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Collective Effects: the viewpoint of HEP MC codes

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Abstract

Collective effects are observed in high-multiplicity pp events, similar to the signals traditionally attributed to the formation of a Quark Gluon Plasma in heavy ion collisions. In core–corona models it is assumed that a partial plasma formation is indeed possible also in pp, but here the focus is on several recent models that attempt to explain pp data without invoking plasma formation. These attempts are partly successful, but there is still not a unified framework.

Keywords: collectivity, flow, small systems, jet universality, quark gluon plasma, event generators, hadronization

1. Introduction

The relationship between the pp and the AA communities at the LHC is changing. This has been brought about by a set of unexpected observations, wherein high-multiplicity pp events seem to attach smoothly to the behaviour observed in pA and AA collisions, with respect to flavour composition [1] and flow [2, 3, 4, 5, 6, 7].

For pp we have been used to a simple picture of hadronization, wherein the density of colour fields and hadrons has been assumed low enough that interactions between them can be neglected. Then e^+e^- and pp events should share many common traits, "jet universality". This picture is embedded in the greater context of event generators [8], wherein also all other aspects of pp events are simulated. These programs provide an overall description of event properties that in the past appeared reasonably successful, and that still today can describe the bulk of data distributions quite well.

For the AA community the key concept has instead been the Quark Gluon Plasma (QGP), how it is created, what properties it has, and how it reverts back to ordinary matter. Catchwords include deconfinement, hydrodynamics, flow, perfect liquid, and more, all unknown in traditional pp approaches. This split has been encouraged by standard QGP theory, where the belief has been that pp collisions cannot generate a sufficiently large volume sufficiently long for a QGP to form [9, 10, 11].

Thus both communities have acted to keep a barrier between pp and AA physics. But now it is time to open up the discussion and ask some tough questions. Is a QGP formed in high-multiplicity pp events? If not, what other mechanisms could one imagine as being at the origin of the observed pp behaviour? How can these be tested? Specifically, which are the ironclad signals of QGP formation?

Answering these questions will keep us busy in the years to come. In this talk some of the attempts already made will be discussed, within the context of the traditional event generators used to describe pp collisions. Other presentations at this conference provide the view from other vantage points.

2. pp physics and generators

Hadronization is traditionally assumed to be environment-independent. Since it is a nonperturbative process, free parameters are needed for incalculable quantities, but these can be determined e.g. from LEP e^+e^- data and then be applied unchanged for LHC pp collisions. The modelling of the partonic state that is to hadronize has to be different in the two processes, of course. In e^+e^- events only final-state radiation and hadronization needs to be considered, while the composite nature of the proton additionally leads to parton distribution functions, initial-state radiation, beam remnants, and multiparton interactions (MPIs) [12].

MPIs imply several subcollisions in an average pp event, typically with the outgoing scattered partons having $p_\perp$ scales of a few GeV and being colour-connected to the beam remnants. Thereby a number of colour confinement fields — strings [13] — are stretched essentially longitudinally between the two remnants. A rule of thumb is that a single string gives about one charged particle per unit of rapidity, i.e. a typical LHC value $\langle dn_{charged}/dy \rangle \approx 6$ would correspond to the order of six strings being pulled out. It is also useful to note that the tail to higher multiplicities is driven by events with many MPIs, rather than e.g. events with a pair of high-$p_\perp$ jets.

In such a picture there are no collective effects of any importance. The observation of a rising $\langle p_\perp \rangle (n_{charged})$ at the Sp$\overline{\mathrm{p}}$S was addressed by the introduction of Colour Reconnection (CR), however [14]. Here the colour fields of the event can be redirected, relative to the naive picture of colour-separated MPIs, in such a way that the total string length is reduced. Several different CR scenarios have been proposed, and for each such the $\mathcal{P}(n_{charged})$, $\langle p_\perp \rangle (n_{charged})$ and other data can be used to tune free parameters. CR can give some effects that are of a collective-flow character, by providing transverse boosts to reconnected string pieces, that e.g. gives heavier hadrons higher $\langle p_\perp \rangle$, but CR does not address many other issues.

Currently the most successful realistic approach to collective effects in pp is the core–corona one, as implemented in the EPOS event generator [15, 16]. In it the MPIs give rise to (mainly) longitudinally stretched strings. As long as these strings are well separated they hadronize independently, a "corona", but in case of close-packing they are assumed to collectively give rise to a local QGP, a "core", which expands according to hydrodynamics and hadronizes according to a statistical model. An event can be a mixture of the two. In low-multiplicity events only the corona may exist, but with increasing multiplicity the core fraction increases. EPOS works not only for pp events, but extends the same formalism to pA and AA, where the core QGP component dominates. Obviously this formalism is very economical, in that it does not require the introduction of any new principles. A smooth transition between two extreme behaviours is obtained by changing the admixture, but the core and corona components in a given event are discontinuously separated. EPOS is primarily a model for soft physics, however, not for hard processes and the underlying events associated with them, and therefore is not suited for much of the pp studies at the LHC.

The physics of EPOS is already well known within the AA community, and therefore it will not be discussed any further here. Instead the attention will be turned to other models that have been proposed, specifically within the context of the event generators normally used for pp studies. These are especially interesting insofar as they do not assume the formation of a QGP, but instead introduce alternative physics mechanisms that could be at play. The flip side is that these models are not yet extended to pA and AA collisions.

The three main pp event generators are Pythia [17, 18], Herwig [19, 20] and Sherpa [21]. While sharing the same overall common structure, there are still many physics differences, and philosophy ones.

- PYTHIA has its roots back in the string fragmentation studies in the late 70ies. A string can stretch e.g. from a quark end via a number of (colour-ordered) intermediate gluons to an antiquark end, and fragments along its full length [22]. Studies of soft physics have always been central, like MPIs and CR [12]. The Fritiof model for AA collisions [23, 24] was a separate offshoot, but recently the related Angantyr pA/AA model is a fully integrated part of PYTHIA [25]. Many other event generators are built on top of PYTHIA code, and so are most of the alternative scenarios to be discussed here.

- Herwig was begun in the mid-80ies, to study coherent parton shower evolution [26]. Hadronization is based on cluster fragmentation [27], wherein gluons are forced to break up into quark–antiquark pairs at the end of the shower, such that lower-mass clusters replace the long strings. Both MPIs and CR are modelled, but along somewhat different lines than in PYTHIA.

- SHERPA grew out of matrix-element generator activities in the late 90ies, and the focus of attention has been in the matching and merging of matrix elements and parton showers. Cluster fragmentation is default, but the program can be linked to PYTHIA for string fragmentation. The default MPI/CR machinery is inspired by the PYTHIA one, but the KMR model implemented in the SHRiMPS code will be made available as an alternative [28].

3. Flavour composition

A significant strangeness enhancement is observed in high-multiplicity pp events [1]. This is visible in K^0_S and Λ production, but in particular in the multistrange Ξ and Ω production. The proton fraction, on the other hand, remains fairly constant, so the effect does not appear to be related to baryon number or particle mass. ALICE shows that this phenomenon is not described by the standard string fragmentation framework, which has an essentially multiplicity-independent particle composition, while the core–corona model in EPOS has the right trends but overshoots, and the rope model in DIPSY/PYTHIA [29] provides a decent description. Let us study expectations further.

In the standard string model, the string tension κ is assumed to be a constant, $\kappa \approx 1$ GeV/fm. When such a string is pulled out between two receding colour charges, it can break by the production of a quark–antiquark pair that screens the endpoint colour charges. Such a break can be viewed as a tunneling process, where the pair is created in one common point but then q and $\overline{\mathrm{q}}$ each has to tunnel out a distance $d = m_{\perp\mathrm{q}}/\kappa$ to become on shell, where $m_{\perp\mathrm{q}} = m_{\perp\overline{\mathrm{q}}}$ is the transverse mass of the quark. This gives a relative probability

$$\mathcal{P} \propto \exp\left(-\frac{\pi m_{\perp\mathrm{q}}^2}{\kappa}\right) = \exp\left(-\frac{\pi p_{\perp\mathrm{q}}^2}{\kappa}\right) \times \exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa}\right) , \tag{1}$$

i.e. a common Gaussian $p_\perp$ spectrum for all quarks, and a suppression of the production of heavy quarks. Quark masses are ill-defined, so the strangeness suppression is viewed as a free parameter, of the order of 0.2 - 0.25, while charm and bottom are so suppressed that their nonperturbative production can be neglected. Other aspects also influence the meson production, such as the relative rate of pseudoscalars and vectors.

The real problem is baryon production. In the simplest approach a colour antitriplet diquark is viewed as equivalent to an antiquark, and produced by the same tunneling process as above. Different diquarks are again suppressed in relation to their squared masses, with some free parameters to represent the uncertainty in diquark mass patterns. Unfortunately the diquark model gives too strong a suppression of multistrange and spin-3/2 baryons. An extension is the popcorn model [30], wherein quark–antiquark pairs are created one at a time, and the suppression of rare hadrons is not as extreme, but still too large e.g. for Ω production. There are also problems e.g. with azimuthal correlations in baryon pairs [31], so it is clear we still lack some fundamental insight on baryon production, at least in the string context.

The transverse size of a string is of the order of the proton radius. Therefore, when two protons collide and several strings are formed by MPIs, it is almost unavoidable that these strings come to overlap in space–time. This has been used as an argument for colour reconnection, but otherwise the possibility of collective effects has largely been neglected. In the past few years some explicit models have appeared, however.

- The rope model [32, 33, 29] assumes that several nearby strings can be intertwined into a rope, which represents the field drawn out by the combination of several colour charges. Consider the example of two parallel strings, for which $3 \otimes 3 = 6 \oplus \overline{3}$, where the sextet has a Casimir colour factor $C_2^{(6)} = \frac{5}{2} C_2^{(3)}$. In the first break of such a rope the effective string tension is proportional to $C_2^{(6)} - C_2^{(3)}$, i.e. $\kappa_{\mathrm{eff}} = \frac{3}{2}\kappa$ should be used in eq. (1). For a second break (in the same region) the string tension is back to the normal one. For multiple (almost) collinear strings one could expect some kind of random walk in colour space, allowing higher colour charges to be reached, and thereby also larger κ_{eff}. In those string breaks the mass suppression of strangeness and baryon production would be reduced. The rope model describes the production of (multi)strange baryons fairly well, as already mentioned, but does predict a rise of the p/π ratio with increasing multiplicity, in conflict with data.
- Most simple CR models do not change the hadron composition, but a QCD-colour-factor-based CR model does [34]. Again consider the relation $3 \otimes 3 = 6 \oplus \overline{3}$, but now for the $\overline{3}$ possibility that two parallel strings may fuse to produce a normal string, although with the colour flow in the opposite direction. Near either endpoint, where either two q or two $\overline{\mathrm{q}}$ are located, the fused string needs to split into two that stretch to the two endpoint quarks, and the point of splitting is a so-called junction. It becomes associated with a baryon number, and an antijunction at the other end with an antibaryon. Since the number of reconnections increases faster than the number of individual strings, it means that the baryon fraction increases with multiplicity. Furthermore, since a junction baryon consists of the flavours produced at the three separate string breaks closest to the junction in each of the three string legs out from it, production of multistrange baryons is not suppressed by a large strange diquark mass in the tunneling expression. Qualitatively it therefore describes the ALICE trends of Ξ and Ω being more common at high multiplicities, but unfortunately some of the rise is also present for p and Λ.
- From ISR days (pp collisions up to $\sqrt{s} = 62$ GeV) it has been known that hadron production $p_\perp$ can be given a thermodynamical-like description, e.g. in terms of a mass-dependent $p_\perp$ spectrum
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_\perp} = N \exp\left(-\frac{m_{\perp\mathrm{had}}}{T}\right) \ , \ m_{\perp\mathrm{had}} = \sqrt{m_{\mathrm{had}}^2 + p_\perp^2} \ , \qquad (2)$$
where N and T are (approximately) common for all hadrons. An effectively exponential fall-off could arise also starting from the Gaussian one in eq. (1), assuming that the string tension is fluctuating along its length, also in the absence of other strings [35]. An option has been added to the Pythia string model based on an exponential suppression, but with local flavour and $p_\perp$ conservation [36]. Such an ansatz gives an overall decent description of the particle composition with only a few free parameters, but does overestimate the rate of multistrange baryons. A variable string tension or "temperature" is used in cases of close-packing of strings, with a continuous change as strings become squeezed into smaller transverse areas, with results similar to those of the (discrete-step) rope model.

In summary, a few different ways have been introduced whereby the string model can be made to display a rising trend of multistrange baryon production. All of them share the problem that this rise inherently is accompanied by a rise of the overall baryon production rate, in contradiction with ALICE data.

In Herwig the cluster model has been improved in two ways [37]. Firstly, if three quark–antiquark clusters are aligned in parallel, then the three quarks can reconnect to a baryon cluster, and the three antiquarks to an antibaryon one. Secondly, nonperturbative $\mathrm{g}\to\mathrm{s}\overline{\mathrm{s}}$ branchings have been introduced, in addition to the conventional $\mathrm{g}\to\mathrm{u}\overline{\mathrm{u}}$ and $\mathrm{g}\to\mathrm{d}\overline{\mathrm{d}}$ ones. Together these two changes gives significant improvements in a number of respects, such as the K/π and p/π $p_\perp$ spectra. The rate of Λ, Ξ and Ω production is significantly increased, even if still below data. The fraction of strange baryons increases with multiplicity, since the chance of baryon reconnections increases in events with many MPIs, but unfortunately then so does the fraction of protons, just like for the Pythia modifications.

4. Collectivity and flow

Colour Reconnection can induce some of the signals often attributed to collectivity. The rising $\langle p_\perp \rangle (n_{\mathrm{charged}})$ is a prime example. Without the CR, the event multiplicity would rise approximately proportionally to the number of MPIs, but with CR each further MPI contributes successively fewer further hadrons. Hence the perturbative $p_\perp$ associated with the MPIs is be shared among fewer hadrons, giving a larger average.

Heavier hadrons also have harder $p_\perp$ spectra, with K/π and p/π $p_\perp$ yield ratios that increase rapidly from almost zero at low $p_\perp$ scales to maximal at around 2–3 GeV [38, 39], in decent agreement with EPOS and Pythia. Three effects contribute: resonance decays, which tends to produce many π at small $p_\perp$ values, (mini)jet fragmentation, wherein heavier hadrons take a larger fraction of the parton momentum, and transverse string (or cluster) boosts, wherein a string piece moving with a fix transverse velocity will impart that velocity (on the average) to the hadrons produced from its fragmentation. The latter mechanism is enhanced significantly by CR [5]. The p/π fraction drops above the peak position, and this drop is underestimated e.g. in Pythia [5], suggesting that the transition to baryon production in jets is not so well modelled.

In a related characterization, the $\langle p_\perp \rangle$ is rising significantly as a function of the hadron mass [6], which could be interpreted as a sign of collective flow. The same three mechanisms as above combine to produce a decent description in Pythia and Sherpa. The trend is somewhat underestimated, however, and this gap is difficult to close [36]. A model with an exponential $m_\perp$ spectrum, e.g., intrinsically does give a steeper $\langle p_\perp \rangle(m_{\mathrm{had}})$ than the Gaussian $p_\perp$ default, and so should fit better. But most pions come from decays of heavier particles and thus pion changes are more related to the m_ρ scale than to the m_π one, thereby suppressing differences. Likely some reasonable amount of hadronic rescattering in the final state is needed to bring agreement between data and models. This is already standard in AA generators, using programs such as UrQMD [40] or SMASH [41]. As a first step, the space–time production process in string fragmentation has recently been mapped out [42], confirming that indeed hadrons are produced very closely packed.

One of the most spectacular signals of collective behaviour is the ridge effect [2, 3, 4], which is not predicted in conventional pp models. It is possible to obtain a realistic model [43] based on the concept of shoving [44], i.e. that strings that overlap in space–time repel each other and thereby build up a transverse velocity. Initially strings are assumed to have zero width, but as they are pulled out in the longitudinal direction they also grow towards full transverse size. Therefore shoving always start at the middle of the local longitudinal rest frame and spreads outwards. For a practical implementation the event is sliced up into one unit wide rapidity ranges, and the net amount of shove on each string spanning that range is calculated. The resulting transverse momentum kick — balanced so as to preserve total momentum — is represented by a single gluon located along the string at the relevant rapidity. The shoving effects on azimuthal correlations become more important at higher multiplicities, in good agreement with data.

Collective flow can be characterized by the commonly-used v_n coefficient, which are non-vanishing not only in AA but also in pp collisions [4, 7]. Part of this "flow" in pp comes from trivial sources, such as back-to-back (mini)jet pairs, but also colour reconnection and string shoving can contribute to the overall level of the signal e.g. in $v_2\{2\}$ [45]. Unfortunately this signal is reduced appreciably when a gap is added to the $v_2\{2\}$ extraction, and the enhancement from CR is almost gone, while shove still gives a small positive contribution. Further studies are under way.

In summary, we have bits and pieces of an understanding how collective flow can arise in pp also without a QGP, but not yet a complete view.

5. Summary and outlook

While a number of interesting and revealing studies have appeared in recent years, the multiplicity dependence of different pp event properties could be investigated further. Are there signs of jet quenching at high multiplicities? A pattern of gradual $\Upsilon(1\mathrm{s}, 2\mathrm{s}, 3\mathrm{s})$ suppression? A changing temperature of a soft prompt photon spectrum? Changing flavour correlations, e.g. between baryons and antibaryons? Is the flavour composition in jets more similar to $\mathrm{e}^+\mathrm{e}^-$ events or to the underlying event? And so on.

Some of these issues can be studied in the context of existing models coming from the AA side, such as core–corona ones. A shortcoming of implementations such as the EPOS generator is that these are focused on soft physics, and therefore do not currently have the full capability to study the interplay between hard and soft aspects. This is where traditional pp event generators such as Pythia, Herwig and Sherpa may offer an advantage. But for too long it was assumed that the combination of multiparton interactions and colour reconnection would generate all the collective effects needed to offer a reasonable description in pp, although we always knew that strings or clusters by necessity would come to be closely packed during the hadronization process, and that this should have repercussions. This is what we now try to remedy. Effects can occur before the strings/clusters start to hadronize, exemplified by shoving or junction formation, during it, like ropes or a gradual change of the string tension, or after it, like hadronic rescattering. So far the formation of a QGP has not been invoked, however, so comparisons with EPOS will remain relevant where possible.

Quite apart from the close-packing issues, but probably exacerbated by them, current models for baryon production fail to provide a convincing description. The string model with a Gaussian suppression of quark and diquark masses, or for that matter an alternative with a Gaussian suppression of hadron masses, suppresses the heavier multistrange baryons too much, while an alternative exponential formulation provides too little suppression. Correlations also are poorly described.

While we do have problems, recent and ongoing studies show that all is not hopeless. Some of the ideas do seem to provide a better understanding of data, but more is needed. It is also necessary to combine all the new pieces into a consistent framework. This could be achieved by upgrading existing AA-style generators to provide more complete descriptions of all kinds of pp event, or by extending pp generators to also simulate AA collisions. A simple stacking of (soft and hard) pp events here offers a possible starting point [46], but the Angantyr model is somewhat more sophisticated, with further developments intended to provide realistic descriptions of all pp/pA/AA collision types.

A key objective for current and future studies should be to better understand which experimental features are ironclad signatures of the formation of a quark gluon plasma, and which could be explained by other effects. The alternative explanations would likely also be of a collective character, like the models presented here, but not require a phase transition to another state of matter.

In summary, a whole new field of study has opened up in the last few years, and (seemingly?) made the borders between pp, pA and AA events crumble. Further experimental input will be crucial to understand what is going on, with model building in the context of event generators offering the main route to providing a global view of all possible effects.

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