Glueballs amass at RHIC and LHC Colliders! - The early quarkless 1st order phase transition at $T = 270$ MeV - from pure Yang-Mills glue plasma to GlueBall-Hagedorn states

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The early stage of high multiplicity pp, pA and AA collider is represented by a nearly quarkless, hot, deconfined pure gluon plasma. According to pure Yang - Mills Lattice Gauge Theory, this hot pure glue matter undergoes, at a high temperature, $T_c = 270$ MeV, a first order phase transition into a confined Hagedorn-GlueBall fluid. These new scenario should be characterized by a suppression of high p_T photons and dileptons, baryon suppression and enhanced strange meson production. We propose to observe this newly predicted class of events at LHC and RHIC.

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The proper understanding of the initial and the early stage of ultra-relativistic pp-, pA- and heavy ion AA-collisions is a topic of great importance for our understanding of hot and dense QCD matter formed in the laboratory and its phase structure.

At present, the community favors a paradigm of an extremely rapid (t_{eq} less than 0.3 fm/c) thermalization and chemical saturation of soft gluons and light quarks, their masses and momenta emerging from the decay of coherent massive color flux tubes of strings, which are formed in the primary hadron-hadron collisions.

However, for a long time also another scenario has been discussed, namely the hot glue scenario, where the initial stage is dominated by gluons [5, 57, 68, 105].

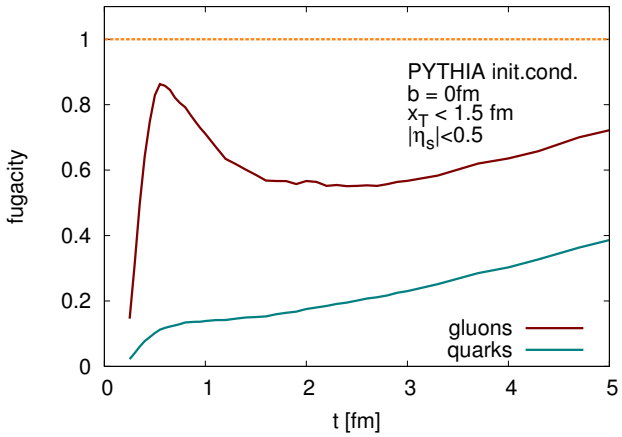
We ask the question whether due to initial state color coherence fluctuations two quite distinct classes of events may exist in collider experiments, or in ultra high energy cosmic ray events, UHECR events. They could be experimentally distinguished in a high statistics analysis of the collider data at RHIC, LHC, and the FCC, from UHECRs, or from high intensity fixed target experiments at FAIR [2–4, 29, 38–40, 42, 43, 47, 48, 50, 58, 61, 62, 64, 89–99], NICA [56] and J-Parc.

Do soft particles at midrapidity in pp-, pA-, and AA-collider experiments develop from an initially quark-free color glass condensate, CGC, through a pre- equilibrium Glasma-stage into a rapidly chemically saturated, thermalized quarkless pure gluon plasma [110] (see Fig. 1(a)) [36]?

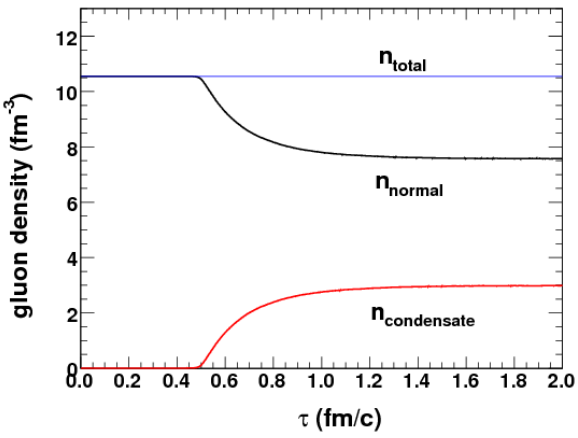
The CGC model predicts that the early Glasma is strongly overpopulated - that means that a 'simple' thermally equilibrated Bose-Einstein distribution can NOT exist, as it can not accommodate the overabundant gluons.

Hence, dynamically a temporary gluon condensate [19, 111] may be formed in order to accomodate those excess gluons, at least transiently, see for example Fig. 1(b).

The surprising finding is that only very few soft quarks are present in this early stage according to modern transport calculations [9, 10, 18, 35, 84, 107] (see, however, also [85, 86], where opposite conclusion of quark equilibration is drawn, mostly due to that they put massive gluons there which can easier produce the lighter quarks, while considering Debye screening and other non-perturbative



(a)Fugacity of gluons and quarks, respectively.



(b)number density of gluons and gluon condensate in overpopulated case.

FIG. 1: (a) Time evolution for fugacity of gluons and quarks calculated by BAMPS. Within BAMPS, partons scatter via $2 \leftrightarrow 2$ interactions in leading-order pQCD and via inelastic $2 \leftrightarrow 3$ processes calculated by the improved Gunion-Bertsch (GB) approximation while considering a running coupling for each scattering evaluated at the microscopic level. The depicted time evolutions are calculated for a cylindrical tube of $x_T < 1.5$ fm and space-time rapidity $\eta_s < 0.5$ in Au+Au collisions with $\sqrt{s} = 200$ AGeV and an impact parameter of b=0 fm. (b) Time evolution for number density of gluons and gluon condensate start with an overpopulated initial condition $f_0 = 0.4\theta(p - Q_s)$ within BAMPS BOX calculation.

chromomagnetic effects).

As a consequence, only few electric charges are produced, and, thus, there will be hardly any electromagnetic signal from the few soft quarks in the early phase beyond the photons from hard scattering and direct Drell-Yan dileptons[113].

Yaffe and Svetitski had predicted a sharp first order phase transition in pure SU(3) Yang-Mills gauge theory [100], and modern high accuracy pure LGT results confirm a clear first order character of this pure gauge phase transition into a confined pure GlueBall phase [11, 25, 26, 41, 54, 87]. The critical temperature of this first order transition in pure Yang-Mills $SU(3)_c$ LGT, or quenched $SU(3)_c$, has recently been measured to $T_c = 270$ MeV. The glueball EOS will affect the expansion rate of the fireball quite significantly.

The presence of a large number of color-confined glueballs in strongly interacting matter must have drastic consequences for the understanding of the dynamics in high multiplicity pp, pA and AA collisions, as proposed in the pure gauge scenario presented in this paper.

Let us try to recover and understand qualitatively the time evolution of the (initially pure) hot glue system within the so-called "Columbia plot" [15], Fig. 2.

Time dependent effective fugacities, i.e. suppressed light quark numbers, can be toy-modelled by suppression of quark densities through the use of heavy quark masses, see the nearly diagonal arrow drawn to guide the eye (see Fig. 2):

The first phase of the relativistic collision rapidly creates a thermalized gluon fluid, with initially 'no' (and even up to $t \sim 3$ fm/c only very few) soft lighter on-shell quarks and antiquarks present [5]. Also the virtual quark- antiquark loops are suppressed by $1/N_c$ [65, 80]. This situation is represented by the upper right hand side corner of the Columbia plot (Fig. 2).

Then, as the system expands, the quarkless, deconfined Yang-Mills matter, hence the pure glue plasma, hits the first order phase transition, at the critical temperature of 270 MeV, see Fig. 3. Here the deconfined pure glue matter transforms into the confined state of the pure YM theory, i.e. into a GlueBall fluid. This surprising prediction holds as long as there are not sufficiently many (virtual and real) quarks formed, as in this situation a (possibly even supersaturated) deconfined hot pure gluon plasma has only one confined exit channel, namely forming a glueball fluid.

Entropy conservation (adiabatic cooling and expansion) forces the volume of the system to expand at the constant critical temperature T_c of the phase transition, and only after all glue plasma has completely transformed into the GlueBall fluid, at $T_c = 270$ MeV, will it be possible to cool the system further: possibly the heavy glueballs in this dilute (!) glueball fluid collide and decay - into lighter GlueBalls, but this is the end of the pure gauge story.

This new pure Yang-Mills scenario, with its radically different collision history is sketched in Fig. 3.

In a more realistic description of pp, pA and AA collision, one shall include the fact that some quarks will already be produced before and during the first order phase transition, FOPT [108].

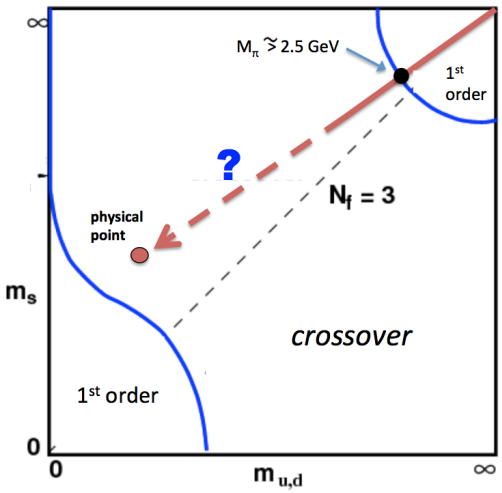


FIG. 2: "Columbia plot" exhibits the dependence of the QCD phase structure, in full equilibrium QCD, on the masses of the different (u,d and s) lighter quarks. For both, very small and very high, but nearly equal lighter quark masses, QCD exhibits strong first-order phase transitions, FOPT, between the confined phase and the deconfined phase, i.e. either between the hadronic and quark-gluon plasma QGP phase, lower lhs corner of the Columbia plot, and, respectively, between the pure glue plasma phase and the GlueBall phase, upper rhs corner of the plot. Early stages of pp, pA and heavy-ion AA collisions are not fully equilibrated, so they can not be represented quantitatively in this plot. However, the dynamical path of the system may be qualitatively visualized by projecting the time dependent, fugacity weighted composition and phase structure of the system on the Columbia plot, as it would be resulting from a suppression of the real and virtual lighter quark - antiquark pair numbers in Lattice Theory. In particular for the early times, $t < 3$fm/c, a large effect should be experimentally observable: Effectively, the change of the QCD phase structure with the different, however small, quark fugacities could easily be numerically estimated by choosing different, but small, flavor numbers in the lattice simulations. The various 'small N_f value' equations of state, EoS, could then in turn be used in hydro simulations in order to get better approximations for the time evolution of the system. The EoS for the small lighter quark fugacities as calculated on the lattice can be interpolated between the different SMALL quark fugacities, as simulated by equilibrium LGT with small N_f values (say $N_f^{effective}$ =0.1, 0.3, 0.5, 1.2, 1.8...)

This could be modeled by moving from the upper right hand side of the Columbia plot along the diagonal to effectively less heavy quark masses in the plot, as indicated in Fig. 2, until the boundary line of the upper r.h.s. quadrant, which indicates that the phase transition changes its order from first to second order, is reached. This will happen at a critical temperature, $T_{2ndorder} \simeq 204$ MeV, about 10% below the pure gauge $T_c = 270$ MeV [16].

But even beyond this transition line, in the crossing region of the Columbia plot, the lower temperature confined phase is heavily populated by GlueBalls and

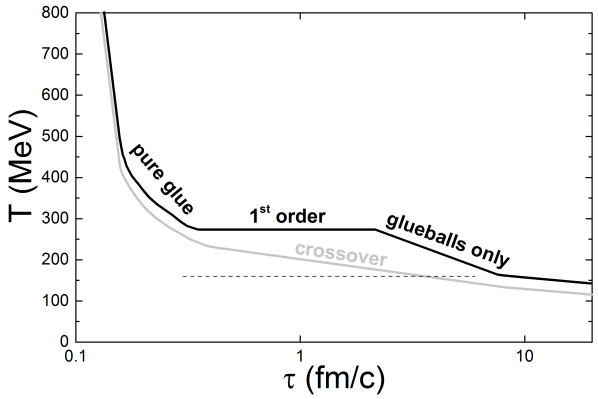


FIG. 3: Sketch of the time evolution of a high-energy collision in the pure glue scenario with Yang-Mills 1sr order phase transition to GlueBalls.

GlueBall-Hagedorn resonances [16, 73, 74]:

Recently, an increasing number of lattice calculations have studied GlueBalls both in pure SU(3) gauge theory [21–23, 69, 72, 73] as well as in full 2+1 flavor LQCD, reasonably close to the physical point [11, 12, 45, 83]. Although the dynamical quarks in full 2+1 flavor LQCD introduce some hadronic mixing (see, for example, [76]) and therefore change the masses of the GlueBalls as measured on the lattice, it can be stated that these peculiar, (mostly) fermion-free confined heavy hadrons are firmly predicted by the theory of strong interactions (see also [49, 71, 79]).

On the other hand, the study of unquenched QCD thermodynamics and the associated phase transition with small quark masses has made substantial progress [7, 8, 12–14].

Combining both research thrusts, the role of the GlueBalls for the equation of state of strongly interacting matter has gained quite some interest lately [21, 22, 44, 67, 70]. Thermal lattice QCD calculations have found substantial contributions from glueballs to pressure and entropy of the hadron resonance gas HRG, both below and above the crossing transition from deconfined to confined matter, and strong evidence for exponentially increasing Hagedorn towers of GlueBalls has been presented [12, 67]-see also[20]. The hadron resonance gas model HRG needs to incorporate not only the measured states from the PDG, but also states which are new (X, Y, Z, pentaquarks, four quark states and/or other exotica as predicted by QCD/LQCD, like glueballs). For refs see eg [75].

The GlueBalls and the heavy GlueBall-Hagedorn resonances can decay rapidly in a consecutive cascade, a chain of two body decays, into light and heavy Hagedorn states [17]. The bulk of the hadronic final state will be produced from the lighter GlueBall Hagedorn states which decay finally into hadronic resonances and light hadrons. Not too surprising is the fact that both the final hadronic yields and the slopes of the spectra do approach

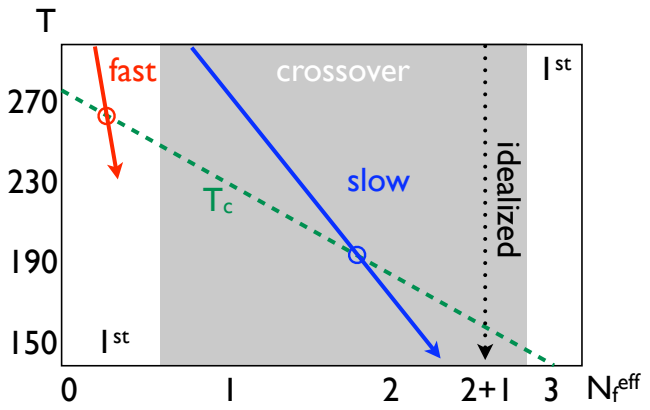


FIG. 4: Transition temperature versus the effective number of flavours.

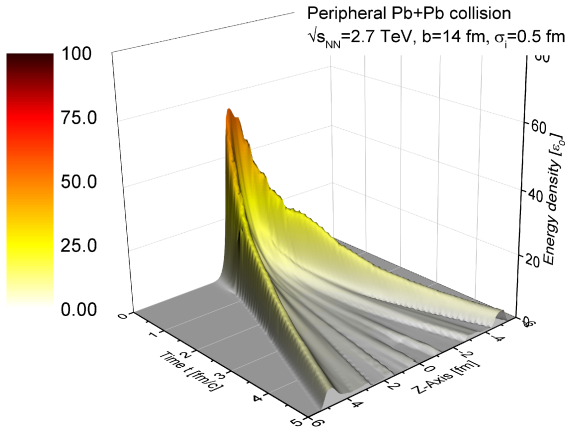


FIG. 5: Gluon density along with z-axis in supercooled pure glue hydrodynamic expansion.

the experimental data in a natural way, as predicted by Hagedorn decades ago, and as recently shown by Beitel et al., by comparing their covariant Frautschi - Hagedorn modell directly to the RHIC and LHC data of the STAR and ALICE collaborations.

As the temperature of the pure gauge first order phase transition, FOPT, is much higher, $T_c \sim 270MeV$, than the crossover temperature, T_{cr}, of full LQCD at the 2+1 flavor 'physical point' of a fully equilibrated, thermalized quark-gluon system, $T_{cr} = 155 \pm 20$ MeV, this idealized (= infinitely slow transition) 'physical point' of full 2+1 flavor hot QCD may not even be reached in RHIC and LHC at high multiplicity pp, pA, and also not in the initial stage AA collisions (See Fig. 4), as the Glue-Ball states may decay directly from a higher temperature phase.

One interesting aspect to investigate would be the dynamics of passing through the first-order gluonic transition. As has been discussed in [31], passing a 1st order transition might take a long time. A sudden transition of a supercooled state, however, could speed up this process significantly [32]. To our knowledge no quenched lattice QCD calculation exists that studies the range of temperatures where supercooling and -heating is possible, i.e., determining the parameters of the spinodal instabilities (see some early attempts in [33, 60, 81, 82]). Such a calculation would be very relevant in this context. Here we show pure glue hydro simulations [104]: Fig. 5 depicts gluon density along z-axis in a supercooled pure glue hydrodynamic expansion and Fig. 6 shows bubble formation in supercooled rapid phase transition of pure glue model.

Pisarski and Wilzcek had predicted already in the 1980ies that fully thermalized QCD with massless quarks (in the chiral limit) will exhibit a soft crossing rather than a sharp first order transition, which has been confirmed by numerous lattice simulations lately [7, 8, 12–14, 78], see also the review by O. Philipsen [79].

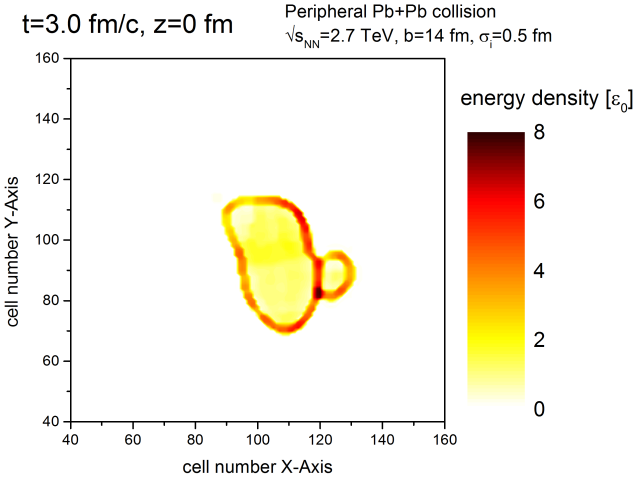


FIG. 6: Bubble formation in supercooled rapid phase transtion of pure glue model.

The success of the hydrodynamic model in describing the bulk of hadronic production in Au+Au collisions at RHIC has led to paradigmatic shift in our view of the QGP: instead of behaving like a gas of weakly interacting quarks and gluons, as naively expected on the basis of asymptotic freedom in QCD, its collective properties rather reflect those of a perfect fluid with almost vanishing viscosity at the crossing transition [59, 101–103, 106]. Actually it is the most perfect fluid created in the laboratory. It is also highly opaque to colored probes, as indicated by the observed large parton energy loss. Actually these two phenomena are fundamentally related to each other, and complement each other to bring about a strongly coupled plasma [51].

However, as the virtual quark loops are suppressed like $1/N_c$ and soft lighter quarks, which could screen the gluon interaction and therefore push down the critical temperature, are not yet produced in appreciable numbers in the first stage of the systems time evolution, $t < 3$fm/c (which in turn also means that, $N_f \ll 1$ at $t < 3$ fm/c, i.e. the effective number of flavors is small), the often used assumption of an immediate fully saturated thermal and chemical equilibration, $t = 0$, which would allow the use a full $N_f = 2 + 1$ QCD EoS in hydro calculations, is - at least during the early, $t < 3$fm/c, stage of the time evolution of the system, not justified. Therefore, as alternative paradigm, the pure glue scenario, $N_f \sim 0$, as discussed above, is more appropriate to study the fate of the system for the early time evolution, and should also be applied in hydrodynamic modelling of the collision - with time dependent fugacities until quark saturation is reached, and a phase structre and an equation of state appropriate for the small time dependent effective flavor number $N_f(t)$ [108].

Thus, the pure gauge theory scenario as outlined above, if realized in nature, may prevent us from seeing the lower temperature crossing at $T_{cd} \sim 155$ MeV, due to the small quark number and small net quark densities in high multiplicity pp and pA events and in the early phase of peripheral (and possibly even in the early phase of central) AA collisions.

If such a situation occurs in current laboratory experiments this is truely a fortiori in the extensive air showers initiated by ultrahigh-energy cosmic rays (UHECR). The initial interaction of the cosmic-ray particle with the atmosphere represents essentially a nucleon-nucleus or nucleus-nucleus collisions at energies much higher than what can be achieved in man made experiments [53]. The projectile energies are 6×10^{19}eV at the GZK cutoff [46, 112]. At these yet higher energies, the relative dominance of the gluons over the quarks should be even more pronounced.

If the Higgs sector is only a low-energy manifestation of a new strongly interacting gauge sector, these comic-ray energies might even be sufficient to trigger a similar scenario in this new gauge sector [34]. For technicolor, UHECR energies are what RHIC energies are for QCD.

The pure glue scenario is expected to occur also, however for a fleeting moment only, in the early universe: At the QCD phase transition, 10^{-5} seconds into the expansion of the universe, the dynamics allows the quarks to catch up with the gluons.

Likewise, at the electroweak phase transition one may search for the pure gauge transition, if the expansion rate of the universe is not too slow to allow for a gauge-boson dominated phase transition as a strongly interacting mechanism for electroweak symmetry breaking.

Conclusions: The early stage of high multiplicity pp, pA and AA collider events can represent a new class of events: a nearly quarkless, hot, deconfined pure gluon plasma. According to pure Yang - Mills Lattice Gauge Theory, this hot pure glue matter undergoes, at a high temperature, $T_c = 270$ MeV, a first order phase transition into a confined Hagedorn-GlueBall fluid. These events should be characterized by a suppression of high p_T photons and dileptons, baryon suppression and enhanced strange meson production. We propose to observe this newly predicted class of events at LHC and RHIC.

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