LU TP 15-35
MCnet-15-26
September 2015

Hard Diffraction in Pythia 8

Christine O. Rasmussen

Theoretical Particle Physics,
Department of Astronomy and Theoretical Physics,
Lund University,
Sölvegatan 14A,
SE-223 62 Lund, Sweden

Abstract

We present an overview of the options for diffraction implemented in the general–purpose event generator Pythia 8. We review the existing model for low– and high–mass soft diffraction and present a new model for hard diffraction in pp and $p\bar{p}$ collisions. Both models uses the Pomeron approach pioneered by Ingelman and Schlein, factorising the single diffractive cross section into a Pomeron flux and a Pomeron PDF. The model for hard diffraction is implemented as a part of the multiparton interactions framework, thereby introducing a dynamical rapidity gap survival probability that explicitly breaks factorisation.

Presented at the 16th conference on Elastic and Diffractive scattering (EDS Blois 2015)

1 Introduction

While most phenomena in high–energy hadronic collisions have been explained by QCD, the effects of the softer hadronic collisions remains a mystery. We observe these collisions in experiments, and can motivate why they should be present, but the explanation of how they occur is still largely based on phenomenological models. These models should be able to describe all aspects of such collisions, like differential cross sections, one–particle distributions and global event characteristics. The models should also describe the exclusive topologies of these softer collisions, specifically the occurrence of rapidity gaps.

Many models, including the models used in Pythia 8 [1], are based on Regge theory. In this theory, poles in the plane of complex spin α can be seen as hadronic resonances. These appear to lie on linear trajectories, $\alpha(t) = \alpha(0) + \alpha' t$. Most important for high-energy collisions is the Pomeron ($\mathbb{P}$) trajectory, with its $\alpha(0) > 1$ explaining the rise of the total cross section. This state is a colour-singlet carrying the quantum numbers of the vacuum. From a modern viewpoint it (predominantly) consists of gluons and could thus be called a glueball, or a gluonic ladder if present in the final state (a cut Pomeron). A topological expansion can be defined, with increasingly complex processes. The simplest possible exchange is a single–Pomeron one, which gives rise to elastic scattering. Multi–Pomeron exchange is also possible, e.g. involving the triple–Pomeron vertex. This way various diffractive topologies can be constructed. In this paper we focus on the single diffractive (SD) topologies, since these have the largest diffractive cross section and form the starting point on the road towards more complex configurations.

Ingelman and Schlein [2] proposed a model in which the exchanged Pomeron can be viewed as a hadronic state. This opened up the possibility for using Pomeron parton distribution functions (PDFs) to be combined with a probability for taking out a Pomeron from the initial hadronic state, the Pomeron flux. The diffractive system can be viewed as a hadron–hadron collision at reduced energy, and existing hadron–hadron event generators can be used for modelling the diffractive events. The simplest model does not allow for multiparton interactions (MPIs), however, or equivantly for the final–state effects of multiple cut Pomerons. These MPIs create additional colour strings in the event, each string giving rise to hadronic production. Hence we risk filling up the rapidity gap created by the exchange of the 'first' Pomeron. As a rapidity gap is needed to trigger on diffractive events, we risk losing a large fraction of the could–have–been diffractive events by these MPIs. This introduced the concept of rapidity gap survival probability (RGSP), which is unique to hadron–hadron collisions, given credibility by the lower observed rate of hard diffractive processes at the Tevatron than expected from HERA flux/PDF determinations [3].

2 Soft diffraction in Pythia 8

The soft diffraction machinery available in Pythia 8 was originally developed for Pythia 6 [4], but rewritten and expanded for the new version, and now includes both single–, double– and central–diffractive systems (SD, DD, CD) as well as elastic collisions and non–diffractive topologies [5]. The total hadronic cross section is calculated using the Donnachie–Landshoff parametrisation [6], with a Pomeron and Reggeon term. The elastic and diffractive cross sections are based on the Schuler–Sjöstrand model [7] and the non–diffractive cross section is inferred from these two models.

The Schuler-Sjöstrand model is also based on Regge theory and gives an approximate dM/M^2 mass dependence as well as an exponential t dependence. Fudge factors have been introduced to the model, to dampen the cross sections close to the kinematical limits, as well and to dampen the DD cross section where two diffractive systems overlap. Other Pomeron–flux models have also been implemented in Pythia 8 (see the manual [8]). The subsequent hadronisation of a diffractive system is a separate chapter, and the same for all Pomeron–flux models. Particle production depends strongly on the mass of the diffractive system, however, and hence it has been split into two regions.

2.1 Low–mass soft diffraction

In the low–mass regime, $M \leq 10$ GeV, energies are not sufficiently high to apply a perturbative framework to the Pomeron–proton subcollision. Instead we visualise the event as an interaction where the Pomeron has "kicked out" a parton from the diffractively excited hadron. If a valence quark is kicked out then a single colour string is stretched between it and the diquark remnant. A kicked–out gluon gives a hairpin string topology, stretching from one quark in the proton remnant to the gluon and then back to the remaining diquark of the remnant. The probability for the Pomeron to interact with either a quark or a gluon is mass–dependent, $P(q)/P(g) = N/M^p$ with p being a tunable parameter, making the gluons dominate at higher mass. There are no additional MPIs in the low–mass regime. The strings are hadronised using the Lund string fragmentation model [9] and gives rise to low–p_T activity in the diffractive system.

2.2 High–mass soft diffraction

In the high–mass regime, $M > 10$ GeV, a perturbative description is attempted. So as not to give any discontinuies, and possibly also representing a real physics evolution, the fraction of perturbative events gradually increases with M and dominates for $M > 20$ GeV.

In the new component the Pomeron is viewed as a particle with partonic content a la Ingelman and Schlein. Thus, once M and t have been selected, the system is set up as a $\mathbb{P}$p collision and a semi–hard perturbative $2 \to 2$ partonic interaction is selected by the MPI machinery. Inside the Pomeron–hadron system the full interleaved evolution of initial– and final–state showers (ISR and FSR) and MPI is applied using the Pomeron PDFs. The MPI activity in the subsystem has been tuned to give approximately the same amount of activity as in non–diffractive events of the same mass, by introducing an effective total Pomeron–proton cross section. This (tunable) total cross section is set to a constant value of 10 mb, slightly higher than other numbers found in the literature. The colour strings obtained in the evolved diffractive system are hadronised using the Lund string fragmentation model. Jets can be produced in the $2 \to 2$ partonic processes.

Although the models for soft diffraction available in Pythia 8 are largely successful, some minor issues show up. Not all aspects of the data are described using the default model and settings, both on the level of differential cross sections and on that of particle spectra. A retune of parameters used in the default model could fix some issues, in particular if allowing for more flexible shapes e.g. for the Pomeron flux. We intend to improve the default models in the near future.

3 The new model for hard diffraction in Pythia 8

The model described above does allow for QCD $2 \to 2$ processes at all p_T scales, but is primarily intended for lower p_T values. It is not intended for the study of truly hard processes, either in QCD or beyond. Instead a model for hard diffraction has been developed [10] based on the assumption that the proton PDF can be separated into a non–diffractive and a diffractive part, with the diffractive part described using the factorisation approach,

$$f_{i/\mathrm{p}}(x,Q^2) = f^{\mathrm{ND}}_{i/\mathrm{p}}(x,Q^2) + f^{\mathrm{D}}_{i/\mathrm{p}}(x,Q^2),$$

$$f^{\mathrm{D}}_{i/\mathrm{p}}(x,Q^2) = \int_x^1 \int_{t_{min}}^{t_{max}} \mathrm{d}t\ \mathrm{d}x'\ \mathrm{d}x_{\mathbb{P}}\ f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}},t)\ f_{i/\mathbb{P}}(x',Q^2)\ \delta(x - x'x_{\mathbb{P}})$$

$$= \int_x^1 \frac{\mathrm{d}x_{\mathbb{P}}}{x_{\mathbb{P}}}\ f_{\mathbb{P}/\mathrm{p}}(x_{\mathbb{P}})\ f_{i/\mathbb{P}}(\frac{x}{x_{\mathbb{P}}},Q^2). \tag{1}$$

The probability of diffraction on one side is then given as the ratio of diffractive to inclusive PDFs,

$$P^{\mathrm{D}}(x_i,Q^2) = f^{\mathrm{D}}_{i/\mathrm{p}}(x_i,Q^2)/f_{i/\mathrm{p}}(x_i,Q^2). \tag{2}$$

At high energies most interactions occur at low x where $P^{\mathrm{D}}(x,Q^2) \sim 0.1$. Hence we expect approximately 10–15% of the events to be diffractive based only on Eq. 2.

In addition the model implements a dynamical gap survival. This means we do not allow any further MPIs to occur between the two incoming hadrons, so as to ensure the gap survives. In practise the tentative classification as diffractive, based on Eq. 2, initially has no consequences: all events are handled as non–diffractive hadron–hadron collisions. Only if no additional MPIs occur does a diffractive classification survive and only then is the $\mathbb{P}$p subsystem set up. A full evolution of ISR, FSR and MPIs is performed in this $\mathbb{P}$p system, along with hadronisation of the colour strings in the event. At this stage all non–diffractive events can be discarded for a pure diffractive sample, or can be kept and hadronised as usual for an inclusive sample.

The restriction on the number of MPIs in the hadron–hadron system introduces an additional suppression factor of ~ 0.2. With this method we can explain the observed “factorisation breaking” at the Tevatron, without introducing any new parameters. Our model predicts approximately 2–3% diffractive events without phase–space cuts, e.g. in diffractive Z–production in p$\bar{\mathrm{p}}$ at $\sqrt{s} = 1.8$ TeV we obtain 2.64%, where data from D0 implies approximately 1.44% [11]. Restricting the phase space in the event generation, by applying the cuts used in the experiments, further reduces the fraction of diffractive events, bringing our model closer to data. But the fraction of diffractive events is not the complete story. The model should also be able to describe particle spectra, and it is thus important to compare the kinematical distributions to data.

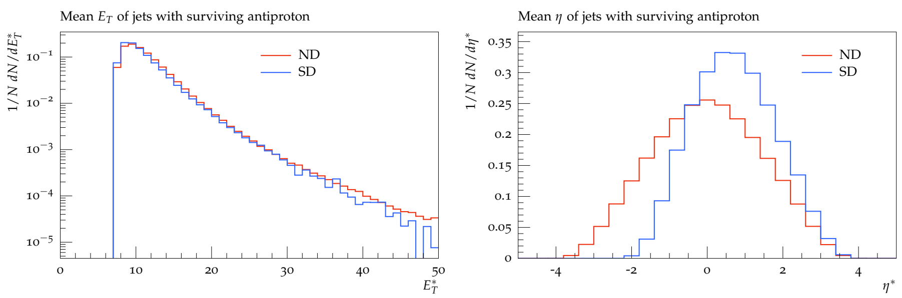

Figure 1: Kinematical distributions of diffractive dijet (SD) events compared to non–diffractive dijet (ND) events in p$\bar{\mathrm{p}}$ collisions at $\sqrt{s} = 1.8$ TeV obtained with Pythia 8.

In Fig. 1 we show some preliminary results obtained with the new model. We study diffractive dijet production at the Tevatron, p$\bar{\mathrm{p}} \to \bar{\mathrm{p}}X, [X \to JJX']$ at $\sqrt{s} = 1.8$ TeV. We show the mean E_T and η distributions, where the data obtained at the Tevatron showed significant differences compared to non-diffractive dijet events. SD data revealed a faster falloff in the mean E_T distribution compared to ND events, and the events were shifted towards positive η, the proton direction. These differences implied a steeper x dependence in the SD events than in ND events.

Unfortunately, our model does not capture all of these effects. The SD events generated with the new model are boosted towards positive η which is fine, but the falloff in E_T^* is not significantly steeper than the ND distribution. Our model simply allows for too many high–p_T events. While it may not solve all problems, we intend to develop a new description of the Pomeron flux to improve this spectrum. This should also improve the soft diffraction model implemented in Pythia 8.

4 Conclusion

We have presented a review of the soft diffraction models implemented in the general–purpose event generator Pythia 8. This soft diffraction machinery allows for QCD interactions and gives an decent description of diffractive phenomena. Comparisons to data shows that there is room for improvement in the default settings and a new parametrisations of the Pomeron flux is called for. A new model for hard diffraction has also been presented, now for the first time allowing for non–QCD processes as well has very high–p_T QCD processes in diffractive systems. The model is successful in describing the RGSP, and diffractive fractions obtained with the model agrees reasonably with data. Particle spectra obtained with the model has been compared to the data, unfortunately not capturing all aspects of the data. Hence the required improvements and updates needed in the soft diffraction regime is also needed in the model for hard diffraction.

Acknowledgements

Work supported by the MCnetITN FP7 Marie Curie Initial Training Network, contract PITN-GA-2012-315877.

References

[1] T. Sjöstrand *et al.*, Comput. Phys. Commun. **191** (2015) 159 [arXiv:1410.3012 [hep-ph]].

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

[3] T. Affolder *et al.* [CDF Collaboration], Phys. Rev. Lett. **84** (2000) 5043.

[4] T. Sjöstrand, S. Mrenna and P. Z. Skands, JHEP **0605** (2006) 026 [hep-ph/0603175].

[5] S. Navin, arXiv:1005.3894 [hep-ph].

[6] A. Donnachie and P. V. Landshoff, Phys. Lett. B **296** (1992) 227 [hep-ph/9209205].

[7] G. A. Schuler and T. Sjöstrand, Phys. Rev. D **49** (1994) 2257.

[8] `http://home.thep.lu.se/Pythia/pythia82html/Welcome.html`

[9] B. Andersson, G. Gustafson, G. Ingelman and T. Sjöstrand, Phys. Rept. **97** (1983) 31.

[10] C. O. Rasmussen and T. Sjöstrand, in preparation.

[11] V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **574** (2003) 169 [hep-ex/0308032].