Bridging analytical and numerical methods for quantum field theory

Monday 25 August 2025 - Friday 29 August 2025

ECT*

Book of Abstracts

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Effective string theory on a torus: the 3d Ising interface

Authors: José Matos[1]; João Penedones[1]; João Viana[2]; David Lima[None]

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We use effective string theory (EST) to describe a toroidal 2d interface embedded in a 3d torus.
In particular, we compute the free energy of the interface in an expansion in inverse powers of the area, up to the first non-universal order that involves the Wilson coefficient γ_3.

In order to test our predictions, we simulate the 3d Ising model with an anti-periodic boundary condition with a two-step multicanonical algorithm that delivers high-precision free-energy data.

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Flux Tubes and Confinement in Lattice QCD

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We present lattice QCD measurements of the field strength tensor and current distributions generated by a static quark–antiquark pair. We perform measurements on smeared Monte Carlo QCD configurations with (2+1) HISQ dynamical flavors with pion mass 140 MeV. Results are discussed both at zero temperature and at finite temperature below and above the chiral transition.

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Stochastic Normalizing Flows for lattice gauge theory and defects

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In recent years, flow-based samplers have emerged as a promising alternative to traditional sampling methods in lattice field theory. In this talk, I will introduce a class of flow-based samplers known as Stochastic Normalizing Flows (SNFs), which combine neural networks with non-equilibrium Monte Carlo algorithms. I will then show that SNFs exhibit excellent scaling with volume in lattice SU(3) gauge theory. Afterward, I will focus on gauge theories with defects and outline a general strategy for applying flow-based samplers to these systems. In particular, I will present an application

to SU(3) gauge theory with open boundary conditions, broadening the scope of modern sampling techniques.

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Casimir effect in critical O(N) models with non-equilibrium methods

Authors: Alessando Nada[None]; Andrea Bulgarelli[1]; Marco Panero[None]; Michele Caselle[None]

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Lattice systems, when tuned to criticality, exhibit long-range fluctuations that are sensitive to the geometry in which they are confined. The critical Casimir amplitude encodes universal information on this behavior, and it is part of the CFT data at finite temperature. Predicting this quantity in models with O(N) symmetry would have a broad range of applications, from high-energy physics to condensed matter, but so far different calculations have yielded conflicting results. Using a new numerical technique, we push the theoretical predictions to a range of parameters never studied before, revealing a non-trivial dependence on the number of spin components, N, and comparing our results to bootstrap calculations.

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The Mass of the Baryon Junction: a lattice computation in $2 + 1$ dimensions

Authors: Dario Panfalone[1]; Lorenzo Verzichelli[2]; Michele Caselle[1]; Nicodemo Magnoli[3]

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We present a systematic study of baryonic flux tubes in $\mathrm{SU}(3)$ Yang–Mills theory in $(2 + 1)$ dimensions. A recent next-to-leading–order derivation within the Effective String Theory framework has, for the first time, made explicit the corrections proportional to the baryon–junction mass M, up to order $1/R^2$ (where R is the length of the confining strings), opening the possibility of its non-perturbative determination. Through high-precision simulations of the three-point Polyakov-loop correlator, we measure the baryon–junction mass. By isolating the predicted $1/R^2$ term in the open-string channel, we obtain the value $\frac{M}{\sqrt{\sigma}} = 0.1355(36)$, similar to the phenomenological value which is used to describe hadrons. In addition, studying the high temperature behaviour of the baryon, we present a new test of the Svetitsky–Yaffe conjecture for the $\mathrm{SU}(3)$) theory in three dimensions. Focusing on the high-temperature regime just below the deconfinement transition, we compare our lattice results for Polyakov-loop correlators with the quantitative predictions obtained by applying conformal perturbation theory to the three-state Potts model in two dimensions, and find excellent agreement.

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The spectrum of open confining strings in the large-N_c limit

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We present a comprehensive study of the spectrum of the open confining string (open flux tube) in 3+1 dimensions for several $\mathrm{SU}(N_c)$ gauge groups, with a focus on the large-N_c limit and the possible emergence of world-sheet axion states. Specifically, we analyze the excitation spectra of flux tubes formed between static quark-antiquark pairs for $N_c = 3, 4, 5$, and 6. Our study includes a detailed analysis of a wide range of radial excitations and eight irreducible representations, classified by the angular momentum quantum number Λ, charge conjugation and parity η_{CP}, and the reflection symmetry ϵ for $\Lambda = 0$. To extract the spectrum, we employ an anisotropic lattice action, smearing techniques, a diverse basis of operators, and solve the generalized eigenvalue problem. We compare our results to the predictions of the Nambu–Goto string model to identify potential discrepancies that may signal new physical phenomena. Notably, we observe clear evidence for a massive axion-like excitation on the world-sheet, with a mass matching that of the axion previously identified in the closed flux-tube spectrum. This strongly supports the conjecture that the axion is an intrinsic world-sheet excitation of the QCD string.

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Intrinsic width of the flux tube in 2+1 dimensional Yang-Mills theories

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We study the profile of the flux tube in non-Abelian gauge theories in the confined phase in 2+1 dimensions, by means of precise lattice numerical simulations. We observe a non-Gaussian profile with prominent exponentially decaying tails. From the characteristic decay length length, we extract the intrinsic width of the flux tube. We compute this scale at different values of the temperature in the confined phase.
At low temperature, the profile of the flux tube is well described by the Clem formula, which has been originally proposed in the context of dual superconductivity models. We compare the value of the intrinsic width extracted from fits assuming the Clem formula with the mass gap of the gauge theory and with the critical distance of the Effective String Theory.
At high temperature, on the other hand, it is possible to predict the profile of the flux tube assuming the Svetitsky-Yaffe mapping. We test this prediction against the numerical data, finding a very good agreement, also in the numerical value of the intrinsic width.

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Peculiar phase transitions in three dimensional gauge systems

Author: Claudio Bonati[1]

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We summarize the results obtained from lattice simulations for some peculiar continuous phase transitions of three dimensional gauge systems with scalar matter. In several cases these models display continuous phase transitions whose critical behavior can not be described by a gauge invariant phi^4

effective field theory. The case in which gauge degrees of freedom develop long range correlations is probably the simplest one in which this happens, but theories with discrete gauge groups offers further possibilities. While introducing the topic we will comment on its possible relevance for the nonperturbative definition of three dimensional gauge QFTs and for finite temperature transitions of 4d gauge theories (e.g. the chiral transition).

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Spontaneously Broken Non-Invertible Symmetries in Transverse-Field Ising Qudit Chains

Author: Sergej Moroz[1]

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Recent developments have revealed that symmetries need not form a group, but instead can be non-invertible. Here we use analytical arguments and numerical evidence to illuminate how spontaneous symmetry breaking of a non-invertible symmetry is similar yet distinct from ordinary symmetry breaking. We consider one-dimensional chains of group-valued qudits, whose local Hilbert space is spanned by elements of a finite group G (reducing to ordinary qubits when $G = Z_2$). We construct Ising-type transverse-field Hamiltonians with Rep(G) symmetry whose generators multiply according to the tensor product of irreducible representations (irreps) of the group G. For non-Abelian G, the symmetry is non-invertible. In the symmetry broken phase there is one ground state per irrep on a closed chain. The symmetry breaking can be detected by local order parameters but, unlike the invertible case, different ground states have distinct entanglement patterns. We show that for each irrep of dimension greater than one the corresponding ground state exhibits string order, entanglement spectrum degeneracies, and has gapless edge modes on an open chain – features usually associated with symmetry-protected topological order. Consequently, domain wall excitations behave as one-dimensional non-Abelian anyons with non-trivial internal Hilbert spaces and fusion rules. Our work identifies properties of non-invertible symmetry breaking that existing quantum hardware can probe.

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A new method for measuring high spin glueball states on the lattice

Author: Kieran Twaites[1]

Co-author: Mike Teper [1]

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To test the hypothesis that glueballs lie on the pomeron trajectory, accurate theoretical calculations for the masses of high spin glueball states are required. Current methods have been used to determine glueball masses in $D = 2 + 1$ up to $J = 8$ (arXiv:1909.07430), but these calculations quickly become cumbersome for very high spins. We present a new method, which builds operators by calculating staggered fermion lattice propagators. We look at some preliminary results for masses of low spin glueball states in $2 + 1D$ $U(1)$ and $SU(2)$ theories using the new method, and present the progress made so far in applying this method to high spin states.

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Center-vortex semiclassics on R2xT2 and large-N adiabatic continuity

Author: Yuya Tanizaki[1]

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When the 4d $SU(N)$ Yang-Mills theory is put on $\mathbb{R}^2 \times T^2$ with a nontrivial 't Hooft flux, qualitative features of confinement can be semiclassically described as the gas of center-vortex fractional instantons. We study the condition for the large-N adiabatic continuity via a suitable choice of the N-dependent 't Hooft flux from the viewpoint of both 0-form and 1-form center symmetry.

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Effective strings in QED_3

Author: Ofer Aharony[1]

Co-authors: Netanel Barel ; Tal Sheaffer

[1] *Weizmann Institute of Science*

Corresponding Author: ofer.aharony@weizmann.ac.il

In this blackboard talk I will review the formalism of effective string theory and its generic predictions, and why it breaks down in theories like QED_3 (in UV completions that lead to confinement), for which the mass gap is well below the scale of the confining string tension. A similar breakdown appears for solitonic strings. I will then describe an alternative method to perform computations in such theories, and the results for some properties of strings in QED_3 that differ from standard effective string theory. Based on 2412.01313 written in collaboration with Barel and Sheaffer.

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D-branes in large N gauge theories

Author: Davide Gaiotto[1]

[1] *Perimeter Institute*

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I will describe the potential role of D-branes in the characterization of the String Theories dual to a given gauge theory. I will discuss examples in 2d CFTs, Chern-Simons theory and vector models, as well as potential targets for numerical simulation.

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The Nielsen-Ninomiya theorem versus bosonization

Authors: Aleksey Cherman[1]; Maria Neuzil[1]; Shi Chen[1]

[1] *University of Minnesota*

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I'll discuss how the Nielsen-Ninomiya no-go theorem fits with recent bosonization-inspired lattice discretizations that preserve exact continuous chiral and vector symmetry.

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Emergent termalisation in the Schwinger model

Author: Adrien Florio[1]

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The Schwinger model is a confining theory in one plus one dimensions theory that has a chiral condensate and a chiral anomaly. I will present tensor network simulations of its real-time dynamics. In particular, I will discuss how the system appears to thermalise when subjected to a inhonomogeneous quench reminiscent of the production of hard particles in a QCD jet. I will characterise this approach to equilibrium through the lens of local observables and the rearrangement of entanglement in the system.

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Non-perturbative physics of (1+1)d gauge theories using symmetric matrix product states

We introduce a novel matrix product operator construction for Hamiltonian lattice gauge theories in $(1+1)$ dimensions. This framework enables the study of strongly coupled phenomena such as bound states, string tension, and vacuum structure. We demonstrate the effectiveness of our method by applying it to the massive Schwinger model and adjoint QCD_2

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The simplicity of confinement

Motivated by recent literature on the possible existence of a second higher-temperature phase transition in Quantum Chromodynamics (QCD), I revisit the proposal that colour confinement is related to the dynamics of magnetic monopoles using methods derived from Topological Data Analysis, which provide a mathematically rigorous characterisation of topological properties of quantities defined on a lattice. After introducing homology, I shall discuss how this concept can be used to quantitatively analyse the behaviour of monopoles across the deconfinement phase transition. The proposed approach is first demonstrated for Compact U(1) Lattice Gauge Theory, which is known to have a zero-temperature deconfinement phase transition driven by the restoration of the symmetry associated with the conservation of the magnetic charge. For this system, I perform a finite-size scaling analysis of observables capturing the homology of magnetic current loops, showing that the approach reproduces the expected value of the deconfinement critical coupling. Then, I extend this method to SU(3) gauge theory, in which Abelian magnetic monopoles are identified after projection in the Maximal Abelian Gauge. Specifically, I define an observable called "simplicity", which measures the number of topologically non-trivial loops per connected component in a current network. A finite-size scaling of the ensemble-averaged simplicity of Abelian magnetic currents provides the expected value of the critical coupling with an accuracy that is generally higher than that obtained with conventional thermodynamic approaches at comparable statistics, suggesting the relevance of the topological properties of monopole currents for confinement. Finally, preliminary results from a study of simplicity in QCD will be briefly discussed.

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Casimir effect in critical O(N) models with non-equilibrium methods

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Three-dimensional U(1) strings beyond effective string theory

Effective string theory provides a successful description of the confining string in non-Abelian gauge theories. On the other hand, U(1) gauge theory in three spacetime dimensions, while confining, displays some peculiar properties (such as the impossibility of holding both the mass and string tension fixed in the continuum limit) which question the applicability of effective string theory to its confining string. In this talk, we report the results of numerical calculations of the ground state energy of the confining string in 3D U(1) gauge theory, and to what extent our results can be described by either effective string theory or alternatives, such as a recent proposal by Aharony, Barel and Sheaffer.

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Aspects of Superconducting Strings

I will examine Abrikosov–Nielsen–Olesen (ANO) vortex strings in variants of Abelian Higgs models. In the large flux limit, the equations governing them simplify, and the resulting giant strings realize two sharply distinct phases. I will explore qualitative features of these strings and identify patterns in their physical properties. I'll also discuss the spectrum of small fluctuations and the associated low energy effective action. I will end by comparing these results to features of confining strings in Yang Mills theory.

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Training Neural Networks

Author: Luigi Del Debbio[None]

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Regulated chiral gauge theory and the strong CP problem

Four-dimensional chiral gauge theory can be formulated as the boundary theory on a five-dimensional manifold in a manner that may be realized on a finite lattice. There are interesting features of these theories which defy a purely four-dimensional conception of universality. We find that QCD as embedded in a chiral gauge theory (the Standard Model) when regulated this way appears to suffer neither from a $U(1)_A$ problem nor a strong CP problem, with a central role played by fermion zeromodes localized far away in the fifth dimension. In this way it differs from conventional lattice QCD formulated as a stand-alone theory.

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Yang-Lee Criticality in Various Dimension

Yang-Lee criticality is the simplest non-Hermitian conformal field theory. The model was first reported as a phase transition of Ising model in imaginary longitudinal magnetic field more than half a centry ago. Since then, many qualitative and quantitative properties of YL criticality have been studied, remarkably, including the fact that the model can be described in Landau-Ginzburg scheme with a scalar $i\phi^3$ theory in $D < 6$ and the fact that the 2D version is an exactly solvable minimal model. In higher dimensions, the model lacks the same level of understanding as the Ising criticality due to its non-Hermitian nature. We report a new study of 3D YL criticality as a phase transition of Fuzzy Sphere model, which facilitates a direct survey of many quantities such as the spectrum and OPE coefficient to high precision. These quantitative results show a beautiful agreement with conformal symmetry and previous estimates from $(6 - \epsilon)$ expansion, high temperature expansion and conformal bootstrap. We also discuss possible approaches in dimensions higher than 3.

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Center-vortex semiclassics on R2xT2 and large-N adiabatic continuity

When the 4d $SU(N)$ Yang-Mills theory is put on $\mathbb{R}^2 \times T^2$ with a nontrivial 't Hooft flux, qualitative features of confinement can be semiclassically described as the gas of center-vortex fractional instantons. We study the condition for the large-N adiabatic continuity via a suitable choice of the N-dependent 't Hooft flux from the viewpoint of both 0-form and 1-form center symmetry.

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Emergent thermalisation in the Schwinger model

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Non-perturbative physics of (1+1)d gauge theories using symmetric matrix product states

Authors: Anna-Maria Glück[None]; Benjamin Søgaard[1]; Ross Dempsey[None]; Silviu Pufu[None]

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We introduce a novel matrix product operator construction for Hamiltonian lattice gauge theories in $(1+1)$ dimensions. This framework enables the study of strongly coupled phenomena such as bound states, string tension, and vacuum structure. We demonstrate the effectiveness of our method by applying it to the massive Schwinger model and adjoint QCD_2

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The simplicity of confinement

Authors: Xavier Crean[1]; Jeffrey Giansiracusa[2]; Biagio Lucini[3]

[1] *Swansea University*

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Motivated by recent literature on the possible existence of a second higher-temperature phase transition in Quantum Chromodynamics (QCD), I revisit the proposal that colour confinement is related to the dynamics of magnetic monopoles using methods derived from Topological Data Analysis, which provide a mathematically rigorous characterisation of topological properties of quantities defined on a lattice. After introducing homology, I shall discuss how this concept can be used to quantitatively analyse the behaviour of monopoles across the deconfinement phase transition. The proposed approach is first demonstrated for Compact U(1) Lattice Gauge Theory, which is known to have a zero-temperature deconfinement phase transition driven by the restoration of the symmetry associated with the conservation of the magnetic charge. For this system, I perform a finite-size scaling analysis of observables capturing the homology of magnetic current loops, showing that the approach reproduces the expected value of the deconfinement critical coupling. Then, I extend this method to SU(3) gauge theory, in which Abelian magnetic monopoles are identified after projection in the Maximal Abelian Gauge. Specifically, I define an observable called "simplicity", which measures the number of topologically non-trivial loops per connected component in a current network. A finite-size scaling of the ensemble-averaged simplicity of Abelian magnetic currents provides the expected value of the critical coupling with an accuracy that is generally higher than that obtained with conventional thermodynamic approaches at comparable statistics, suggesting the relevance of the topological properties of monopole currents for confinement. Finally, preliminary results from a study of simplicity in QCD will be briefly discussed.

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Aspects of Superconducting Strings

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I will examine Abrikosov–Nielsen–Olesen (ANO) vortex strings in variants of Abelian Higgs models. In the large flux limit, the equations governing them simplify, and the resulting giant strings realize two sharply distinct phases. I will explore qualitative features of these strings and identify patterns in their physical properties. I'll also discuss the spectrum of small fluctuations and the associated low energy effective action. I will end by comparing these results to features of confining strings in Yang Mills theory.

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Regulated chiral gauge theory and the strong CP problem

Authors: David Kaplan[1]; Srimoyee Sen[2]

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Four-dimensional chiral gauge theory can be formulated as the boundary theory on a five-dimensional manifold in a manner that may be realized on a finite lattice. There are interesting features of these theories which defy a purely four-dimensional conception of universality. We find that QCD as embedded in a chiral gauge theory (the Standard Model) when regulated this way appears to suffer neither from a $U(1)_A$ problem nor a strong CP problem, with a central role played by fermion zeromodes localized far away in the fifth dimension. In this way it differs from conventional lattice QCD formulated as a stand-alone theory.

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Yang-Lee Criticality in Various Dimension

Author: Yuan Xin[1]

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Yang-Lee criticality is the simplest non-Hermitian conformal field theory. The model was first reported as a phase transition of Ising model in imaginary longitudinal magnetic field more than half a centry ago. Since then, many qualitative and quantitative properties of YL criticality have been studied, remarkably, including the fact that the model can be described in Landau-Ginzburg scheme with a scalar $i\phi^3$ theory in $D < 6$ and the fact that the 2D version is an exactly solvable minimal model. In higher dimensions, the model lacks the same level of understanding as the Ising criticality due to its non-Hermitian nature. We report a new study of 3D YL criticality as a phase transition of Fuzzy Sphere model, which facilitates a direct survey of many quantities such as the spectrum and OPE coefficient to high precision. These quantitative results show a beautiful agreement with conformal symmetry and previous estimates from $(6-\epsilon)$ expansion, high temperature expansion and conformal bootstrap. We also discuss possible approaches in dimensions higher than 3.

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Three-dimensional U(1) strings beyond effective string theory

Author: Alessandro Mariani[None]

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Effective string theory provides a successful description of the confining string in non-Abelian gauge theories. On the other hand, U(1) gauge theory in three spacetime dimensions, while confining, displays some peculiar properties (such as the impossibility of holding both the mass and string tension fixed in the continuum limit) which question the applicability of effective string theory to its confining string. In this talk, we report the results of numerical calculations of the ground state energy of the confining string in 3D U(1) gauge theory, and to what extent our results can be described by either effective string theory or alternatives, such as a recent proposal by Aharony, Barel and Sheaffer.

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Using space-time geometry as a tool

Author: Antonio Gonzalez-Arroyo[None]

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I will review a collection of results obtained over the years using the space-time topology and size to probe the dynamics of Yang-Mills fields. In particular our goal is to connect the region well described by perturbative and semiclassical methods to the confinement regime and its string-like behaviour. We will start by looking at the simpler 2+1 dimensional case and then move on to 3+1 dimensions, including the lastest results with a T_2xR^2 geometry.

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Proving chiral symmetry breaking in QCD with 't Hooft anomaly matching

Authors: Luca Ciambriello[None]; Roberto Contino[None]; Andrea Luzio[None]; Marcello Romano[None]; Ling-Xiao Xu[1]

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Chiral symmetry breaking in QCD is a well-established phenomenon, yet it has been a challenge to derive this phenomenon from the theoretical viewpoint. In the seminal 1979 Cargese lectures, 't Hooft showed how to use anomaly matching to prove chiral symmetry breaking, he showed some examples but didn't give the general proof. In this talk, I will present a new strategy which can lead to a general proof.

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Fracton topological phases and Foliated field theories

Author: Masazumi Honda[1]

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I will talk about fracton topological phases (and fracton-like phases) which have quasi-particle excitation like anyons with mobility constraints. It has recently attracted interests in the context of condensed matter physics, quantum information and high energy physics. From condensed matter viewpoint, it describes exotic properties of matter which may be realized in future. From quantum information viewpoint, related lattice models may be useful to make new quantum error correcting codes and quantum hard disks because the models typically have large degeneracy of ground states and can be regarded as generalization of the toric code. From high energy physics viewpoint, fracton topological phases seem to be related to a new type of symmetries called modulated symmetries and a new class of field theories which are partially topological. I will start with explaining relevant concepts and motivations of the topic using some simple examples. Then I will talk about relations to modulated symmetries and foliated field theories.

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The LLR method to compute the density of states in Lattice Gauge Theory

Author: Davide Vadacchino[1]

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In Statistical Mechanics and Quantum Field Theory, the knowledge of the density of states enables the calculation of quantities that are difficult to obtain otherwise, such as interface free energies and latent heats. The LLR method provides a way to obtain a controlled approximation to the density of states. After an introduction to the LLR method, we will demonstrate its application to the computation of observables of cosmological relevance in $SU(3)$ and $\mathrm{S}p(4)$ Lattice gauge Theories.

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Training Neural Networks

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Machine learning methods are ubiquitous by now. The NNPDF collaboraton has used Neural Networks for many years to extract Parton Distribution Functions (PDFs) from experimental data. A quantitative understanding of the trainig process is now mandatory for precision results for the LHC. We discuss recent progress in modelling the training process and present some potential applications.