Science Meeting – Scientific Report

The scientific report (WORD or PDF file - maximum of seven A4 pages) should be submitted online <u>within two months of the event</u>. It will be published on the ESF website.

<u>Proposal Title</u>: eNLarge Horizons

<u>Application Reference N°</u>: 5829

1)   Summary (up to one page)

The international research program entitled "NLarge Horizons" took place at the IFT UAM/CSIC between May 18 and June 5, 2015. During this period, 74 international experts on the field of large-N Yang Mills theories had the opportunity to interact, exchange ideas and present recent work, culminating with a focused workshop between June 1 and June 5.

The so-called large-N approximation in gauge theories is a classic problem in quantum field theory which has generated an astonishing amount of work since its original proposal in the 70's by Gerard 't Hooft. The reason may be found in the fact that it offers one of the few known routes to connect the fundamental short-distance degrees of freedom of QCD (quarks and gluons) to the long-distance degrees of freedom, such as confining strings and hadrons. In particular, the connection to string theory via the AdS/CFT correspondence has brought new perspectives into the field and catalysed connections with many other methodologies.

The meeting was articulated with the purpose of fostering discussion among participants, which were encouraged to stay for at least one week and participate actively in informal exchanges. The daily sessions contained typically one introductory talk by a leading expert, together with other related contributions by other experts on that particular topic, so that each day could be considered as focused on a particular area of research. This modus operandi was applied successfully during the first two weeks of the program, leading to approximately 20 presentations on all topical areas covered by the workshop. The last week consisted on a more standard workshop with 26 presentations of recent results by leading experts on the field.

2)   Description of the scientific content of and discussions at the event (up to four pages)

Essentially all of the main areas of research were covered by international experts in attendance. Having said that, discussions at the meeting were dominated by five broad topics: holography, resurgence, reduction, numerical methods and phenomenology. All of them were covered in devoted discussion sessions during the first two weeks of the workshop consisting in an overview presentation by a leading expert in each topic followed by short presentations and discussions. All participants attending the first two weeks of the workshop were provided office space at the IFT premises and active discussion in smaller groups and collaboration meetings took place during the spare time.

The status of holographic methods applied gauge dynamics was broadly reviewed in sessions led by N. Evans and C. Nuñez. Discussion focused on the dichotomy between top-down and bottom-up methods, namely the systematics involved in trying to deform the well-defined N=4 SYM model towards QCD, versus the semi-phenomenological approach where dual geometries are guessed on the basis of symmetries and universality hypothesis, in analogy to common practice in effective field theory.

A discussion session led by K. Zarembo dealt with the recent confluence of large-N methods, holography, and localisation techniques in exact evaluations of suitable BPS quantities in supersymmetric theories. It turns out that these techniques dovetail nicely with another focus point of the conference: the so-called "resurgence program". Resurgence refers to the virtuous use of generalised notions of Borel summability to capture a hierarchical series of non-perturbative corrections in a massive generalisation of the instanton expansion. G. Dunne led a session which focused on new developments in this program, which was also amply discussed at various talks in the final-week workshop. State-of-the-art analysis of quantum mechanical systems, two-dimensional sigma models and moduli spaces of supersymmetric models were presented, with ample discussion of possible generalisations to less "integrable" situations.

Another major topic of discussion at the meeting was the phenomenon of large-N reduction in its various incarnations, from the reduced matrix models of the Eguchi-Kawai type, to questions of volume independence in certain physical quantities pertaining to fully fledged quantum field theories. There was extensive consideration of twisted Eguchi-Kawai models, a topic discussed by M. Okawa, A. Gonzalez-Arroyo and many other experts, where the latest evidence for the numerical stability of these large-N models was presented. A. Cherman presented a new analysis of the small-volume expansion of twisted partition functions of gauge theories on spheres, showing further evidence for volume independence in the large-N limit.

An important justification for the study of the large-N limit comes from its phenomenological underpinnings. Since the early days of the subject, the broad brush picture of hadron phenomenology which follows effortlessly from large-N power counting, is regarded as a major source of motivation for the whole large-N program. Together with a presentation of recent numerical analysis of confining strings (M. Teper) and thermodynamics (M. Caselle), the more phenomenological issues were addressed by T. Cohen, F. Llanes-Estrada and J. Pelaez, ranging from the subtle question of how

"exotics" can be accommodated in the large-N expansion, to an spirited defence of the discovery of the "sigma meson".

In addition to these major areas of discussion, the workshop served to bring into focus many other topics in the general realm of quantum field theory, such as generalised solitonic strings in supersymmetric theories (M. Shifman), attempts at a riguorous lattice definition of conformal field theories (H. Neuberger), exact results on renormalization-group flows (A. Schwimmer), large-N equivalences (L. Yaffe and A. Armoni), and more. A general purpose colloquium on "The chiral magnetic effect: from quark-gluon plasma to Dirac semimetals" by D. Kharzeev was also organised as one of the workshop activities.

## 3)	Assessment of the results and impact of the event on the future directions of the field (up to two pages)

Despite remaining as a famous open problem for the original case of physical QCD, "large N" has grown into an autonomous field with a vigorous rate of development ranging from numerical approaches to mathematical physics and hadronic phenomenology. The connection to other areas of physics was strengthened by the discovery of the AdS/CFT correspondence, and the field continues to show strength of development. This was made manifest in the success of this workshop, where many experts from different cultures within the broad area of quantum field theory enjoyed a fruitful intellectual exchange. This was particularly fostered by the format of the first two weeks of the workshop that led to active discussion and scientific exchange and cross-fertilisation between different fields. The last week of the workshop with the format of a more standard conference gathered some of the most prominent actors in the field and offered a complete perspective of the present directions of research in this topic and of the new paths being explored.

The program has served its purpose as a diagnostic of the status quo in this field. Ideas and techniques like the twisted Eguchi-Kawai models were shown to be alive and well, becoming efficient numerical tools with potential phenomenological impact, while new developments, such as the resurgence program, promise to continue making a significant dent into the remaining open problems, leading to new insights into the general structure of path integrals.

In the long run, the goal of the large-N method could be encoded by the slogan "mastering the master field", a colloquial term for the infinite-dimensional gauge field configuration which becomes a classical saddle point in the strict large N limit. While we are still far from such a goal, especially for the physical case of QCD, the continuous flux of surprising structures emerging out of good old quantum field theory suggest that such an object should eventually come within our grasp. The AdS/CFT correspondence in its more precise form (maximally supersymmetric Yang-Mills theory) serves as a target for numerical analysis and mathematical physics alike. It provides us with the most explicit example of a true "master field" in four dimensions, in the form of an infinite set of predictions, to be checked by "ab initio" calculations, either numerically or using the most advanced analytical arsenal in the form of localisation and resurgence theory. The participants of this workshop, which represented a good portion of all the world-experts working on the subject, agreed that the research program is well-posed, and the situation is ripe for further insights to come and make a qualitative impact on the field.

4)   Annexes 4a) and 4b): Programme of the meeting and full list of speakers and participants

Annex 4a: Programme of the meeting

Talks can be found at http://workshops.ift.uam-csic.es/NLHIFT/program

Week 1 - May 18-22

	Tuesday	Wednesday	Thursday	Friday
Morning	**10:00** Coffee **10:30** Session on AdS/QCD **N. Evans** *Holographic QCD - Why does it work? What's it good for?*			**11:30** Coffee **12:00** Colloquium **D. Kharzeev** *The chiral magnetic effect: from quark-gluon plasma to Dirac semimetals*
Afternoon	**15:00** Session on Localization and Holography **K. Zarembo** *Localization at large N and holography* + contribution by **N. Drukker** *Localization in Matrix models*	**15:00** Session on large N phenomenology **T. Cohen** *Exotics and Universality in QCD(AS)* + contribution by **F. Llanes Estrada** *Non-ordinary light meson coupling and the 1/N expansion*	**15:00** Session on large N strings **M. Shifman** *Non-Abelian strings: Large–N solution of the world-sheet theories*	**15:00** Session on large N equivalences **L Yaffe** *Large N limits: old questions and new puzzles*

Week 2 - May 25-29

	Tuesday	Wednesday	Thursday	Friday
Morning	**10:00** Coffee **10:30** Session on Holography **C. Nuñez** *Aspects of Gauge Strings Duality* + contribution by **R. Yaresko** *Holographic Modelling of SU(N) Yang-Mills and QCD Equations of State and Bulk Viscosity*	**10:00** Coffee **10:30** Session on Resurgence **G. Dunne** *Resurgence, Trans-series and Non-perturbative Physics* + contribution by **M. Spalinski** *Hydrodynamics Beyond the Gradient Expansion: Resurgence and Resummation*	**10:00** Coffee **10:30** Session on Reduction **A. González-Arroyo** *Meson masses at large N from twisted reduction* + contributions by **P. Buividovich** *Diagrammatic Monte-Carlo algorithms for large-N quantum field theories from Schwinger-Dyson equations* **M. Koren** *x-scaling in 2+1 dimensional SU(N) gauge theories with twisted b.c.* **A. Ramos** *Dimensional reduction in large N gauge theories*	**10:00** Session **11:00** Coffee **11:30** Session on QFT **A. Schwimmer** *Review of Constraints on Renormalization Group Flows* **&** **H. Neuberger** *Lattice Methods for Euclidean Conformal Field Theory*

Week 3 - June 1-5

Monday, June 1 - Chairs: Y. Makeenko / M. García Pérez

Time	Speaker	Title
9:45 - 10:00	Welcome	
10:00 - 11:00	G. Dunne	Uniform Resurgence and Large N
11:00 - 11:30	Coffee	
11:30 - 12:30	M. Unsal	Analytic continuation of path integrals and new exact saddles
12:30 - 13:00	M. Anber	Thermal phase transitions in pure Yang-Mills via supersymmetry for all gauge groups
13:00 - 15:00	Lunch	
15:00 - 16:00	A. Pineda	Phenomenology of renormalons and the OPE from lattice regularization: the gluon condensate and the heavy quark pole mass
16:00 - 16:30	Coffee	
16:30 - 17:30	M. Caselle	Hagedorn spectrum and thermodynamics of SU(N) Yang-Mills theories.
17:30 - 18:00	R. Pourhasan	Holographic Renyi entropy for Lovelock theory

Tuesday June 2 - Chairs: A. Schwimmer / R. Narayanan

Time	Speaker	Title
10:00 - 11:00	E. Poppitz	Strings from domain walls in SYM and QCD(adj)
11:00 - 11:30	Coffee	
11:30 - 12:30	P. Orland	Exact Correlator at Large-N at Large and Small Distances
12:30 - 13:00	L. Jonke	Dynamical and Quenched Random Matrices and Homolumo Gap
13:00 - 15:00	Lunch	
15:00 - 16:00	M. Okawa	Recent results in twisted reduced models
16:00 - 16:30	Coffee	
16:30 - 17:30	A. Cherman	Emergent symmetries in large N gauge theories
17:30 - 18:00	A. Chatzistavrakidis	The SO(d,d) matrix model
18:00 - 18:30	A. Misra	Non-Kaehler Resolved Warped Deformed Conifolds and Black M3-Branes in a Large-N Limit

Wednesday, June 3 - Chairs: M. Panero / C. Hoyos

Time	Speaker	Title
10:00 - 11:00	M. Teper	The spectrum of confining flux tubes: lattice calculations and theoretical interpretation
11:00 - 11:30	Coffee	
11:30 - 12:30	B. Lucini	The spectrum of Large-N gauge theories
12:30 - 13:00	N. S. Karthik	Phase of the fermion determinant using Wilson fermions
13:00 - 15:00	Lunch	
15:00 - 16:00	S. Sugimoto	Holographic study of 3 dim YM-CS theory with defects
16:00 - 16:30	Coffee	
16:30 - 17:30	S. Bolognesi	Solitons, Large N and Holography
17:30 - 18:00	H. Steinacker	Squashed fuzzy extra dimensions from coadjoint orbits in N=4 SYM with large rank

Thursday, June 4 - Chairs: J.L. Barbón

Time	Speaker	Title
10:05 - 11:05	A. Armoni	The Quark Condensate in Multi-Flavour QCD - Planar Equivalence Confronting Lattice Simulations
11:05 - 11:35	Coffee	
11:35 - 12:35	J. R. Peláez	Light scalars as non-ordinary mesons from their Nc behavior
12:35 - 13:05	V. Filev	Testing AdS/CFT with flavours on a computer
13:05	Lunch - catering	

Friday, June 5 - Chairs: A. Armoni / H. Neuberger

Time	Speaker	Title
11:00 - 11:30	Coffee	
11:30 - 12:30	R. Yacoby	On 3d Bosonization from Supersymmetry
12:30 - 13:00	H. Soltanpanahi	Nonequilibrium dynamics in nonconformal plasma
13:00 - 15:00	Lunch	
15:00 - 16:00	M. Bochicchio	An asymptotic solution of large-N QCD, and of large-N n=1 SUSY YM
16:00 - 16:30	Coffee	
16:30 - 17:30	S.- J. Rey	Planar Limits, Newton's Constants, and AdS/CFT Interpolation

Annex 4b: Full list of speakers and participants

List of Speakers

1. Dr. Mohamed Anber, Ecole Polytechnique Federal de Lausanne, (CH)
2. Prof. Adi Armoni, Swansea University, (UK)
3. Prof. Marco Bochicchio, INFN Rome1, (IT)
4. Prof. Stefano Bolognesi, Universitá di Pisa, (IT)
5. Dr. Pavel Buividovich, Regensburg University, (DE)
6. Prof. Michele Caselle, Dipartimento di Fisica Università di Torino, (IT)
7. Dr. Athanasios Chatzistavrakidis, Leibniz University Hannover, (DE)
8. Dr. Aleksey Cherman, University of Minnesota, Minneapolis, (US)
9. Prof. Thomas Cohen, University of Maryland, (US)
10. Dr. Nadav Drukker, King's College London, (UK)
11. Prof. Gerald Dunne, University of Connecticut, (US)
12. Prof. Nicholas Evans, University of Southampton, (UK)
13. Dr. Veselin Filev, Dublin Institute for Advanced Studies, (IE)
14. Dr. Larisa Jonke, Rudjer Boskovic Institute, Zagreb, (HR)
15. Dr. Nikhil S. Karthik, Florida International University, (US)
16. Prof. Dmitri Kharzeev, Stony Brook University and BNL, (US)
17. Dr. Mateusz Koren, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
18. Prof. Felipe Llanes-Estrada, Universidad Complutense de Madrid, (ES)
19. Prof. Biagio Lucini, Swansea University, (UK)
20. Prof. Aalok Misra, Indian Institute of Technology Roorkee, (IN)
21. Prof. Rajamani Narayanan, Florida International University, (US)
22. Prof. Herbert Neuberger, Rutgers University, (US)
23. Prof. Carlos Nunez, Swansea University, (UK)
24. Prof. Masanori Okawa, Hiroshima University, (JP)
25. Prof. Peter Orland, Baruch College of the City U of New York, (US)
26. Prof. Jose Pelaez, Universidad Complutense de Madrid, (ES)
27. Prof. Antonio Pineda, Universitat Autonoma de Barcelona, Barcelona, (ES)
28. Prof. Eric Poppitz, University of Toronto, (CA)
29. Dr. Razieh Pourhasan, University of Iceland, (IS)
30. Prof. Soo-Jong Rey, Seoul National University, (KR)
31. Prof. Adam Schwimmer, Weizmann Institute, (IL)
32. Prof. Mikhail Shifman, Minnesota University, (US)
33. Dr. Hesam Soltanpanahi, Jagiellonian University, Krakow, (PL)
34. Prof. Michal Spalinski, National Centre for Nuclear Research, Warszawa, (PL)
35. Dr. Harold Steinacker, University of Vienna, (AT)

36. Prof. Shigeki Sugimoto, Yukawa Institute, Kyoto, (JP)
37. Prof. Michael Teper, University of Oxford, (UK)
38. Prof. Mithat Unsal, North Carolina State University, (US)
39. Dr. Ran Yacoby, Princeton University, (US)
40. Prof. Laurence Yaffe, Washington University (Seattle), (US)
41. Mr. Roman Yaresko, Helmholtz-Zentrum Dresden-Rossendorf, (DE)
42. Prof.Konstantin Zarembo, Nordita, (SE)

List of Participants

1. Prof. Jose F. Barbon, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
2. Dr. Paolo Benincasa, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
3. Mr. Marco Cè, Scuola Normale Superiore, Pisa, (IT)
4. Dr. Eduardo Follana, Universidad de Zaragoza, (ES)
5. Dr. Patrick Fritzsch, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
6. Prof. Juan Garcia-Bellido, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
7. Mr. Guillermo Garcia-Fernandez, Universidad Complutense de Madrid, (ES)
8. Prof. Margarita Garcia-Perez, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
9. Mr. Miguel Garcia-Vera, DESY Zeuthen, (DE)
10. Prof. Antonio Gonzalez-Arroyo, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
11. Mr. Jesus Guerrero-Rojas, Universidad Complutense de Madrid, (ES)
12. Dr. Gregorio Herdoíza, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
13. Dr. Rafael Hernández, Universidad Complutense de Madrid, (ES)
14. Dr. Carlos Hoyos, Universidad de Oviedo, (ES)
15. Mr. Eduardo Ibanez-Bribian, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
16. Dr. Liam Keegan, CERN, Geneva, (CH)
17. Prof. Christian Korthals Altes, Centre de Physique Theorique, Marseille, (FR)
18. Prof. Karl Landsteiner, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
19. Prof. Yuri Makeenko, ITEP&NBI, Copenhagen, (DK)
20. Mr. Pablo Martin-Ramiro, DESY Zeuthen, (DE)
21. Prof. Denjoe O'Connor, Dublin Institute for Advanced Studies, (IE)
22. Prof. Marco Panero, Dipartimento di Fisica Università di Torino, (IT)
23. Prof. Carlos Pena, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
24. Mr. Victor Perez-Fernandez, Universidad Complutense de Madrid, (ES)
25. Prof. Carmelo Perez-Martin, Universidad Complutense de Madrid, (ES)
26. Dr. Alberto Ramos, CERN, Geneva, (CH)
27. Prof. Agustin Sabio-Vera, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
28. Dr. Juan Jose Sanz-Cillero, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)

29. Mr. Ali Teimouri, Lancaster University, (UK)
30. Prof. Angel Uranga, Instituto de Física Teórica UAM-CSIC, Madrid, (ES)
31. Mr. Davide Vadacchino, Università degli Studi di Torino - INFN Torino, (IT)
32. Mr. Semen Valgushev, Regensburg University, (DE)