

## QCD@Work 2024: Highlights

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**Abstract.** The highlights of QCD@Work 2024 are summarized.

The XI edition of QCD@Work - International Workshop on Quantum Chromodynamics - Theory and Experiment, was held in the year of the 50th anniversary of the discovery of the  $J/\psi$  which proved the existence of the charm quark. This was a turning point for the Standard Model of the electroweak interactions and for the theory of strong interactions QCD. The path leading to the formulation of QCD is rather recent, and one can identify two milestones reached in the seventies of the last century. The first one is understanding that nonabelian gauge theories enjoy the property of asymptotic freedom, which opened the way to build QCD as a gauge theory described by the SU(3) group. Elementary constituents of hadrons, the quarks, had already been introduced as tools to classify the wealth of observed hadronic states. However, as always in science since Galilei, the verdict came from experiments. Thanks to the observation of the Bjorken scaling in deep inelastic experiments, the presence of pointlike partons inside nucleons was established. The second milestone reached in November 1974 was the observation of the  $J/\psi$ , hence of the charm quark, which proved that quarks are real entities. This was 50 years before QCD@Work 2024.

Fascinating features of QCD, asymptotic freedom and confinement, are still under scrutiny by theory and experiment. They are both represented in this edition of the workshop with developments at the frontier of particle physics.

Asymptotic freedom allows us to perform perturbative calculations at high orders in the strong coupling constant  $\alpha_s$ ; the session "New challenges in perturbative QCD" has collected important contributions. Two eminent Italian Physicists who greatly contributed to this sector sadly passed away last year: Stefano Catani and Marcello Ciafaloni. The workshop was opened by Giovanni Ridolfi with a personal selection of Stefano's and Marcello's far-reaching scientific achievements [1].

Presented advances in theory concern the forward Higgs production, with the related difficulties in perturbative QCD [2]. New computations of the event shape distributions have been discussed [3], together with algorithms to find Cwebs in multiparton scattering amplitudes [4]. A method to measure the top quark mass using leptonic final states, with leptons coming from  $W$  and  $B$  decays, has been presented together with the results obtained by the ATLAS Collaboration using this method [5].

For proton-proton collisions, the general mass variable flavour number schemes ACOT and the simplified S-ACOT have been discussed. In particular, the calculation of  $Z$  hadronic production with at least one  $b$  quark beyond the leading order in QCD has been presented [6]. New studies of the Transverse Momentum Distributions allow to gain insights into the hadron properties. The conformal features of TMD operators have been discussed, and the result of the conformal rapidity evolution of such operators in the Sudakov region has been given [7]. The problem of the transverse  $\Lambda$  polarization in unpolarized production processes

( $e^+e^-$  and  $pp$  collisions, semi-inclusive DIS) has been analyzed. The TMD approach has been illustrated, and universality tests for the TMD polarizing fragmentation function have been discussed [8].

New experimental results in  $pp$  collisions at the LHC energy were presented by the ATLAS and CMS Collaborations. In particular, in the ATLAS contribution the impact of LHC data in the PDF determination was shown to be more and more relevant [9]. The most precise determination of  $\alpha_s$  in a single measurement from the  $Z$   $p_T$  spectrum was presented [9], together with the newest results on a benchmark QCD process, the Drell-Yan W/Z di-lepton production [10]. Among the CMS results, the most stringent limit on rare decays of Higgs boson into a photon and a meson, the observation of quantum entanglement in top quark pair production and the first evidence of time-dependent CP violation in  $B_s^0 \rightarrow J/\psi \phi(1020)$  decays are worth to be highlighted [11].

The nonperturbative regime of QCD, related to the quark and gluon confinement inside hadrons, was discussed in the session "Low-Energy and Nonperturbative QCD". A spectacular feature of low-energy QCD is the hadron spectrum. New results have been presented by the BESIII [12, 13], LHCb [14] and CMS Collaborations [15]. In particular, in the BESIII contribution the determination of the quantum numbers of  $X(2370)$ , an important glueball candidate, is discussed. A new state  $X(1880)$  is observed in  $J/\psi \rightarrow (3\pi^+\pi^-)\gamma$  and an exotic isoscalar state is found in  $J/\psi \rightarrow \eta\eta'\gamma$  [12]. BESIII also reported results on hyperons, including the measurement of the polarizations of  $\Xi^-$  and  $\Xi^0$ , which are useful to test the CP asymmetry in hyperons with more than one strange quark [13]. Three-body decays of  $B$  mesons to light states, analyzed by LHCb, reveal a wealth of information on the light quark spectroscopy [14]. Among the experimental contributions, CMS has reported the observation of new structures in the di-charmonium mass spectrum, hinting at exotic states comprising two charm quarks [15]. The issue of conventional and nonconventional hadrons has been lively discussed, considering examples of flavour-cryptoesotic tetraquarks [16] and tetraquarks in two-dimensional QCD [17]. The use of a quantity called "configuration entropy" in holographic models to characterise the different kinds of hadrons has been developed [18].

The treatment of single flavour baryons at large  $N$  in low-energy QCD has been discussed. Since it cannot be done in terms of Skyrmions, a description has been proposed in terms of a pancake-shaped sheet. How this possibility can be realised in a holographic model of QCD has been discussed at the workshop [19].

QCD is almost everywhere in particle physics. Even while probing other kinds of interactions it is not possible to avoid considering that quarks are strongly bound inside hadrons. This interplay is behind most of the research presented in the session "Heavy Quarks". We had the honour to have as a speaker Prof. Andrzej J. Buras, the recipient of the 2024 J.J. Sakurai prize of the American Physical Society awarded to recognize outstanding contributions to particle theory. In his talk, a new strategy in the search for physics beyond the Standard Model in the flavour sector has been discussed in details. The strategy, based on rare  $B$  and  $K$  decay modes, has the important feature of avoiding the use of the CKM matrix elements  $|V_{cb}|$  and  $|V_{ub}|$  elements, which are subject to tensions. A shopping list of desired measurements has been suggested, for the benefit of the programme of the experimental collaborations [20].

Experimental news in rare kaon decays obtained by the NA48/2 and NA62 Collaboration confirmed the importance of the kaon modes [21]. In particular, the branching ratio and the di-photon mass spectrum of the mode  $K^+ \rightarrow \pi^+\gamma\gamma$ , obtained by NA62 Collaboration, has been presented. Preliminary results for the branching fraction of  $\pi^0 \rightarrow e^+e^-$  have been given. The first observation and measurement of the branching fraction of the  $K_{\mu\nu}^{00}$  mode:  $K^\pm \rightarrow \pi^0\pi^0\mu^\pm\nu$  obtained by the NA48/2 Collaboration at CERN have also been reported.

Rare decay modes of heavy mesons and baryons have been discussed, namely the radiative modes  $B_c \rightarrow (B^*, B_1)\gamma$  [22] and the FCNC transitions of spin 1/2 double heavy baryons [23]: they are included in the physics programmes of the LHC experiments. The presentation by the Belle II Collaboration enriched the experimental view in flavour physics. New results have been presented on hadronic  $B$  decays, on the angle  $\phi_3/\gamma$ , on time-dependent CP violating processes, on semileptonic  $B$  decays and the debated ratios  $R(D)$  and  $R(D^*)$ . New analyses of electroweak and radiative penguin processes have been discussed, in particular for the very rare  $B^+ \rightarrow K^+\nu\bar{\nu}$  mode. For the bottomonium spectroscopy, results have been quoted about  $Y(10753)$  [24].

Developments have also been presented for the QCD effective theory suitable for heavy hadrons, the Heavy Quark Effective Theory. Improvements have been implemented in perturbative calculations and in the determination of nonperturbative quantities such as local and nonlocal matrix elements [25]. In this framework, the inclusive  $\Lambda_b \rightarrow X_s\gamma$  decay, with the related spin effects, has been discussed, with a proposal of a novel expression for the shape function [26].

An important observable to test the Standard Model is the anomalous magnetic moment of the muon, the measurement of which is in tension with theoretical determinations. The uncertainty connected to the leading order hadronic vacuum polarization contribution to  $(g - 2)_\mu$  has been described in details, considering the methods currently used to determine such a term. The perspectives provided by the experiment MUonE, which is designed to collect data in the space-like region, have been discussed. The required improvements for the theoretical calculations of the elastic  $e - \mu$  scattering have been described [27].

Searches for physics beyond the Standard Model include the dark photon. Systematic uncertainties related to the effects of the momentum distribution of the atomic electrons need to be precisely assessed, and they were discussed at the workshop [28]. They are relevant for dark matter searches (PADME, NA64, ...) and precision measurements (MUonE, ...) in fixed target experiments. In scenarios comprising vector dark matter, the electroweak phase transition can be characterized [29]. In this respect, new methods for computing the collision integrals involved in the description of cosmological phase transitions have been described [30].

Various formal studies related to the physics of strongly coupled systems have been presented at the workshop. They include the renormalized entanglement entropy [31], the quantum anomalies for chiral states of matter [32], the gravitational form factor of pion and proton [33], deterministic approaches to the dynamics of quantum fields [34]. The topology of the large  $N$  expansion in  $SU(N)$  Yang-Mills and the way to restore a puzzling violation of the spin-statistics theorem have been considered in details [35]. The fluctuations of a thermal field in a chiral Lagrangian with broken scale invariance have been discussed [36]. An example of synergy between particle physics and gravitational waves, represented by Feynman integrals, has been illustrated [37].

Insights on strong interactions come from heavy ion experiments and the related theoretical studies, presented in the session "QCD in extreme conditions of temperature and density". For the search of the critical point in the QCD phase diagram, data from the Beam Energy Scan program at the BNL Relativistic Heavy Ion Collider qualitatively suggest that the critical point should have a baryonic critical potential  $\mu_B > 420$  MeV. This hint comes by looking at the plots of  $n = 2, 3, 4$  factorial cumulants, which show a non-monotonic behavior expected in the presence of a critical point [38]. The QCD phase diagram at finite isospin chemical potential can be theoretically explored using AdS/CFT inspired methods. Using the Witten-Sakai-Sugimoto model, it is found in the baryon - isospin chemical potential plane at  $T = 0$ , that the pion mass increases with baryon density; at low baryon chemical potentials

the baryons are absent. In the same model, the neutron star is constructed in agreement with experimental constraints for mass, radius, and tidal deformability [39].

At low  $T$ , for vanishing baryonic chemical potential and finite isospin chemical potential, a transition occurs from the hadronic phase to a superconducting one. In the Ginzburg-Landau theory, depending on the value of the coupling, a type I or type II superconducting phase can be realized. At the transition, a BPS bound is saturated by multi-vortex configurations. The BPS bound has been computed in chiral perturbation theory minimally coupled to electrodynamics, obtaining a critical value of the isospin chemical potential [40].

Heavy ion collisions provide a laboratory to study exotic charmonia, due to the large number of produced heavy quarks. A multi-quark state of two charm ( $c\bar{c}$ ) and two light quarks ( $q\bar{q}'$ ) can have a molecular or compact structure. This environment can help shedding light on the structure of the  $X(3872)$  comparing the production yield to that of  $\psi(2S)$ . Using an effective Lagrangian approach, the time evolution of the ratio  $\mathcal{R}$  between the yields of  $X(3872)$  and  $\psi(2S)$  has been computed.  $\mathcal{R}$  is different if  $X(3872)$  is a molecule or a compact tetraquark. The ratio can be measured at LHC [41].

News from the ALICE Collaboration have been presented at the workshop, in particular concerning the production of nuclei and hypernuclei in Pb-Pb collisions [42], the heavy flavour production in pp collisions [43] and the quark-gluon plasma (QGP) features in small colliding systems [44]. Technological developments foreseen for the future runs have been described [45].

Spin polarization can be used to study the QGP. A numerical calculation in a hydrodynamic model, simulating Au-Au collisions at  $\sqrt{s} = 200$  GeV and Pb-Pb collisions at  $\sqrt{s} = 5.02$  TeV, shows that the spin polarization of  $\Lambda$  hyperons is very sensitive to initial conditions and bulk viscosity of the plasma. Hence, the azimuthal dependence of spin polarization can constrain the initial hydrodynamic conditions and the transport coefficients of the QGP [46]. Tensions are found for vector mesons, since the measured spin alignment is larger than expected. During the workshop, it has been proposed that local spin density fluctuations of quarks due to axial-vector and tensor interactions between quarks can induce the spin alignment of  $\phi$  and  $K^{*0}$  mesons [47].

In many cases, dynamical calculations are needed to compute features of the QGP to be compared to data. To study the evolution of the electromagnetic fields produced in Ru+Ru and Zr+Zr collisions at  $\sqrt{s_{NN}} = 200$  GeV, the effect of the electric and magnetic conductivities must be taken into account [48]. Moreover, to connect the nuclear structure to heavy-ion measurements, the elliptic shape of the initial entropy density distribution, which depends on the density of the colliding nuclei, has been studied through a cluster expansion decomposition, assuming scale invariance for the initial state [49].

Data from heavy ion collision experiments can constrain the Hagedorn temperature  $T_H$ . For a strongly-coupled confining gauge theory,  $T_H$  has been computed in a holographic model as a perturbative expansion in the coupling  $1/g$ . A remarkable agreement with an independent result is achieved, a non-trivial test of the holographic correspondence. Extrapolating the results to  $SU(3)$  Yang-Mills, the prediction  $T_H/T_c \sim 1.19$  has been obtained [50]. Other features of the QCD phases in a holographic approach have been investigated [51].

Looking at the future facilities, the perspectives for ePIC at the Electron Ion Collider have been discussed [52] together with some technological developments for the detectors [53, 54]. Various options for new high-energy colliders have been described, potentially operational after the conclusion of the LHC and High Luminosity-LHC programmes. The physics potential of various projects has been animatedly discussed, together with the technical requirements and various kinds of constraints [55]. The projects include lepton colliders, mainly dedicated to precision physics, proton-proton and multi-TeV muon colliders to explore the high-energy frontier. The process for defining the European Strategy for Particle

Physics has just started. It will involve the entire community in shaping the future of our science, which is foreseen to be bright.

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