Lattice QCD in CeFEMA

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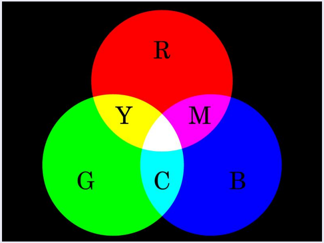
The lattice QCD group at CeFEMA researches hadronic physics with high performance computing. Lattice QCD applies discrete techniques to the QCD Lagrangian. We develop CUDA codes for NVIDIA graphics boards with a large number of cores. We generate our gluon configurations using Monte Carlo techniques, and collaborate with other groups for the configurations with quarks. To study colour confinement, a main open problem in theoretical physics, we study flux tubes, similar to type II superconductors vortices. Moreover we have been studying tantalizing exotic hadronic resonances, recently observed experimentally, such as tetraquarks and hybrids.

Lattice in CeFEMA Hadronic and nuclear physics in CeFEMA

We are an important part of the Theory Group of CeFEMA, where circa half of the staff members research in hadronic or nuclear physics; most of the H&N staff of the DF of IST are in CeFEMA.

http://cefema.tecnico.ulisboa.pt/research/group/theorphys/

Lattice in CeFEMA The colour of quarks



- Quantum Chromodynamics (QCD) was developed in the 70's to make the hadronic wavefunction of the 3-quarks, i e 3-fermions, antisymmetric. Quarks are not observed isolated. They are **confined**. This suggested the new SU(3) symmetry to be local, as a gauge symmetry.
- The new symmetry was named colour since 3 coloured quarks combine in a white baryon.

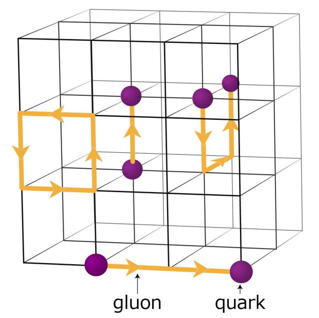
- In the QCD Lagrangian, ψ is the quark field spinor and A^a_μ is the gluon field. **g** is a dimentionless coupling constant.
- When $m \to 0$, classical QCD is conformal invariant.

$$\mathcal{L}_{QCD} = \bar{\psi}\left(\gamma_\mu D^\mu + m\right)\psi + \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \ ,$$

$$D_\mu = \partial_\mu - i\, g A^a_\mu \frac{\lambda^a}{2} \ ,$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu \ .$$

Lattice in CeFEMA Discretizing QCD



- To discretize Quantum Chromodynamics (QCD) in a finite space-time lattice, we utilize the Wick rotation to Euclidian space and finite differences.
- Different points in the lattice must be connected by gauge links to preserve gauge invariance. Thus the quarks field are placed on the lattice vertices and the gluon fields on the links.
- Each gluonic link is a $SU(3)$ matrix.
- While the quark action is straightforward, the gluon action is obtained with the plaquette

$$\sum_c F^c_{\mu\nu} F^c_{\mu\nu} = \frac{2\beta}{a^4} P_{\mu\nu} + \mathcal{O}(a) \ ,$$

where the plaquette is a closed four-link loop,

$$P_{\mu\nu}(\mathbf{r}) = 1 - \frac{1}{3} \mathrm{Re\,Tr} \left[U_\mu(\mathbf{r}) U_\nu(\mathbf{r}+\mu) U^\dagger_\mu(\mathbf{r}+\nu) U^\dagger_\nu(\mathbf{r}) \right] \ .$$

http://www.jicfus.jp/en/promotion/pr/mj/guido-cossu/

Lattice in CeFEMA Pros and cons of Lattice QCD

- Comparing to the other approaches to QCD, either pertubative QCD or effective models, lattice QCD offers a very special perspective.
- Solving a fundamental problem of quantum physics and mathematics, may open doors in physics and materials science. 

techniques

- Euclidean time
- Metropolis-like Monte Carlo
- configuration average
- position space propagator
- exponential fit to time decay

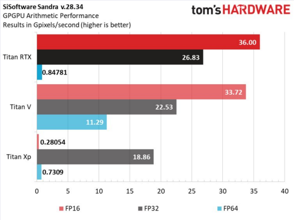
pros

- gauge invariant
- gluons easy
- fluxtubes easy
- glueballs easy
- finite T easy
- tests gauge theories
- works in different dimensions

cons

- compute numerical path integrals
- hadronic physics needs lattice $> 100^4$
- fermions expensive
- imaginary decay widths hard to get
- finite density μ extremely hard

Lattice in CeFEMA Graphics Processing Units

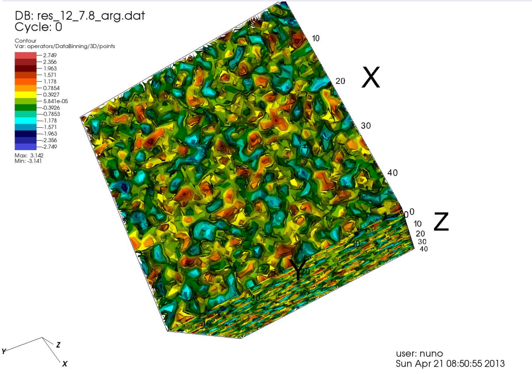


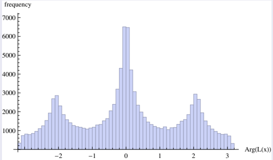
- The PC answer to the gaming demand is the powerful Graphics Processing Units (GPUs), turning PCs into supercomputers.
- NVIDIA and AMD/ATI are world leaders.
- Specs of the champion GTX TITAN RTX:
  - **NVIDIA CUDA ® Cores 4,608**
  - Tensor Cores 576, RT Cores 72
  - **GPU Memory 24 GB GDDR6**
  - Memory Interface 384-bit
  - Memory Bandwidth Up to 672 GB/s
  - Tensor Performance 130 TFLOPS
  - NVIDIA NVLink Connects 2 GPUs
  - System Interface PCI Express 3.0 x 16
  - Power Consumption 280 W
- Since 2008 we develop codes, using C++ / CUDA, with TFLOPS performances.

https://www.tomshardware.com/reviews/nvidia-titan-rtx-deep-learning-gaming-tensor,5971.html
https://www.nvidia.com/en-us/titan/titan-rtx/

Lattice in CeFEMA Our configurations and Z_3 symmetry

$T > T_c$

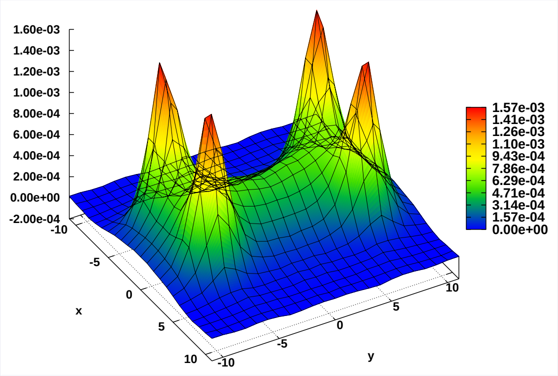




- We generate our own gluon configurations. We compute the Polyakov loop and the average of its argument in a $48^3\, a^3$ volume at $\beta = 7.80$.

Lattice QCD computation of the SU(3) String Tension critical curve, N. Cardoso, P. Bicudo, Phys.Rev. D85 (2012) 077501
Colour field flux tubes and Casimir scaling for various SU(3) representations, N. Cardoso, M. Cardoso, P. Bicudo, Phys.Lett. B710 (2012)

Lattice in CeFEMA Flux Tubes in QCD

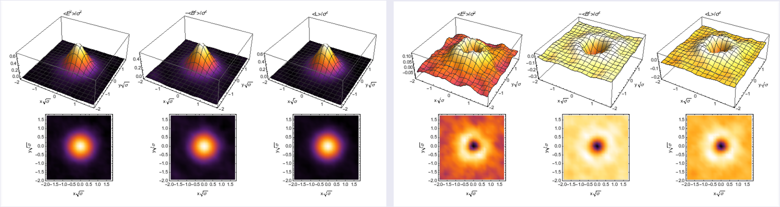


- *One of our studies.* The tetraquark flux tube, computed with SU(3) lattice QCD and four static quark and antiquark charges, showing how confinement squeezes the colour fields into flux tubes.

Colour Fields Computed in SU(3) Lattice QCD for the Static Tetraquark System, N. Cardoso, M. Cardoso, P. Bicudo, Phys.Rev. D84 (2011)

Lattice in CeFEMA Flux Tubes in QCD

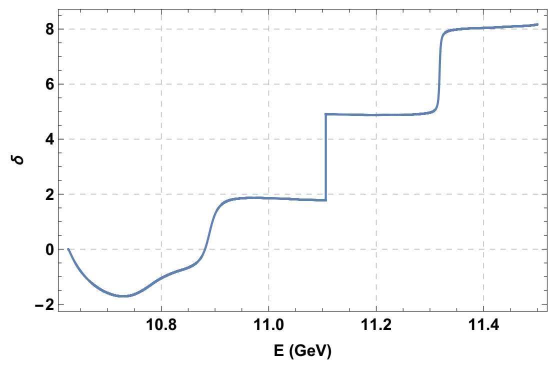
The density of excited flux tubes in the mediator plane



- 3D plots of the Lagrangian $\mathcal{L}$, E^2 and B^2 field densities in the mediator plane. We show the groundstate respectively for the quantum numbers Σ_g^+ (left) and Π_u (right).
- While Σ_g^+ has a normal Gaussian-like profile, Π_u has a negative density in the centre typical of a constituent gluon.

Lattice in CeFEMA Phase shifts of bottonomium

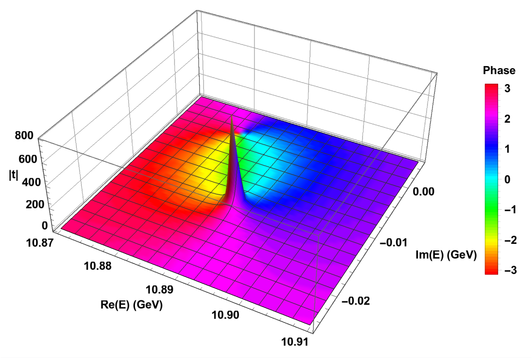
Phase shifts for the median parameters of the potential (real energy E)



Phase shift δ_l as a function of the energy E. We clearly see 3 resonances at E=10.9 GeV, 11.2 GeV and 11.3 GeV, perhaps another one below 10.8 GeV.

Lattice in CeFEMA S Matrix complex energy poles

Pole in the complex plane of $E \in \mathbb{C}$ for the median parameters of the potential

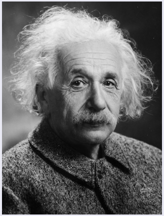


3D plot of t_1 as a function of the complex energy E close to the 1st resonance at re(E) $\simeq$ 10.9 GeV. The vertical axis shows the norm $|t_1|$, the colours represent the phase $\arg(t_l)$.

Lattice in CeFEMA perhaps related: Q gravitation

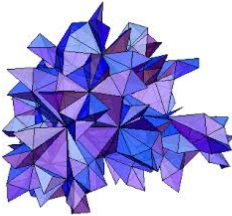
Fundamental problems are cross-disciplinary. Lattice QCD uses condensed matter and molecular physics techniques. And then it may inspire us for the unification of Gravitation with other interactions, attempted by Einstein for many years.

Albert Einstein



Presently the quantization of General Gravity is addressed with ideas inspired in QCD and in lattice QCD.

- string theories are inspired in QCD strings,
- Loop Quantum Gravity discretizes space
- Causal Dynamical Triangulation discretizes space-time
- Gravity screening (for dark energy and MOND) could be related to QCD screening



Lattice in CeFEMA Summary

The research in lattice QCD at CeFEMA may open many doors to solve fundamental physics problems and to apply HPC in science and in engineering.

- Lattice field theory offers a different perspective to field theory and addresses many open problems.
- Because CPUs are approaching a physics wall, we develop CUDA codes for NVIDIA GPUS as the low cost tunnel for HPC.
- Our group is able to compute interesting results in different QCD topics : confinement, strong interaction, flux tubes - vortices, gauge fixing, phase transitions, hadron spectrum.
- We have been collaborating with colleagues in Frankfurt, Coimbra / Trento, CERN / Dublin / Munchen and Swansea in state of the art topics of lattice QCD.