Physics Letters B 718 (2013) 1345–1350

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Antenna showers with hadronic initial states

M. Ritzmann [a,*], D.A. Kosower [a], P. Skands [b]

[a] Institut de Physique Théorique, CEA Saclay, F-91191 Gif-sur-Yvette cedex, France
[b] CERN TH, Geneva 23, CH-1211, Switzerland

ARTICLE INFO

Article history:
Received 2 November 2012
Accepted 3 December 2012
Available online 5 December 2012
Editor: G.F. Giudice

Keywords:
Parton showers
Quantum chromodynamics
Hadronic collisions

ABSTRACT

We present an antenna shower formalism including contributions from initial-state partons and corresponding backwards evolution. We give a set of phase-space maps and antenna functions for massless partons which define a complete shower formalism suitable for computing observables with hadronic initial states. We focus on the initial-state components: initial–initial and initial–final antenna configurations. The formalism includes comprehensive possibilities for uncertainty estimates. We report on some preliminary results obtained with an implementation in the VINCIA antenna-shower framework.

1. Introduction

Parton-shower algorithms offer a universal and fully exclusive perturbative resummation framework for high-energy processes. In the context of Monte Carlo event generators [1], they also provide the perturbative input for hadronization models. As such, they are complementary to more inclusive techniques, such as fixed-order calculations (limited to small numbers of hard and well-separated partons) and more inclusive resummation approaches (limited to a fixed set of observables).

Sjöstrand derived the first consistent parton-shower algorithm [2] for so-called “backwards evolution” of initial-state partons a quarter-century ago. The central point is that an initial-state parton defined at a high factorization scale, Q_F, can be evolved “backwards”, towards earlier times, to find the parton from which it originated at some low scale, $Q_0 \sim 1$ GeV. During this evolution, which is governed by the Altarelli–Parisi (AP) splitting kernels [3] supplemented by parton-distribution function (PDF) ratios (a point which is crucial to the backwards-evolution formalism), initial-state radiation is emitted, which in turn gives rise to its own final-state radiation, and the character of the evolving parton changes, migrating towards successively higher x values and towards the more valence-dominated flavor content at low Q.

As an alternative to Altarelli–Parisi evolution, Gustafson and Pettersson proposed a final-state algorithm based on QCD dipoles [4], which has been implemented in ARIADNE [5]. There, however, initial-state radiation does not rely on backwards evolution. Instead, it is treated essentially as final-state radiation off dipoles stretched between the hard process and the beam remnants, and thus depends on the non-perturbative makeup of the remnants. Winter and Krauss took a first step towards combining the dipole formalism with backwards evolution (and thus also eliminating the dependence on the remnants) in Ref. [6]. Our construction differs in the antenna functions, evolution variables, and recoil strategy. In particular, it differs in the treatment of collinear singularities in initial–final antennæ. We have checked that our antennæ properly reproduce all QCD singularities.

Our approach merges the Lund dipole language with that of fixed-order antenna factorization [7–10], and is complementary to ARIADNE. It is embodied in the VINCIA [11–13] parton shower, implemented as a plug-in to PYTHIA 8. (Note: we henceforth use the term “antenna” rather than “dipole” to avoid ambiguities of historical origins, see e.g., Ref. [14].) So far, however, the VINCIA formalism has been applied only to final-state showers. In this Letter, we present all the ingredients necessary to construct a consistent initial-state shower based on QCD antennæ. A further important ingredient is comprehensive possibilities for uncertainty estimates, in line with the framework for automated theory uncertainties proposed in Ref. [15].

2. Antennæ and antenna showers

Throughout this Letter, we use the following notation convention: capital letters for pre-branching (parent) partons and lowercase letters for post-branching (daughter) ones. Also, we use a, b, for incoming partons and letters starting from $h, i, j, \ldots$ for outgoing ones. Fig. 1 illustrates these choices for the two basic types of configurations we consider. We will also indicate incoming

* Corresponding author.
E-mail address: Mathias.Ritzmann@cea.fr (M. Ritzmann).

0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2012.12.003

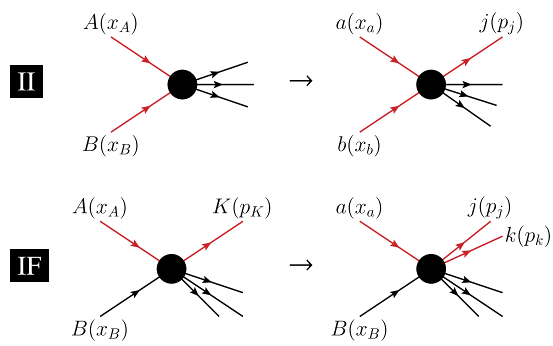

Fig. 1. Illustration of initial–initial and initial–final branchings: $AB \to ajb$ and $AK \to ajk$, respectively. For the II case, the recoil of the hard system is illustrated by the change in orientation of the three outgoing lines representing the original final-state system.

particles with a preceding minus sign in the arguments to antenna functions. We adopt the convention that particle energies are always positive, whether the particle is in the initial or the final state. As a result, $s_{ij} = (k_i + k_j)^2$ is always positive.

The key building block for parton showers is the Sudakov factor, which represents the non-emission probability between two values of the evolution scale, see [1,16] for reviews. In the context of an antenna shower, the Sudakov factor for the branching of one antenna is

$$\Delta\big(Q^2_{\text{start}}, Q^2_{\text{emit}}\big) = \exp\big[-\mathcal{A}\big(Q^2_{\text{start}}, Q^2_{\text{emit}}\big)\big], \tag{1}$$

with

$$\mathcal{A}\big(Q^2_{\text{start}}, Q^2_{\text{emit}}\big) = \int_{Q^2_{\text{start}}}^{Q^2_{\text{emit}}} a_c \frac{f_a(x_a, Q^2)}{f_A(x_A, Q^2)} \frac{f_b(x_b, Q^2)}{f_B(x_B, Q^2)} \, \mathrm{d}\Phi_{\text{ant}}. \tag{2}$$

In this equation, $\mathrm{d}\Phi_{\text{ant}}$ represents the antenna phase-space factorization, which provides an exact Lorentz-invariant mapping from 2 to 3 on-shell partons, that conserves global energy and momentum. Specific forms appropriate to initial–final and initial–initial antenna configurations are defined in Sections 3 and 4, respectively.

The evolution variable Q^2 is a function of the phase-space point and must vanish in the unresolved limits [17]. The general formalism permits us to study different evolution variables [11,15], though in this Letter we will restrict ourselves to a transverse-momentum type variable, defined in Section 5. As in all parton showers, the description is expected to be accurate only in the strongly-ordered limit for the Q^2 of successive emissions.

The dressed or colored antenna function a_c is defined as[1]

$$a_c = 4\pi\alpha_S\big(Q^2\big)C\bar{a}, \tag{3}$$

where C is a color factor (we recall that we use normalization conventions such that gluon and quark emission antennæ have $C = C_A$ and $C = 2C_F$, respectively, and gluon-splitting ones have $C = 1$), and $\bar{a}$ is a color-ordered antenna function, which embodies the factorization of QCD matrix elements in all single-unresolved soft and collinear limits. We don't take the functions $\bar{a}$ to be fixed; instead we use different antenna functions with the same singular limits as one estimate of the shower uncertainty.

We use so-called global antenna functions [4] (called sub-antenna functions with uniquely identified radiators in Ref. [9]) which are active over all of phase space. A backwards-evolution shower based on sector antennæ in analogy to Refs. [18,13] is left for future work. Some, but not all, antennæ needed for initial-state radiation can be chosen to be the crossings of their final–final counterparts. An incoming particle is necessarily a hard radiator in an antenna. Therefore, a gluon emission antenna function with an incoming gluon has to reproduce the AP splitting function on its own, e.g.

$$\bar{a}(-a_g, j_g, k_x) \xrightarrow{p_j \to z p_a} \frac{1}{s_{aj}} \frac{1}{1-z} P_{gg\to G}(1-z) \tag{4}$$

whereas if both gluons are in the final state, the collinear singularity is reproduced by the sum of two antenna functions

$$\bar{a}(h_x, i_g, j_g) + \bar{a}(i_g, j_g, k_x) \xrightarrow{p_j \to z p_{i+j}} \frac{1}{s_{ij}} P_{gg\to G}(z) \tag{5}$$

where the first antenna function is singular for i becoming soft, the second for j becoming soft.

In pure final-state showers, the x values of the incoming partons are not modified by the phase-space factorization, hence the PDF ratios in Eq. (2) drop out, yielding the ordinary form of the final–final Sudakov form factor [11,15].

For initial–final antennæ, only one of the PDF x values changes, and a Sudakov factor very similar to that of conventional AP showers results, with a single PDF ratio in the kernel, $f_a(x_a, Q^2)/f_A(x_A, Q^2)$. Unlike conventional showers, however, we must also consider the backwards evolution of two initial-state partons simultaneously, generally requiring two separate parton-density factors in initial–initial antennæ.

The consideration of initial–initial and initial–final antennæ gives rise to one more subtlety. The basic antenna functions are color-ordered, so that in a final–final gluon-emission antenna, for example, the emitted gluon is color adjacent to both other (hard) daughter partons. That is, it is the middle parton of the color trio which is emitted. The leading-color approximation inherent in parton showers along with the symmetry of final-state phase space allows us only antennæ with this ordering. When considering initial-state antennæ, however, the emitted parton need not be color-adjacent to both other daughter partons; the middle parton, adjacent to both, may end up in the initial instead of the final state. We will call antennæ in which the middle parton is emitted into the final state, 'emission' antennæ; and those in which the middle parton ends up in the initial state, 'conversion' antennæ.

For those antennæ in which the type (spin) of the initial-state partons does not change after branching, we can redistribute collinear singularities to neighboring antennæ so as to replace 'conversion' antennæ by 'emission' antennæ. For those antennæ in which the type of the initial-state partons changes during branching — in which a quark backwards-evolves into a gluon or vice versa — we cannot avoid a consideration of both types of antenna function and non-emission probability.

3. Initial–final configurations

The pre- and post-branching partons for initial–final configurations are labeled by $AK \to ajk$, with the other incoming parton, B, acting as a passive spectator, see the illustration in Fig. 1.

In general, the incoming momentum after branching will no longer be parallel to the beam direction. We could boost it back to the beam direction; this will transfer some of the transverse momentum generated in the emission to the rest of the event. This is the antenna analog of the recoil considered in Ref. [19]. In the present Letter, we will instead restrict the branching so that the incoming momentum remains parallel to the beam axis after branching.

[1] Note that in [15] the normalization was $a_c = \alpha_S/(4\pi)C\bar{a}$.