STUDY OF THE HELIX STRUCTURE OF QCD STRING*

Šárka Todorova-Nová

Tufts University, 4 Colby St., Medford, MA 1255, USA

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The properties of a helix-like shaped QCD string are studied in the context of the Lund fragmentation model. The model predictions are supported by the experimental data. There are similarities between particle correlations stemming from the helix-like string structure and those commonly attributed to the Bose–Einstein interference.

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1. Introduction

The idea of the helix-like shaped QCD string first appeared in the study of the properties of soft gluon emission by Andersson *et al.* [1]. The replacement of the 1-dimensional Lund string with a 3-dimensional object provides an alternative way of modeling of the intrinsic momentum of a direct hadron. In the standard Lund model [2], the quark–antiquark pair created in the string breakup via tunneling acquire a transverse momentum sampled from a tunable Gaussian distribution, and the sum of these momenta over adjacent — uncorrelated — string breakups translates into the transverse momentum of the resulting direct hadron. In the helix string scenario, the transverse momentum of the hadron can be entirely generated by the transverse component of the string tension. It should be noted that such a model removes two degrees of freedom from the simulation and introduces a strong correlation between the longitudinal and transverse components of the direct hadron, as well as azimuthal correlations between direct hadrons.

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2. Model implementation

The parametrization of the helical shape of the string is related to the measure of the "distance" between soft gluons with approximately the same transverse momentum, defined as [1]

$$d = \sqrt{2[\cosh(\Delta y) - \cos(\Delta\phi)]}\,, \tag{1}$$

where Δy ($\Delta\phi$) stands for the difference in rapidity (azimuthal angle) of gluons with respect to the string axis. In the original helix string proposal [1], the ϕ dependence has been neglected, and the helix string shape parametrized as a function of the rapidity difference along the string. The experimental signature of the model was searched by DELPHI [3] but no significant signal was found.

An alternative parametrization of the helix string can be obtained from Eq. (1) assuming $\Delta\phi \gg \Delta y \sim 0$, *i.e.* considering gluons as separated mainly in the transverse plane. This variant of the model is characterized by the regular helix winding, with helix phase difference proportional to the amount of energy stored in the string [4]

$$\Delta\phi = SM\,, \tag{2}$$

where M stands for string mass and S is a parameter.

The modified helix string parametrization has been implemented in a Pythia [5] compatible fragmentation code [6] and compared with the experimental data.

3. Comparison with the experimental data

3.1. Inclusive p_{T} spectra

Using the DELPHI data [7], it has been found that the helix string model provides a better description [9] of the inclusive particle spectra than the standard Lund model. In particular, a significant improvement is observed in the description of the mean p_{T} measured as a function of reduced particle momentum x_{P} (Fig. 1). The tuning of the helix string parameters with the help of Rivet [10] and Professor [11] tools indicates the helix radius in the range $R \sim 0.4$–0.5 fm (assuming $\kappa \simeq 1$ GeV/fm) and the parameter $S \sim 0.5$–1.0 rad/GeV.

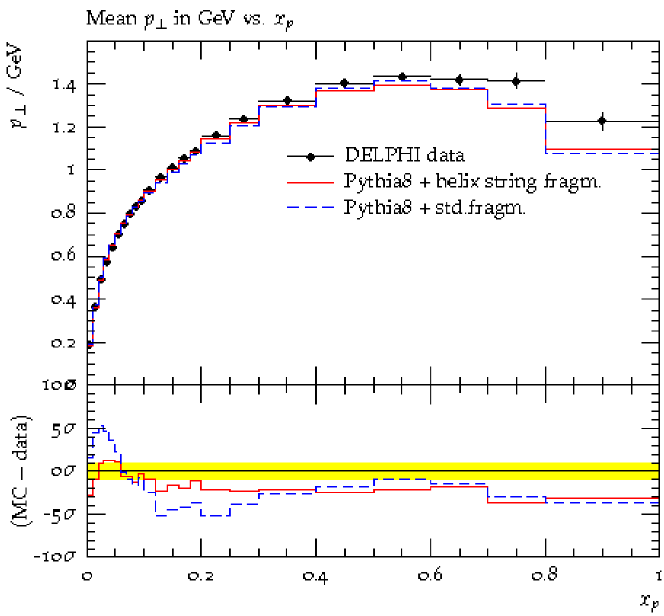

Fig. 1. (Color online) The comparison of the DELPHI data [7] with tuned predictions of Pythia8 using the standard fragmentation (dashed/blue line) and the helix string fragmentation (solid/red line).

3.2. Azimuthal ordering of hadrons

The helix-like structure of the QCD string translates into a helical ordering of direct hadrons along the string which can be detected with help of particle correlations.

A dedicated measurement by ATLAS [8] reveals the existence of correlations which correspond to the expected signal of the helical QCD string. The signal is stronger than expected and in order to describe it, the decay of short-lived resonances needs to be treated as a continuation of the fragmentation of the helical string. Figure 2 shows the comparison of the ATLAS data and of the tuned helix string model for observable S_E defined in [8]. S_E is a power spectrum designed to reveal correlations between the azimuthal opening angle of hadrons and their longitudinal separation along the string.

As shown in [9], the parameters of the helical structure found in the fit of the model to the ATLAS data are consistent with the range indicated by the Z^0 data.

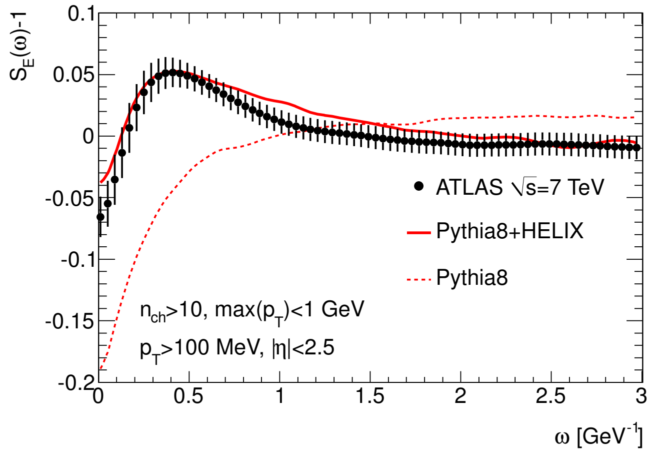

Fig. 2. The comparison of the ATLAS data [8] with tuned prediction of the helix string model extended to the decay of short-lived resonances (solid line). To illustrate the effect of the helix string structure, the predictions of the model with the standard string fragmentation and resonance decay are indicated (dashed line), for the same parameter setup.

4. Particle correlations in the helix string model

The amount of correlations introduced in the model by extending it to the decay of short lived resonances (ρ, K^*) is such that they should be readily visible in the measured momentum difference of charged particles $Q = \sqrt{-(p_i - p_j)^2}$. Figure 3 shows the ratio of the Q distribution generated with the helix string model and of its equivalent obtained with the standard Pythia8 simulation, for the minimum bias proton–proton collision sample at $\sqrt{s} = 7$ TeV (for simplicity, all charged particles are assigned a pion mass in Figs. 3, 5). The helix string model provides a clear experimental signature at low Q, with a characteristic bump at $Q \simeq 0.3$ GeV and an enhancement of the low Q region.

Experimentally, the existence of particle correlations in this region is very well established. The correlations observed in the data exhibit a strong charge-combination asymmetry (enhanced presence of close like-sign pairs of hadrons) and, traditionally, they are attributed to the Bose–Einstein interference between identical hadrons.

However, the attempts to describe the data with the production amplitude symmetrized according to the Bose–Einstein statistics did not provide satisfactory results in what concerns the strength of observed correlations [12] and it is of utmost interest to see another source of such correlations emerging.

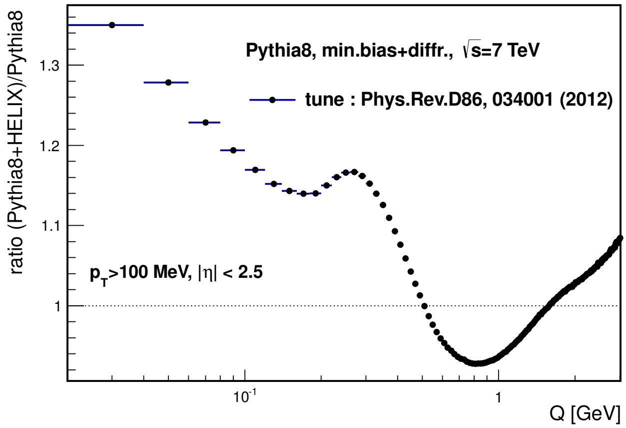

Fig. 3. The ratio of the Q distributions obtained from the helix string model tuned to the ATLAS data [9] and from the Pythia8 with standard Lund string fragmentation. Minimum bias sample at $\sqrt{s} = 7$ TeV.

4.1. The charge-combination asymmetry

The difference in the strength of correlations between pairs of like-sign and unlike-sign hadrons in the helix string model has been studied in [9] and the behavior of the model is illustrated with help of toy scenarios for hadron content of a hadronic Z^0 decay in Fig. 4. If the hadronization produces direct hadrons predominantly, as it is the case in the toy model with suppressed resonance production in Fig. 4 (upper panel), the low Q region is significantly enhanced by the helix string modeling and dominated by the unlike-sign pair contribution. This is a direct consequence of local charge conservation in the string break-up vertex, which prevents creation of adjacent like-sign pairs. However, the relative size of contributions from like-sign and unlike-sign pairs at low Q is reversed if the sample is dominated by decay products of the short-lived resonances, as in the toy model in Fig. 4 (lower panel) with the Z^0 fragmenting into a set of ρ^0 resonances. Thus, we obtain additional argument for extending the helix string model to the resonance decay — the resonances seem to play a significant rôle in the charge-combination asymmetry of helix string induced particle correlations.

Qualitatively, there is not much difference between the model predictions for the Z^0 decay as measured by LEP experiments and for the minimum bias samples obtained at LHC.

Figure 5 shows the ratio of Q distributions obtained in the proton–proton collisions at $\sqrt{s} = 7$ TeV with and without helix string model, in the case of enforced ρ_0 production. This toy scenario can be viewed as an estimate of the maximal size of correlations possibly coming from the helix string structure (the presence of neutral hadrons a long lived resonances is neglected).

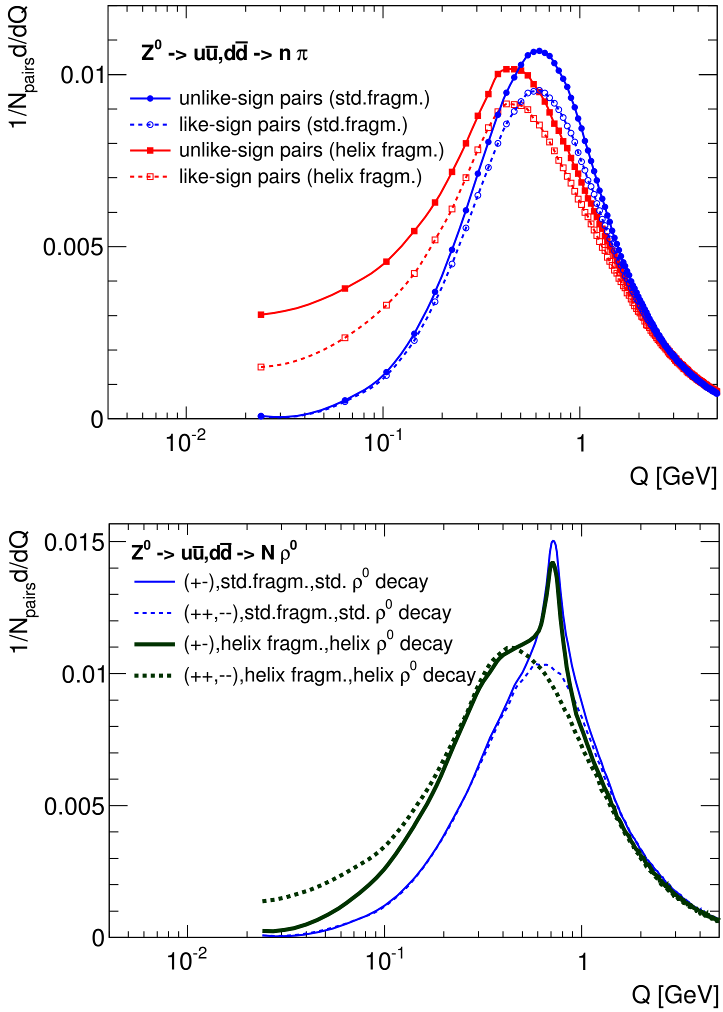

Fig. 4. The comparison of the momentum difference distribution for pairs of charged pions obtained via standard fragmentation (open and full circles (blue), upper panel), via helix string fragmentation (open and full squares (red), upper panel), and via the helix string fragmentation incorporating the resonance decay (thick dotted and solid (green) lines, lower panel). The contributions from pairs with identical charge (like-sign) are indicated by dashed lines, the unlike-sign charge combinations correspond to full lines. Upper panel: Hadronic Z^0 decay with suppressed resonance production. Lower panel: Hadronic Z^0 decay with forced ρ_0 resonance production.

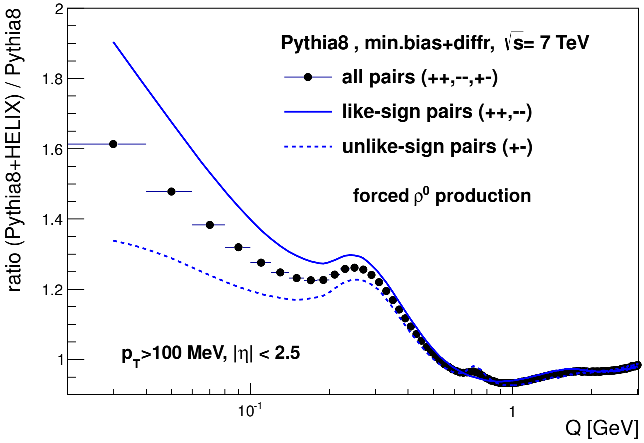

Fig. 5. The ratio of the Q distributions obtained from the helix string model and from the Pythia8 with standard Lund string fragmentation, with enforced ρ_0 production (toy model). Minimum bias sample at $\sqrt{s} = 7$ TeV.

5. Conclusions

The amount of the experimental evidence supporting the concept of the helix-like structure of the QCD string is growing. There seems to be no shortage of observables sensitive to the additional constraint imposed by the helix-like shaped QCD string, and the model is rather successful in description of some less understood properties of the dynamics of the hadron production. A good agreement with the data is observed despite diminished number of degrees of freedom in the modeling, suggesting the model captures some of essential properties of the QCD field. The most intriguing property of the model is, without doubt, the fact that it represents an alternative source of particle correlations observed in hadronic data and traditionally interpreted as a signature of the Bose–Einstein interference. There is yet much to learn from the experimental data in this respect, in particular in the study of the charged-combination asymmetry of particle correlations.

In summary, the idea of the helix-like ordering of the gluon field seems to be particularly fruitful even though a large theoretical uncertainty still hangs over the model.

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