

Bulk Dynamics in High Energy Collisions

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Abstract. Empirical scaling laws abstracted from observations pertaining to soft particle production in heavy ion collisions provide interesting connections with phenomena observed in elementary collisions (p+p, e^+e^-). Connections are made between these simple empirical rules and Landau's hydrodynamical model. The implications and problematics of the Landau initial conditions for strong interaction phenomenology are discussed, with some emphasis on their relevance to elementary collisions.

1. Introduction

The understanding of the total multiplicity of charged particles appears to be an intrinsically challenging problem for strong interaction phenomenology. Fittingly, multiplicity measurements are sometimes considered to be “signal”, indicative of different physics processes, but are also sometimes treated as mere “background”, something too complicated to ever model properly and thus only amenable to judicious parameterization.

In the context of e^+e^- annihilations decaying into recoiling quark-antiquark pairs, the average total multiplicity is typically presumed to be linearly related to the average number of gluons radiated as the quarks fragment, i.e. $N_{hadron} \propto N_{parton}$. This is usually referred to as the principle of “Local Parton-Hadron Duality” (LPHD) which has had several notable successes both for jets at e^+e^- colliders as well as for very high E_T jets at the TeVatron[1]. In this picture, the hadronization process is “soft” in that it does not introduce any substantially new entropy as the system evolves.

It is generally thought that the final state multiplicity in proton-proton collisions reflects a somewhat more complicated dynamical scenario. The initial state allows the possibility for hard parton-parton scattering, quantified by means of the nucleon PDFs extracted from DIS data as well as pQCD cross sections for jet production. However, the bulk of the particles are thought to be characterized by various empirical features (“boost invariant” longitudinal phase space, thermal transverse spectra) that can be incorporated into models as a “soft” component in the total production [2].

Nucleus-nucleus collisions introduce several more wrinkles into the overall dynamical picture. First of all the initial-state parton distributions are expected to show “shadowing” phenomena due to the overlapping nucleon wave functions [3]. It is expected that those partons liberated in the initial state can reinteract. Further dynamical effects may be generated due to the large transverse size of the reaction zone and the large energy densities produced at colliders. It has become commonplace to use ideal relativistic hydrodynamics (i.e. zero viscosity) to model these

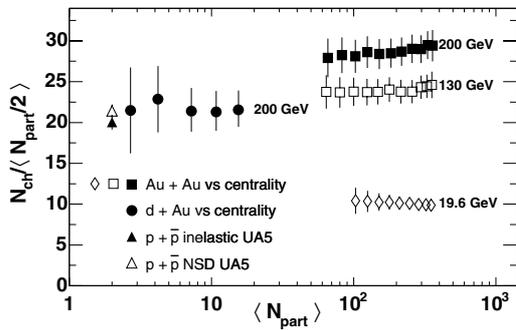


Figure 1. N_{part} -scaling in d+Au and Au+Au collisions, from Ref. [9].

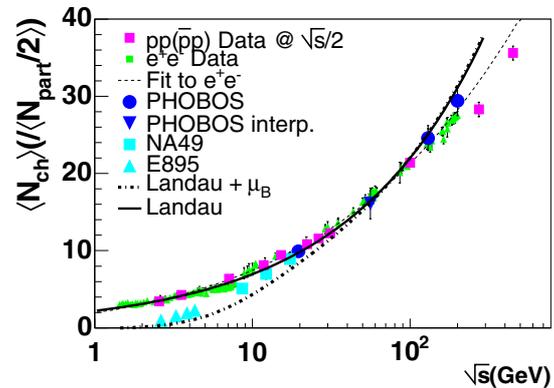


Figure 2. Systematics of total multiplicity, from Ref. [22].

new effects [4]. These models imply that azimuthal asymmetries in the initial state should map into the final state via large pressure gradients.

Given these apparent differences in the essential dynamics between these systems, it would seem to make little sense to compare them directly, except perhaps in the context of very high p_T processes (where one expects pQCD fragmentation to be universal). It will be argued in this proceedings that comparisons of particle production even in the soft sector may well be meaningful, but may require some rethinking of the basic assumptions underlying the dynamical description.

2. Features of Particle Multiplicities in A+A Collisions Compared to Elementary Systems

The particle density measured in central heavy ion collisions at mid-rapidity as a function of collision energy was typically the first measurement made at each RHIC energy, and was useful in elucidating the limits of various theoretical approaches [5]. Models based on purely hadronic dynamics predicted lower multiplicities, while those based on minijets above a fixed scale (e.g. 2 GeV) predicted larger multiplicities than that seen in the data [2]. The centrality dependence of the mid-rapidity density scaled by the number of “participant pairs” $N_{part}/2$, $dN_{ch}/d\eta|_{|\eta|<1}/\langle N_{part}/2 \rangle$, was an even more stringent discriminator of model calculations, and has been interpreted as evidence of parton saturation effects in the RHIC data [6].

Despite the variety of dynamical approaches applied to heavy ion data, the situation appears much simpler when studying multiplicity data taken over the full solid angle as a function of collision centrality [7]. In the 1970’s, p+A collisions at fixed-target energies were found to have a total multiplicity that scaled linearly with N_{part} , with the constant of proportionality given by the total multiplicity in proton-proton collisions [8]. RHIC data on d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV found a similar result [9]. The mysterious aspect of this stems from the fact that the shape of the pseudorapidity changes significantly with centrality, but in such a way that the total multiplicity is conserved. A similar set of features was observed in Au+Au collisions as a function of centrality, with the interesting result that they too produce particles linearly with the number of participants, but with a constant of proportionality 30-40% higher than p+p collisions at the same $\sqrt{s_{NN}}$ [10].

Some insight into this latter difference was gained by a systematic comparison of the total multiplicity measured in a wide variety of strongly-interacting systems, including p+p, A+A, and e^+e^- reactions into multiple hadrons over a wide range of collision energies [10], as shown in Fig. 2. First of all, the e^+e^- data is approximately 30-40% higher than p+p data over the

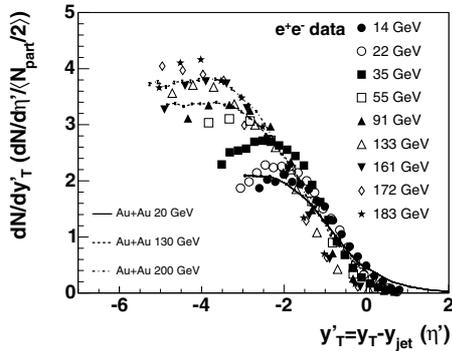


Figure 3. “Limiting fragmentation,” as seen in A+A and e^+e^- reactions, from Ref. [23].

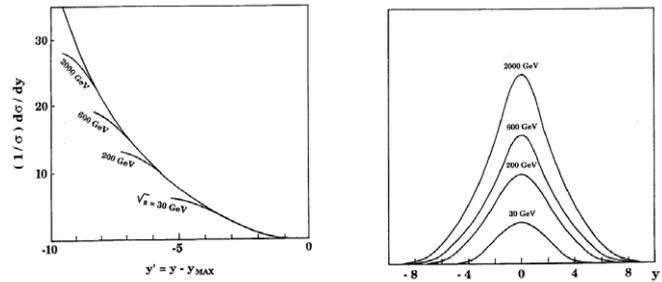


Figure 4. pQCD predictions for dN/dy in two-jet events from Ref. [15].

full energy range. However, correcting for the typical leading-particle effect, where the forward-going baryons typically take half their incoming energy away from the reaction[12], brings the $p + p$ data in approximate agreement with e^+e^- , where similar leading particle effects are not present. The Au+Au data (always divided by $N_{part}/2$) is suppressed relative to both p+p and e^+e^- reactions at very low energies, but joins smoothly with e^+e^- at around $\sqrt{s_{NN}} \sim 20 - 30$ GeV, tracking it for a factor of 10 in CMS energy. This agreement of A+A with e^+e^- and leading-particle-corrected p+p data was argued in Ref. [10] to suggest that any leading particle effect in A+A must be substantially attenuated, perhaps by the multiple collisions experienced by a typical participant in collisions of heavy nuclei. A similar viewpoint has also been pursued more recently in Ref. [11].

While it seems surprising that bulk particle production in A+A collisions does not gain any new qualitative features as a function of energy, it is interesting to see where the additional particles are produced in phase space. This is summarized in the observation of “limiting fragmentation”, where, for a fixed collision centrality, particle yields are invariant with beam energy when observed in the rest frame of either of the projectile, typically expressed at $\eta' = \eta - y_{beam}$, as shown by the curves in Fig. 3, adapted from data shown in Ref. [7]. Additional particles appear to be produced at lower η' as the energy increases. It should not be forgotten that limiting fragmentation is also a feature of p+p and $\bar{p}+p$ collisions up to the highest beam energies [13]. It was also noted recently that jets in e^+e^- annihilation also show limiting fragmentation relative to the jet rapidity $y_{jet} = \ln(\sqrt{s}/M_j)$ [14], shown by the data points in Fig. 3.

This may have been expected, since it has been found by at least one author to be a theoretical expectation from pQCD[15]. In this work, it is similar to “Feynman scaling”, where cross sections are found to be invariant with x_F . This point is made clear by the simple relationship between x_F and y' , $x_F = (m_T/M_p) \exp(-y')$. Thus, it appears that Feynman scaling (invariance with x_F) appears to be a generic phenomenon in a variety of systems.

3. Landau Hydrodynamics and Multiparticle Production

It is not a tremendous conceptual jump to move from a discussion of multiplicity measurements to hydrodynamics. It was precisely the study of bulk features of multiparticle phenomena that led to the work of Fermi and Landau in the 1950’s [16, 17]. The fundamental innovation of Landau’s hydrodynamic model was not the use of relativistic hydrodynamics, which is well known and used in a variety of fields (astrophysics, cosmology). Rather, he made perhaps the most extreme assumptions to date of their domain of applicability, which is the moment of

total overlap of two subatomic projectiles. Since the hydrodynamic equations is scale-invariant, the theory can apply in principle to small systems, such as nucleon-nucleon collisions, as well as nuclear collisions, provided the interactions are sufficiently strong. Once the initial conditions are established, the subsequent evolution stems from the application of the hydrodynamic equations until the temperature is smaller than the pion Compton wavelength, or $T \sim m_\pi$, whereupon particles “freeze out” into non-interacting quanta. And yet, it should not be forgotten that Landau made no assumptions that the relevant degrees of freedom during the hydrodynamic evolution were in fact the final-state particles. Rather, he just assumed that full thermal equilibrium of whatever degrees of freedom were present (provided they obeyed the blackbody equation of state $p = \epsilon/3$) is maintained until freezeout [16, 18]. Thus, he arrived at a scenario where the only scales of the problem were the initial geometry, and the final temperature. Everything else derived from the universal application of the hydrodynamic evolution equations.

From this physics scenario, several simple results were achieved in them mid-1950s and explored more systematically in the 1970’s [19, 20]. The total entropy for a nucleon-nucleon collision, which is proportional to the measured multiplicity, was found to scale proportional to $s^{1/4}$, with the precise value of the exponent determined by the equation of state. The extension of the multiplicity formula to nuclear collisions turned out to be a simple linear scaling with the initial volume, which itself is proportional to N_{part} . This is because the initial energy density for p+p and A+A collisions at the moment of full overlap is the same in Landau’s scenario (even if an extremely large value $\epsilon \sim 4 \text{ TeV/fm}^3$ at RHIC energies!). Finally, the rapidity distribution of final state particles is expected to be a Gaussian with $\sigma = \sqrt{\ln(\sqrt{s}/2M)}$. This last result proved to be surprisingly close for data on rapidity distributions for p+p and heavy ion collisions, good to about 10% over a large range in $\sqrt{s_{NN}}$ [21]. Strangely, it also turned out to be a predicted behavior in some analytic pQCD calculations (e.g. [15]).

One unexpected result of the Landau formulas, combining the variation of the total multiplicity as well as the width of the rapidity distribution, is the presence of an approximate “limiting fragmentation” behavior in dN/dy [22, 23]. It is approximate since it is systematically violated with increasing energy, but very slowly, in a way that is consistent with existing $\bar{p}p$ and A+A data. And yet, it remains an intriguing result, since it implies some kind of accidental “ x_F scaling”, implicit in the model while not being an inherently-obvious consequence of the initial conditions, as mentioned in Ref. [19].

4. Implications and Problematics

The success of the Landau formulas is not trivial, as they ultimately predicted some features of bulk particle production which have eluded more sophisticated models. More importantly, the physical assumptions lead to results which are distinct from a popular scenario proposed by Bjorken in 1983 [24]. In Bjorken’s picture, Landau’s complete stopping is replaced by only a partial one, such that the particle production at mid-rapidity is causally disconnected from that at forward rapidities. This assumption leads directly to the assumption of “boost invariance” [25] implying flat rapidity distributions which are not observed in any system for which collider data is available. On the other hand, the presence of Gaussian rapidity distributions, as predicted by Landau, suggests that bulk features of soft particle production are not simply “thermal” behavior or “phase space” dominance, but a consequence of the rapid and powerful explosion of a highly-compressed initial state, which should thus be treated as collective and very strongly-interacting from very early times.

And yet, taking the Landau initial conditions seriously tends to evoke serious objections as well, since it requires thermalization times much shorter than previously envisioned, and which get shorter with increasing beam energy. And yet, if one accepts it for heavy ion collisions, one must be careful in categorically rejecting it for p+p and $\bar{p}+p$. The model was considered in those contexts at various times (e.g. by Cooper/Frye), and so was not always seen as illogical.

Moreover, as we have seen, many of the the bulk observables look similar, especially when one divides out the “trivial” volume factor of $N_{part}/2$. The typical objection to assuming any kind of “thermal” or “hydro” behavior in p+p is that the multiplicities in heavy ions are sufficiently large to make thermalization a reasonable assumption, while this is not true for elementary collisions [26]. Besides being a claim without quantitative justification at present, it seems to presume that thermalization is established by reinteractions of the final state particles and higher mass resonances [26]. This argument does not consider the possibility that the degrees of freedom of this “pre-matter” (a term coined by Carruthers [19]) may be entirely different than those afterward. These pre-hadronic degrees of freedom may be strongly interacting, but then convert into hadrons without introducing additional entropy (similar to the LPHD hypothesis).

One major objection to assuming any kind of thermalization in e^+e^- typically stems from the fact that perturbative calculations are able to reproduce even features of bulk particle production in jets, i.e. fragmentation products characterized by transverse momentum scales of 1 GeV or less. Given the peculiar agreement (to 10%, shown in Fig. 2 as “ e^+e^- fit”) between the multiplicity formulas extracted from the Landau-Fermi approach and that of Mueller [27] and others in perturbative QCD calculations, it seems that there are several logical options available. The correspondences between A+A and more elementary collisions are mere accidents, not worthy of further consideration. They may also reflect some trivial feature of particle production, e.g. “phase space dominance”. However, it is also possible that they reflect a similar underlying dynamical mechanism, which may well have an expression both in terms of hydrodynamics and quantum field theory, the choice of language being one of convenience relative to the problem at hand. Despite being a fairly radical-sounding suggestion, this last option is not logically excluded by the success of either hydrodynamics in A+A, or pQCD in e^+e^- . It may well provide an interesting way to look at the problem, suggesting that a primary question for the strong interaction is exactly how it is able to thermalize systems that should be too small and short-lived to achieve full equilibration. This does not seem to be the natural domain of pQCD, which deals with weakly interacting partons. And yet, we are becoming aware of other ways of approaching QCD more relevant to soft particle production (e.g. Color Glass Condensate [6], or the AdS/CFT correspondence [28]) which may well help us address the issues raised in this work.

References

- [1] Y. L. Dokshitzer, Phil. Trans. Roy. Soc. Lond. A **359**, 309 (2001).
- [2] V. Topor Pop *et al.*, Phys. Rev. C **68**, 054902 (2003).
- [3] G. Piller and W. Weise, Phys. Rept. **330**, 1 (2000).
- [4] P. F. Kolb and U. Heinz, arXiv:nucl-th/0305084.
- [5] B. B. Back *et al.*, Phys. Rev. Lett. **88**, 022302 (2002).
- [6] D. Kharzeev and E. Levin, Phys. Lett. B **523**, 79 (2001).
- [7] B. B. Back *et al.*, Phys. Rev. Lett. **91**, 052303 (2003).
- [8] J. E. Elias *et al.*, Phys. Rev. D **22**, 13 (1980).
- [9] B. B. Back *et al.*, arXiv:nucl-ex/0409021. B. B. Back *et al.*, arXiv:nucl-ex/0410022.
- [10] B. B. Back *et al.*, arXiv:nucl-ex/0301017.
- [11] E. K. G. Sarkisyan and A. S. Sakharov, arXiv:hep-ph/0410324.
- [12] M. Basile *et al.*, Phys. Lett. **B92**, 367 (1980). M. Basile *et al.*, Phys. Lett. **B95**, 311 (1980).
- [13] G. J. Alner *et al.*, Z. Phys. C **33**, 1 (1986).
- [14] B. B. Back *et al.*, arXiv:nucl-ex/0410022.
- [15] K. Tesima, Z. Phys. C **47**, 43 (1990).
- [16] L. D. Landau, Izv. Akad. Nauk Ser. Fiz. **17**, 51 (1953).
- [17] E. Fermi, Prog. Theor. Phys. **5**, 570 (1950).
- [18] S. Z. Belenkij and L. D. Landau, Nuovo Cim. Suppl. **3S10**, 15 (1956) [Usp. Fiz. Nauk **56**, 309 (1955)].
- [19] P. Carruthers, Annals N.Y.Acad.Sci. **229**, 91 (1974).
- [20] F. Cooper, G. Frye and E. Schonberg, Phys. Rev. Lett. **32**, 862 (1974).
- [21] I. G. Bearden *et al.*, arXiv:nucl-ex/0403050.

- [22] P. Steinberg, arXiv:nucl-ex/0405022.
- [23] P. Steinberg, arXiv:nucl-ex/0412009.
- [24] J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).
- [25] R. P. Feynman, Phys. Rev. Lett. **23**, 1415 (1969).
- [26] P. Braun-Munzinger, K. Redlich and J. Stachel, arXiv:nucl-th/0304013.
- [27] A. H. Mueller, Nucl. Phys. B **213**, 85 (1983).
- [28] H. Nastase, arXiv:hep-th/0501068.