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Modelling pp, pA and AA in Pythia8

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Abstract. We present a new model for generating complete exclusive hadronic final states in high energy collisions involving heavy ions. The model is called Angantyr and is inspired by the old Fritiof model, building on the concept of wounded nucleons.

1 Introduction

As of version 8.230, the Pythia8 program [1] is able to generate complete exclusive hadronic final states in high energy collisions involving heavy ions. The model used for this is called Angantyr and is built on the ideas presented in [2] and elaborated in detail in a recent article [3]. Here we will present the main features of this model together with some sample results and predictions.

The main idea is to use the fact that Pythia8 gives a very realistic description of proton–proton collision events, both for minimum bias and hard-scale collisions, and to extend this to describe individual nucleon–nucleon collisions in heavy ion collisions. In doing so we try to limit the introduction of extra parameters as far as possible.

2 The main ingredients

The Angantyr model can be said to be a development of the Fritiof program [4, 5] which gave a very reasonable description of lower energy heavy-ion collisions. That program was based on the concept of wounded nucleons [6] where participants in a collision populates the final state with hadrons according to a multiplicity function. In Fritiof this was achieved by stretching out a string from each wounded nucleon according to a mass distribution $\propto dM^2/M^2$ which was subsequently hadronised using the Lund string fragmentation model [7, 8].

At the high energies achievable today at eg. the LHC, we know that hard processes become increasingly important, and it is not possible to to use only non-perturbative string fragmentation to describe the particle production. Perturbative parton showers and multiple (semi-hard) scatterings are crucial ingredients needed to get a good description of hadronic final states for energies around 100 GeV and beyond, and the starting point for Angantyr is the comprehensive set of models for this implemented in Pythia8.

Perturbative processes give large fluctuations in the distribution of final state hadrons, but also the fluctuations in the initial state are important. Besides fluctuations in the positions of the nucleons in a nuclei, also fluctuations in the wave function of individual nucleons need to be taken into account, as was pointed out long ago by Gribov [9], and more recently discussed by Strikman et al. (see eg. [10, 11]). The latter resulted in the so-called Glauber–Gribov model where a fluctuating nucleon–nucleon cross section is introduced, which gives interesting results for pA collisions (see eg. [12]). In order to also treat fluctuations in AA collisions we have in Angantyr developed this model further to treat fluctuations in the individual nucleons rather than only looking at the combined fluctuations in the cross section.

Fluctuations in the nucleon wave function are related to diffractive excitation, as is manifest in the Good–Walker formalism [13, 14], and in our implementation the fluctuations are parameterised in a way such that both the non-diffractive and diffractive nucleon–nucleon cross sections are well reproduced. In this way we can for any nucleon–nucleon pair in a heavy ion collision model the probability, not only that the pair interacts, but also if the interaction is diffractive or non-diffractive, as described in [3].

In a heavy ion collision a single projectile nucleon may interact with several target nucleons and vice versa. If an interaction is non-diffractive it is in principle easy to model the corresponding contribution to the final state as a single pp event generated by Pythia8. However, if a nucleon interacts non-diffractively with several others, there are nuclear shadowing corrections as well as effect of momentum conservation to take into account. In Angantyr the strategy is to order each possible nucleon–nucleon interaction in increasing impact parameter. The resulting list is then iterated over, and each time an interaction is found where neither of the participating nucleon pair has been wounded in a previous interaction, it is labelled *primary*, and a corresponding nucleon–nucleon sub-event is generated using the full pp machinery in Pythia8. If, however, one of the nucleons has already been wounded, the interaction is labelled *secondary*.

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Primary non-diffractive interactions are simply generated as a normal Pythia minimum bias event. A secondary non-diffractive interaction, on the other hand, is treated as a singe additional additional wounded nucleon. Here we take inspiration from from the Fritiof program where a wounded nucleon contributes to the final state with a string stretched out, corresponding to a diffractive excitation with a diffractive mass distribution $\propto dM^2/M^2$. Rather than a single string, however, we use the full Pythia8 machinery for single diffractive excitation where the diffractive system is treated as a non-diffractive Pomeron–nucleon scattering (à la Ingelman–Schlein [15]) including perturbative parton showers and multiple semi-hard scattering.

In [3] we describe in some detail how we adjust the parameters in Pythia8 to make these events look as much as possible as standard non-diffractive nucleon–nucleon events in the direction of the wounded nucleon. The thus produced diffractive event is then stripped of the elastically scattered nucleon before being added to the sub-event of the corresponding primary interaction.

After the non-diffractive sub-events have been generated in this fashion, the list of interactions is iterated over again to treat also purely diffractive nucleon–nucleon interactions as detailed in [3]. In the end all the produced sub-events are merged together with nucleus remnants, consisting of all non-interacting nucleons, into a single nucleus–nucleus collision.

It should be stressed that the sub-events are currently added together without any modelling of possible collective effects in the final state. Since it is firmly rooted in Pythia8 with its excellent modelling of high energy hadron collisions, Angantyr should therefore give a very reasonable extrapolation of proton–proton dynamics to heavy ions *in the absence of* collective effects such as hydrodynamical evolution. As such it is very useful for estimating non-collective effects on experimental observables of collectivity. But it also provides a testbed for investigating different models of collectivity. We have recently developed two such models based on string interactions, called “Rope hadronisation” [16] and “String shoving” [17], giving encouraging results in pp, and we plan to study these for heavy ions using the Angantyr model.

3 Sample results

We will here present a small sample of results to show that the Angantyr model actually gives a quite good description of the overall particle production in heavy ion collisions. We start by looking at pA collisions, both because they are a natural step between pp and AA, and because they are especially sensitive to the secondary wounded nucleons described above (as there can be at most one primary collision).

The majority of all experimental pA and AA results are presented as a function of percentiles of centrality. Centrality is often based on an observable measuring the activity in the forward region, and is assumed to be well correlated with the overlap of the colliding ions, ie. the overall impact parameter. However, in pA one would expect that this correlation may be weaker, especially for the most central events where the activity in the A-direction may be more sensitive to final-state fluctuations than to small changes in impact parameter.

In figure 1 we show the distribution in the summed transverse energy in the lead direction, $\sum E_\perp^{Pb}$, for pPb collisions at $\sqrt{s_{NN}}$=5 TeV, which is used by ATLAS as a centrality measure [12]. Please note that the data has not been properly unfolded to particle level, so it is difficult to make a completely fair comparison with the Angantyr result. However, it should be clear from the figure that Angantyr gives a reasonable description of the observable. In [3] we show that the observable indeed correlates very poorly with the impact parameter for high $\sum E_\perp^{Pb}$.

In figure 1 we also show the average charged multiplicity as a function of pseudo rapidity in percentile bins of centrality. Here the ATLAS data has been unfolded, but the comparison with Angantyr still contains uncertainties because of the the binning in centrality. To quantify this we have made two different centrality binnings, one based on the experimentally measured $\sum E_\perp^{Pb}$ spectrum and one based on the generated one. The difference is less than 5% and for both cases Angantyr gives a quite satisfactory description of the experimental distributions.

In AA collisions, the centrality observable is less sensitive to final-state fluctuation in central collisions, simply because the the number sub-collisions are so large that such fluctuations are evened out. This also means that basically any reasonable observable based on (forward) event activity will give a good correlation with the impact parameter of a collision when divided into percentiles, especially for central events. Hence, in figure 2 where we look at AA collisions, we use the same centrality observable as for pA above when we compare to ALICE[1] data. In figure 2a we show the average central multiplicity as a function of centrality for PbPb and XeXe collisions as measured by ALICE [18, 19] and it is clear that Angantyr fairly well describes the data. The fact that the dashed lines in the figure, where centrality is binned using the generated impact parameter, is barely visible under the full lines, is a strong indication that the dependence on the choice of centrality observable much smaller here than in pA. In figure 2b, we show the average number of participants as a function of centrality, as calculated using a standard Glauber calculation in [18] compared to the Angantyr calculation. The fact that they agree very well, even though Angantyr includes fluctuations which are absent in the calculation by ALICE, is an indication that also here the fluctuations are washed out due to the sheer multitude of collisions.

In [3] we describe the sensitivity of the Angantyr description of data to the different choices and parameters in the model. It must be pointed out, however, that while the description of pA data can be tuned somewhat, the extrapolation to AA is quite robust. In this connection we want to emphasise that the Pythia8 version used to produce our

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[1] In addition, the centrality observable used by ALICE is extremely difficult to compare with anything that is easily measured in the Angantyr event output.

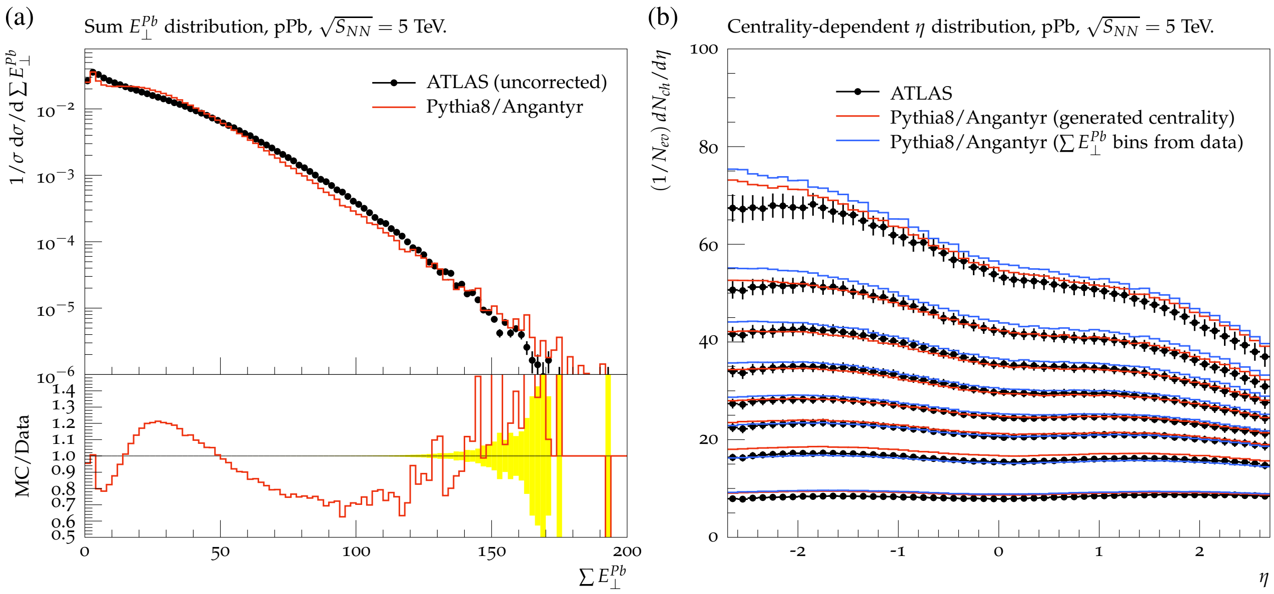

Figure 1. (a) The summed transverse energy in the lead direction ($-4.9 < \eta < -3.2$) for pPb collisions at $\sqrt{s_{NN}}$=5 TeV, as measured by ATLAS [12], compared to results from Angantyr. (b) Comparison between the average charged multiplicity as a function of pseudo rapidity in percentile bins of centrality for pPb collisions at $\sqrt{s_{NN}} = 5$ TeV as measured data from ATLAS [12] and the results from Angantyr. The red line is binned using percentiles of the generated $\sum E_\perp^{Pb}$ spectrum, and the blue line according to the experimental distribution (from top to bottom the centrality is: 0–1%, 1–5%, . . . , 60–90%).

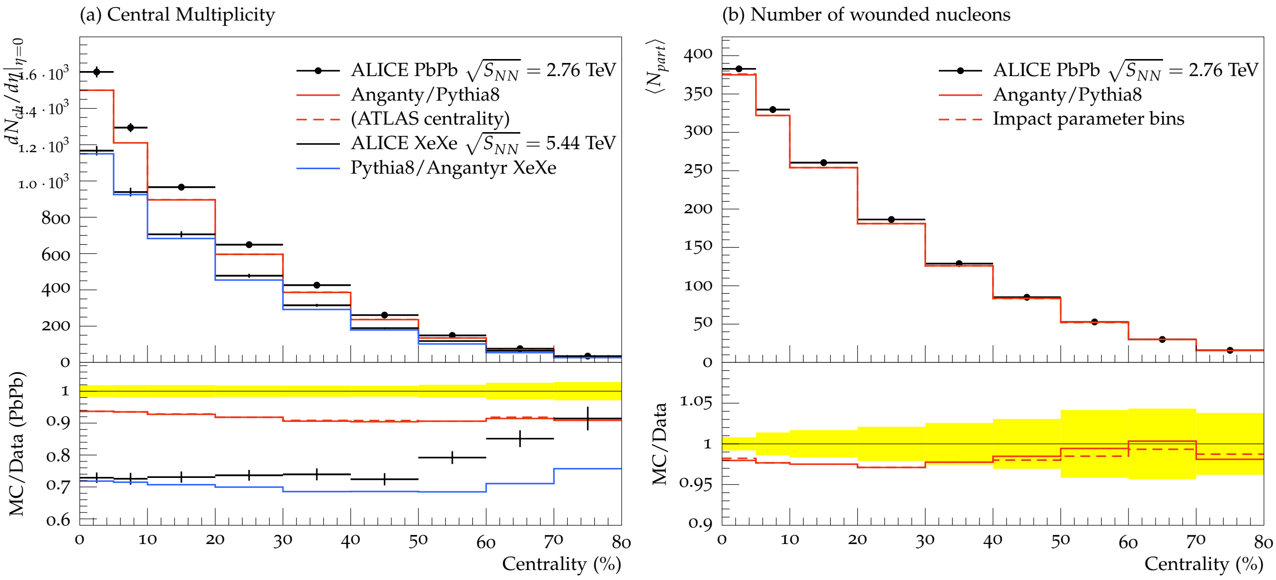

Figure 2. (a) The centrality dependence of the average charged multiplicity in the central pseudo-rapidity bin for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and XeXe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. Data points are from ALICE [18] (PbPb) and [19] (XeXe), while red (PbPb) and blue (XeXe) lines are from Angantyr. (b) Shows the averaged number of wounded nucleons as a function of centrality. The points are from a Glauber-model calculations from ALICE [18], while the red line is the result from Angantyr. For comparison the dashed line, (barely visible under the corresponding full ones) shows the number of wounded nucleons as a function of percentiles in generated impact parameter in Angantyr.

predictions for the XeXe data was released well before the experimental results [19] were published.

4 Outlook and comments

Pythia8 is now able to simulate any collision between any nuclei. It should be noted, however, that the parameterisation used for the distribution of nucleons in impact-parameter space (taken from [20, 21]) is only valid for $A \geq 16$, and for lighter nuclei the parameters need to be set by hand. Furthermore, the parameterisation in Pythia8 of the semi-inclusive cross nucleon–nucleon sections are not well constrained for very low energies, so also here there is a need for manual intervention.

In general it should be noted that Pythia was developed with high energy collision experiments in mind, and Angantyr has the same limitations. This means that for energies below ~ 10 GeV the results may not be trustworthy. Also the far forward proton region (and for Angantyr the far forward ion region) is normally not very well described, which may limit its usefulness for high energy cosmic ray physics.

Angantyr will be developed further. Besides the inclusion of final state collective effects based on string interactions mentioned above, as well as minor technical improvements, a major new development will be to implement lepton–ion scatterings, both for DIS and photoproduction.

For the development of event generators and their underlying models, the availability of data that is easily comparable to generator output is essential. For proton–proton collisions, this has been formalised by the Rivet program [22] where the experiments themselves submit their measurement data, properly corrected for detector effects and unfolded to particle level, together with the analysis code needed to compare directly to event generator output. The work has now begun to also allow Rivet to do the same for heavy-ion collisions. If the experiments commit to publishing their heavy-ion analyses in this framework, this may enable also heavy-ion generators (in general, not only Angantyr), to develop much further and become reliable tools also for the heavy-ion community.

References

[1] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, Comput. Phys. Commun. **191**, 159 (2015), `1410.3012`

[2] C. Bierlich, G. Gustafson, L. Lönnblad, JHEP **10**, 139 (2016), `1607.04434`

[3] C. Bierlich, G. Gustafson, L. Lönnblad, H. Shah (2018), `1806.10820`

[4] B. Andersson, G. Gustafson, B. Nilsson-Almqvist, Nucl. Phys. **B281**, 289 (1987)

[5] H. Pi, Comput. Phys. Commun. **71**, 173 (1992)

[6] A. Bialas, M. Bleszynski, W. Czyz, Nucl. Phys. **B111**, 461 (1976)

[7] B. Andersson, G. Gustafson, B. Söderberg, Z. Phys. **C20**, 317 (1983)

[8] B. Andersson, G. Gustafson, Z. Phys. **C3**, 223 (1980)

[9] V.N. Gribov, Sov. Phys. JETP **29**, 483 (1969), [Zh. Eksp. Teor. Fiz.56,892(1969)]

[10] H. Heiselberg, G. Baym, B. Blaettel, L.L. Frankfurt, M. Strikman, Phys. Rev. Lett. **67**, 2946 (1991)

[11] M. Alvioli, B.A. Cole, L. Frankfurt, D.V. Perepelitsa, M. Strikman, Phys. Rev. **C93**, 011902 (2016), `1409.7381`

[12] G. Aad et al. (ATLAS), Eur. Phys. J. **C76**, 199 (2016), `1508.00848`

[13] M.L. Good, W.D. Walker, Phys. Rev. **120**, 1857 (1960)

[14] H.I. Miettinen, J. Pumplin, Phys. Rev. **D18**, 1696 (1978)

[15] G. Ingelman, P.E. Schlein, Phys. Lett. **152B**, 256 (1985)

[16] C. Bierlich, J.R. Christiansen, Phys. Rev. **D92**, 094010 (2015), `1507.02091`

[17] C. Bierlich, G. Gustafson, L. Lönnblad, Phys. Lett. **B779**, 58 (2018), `1710.09725`

[18] K. Aamodt et al. (ALICE), Phys. Rev. Lett. **106**, 032301 (2011), `1012.1657`

[19] S. Acharya et al. (ALICE) (2018), `1805.04432`

[20] W. Broniowski, M. Rybczynski, P. Bozek, Comput. Phys. Commun. **180**, 69 (2009), `0710.5731`

[21] M. Rybczynski, G. Stefanek, W. Broniowski, P. Bozek, Comput. Phys. Commun. **185**, 1759 (2014), `1310.5475`

[22] A. Buckley, J. Butterworth, L. Lönnblad, D. Grellscheid, H. Hoeth, J. Monk, H. Schulz, F. Siegert, Comput. Phys. Commun. **184**, 2803 (2013), `1003.0694`