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Perfect QCD – a new Universal approach to soft QCD

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The ideas presented in this proceeding aims to be a first step towards a description of hadronic collisions where all soft processes are fundamentally strongly coupled and the same Universal strongly coupled physics drives both initial and final-state interactions.
As it is not currently possible to derive such a picture from first principles, instead, an attempt to generalize the perfect liquid observation to a "perfect QCD" guiding principle is presented, focusing on implications for particle production in small systems. The first steps towards a microscopic model is taken by arguing that "perfect QCD" suggests that the screening in the initial state is so large that multi-parton interactions are of little or no importance. Instead, a target and projectile remnant is coherently excited and particle production is mainly driven by radiation in a qualitative similar manner as $e^+e^- \to q\bar{q}$.
Finally, some of the possible implications of this "excited remnant model" are presented. It is argued that the time ordering of soft and hard physics can explain the absence of jet quenching in small systems and that the coherence scale of the projectile and target provides insights into what small systems will exhibit flow.

Keywords: QCD

1 Introduction

The goal of this proceeding for the Winter Workshop 2022 is to present a new picture for hadronic collisions. To be precise, the focus in this paper is only on non-diffractive inelastic collisions and only the soft physics[1], which is expected to be responsible for bulk particle production. When hadronic collisions are mentioned in the following it always refers to this type of collision unless another type is explicitly mentioned. The motivation for doing this is the observation of several phenomena in small systems[2] that has traditionally been associated with the formation of a quark-gluon plasma (QGP) in large systems, see, e.g., Refs. [3, 4] for an overview. These new phenomena can all be explained by the presence of large final-state interactions in small system and many excellent ideas have been presented for describing this with weakly coupled physics, see e.g., [5], but what seems to the author to be a fundamental flaw in these models is that a weakly coupled interaction leads to a non-vanishing mean free path so that the QGP-like effects will build up as the system grows and first dominate at a certain system size [5]. This means that QGP-like effects do not in a natural way extend down to the smallest systems, even if there is no indication in data of an onset [3, 4]. At the same time, a non-vanishing mean free path will introduce diffusion and dissipation effects that will supposedly modify the initial-state correlations, which the author is unaware of experimental evidence for, see e.g. C. A. Pruneau's contribution to these proceedings **[TODO: Add reference]**.

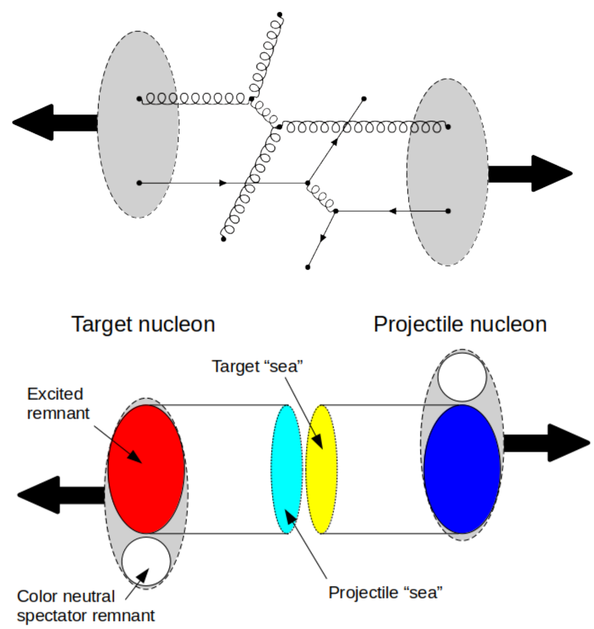

FIGURE 1. Illustration of how the initial soft scatterings are described in different models/pictures. Top: in Pythia, soft and hard interactions are modeled in the same way as leading-order perturbative processes and *multiple* interactions occur in most pp collisions. The strings forming between color charges are not shown. Bottom: in the "perfect QCD" picture a remnant of each nucleon is excited as a whole, as if there was only a *single* interaction, and the picture is therefore denoted the "excited remnant model".

[1] Meaning that momentum transfers are small so that perturbative calculations are inaccurate. As, for example, the Pythia generator [1, 2] for proton-proton collisions treats all interactions perturbatively, this is not a unique definition but part of the motivation for exploring a completely different picture in this paper.

[2] Small systems are taken to mean proton-proton, proton-nuclei and ultra-peripheral nuclei-nuclei collisions.

In this paper, the decision has been to take a fresh look at things from the perspective offered by the new measurements and try to bring forth a picture that is fundamentally strongly coupled with a vanishing mean free path so that large final-state effects are present in all systems and do not introduce diffusion or dissipation (are essentially reversible) thereby hopefully preserving correlations such as those introduced by string breakings or similar processes. In traditional pictures, "soft" can have two very different meanings:

1. The extrapolation from high-momentum transfers to low momentum transfer, e.g., using leading-order perturbative cross sections even for situations where next-to-leading order correlations are large

2. Phenomenological physics such as the Lund string model [6]

The approach in this paper is to claim that point 1 does not work, meaning that next-to-leading order corrections distorts the leading-order picture, and the proposal is instead that "perfect QCD" is a Universal version of point 2 and can provide guidance in that way. This means that any time where soft is mentioned in the text one should in principle be able to apply the "perfect QCD" principle. To help convince the reader that this leads to fundamentally different physics from that found in existing models, one of the main findings will be already discussed here and illustrated in Fig. 1. In pp event generators, such as Pythia [1, 2], one typically treats the initial stages of pp collisions as two interacting parton gases where the scattering of each parton-parton interaction is motivated by perturbative (weakly coupled) QCD, Fig. 1 top. In the Color-Glass Condensate (CGC) model, not shown, one instead considers it as a weakly coupled interaction between dense gluon fields [7] that produce longitudinal Glasma tubes, Fig. 1. In both models the collision can involve one or more interactions and *the number of interactions is the main driving mechanism of the final-state multiplicity*. In the picture motivated in this paper, one considers a strongly coupled scenario where the color field of each projectile parton is neutralized by the target partons. It is argued that this results instead in that the remnant of the projectile and the target is coherently excited, corresponding essentially to a *single* soft interaction. This gives rise to two semi-independent color fields, Fig. 1 bottom, which would mean that most of the particle production is driven by final-state radiation from the colored target and projectile remnants, similar to $e^+e^- \to q\bar{q}$.

Concretely, the idea of this paper is to extend the experimental observation that the QGP behaves like a perfect liquid to a "perfect QCD" principle that can guide our understanding of particle production in general. The goal is not to come up with a full model, but to demonstrate that it is possible using the proposed "perfect QCD" principle to obtain surprising insights into particle production where the physics and the explanations for observed phenomena are very different from those found in existing models, such as Pythia and the CGC.

2 Perfect QCD

One of the most remarkable discoveries of the heavy-ion program at RHIC and LHC is that the Quark-Gluon Plasma (QGP) behaves as a perfect liquid [8–14]. The shear-viscosity-to-entropy density (η/s) is as low as possible [15]. This means that the build up of flow is almost deterministic, which has enabled the precise measurement of fluctuations in the initial distribution of matter, e.g., Refs. [16, 17]. At the Winter Workshop it was further shown how the same minimal η/s is also obtained when analyzing balance functions and momentum correlations **[TODO: Add reference to Claude's proceeding]**.

The perfect nature of the liquid seems to indicate that it is very fundamental and since it is observed in all hadronic collisional systems (pp, p–Pb, and Pb–Pb collisions), see for example Refs. [18, 19] for small systems, one could hope that it provides a deep insight into QCD.

Based on the characteristics of the perfect liquid it is proposed that "perfect QCD" has to have the following two characteristics:

- Strongly interacting
- Minimal entropy production

The minimal entropy production comes from the observation that the hydrodynamic description of the QGP is as close to ideal (reversible) as it can be and means that dissipation and diffusion can play no significant role in the description of the system.

3 The Perfect QCD Picture of Particle Production

It might seem impossible to derive a microscopic picture from a strongly interacting soft QCD model because one looses the perturbative guidance but the surprise is that the proposed picture is extremely simple. The "perfect QCD" principle dictates that the entropy production during the initial collisions should be as small as possible, yet strongly interacting, and this suggests that all that happens is the exchange of a single soft gluon so that only color and essentially no momentum is exchanged. As the interacting hadrons are of course made up of partons, this would require that the screening in the initial state is so strong for the initial interactions that the soft parton-parton (and/or CGC equivalent) interactions are suppressed to a degree where they can be neglected. One will of course have parton-parton interactions for very large momentum transfers but they are not of interest here where the focus is on bulk production.

Let us first treat the rest of the collision, ignoring possible radiation, using the Lund string model [6], which, as it is derived from the confining long-range part of the QCD potential, is a strongly coupled model. In the Lund string model, strings will form between colors and anti-colors that eventually breaks, producing hadrons uniformly in rapidity. In this case, two strings will form as the gluon carries both a color and anti-color. Let us assume that all the energy of each proton is carried by the color and the anti-color systems. If both have half the energy, the total string length will be $\approx 4(y_{\rm beam} - \log 2)$ while if one color (or anti-color) has all the energy one can supposedly form a string of length $2y_{\rm beam}$ (this must be the minimal length for the color field to stretch between the target and projectile). As the average number of particles produced a by a string is proportional to the string length [6], the "perfect QCD" principle tells us that nature will take the 2nd solution. This means that instead of having two remnants with a similar amount of energy, one will have a "valence"-like remnant with almost all the energy and a "sea"-like remnant with almost no energy. This is reminiscent of the BGK picture [20], and so it is naturally to propose that the "valence" remnant in one proton is color-coupled to the "sea" remnant in the other proton, and vice versa, so that one in some sense has two semi-independent systems carrying approximately half the total initial energy each.

Let us finally try to give a partonic picture of how the "perfect QCD" picture can be understood. As the two nucleon penetrate at high energy the partons inside them are interacting strongly but the claim is that they interact in a way that screens the partonic interactions. However, this screening can only happen in a certain regime. If x denotes the usual four momentum fraction then one can maximally "organize" the nucleon into $n \approx 1/x$ constituents. Screening will be impossible when the four momentum transfer, Q^2, is very large because one can resolve individual partons (the hard scattering limit), or when x is large so that the number of constituents is small. The latter argument is why nucleon remnants will be excited as a whole.

In the current picture, $dN_{\rm ch}/d\eta$ at $\eta = 0$ would be independent of $\sqrt{s}$ as all the energy will go to extend the strings in rapidity. What has been ignored is radiation: the color charge carrying most of the energy is, as QCD is strongly interacting, very likely to emit soft or collinear radiation. How to calculate this radiation is not trivial, but one can at least note that one qualitatively get a system very similar to what one has for $e^+e^- \rightarrow q\bar{q}$ (denoted e^+e^- in the following). Comparing particle production in e^+e^- collisions to that of pp collisions, one finds that the former produces *more* particles on the average [10]. The common understanding is that it is possible for part of the proton to escape as a color neutral object, taking away around 50% of the energy [21] (which is in line with the argument in the previous section for how particle production can grow in AA collisions). Based on the observed particle production in e^+e^-, it is concluded that there is no fundamental reason one should not be able to create the observed particle production via radiation also in pp, pA, and AA collisions.

To recap, the general microscopic "perfect QCD" picture of pp, pA, and AA collisions will be that the soft initial interactions will excite a remnant of each nucleon in a "projectile" coherently and that the main particle production at high energy collisions is driven by final-state radiation. For this reason the picture will be denoted the "excited remnant model". This might sound like the Dual Parton Model but it is important to note that the Dual Parton Model contain MPIs [22].

In the limit that particle production is dominated by radiation, the color-connections to the "sea" systems in the "target" can be ignored and one can therefore factorize the soft particle production into $N_{\rm part}$ semi-independent terms. Semi-independent, because there must be some dependence on the nucleon-nucleon impact parameter to explain the slightly increased particle production per participant in AA collisions.

3.1 An Illustration of Particle Production in pp Collisions

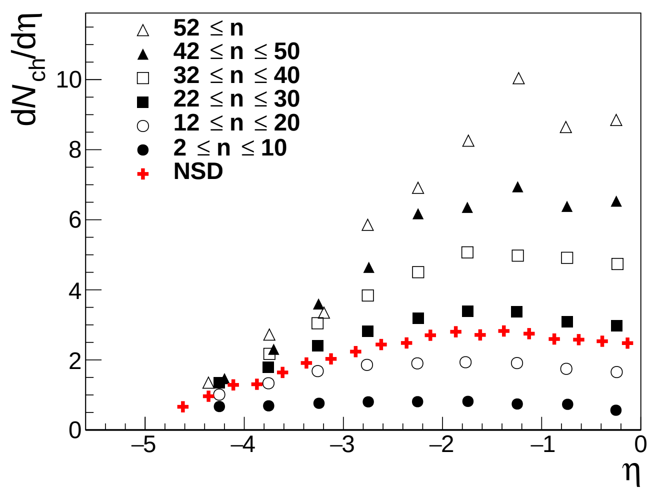

FIGURE 2. $dN_{\rm ch}/d\eta$ measured in $\sqrt{s} = 200$ GeV/c pp collisions by UA5 for NSD events and for events with different final-state charged particle multiplicities, n. The data have been read off from the published figures [23]. As the figure is just meant to illustrate a trend, the statistical uncertainties have not been included for clarity.

The main goal here is to discuss small systems. In these systems, e.g., pp collisions, the full "perfect QCD" picture of a collision is:

1. the initial interactions produce up to three semi-independent systems:
   - coherently excited target and projectile remnants
   - possible color-neutral target and projectile remnants that act as spectators (escape with energy along beam direction)
   - possible hard parton-parton scatterings
2. the excited remnants radiates gluons
3. the color fields decays into partons

4. final-state partonic interactions: flow, strangeness enhancement

5. hadronization

6. possible final state hadronic rescattering

One could in principle try to implement a generator along these lines but the goal here is to illustrate the picture using UA5 data [23]. Fig. 2 shows the $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ measured by UA5 for NSD events as well as for multiplicity selected events. In low-multiplicity events, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ is flat as one would expect for a single long string. As the multiplicity grows, one observes a narrowing of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$, which in the perfect QCD picture should be caused by the radiation adding shorter and shorter (less energetic) strings. In this way the "excited remnant model" is at least qualitatively consistent with the observed trends by UA5.

4 Insights and Predictions for Small Systems

In this section, the hope is to demonstrate for the reader that the perfect-QCD picture of particle production can provide many new insights and predictions.

4.1 A Simple Explanation for the Absence of Jet Quenching in Small Systems

One can immediately notice that, if the time scales involved with the hard interactions are shorter than the formation time for step 2 ("the excited remnants radiates gluons") as one would imagine from the scales of the momentum transfers involved, then one can understand why there is no jet quenching in small systems even if there is a relation between flow and jet quenching in a large system. The medium simply has not been produced yet when the jet propagates. This seems very attractive to the author as this is in line with experimental findings, see, for example, Ref. [24], and it is hard to explain in most existing models.

4.2 Flow in pp Collisions $\gg$ Flow in $\mathrm{e}^+\mathrm{e}^-$ Collisions

It should be clear from the way the "excited remnant model" work that it "postdicts" that the particle production in pp collisions and e^+e^- collisions should be very similar because in this model, and unlike traditional MPI-based models, the growth with $\sqrt{s}$ is in both cases driven by radiation. Indeed this surprising similarity have been noted and discussed much in the past by experimental collaborations [10, 25], even it was never theoretically understood.

It can therefore be surprising that while one observes strong flow in pp collisions, one does not observe it for e^+e^- collisions [26]. However, there could be a simple explanation for that. As the "excited remnant model" postulates that for each nucleon a single "valence" remnant is excited as a whole, then it is clear that the radiation in step 2 will have to have very low transverse momentum, $p_{\mathrm{T}} < 1/R$, where R is the size of the excited remnant. As the p_{T} is so low, the color fields will have to stack and so one will naturally get a quite dense system of parallel color fields with a large energy density. In the "perfect QCD" picture these color fields will be strongly interacting and so they will immediately start to build up collective flow. This makes a big difference when comparing to e^+e^-, where all the energy is located with a single parton and so the radiated gluons can and will typically have very large p_{T}. This means that most energy will be radiated away from the initial color field and so there is little time where system is dense and can build up collective flow.

4.3 How to Control Flow in Ultra-Small Systems

In the previous subsection it was argued that for small systems, the size of the excited remnant determines the flow that can be built up in the final system. This then is naturally in line with the observation of flow in Ultra-Peripheral Collisions (UPCs), where the photon field of one nuclei interacts with the other nuclei, because in this case the photon field has a long wavelength since it is emitted coherently by the protons in the nuclei. Recall that photons can interact as a "hadronic" system by fluctuating into a $q\bar{q}$ pair, which will have a size that reflects the photon four momentum (Q^2). ATLAS has observed flow in UPC Pb–Pb events [27] and CMS has reported non-zero $v_2\{2\}$ in p–Pb events [28], which is in line with the ideas presented here.

By going to electron-proton or electron-ion collisions one can in principle measure the wavelength of the photon from the change in electron four momentum. One can in this way select different sizes of the excited remnants and if the picture is true, control the p_{T} radiation and switch on (low Q^2) and off (high Q^2) flow. ZEUS and H1 has reanalyzed old data both for low and high Q^2 but neither ZEUS [29, 30] nor H1 [31] observes any signatures of collective flow. This clearly goes against the ideas presented here. However, it seems that if there is flow in UPCs at LHC then there would also likely be flow in low Q^2 ep collisions at HERA and vice verse. On the other hand, one knows that flow in small systems is very hard to detect. Looking from the outside, it would be good if one could resolve the situation so that one is as certain as possible that similar procedures have been used before one concludes too strongly on the current results.

5 Conclusions

An attempt to generalize the perfect-liquid nature from flow to particle production has been presented. The "perfect QCD" principle has been proposed to be a Universal principle for soft QCD that applies both in the initial and final state of hadronic collisions. Using the idea of minimal entropy production, a microscopic picture, the "excited remnant model", has been presented. In the microscopic picture, the screening as the two hadronic systems penetrate is so large that subcollisions between constituents does not occur, in contrast to most existing pictures, e.g., MPI and CGC based ones.

No attempt has been done to prove the "perfect QCD" principle in this paper but several surprising insights have been provided, such as simple arguments for why jet quenching is absent in small systems and which collisional systems will exhibit flow. The hope is that the principle can be used to provide novel insights into a wide range of topics, for example, jet quenching in large systems and the relation between diffractive and non-diffractive physics.

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