will require and engender new techniques, new ideas, and new principles.

I will save motivating the particular value of supergravity calculations, and the exciting possibility of perturbative finiteness for $\mathcal{N} > 5$ supergravities, until the full scientific proposal where I have room to set the stage. Here I will rely on the innate appeal of solid clarifying calculations in relevant theories on the edge of being tractable. The work I propose here is quite-literally groundbreaking. I propose to carry out calculations that nobody has ever attempted in gauge or gravity theories – calculations that many believed were absolutely impossible, until the recent multi-loop amplitudes revolution, of which I have been a key player. Yet these very calculations promise to teach us about fundamental principles hidden in our most foundational theories.

Technical Simplicity but Universal Structure. Besides the improved UV behavior, many of the calculations I discuss involve supersymmetry because the associated technical simplicity allows the faster collection of data with less effort. The goal is to find universal structure independent of supersymmetry. The pattern is to identify properties first in maximally supersymmetric theories, then consider theories with less supersymmetry or none (cf. [2]).

Empirical Relevance. Many of these ideas resonate and have direct application in the understanding of Yang-Mills theory for which, through QCD-scale experiment, and soon optical simulations, we have a wealth of data available. Indeed a valuable benefit of this line of investigation is the furthering development of calculational techniques crucial to predicting the background processes relevant to new-physics discoveries at the LHC and next-generation colliders. Furthermore, approaches developed in carrying out and analyzing these perturbative calculations have direct applicability to generic perturbative solutions to non-linear equations of motion. One particularly exciting example, which I mention below, and discuss at length in the fuller proposal, is in the calculation of multi-point correlation functions in the Effective Field Theory of Large Scale Structure – relevant to decoding the primordial signals of the early universe. Although it is too early (and too close to the submission of this proposal) to comment carefully and at length on the recently observed B-mode graviton signals from BICEP II, one thing is clear. Upon verification of these B-mode observations, theoretic understanding for the implication of this data, through explicit graviton calculations, will be of tremendous significance.

Computational Advances = Conceptual Advances. Even though this work is analytic, I must, at key times, employ vast computational resources for symbolic manipulation. I intend to push the envelop of such activity with this proposal, which is why I am requesting non-trivial computational resources. This program can be discussed in terms of analytic

"Big Data," requiring innovation in managing and extracting the critical physical information awash in a sea of generated expressions.

To set the scales, consider that the tree-amplitude describing m gluons scattering is encoded by $(2m-5)!!$ cubic (trivalent) graphs which represent the various potential routings of momentum and color. A 14 particle tree amplitude has 3.16×10^9 graphs. Yet I have shown that one needs only $(m-3)! \sim 4 \times 10^7$ gauge-invariant expressions [3] (known as color-stripped or color ordered partial amplitudes). Why 14-particle interactions? Because it is relevant, via only self-sewing, to the four-particle five-loop correction – a key for understanding the ultraviolet behavior of the $\mathcal{N}=8$ supergravity theory, as I will discuss below. But intriguingly we find that $\mathcal{N}=4$ super Yang-Mills, needs only ~ 500 graph topologies [4] for five-loops. This represents a compression of relevant information spanning 7 orders of magnitude, and 9 if the duality I discuss below can be made manifest. This is exactly the understanding we need to achieve to solve gauge and gravity quantum field theories. To find the representation for the gravity theory involving either order 10^2 or order 1 graphs, however, will require the ability to sift through the data encoded at least by the 500-graph depiction of the gauge theory, if not the 4×10^7 graph representation.

The success of this project will be not only new understanding of the language of relativistic quantum scattering but also in the development of tools to handle large-scale analytic data, aiding researchers in identifying meaningful patterns. The goal, of course, is to extract from this data the correct reformulation obviating the need for such gymnastics. I will describe an important discovery below which sets the stage, but whose story has arguably only just begun.

Gravity from Gauge Theory: Color/Kinematics and Double-copy. I, along with collaborators Z. Bern and H. Johansson, discovered [3] it was possible to extract gravity information from gauge theory amplitudes in a very direct way when organized around certain graphs in a particularly constrained form. The relevant mathematical language is cubic (trivalent) graphs whose vertices, for gauge theories, dually represent the conservation of momentum as well as color. The constrained gauge theory representation (color-dual or BCJ representation) is one where the kinematic weights of contributing graphs manifest Jacobi identities and vertex antisymmetry just as the color factors of the graphs. We refer to this as manifesting a duality or correspondence between color and kinematics. When the gauge theory amplitude is so organized, gravity amplitudes are generated trivially by taking a double copy of the Yang-Mills kinematic factor. Schematically,

$$\text{YM} \propto \sum_{g \in \text{graphs}} \frac{n(g)c(g)}{p(g)} \Rightarrow \text{GR} \propto \sum_{g \in \text{graphs}} \frac{n(g)\tilde{n}(g)}{p(g)},$$

where $n(g)$ are the kinematic numerator factors, $c(g)$ are the color factors, $p(g)$ are the propagators of the graphs given as for a scalar ϕ^3 theory, and $\tilde{n}(g)$ is simply another copy of the Yang-Mills kinematic factor. Quite literally gravitons behave like gluons whose perturbative gauge-group structure-constants are the kinematics of gluons. When the numerators are expressed in terms of color-ordered amplitudes, the venerable and previously mysterious KLT[1] relations naturally emerge.

But unlike the KLT relations, which only exist between classical (tree-level) amplitudes, this relationship between kinematic numerators in gauge and gravity theories generalizes seamlessly to quantum (loop-level) corrections at the integrand level. We have verified this double-copy structure explicitly through four-loops at four-point and through three-loops at five-point in the maximally supersymmetric theory. Furthermore, it is possible to confirm these relationships through a variety of lower-loop calculations in less supersymmetric theories – including pure Yang-Mills, demonstrating its generality beyond constraints of supersymmetry.

[1] Kawai, Lewellen, and Tye demonstrated [5] in 1985 that gluon amplitudes encode all the information necessary to generate graviton amplitudes at tree level.

In fact, a recent paper by Oxburgh and White has argued that to all-loop orders the relevant IR behavior of pure Yang-Mills can be put in a color-kinematic satisfying representation finding that the double-copy matches the well-known IR behavior of Einstein-Gravity.

Revolutionizing calculation using hidden structure. An important consequence is that these relationships between kinematic factors have revolutionized the manner in which we now can calculate finite-color non-planar multi-loop scattering amplitudes in Yang-Mills. One might think, based upon Feynman graph techniques, that going to higher-loop orders would be a losing proposition: the number of graph-topologies increases factorially with loop order. The discovered algebraic structure between graph numerators, however, drastically changes this landscape, rigidly locking the exploding number of graphs at higher-loops to the correct expression of a small number of master graphs. Through all known full multi-loop scattering amplitudes in the maximally supersymmetric theory only one non-vanishing graph needs be specified at each order. The differences between the maximally supersymmetric theories and the pure QCD Yang-Mills contribution can be projected onto the nature and behavior of this finite number of master-numerators [2].

As an immediate tree-level consequence of the color-kinematic duality discussed above, we found new constraining relations between color-ordered scattering amplitudes that have been used to clarify and prove various representations of the earlier discovered tree-level KLT relations. Generalizations have since been found in open string theory and used to arrive at closed-form expressions for stringy KLT, as well as incredibly fascinating all-multiplicity expressions for open string amplitudes as products of "motivic MZV amplitudes" that contain the all-order α' information with field-theory amplitudes (see e.g. [6], and refs. therein).

The computational upshot of all of this is that state of the art calculations of only a few years ago, such as three-loop four-point scattering amplitudes in the maximally supersymmetric theory, can now be done on a blackboard. We can now envision using our vast developed computational expertise to explore higher loops and greater multiplicity than previously imagined as well as attack theories with less supersymmetry – along the way answering certain open questions that have intrigued the community for years. The collection of such data will indeed be valuable, but not simply as an end in and of itself. There are still many mysteries.

When difficulty strikes. At present, the only way we know how to establish a loop-level color-kinematic dual form is by solving functional relations. Of necessity this involves positing an ansatz, elucidating functional constraints, and solving the *exact* relations constrained by symmetries and data (ala unitarity cuts) from the theory under consideration. If the manifest representation is insufficiently close to previous results (via say non-locality, or novel momenta routing) establishing the correct ansatz requires imagination, computational power (to test ideas), and perseverance.

More structure awaits! Benefiting from the affable form generated by color-kinematic satisfying integrand solutions, through explicit calculation and integration, we have discovered a fascinating pattern in the integrated UV divergences of the maximally supersymmetric gauge and gravity theories. In the critical dimension (the dimension in which the theory divergences at a given loop level), the subleading-in-color divergence of the gauge theory is exactly the divergence of the gravity theory. This has been verified through four-loops [7]. Obviously, if such a pattern persists to all loop-orders, the maximally supersymmetric gravity theory would be finite.

While obviously related to the ability for the gauge theory to take on a color-dual kinematic representation, this hints at a structure beyond color-kinematics. Color-kinematics operates at the integrand level for local representations. This is clearly a non-local phenomena that involves cancellations between multiple channels post-integration. What is the non-local analogue to local color-kinematics? This is an entirely open question.

Concrete strategic questions. My program is not a vague one of musing upon "big ideas." Rather it is to follow strategic tractable questions, synthesize the results, and identify the principles they encode. To emphasize this point I list a few such concrete strategic questions, all of which have definite research problems from entirely open-ended, to those suitable for directed novices.

(1) *Loop-level recursion for non-planar theories.* We know through generalized unitarity methods that tree-level data encodes all necessary information (modulo counter terms) for all-loop order quantization. We know how to access this data algorithmically using cut-construction: the systematic building of off-shell expressions for loop-level amplitudes at the integrand level. Promoting this to analytic loop-level recursion would in principle allow all-loop order consideration through analysis of tree-level data.

(2) *The ultraviolet behavior of $\mathcal{N} = 8$ supergravity in four-dimensions.* It is an open question as to how the classical and quantum symmetries of maximally supersymmetric supergravity conspire so as to regulate the high-energy behavior. Are they strong enough to ensure all-order perturbative finiteness? There is mounting evidence that the double-copy structure the gravity theory may be responsible, at least in part, for some of the cancellations observed. A concrete calculation is the D-dimensional full five-loop four-point amplitude. This confronts the first (surviving) prediction of a deviation from the UV behavior of $\mathcal{N} = 4$ super-Yang-Mills related to a possible seven loop divergence in four dimensions.

(3) *Non-local representations for gauge and gravity theories.* It is clear that if maximally supersymmetric supergravity theory is to make manifest the same UV behavior of the maximally supersymmetric gauge theory at five-loops it can only happen in a non-local representation [8, 4]. A first step towards making this concrete would be to find a non-local integrand representation at three-loops that makes manifest the relationship between the subleasing color but leading UV gauge contribution and the leading UV gravity contribution discussed in the **More structure awaits!** section above.

(4) *The ultraviolet behavior of $\mathcal{N} > 4$ supergravity in four dimensions.* The observed UV cancellations in $\mathcal{N} = 8$ supergravity have had many conjectured explanations. There is clear evidence that the $U(1)$ anomaly I clarified [9] with Kallosh, Roiban, and Tseytlin is responsible for the 4-loop divergence [10] in $\mathcal{N} = 4$ supergravity. Such anomalies are not present in the duality groups of higher supergravity theories. Calculating four-dimensional UV behavior of $\mathcal{N} = 5$ supergravity at five-loops is a sharp probe, and should establish predictions for all higher supergravities.

(5) *The nature of the kinematic-structure constants underlying the color-dual satisfying representations.* We have complete understanding in the very limited case of self-duality. Solution of these theories arguably rests on understanding this more generally. Calculations of additional classical gauge solutions in the color-dual framework, solutions that double-copy to classical solutions of gravity theories, would be an excellent probe towards identifying the relevant gauge choices. Among the most exciting classical solutions would be to identify the gauge theory solutions that generate black-hole solutions via double-copy. See e.g. [11] for a double-copied classical shockwave solution.

(6) *The generalization of color-kinematics duality to the Standard-Model.* The imposition of color-kinematics is a fantastically efficient tool for rewriting pure-glue calculations and those theories related by supersymmetry to a minimum number of graphs. But for non-supersymmetric fermions, even in the adjoint representation, with more than one flavor, there are immediate problems related to generalizing the $(n-3)!$ BCJ relations even at tree-level. A natural first step would be the parameterization of the dependence on supersymmetric coupling constants for flavors related by supersymmetry, and to break supersymmetry by varying the coupling constant, while generating a continuation of the color-kinematic relations. This should generate persistent gauge ambiguity in the double-copied expression – the key will be identifying the appropriate gauge-fixing strategy through explicit calculation with predictions from the target gravity

theory. An intriguing alternative, but longer-range, is to understand the relationship of arbitrary non-supersymmetric flavor amplitudes in unitarity state-sums as decomposed into constituent SUSY flavor scattering amplitudes as described at tree-level in ref. [12].

(7) *Applications to real-world data.* While my drive is primarily formal theory, I find that it is important and clarifying to stay grounded to calculations that at least have the potential to touch real data. Some of these can be shorter service projects to assist phenomenological colleagues. Others can be ones where I have more of a long-term vested interest like cosmological large scale structure [13]. In any case, S-matrix techniques can be applied far and wide to effective theories that touch or have the near-term ability to touch real data of significant consequence. Obviously QCD is one such theory, as already demonstrated by my collaborators who have developed the Blackhat collaboration, as well as theories of inflation and phenomenological quantum gravity so as to extract the maximal amount of information from the recently observed CMB B-mode polarization signals of primordial gravitons. More surprisingly, perhaps, calculating multiple-point correlation functions in classical stochastic field theories are another [13] – and one quite relevant for extracting significant information for precision cosmology. I discuss this further in the detailed proposal of B2.

References

[1] **J. J. M. Carrasco** and H. Johansson, "Generic multiloop methods and application to $\mathcal{N} = 4$ super-Yang-Mills," J. Phys. A **44** (2011) 454004 [arXiv:1103.3298 [hep-th]].

[2] **J. J. M. Carrasco**, M. Chiodaroli, M. Gnaydin and R. Roiban, "One-loop four-point amplitudes in pure and matter-coupled $\mathcal{N} \leq 4$ supergravity," JHEP **1303** (2013) 056 [arXiv:1212.1146 [hep-th]].

[3] Z. Bern, **J. J. M. Carrasco** and H. Johansson, "New Relations for Gauge-Theory Amplitudes," Phys. Rev. D **78** (2008) 085011 [arXiv:0805.3993 [hep-ph]]. Z. Bern, **J. J. M. Carrasco** and H. Johansson, "Perturbative Quantum Gravity as a Double Copy of Gauge Theory," Phys. Rev. Lett. **105** (2010) 061602 [arXiv:1004.0476 [hep-th]].

[4] Z. Bern, **J. J. M. Carrasco**, H. Johansson and R. Roiban, "The Five-Loop Four-Point Amplitude of $\mathcal{N} = 4$ super-Yang-Mills Theory," Phys. Rev. Lett. **109** (2012) 241602 [arXiv:1207.6666 [hep-th]].

[5] H. Kawai, D. C. Lewellen and S. H. H. Tye, "A Relation Between Tree Amplitudes of Closed and Open Strings," Nucl. Phys. B **269** (1986) 1.

[6] J. Broedel, O. Schlotterer and S. Stieberger, "Polylogarithms, Multiple Zeta Values and Superstring Amplitudes," Fortsch. Phys. **61** (2013) 812 [arXiv:1304.7267 [hep-th]].

[7] Z. Bern, **J. J. M. Carrasco**, L. J. Dixon, H. Johansson and R. Roiban, "Simplifying Multiloop Integrands and Ultraviolet Divergences of Gauge Theory and Gravity Amplitudes," Phys. Rev. D **85** (2012) 105014 [arXiv:1201.5366 [hep-th]].

[8] Z. Bern, **J. J. M. Carrasco**, H. Johansson and D. A. Kosower, "Maximally supersymmetric planar Yang-Mills amplitudes at five loops," Phys. Rev. D **76** (2007) 125020 [arXiv:0705.1864 [hep-th]].

[9] **J. J. M. Carrasco**, R. Kallosh, R. Roiban and A. A. Tseytlin, "On the U(1) duality anomaly and the S-matrix of $\mathcal{N} = 4$ supergravity," JHEP **1307** (2013) 029 [arXiv:1303.6219 [hep-th]].

[10] Z. Bern, S. Davies, T. Dennen, A. V. Smirnov and V. A. Smirnov, "The Ultraviolet Properties of N=4 Supergravity at Four Loops," Phys. Rev. Lett. **111** (2013) 231302 [arXiv:1309.2498 [hep-th]].

[11] R. Saotome and R. Akhoury, "Relationship Between Gravity and Gauge Scattering in the High Energy Limit," JHEP **1301** (2013) 123 [JHEP **1301** (2013) 123] [arXiv:1210.8111 [hep-th]].

[12] T. Melia, "Getting more flavour out of one-flavour QCD," arXiv:1312.0599 [hep-ph].

[13] **J. J. M. Carrasco**, M. P. Hertzberg and L. Senatore, "The Effective Field Theory of Cosmological Large Scale Structures," JHEP **1209** (2012) 082 [arXiv:1206.2926 [astro-ph.CO]]. **J. J. M. Carrasco**, S. Foreman, D. Green and L. Senatore, "The 2-loop matter power spectrum and the IR-safe integrand," arXiv:1304.4946 [astro-ph.CO]. **J. J. M. Carrasco**, S. Foreman, D. Green and L. Senatore, "The Effective Field Theory of Large Scale Structures at Two Loops," arXiv:1310.0464 [astro-ph.CO].

Section b: Curriculum vitae (max. 2 pages)

PERSONAL INFORMATION

Carrasco, John Joseph
Researcher unique identifier(s): 0000-0002-4499-8488 (ORCID-ID)
J.J.M.Carrasco.1 (InspireHEP)
Date of birth: 19-11-1975
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- EDUCATION

2010 Ph.D., Department of Physics, University of California at Los Angeles, USA
2007 Masters, Department of Physics, University of California at Los Angeles, USA
2005 Bachelors of Science, Department of Physics, Caltech, USA

- CURRENT POSITION

2012 – *current* Research Associate (Academic Research Staff)
Stanford Institute for Theoretical Physics & Department of Physics, Stanford University, USA

- PREVIOUS POSITIONS

2010 – 2012 Postdoctoral Scholar
Stanford Institute for Theoretical Physics & Department of Physics, Stanford University, USA
2002–2004 Research Scientist & Founding Member of Overture Research/Yahoo! Labs[2].
1998–2002 Engineer, Overture Services/Goto.com.
1997 Developer, Jobtrak Corporation.

- FELLOWSHIPS AND AWARDS

2012–2015 John F. Templeton Grant, Co-leader with Renata Kallosh, $\$ 600,000$.
2010–2013 Stanford Institute for Theoretical Physics, Postdoctoral Research Fellow.
2007–2010 Guy Weyl Physics Graduate Research Fellowship, UCLA.

- SUPERVISION OF GRADUATE STUDENTS AND POSTDOCTORAL FELLOWS

2012–*current* Co-supervision of 1 Ph.D. Student
Stanford Institute for Theoretical Physics & Department of Physics, Stanford University, USA

- TEACHING ACTIVITIES

2014 TASI 2014, 3 × 90 minute lectures, Journeys through the Precision Frontier: Amplitudes for Colliders, *(Upcoming)*.
2012 2012 Arnold Sommerfeld School, 4 × 90 minute lectures, New Methods for Field Theory Amplitudes, Sep 2012.
2007 Teaching Associate, Electrodynamics II, UCLA. Prof. Vladimir Vassiliev (Ph 110b)
2007 Teaching Associate, Optics & Lasers, UCLA. Prof. Kumar Patel (Ph 108)
2007 Teaching Associate, Acoustics & Fluids, UCLA. Prof. Seth Putterman (Ph 114)
2006 Teaching Assistant, Electrodynamics II, UCLA. Prof. James Rosenzweig (Ph 110b)
2006 Teaching Assistant, Electrodynamics I, UCLA. Prof. James Rosenzweig (Ph 110a)

[2]Part-time after 1/04 while attending Caltech.

• ORGANISATION OF SCIENTIFIC MEETINGS

Co-organizer: Amplitudes, looking towards the future, SITP, March 2013, JTF grant funded, USA.

Organizer: Color-kinematics, Loops $\ldots\infty$?, SITP, Feb 2011, SITP funded, USA.

• INSTITUTIONAL RESPONSIBILITIES (if applicable)

2014 - *current* Organizer of the Theory Seminar, SITP, Stanford, USA.

2012 - 2013 Organizer of Postdoctoral Offices, SITP, Stanford, USA.

Appendix: All ongoing and submitted grants and funding of the PI (Funding ID)

Mandatory information *(does not count towards page limits)*

On-going Grants

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*
Quantum Gravity Frontiers	John Templeton Foundation	433558	09/2012 - 09/2015(*)	Co-Pi with Renata Kallosh. This funds my current salary and visitor program. Responsible for quarterly project reports, and biannual budget reports.	Precursor to ERC proposal – sets the stage.

(*) My funding through JTF will end when I cease employment at Stanford and join CEA-Saclay on 01/2015 if I am awarded this ERC grant. The non-perturbative aspects of that grant may remain active at Stanford without my being funded.

Applications

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*

Section c: Early achievements track-record (max. 2 pages)

h-index: 19, total-citations: 1542, avg-citations/paper: 53.2
(according to `inspirehep.net` as of 24 March 2014)

All citation counts below *without* self-citations by any author.

- 10 PUBLICATIONS WITHOUT ADVISOR (without Zvi Bern)
  (1) **[41 cites.]** J. J. Carrasco and H. Johansson, "Five-Point Amplitudes in N=4 Super-Yang-Mills Theory and N=8 Supergravity," Phys. Rev. D **85** (2012) 025006 [arXiv:1106.4711 [hep-th]].
  (2) **[32 cites.]** J. J. M. Carrasco and H. Johansson, "Generic multiloop methods and application to N=4 super-Yang-Mills," J. Phys. A **44** (2011) 454004 [arXiv:1103.3298 [hep-th]].
  (3) **[24 cites.]** J. J. M. Carrasco, M. P. Hertzberg and L. Senatore, "The Effective Field Theory of Cosmological Large Scale Structures," JHEP **1209** (2012) 082 [arXiv:1206.2926 [astro-ph.CO]].
  (4) **[16 cites.]** J. J. M. Carrasco, M. Chiodaroli, M. Gunaydin and R. Roiban, "One-loop four-point amplitudes in pure and matter-coupled N $\leq$ 4 supergravity," JHEP **1303** (2013) 056 [arXiv:1212.1146 [hep-th]].
  (5) **[12 cites.]** J. Broedel and J. J. M. Carrasco, "Virtuous Trees at Five and Six Points for Yang-Mills and Gravity," Phys. Rev. D **84** (2011) 085009 [arXiv:1107.4802 [hep-th]].
  (6) **[11 cites.]** J. J. M. Carrasco, R. Kallosh and R. Roiban, "Covariant procedures for perturbative non-linear deformation of duality-invariant theories," Phys. Rev. D **85** (2012) 025007 [arXiv:1108.4390 [hep-th]].
  (7) **[6 cites.]** J. J. M. Carrasco, R. Kallosh, R. Roiban and A. A. Tseytlin, "On the U(1) duality anomaly and the S-matrix of N=4 supergravity," JHEP **1307** (2013) 029 [arXiv:1303.6219 [hep-th]].
  (8) **[5 cites.]** J. Broedel, J. J. M. Carrasco, S. Ferrara, R. Kallosh and R. Roiban, "N=2 Supersymmetry and U(1)-Duality," Phys. Rev. D **85** (2012) 125036 [arXiv:1202.0014 [hep-th]].
  (9) **[5 cites.]** J. J. M. Carrasco, W. Chemissany and R. Kallosh, "Journeys Through Antigravity?," JHEP **1401** (2014) 130 [arXiv:1311.3671 [hep-th]].
  (10) **[5 cites.]** J. J. M. Carrasco, S. Foreman, D. Green and L. Senatore, "The Effective Field Theory of Large Scale Structures at Two Loops," Submitted to JCAP. arXiv:1310.0464 [astro-ph.CO].

- 5 TOP-CITED PUBLICATIONS
  (1) **[187 cites.]** Z. Bern, J. J. M. Carrasco and H. Johansson, "New Relations for Gauge-Theory Amplitudes," Phys. Rev. D **78** (2008) 085011 [arXiv:0805.3993 [hep-ph]].
  (2) **[140 cites.]** Z. Bern, J. J. Carrasco, L. J. Dixon, H. Johansson, D. A. Kosower and R. Roiban, "Three-Loop Superfiniteness of N=8 Supergravity," Phys. Rev. Lett. **98** (2007) 161303 [hep-th/0702112].
  (3) **[115 cites.]** Z. Bern, J. J. Carrasco, L. J. Dixon, H. Johansson and R. Roiban, "The Ultraviolet Behavior of N=8 Supergravity at Four Loops," Phys. Rev. Lett. **103** (2009) 081301 [arXiv:0905.2326 [hep-th]].
  (4) **[106 cites.]** Z. Bern, J. J. M. Carrasco, H. Johansson and D. A. Kosower, "Maximally supersymmetric planar Yang-Mills amplitudes at five loops," Phys. Rev. D **76** (2007) 125020 [arXiv:0705.1864 [hep-th]].
  (5) **[100 cites.]** Z. Bern, J. J. M. Carrasco and H. Johansson, "Perturbative Quantum Gravity as a Double Copy of Gauge Theory," Phys. Rev. Lett. **105** (2010) 061602 [arXiv:1004.0476 [hep-th]].

- PATENTS
  (1) Disambiguation of Search Queries (US Patent No. 7 225 184)
  (2) System and method for rapid completion of data processing tasks distributed on a network (US Patent No. 6 775 831)

- INVITED LECTURES AT SCHOOLS:
  (1) TASI 2014, 3×90 minute lectures, Journeys through the Precision Frontier: Amplitudes for Colliders, June 2014. (UPCOMING)
  (2) 2012 Arnold Sommerfeld School, 4×90 minute lectures, New Methods for Field Theory Amplitudes, Sep 2012.

- SELECTED INVITED PRESENTATIONS AT INTERNATIONAL CONFERENCES:
  (1) The Geometry and Physics of Scattering Amplitudes, SCGP/Stonybrook, December 2013.
  (2) Strings, Amplitudes, and Branes, CERN Theory Institute, July 2013.
  (3) AMPLITUDES 2013, Max-Planck-Institut fur Physik, April 2013.
  (4) STRINGS 2012, Plenary Overview Talk (1 hr), LMU-Munich, Aug 2012.
  (5) Strings, Gauge Theory, and the LHC, Niels Bohr International Academy, Aug 2011.
  (6) The Harmony of Scattering Amplitudes, KITP, April 2011.
  (7) AMPLITUDES 2010, QMU, May 2010.
  (8) Hidden Structures in Field Theory Amplitudes 2009, Niels Bohr International Academy, Aug 2009.

- RECENT HONORS/AWARDS
  (1) John F. Templeton Grant, Co-leader with Renata Kallosh, $600,000 to be awarded over three years (2012-2015).
  (2) Julian S. Schwinger Named Diploma, Erice International School of Subnuclear Physics (2011).
  (3) Best Theoretical Physics Prize, Erice International School of Subnuclear Physics (2011).
  (4) Stanford Institute for Theoretical Physics, Postdoctoral Research Scholar Fellowship (2010-2013).
  (5) Guy Weyl UCLA Physics Graduate Fellowship (2007-2010).
  (6) John S. Bell Named Diploma, Erice International School of Subnuclear Physics (2008).
  (7) Best [open] Question Prize [3], Erice International School of Subnuclear Physics (2008).

[3] re: economy of physical descriptions, c.f. the amount of information encoded in real numbers.