# Modelling of low transverse momentum in hadronic interactions

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The helix structure of the Lund string, first derived from studies devoted to the emission of soft gluons at the end of the parton cascade, may be at the origin of certain characteristic discrepancies observed in the low transverse momentum region at LEP and LHC. Different parametrization of the helix-ordered gluon field are presented and corresponding observable effects are discussed. It is found that a helix structure with a regular winding (proportional to the energy density stored in the string), is supported by data, more precisely by the inclusive single-particle spectra measured in the hadronic decay of $Z^0$.

## 1 Introduction

In contemporary elementary particle physics, dominated by proton collider physics, there is hardly a measurement which does not rely, directly or indirectly, on the understanding of the process of hadronization. The available hadronization models, in particular the semi-classical Lund string model [1], are remarkably successful in describing a large variety of event shapes and properties. Still, there is quite a bit of uncertainty associated with the modelling, and some features in the data are not described by the models. This paper is devoted to the presentation and discussion of one such discrepancy.

The discrepancy under question was readily observed by LEP Collaborations in inclusive measurements of transverse momenta of charged particles, Fig.1. In fact, there are two kinds of discrepancy seen in these figures : in the low transverse momentum region ($\leq$ 1 GeV/c), there is sort of 'bump' around $p_T \sim 0.5GeV$, and in the high transverse momentum region, all models underestimate the data, especially in the 'out' direction (Thrust-minor axis). Here we are more interested in the low $p_T$ region which is dominated by the hadron *intrinsic* transverse momentum, i.e. the momentum it acquires in the hadronization process. It is worth mentioning that similar discrepancy is observed in ATLAS measurements of inclusive charged transverse momenta [2]. It is however difficult to draw any conclusions from LHC data alone, due to additional uncertainty in the description of diffractive processes, multiple interactions, and proton structure. In the following, we therefore refer to LEP data only.

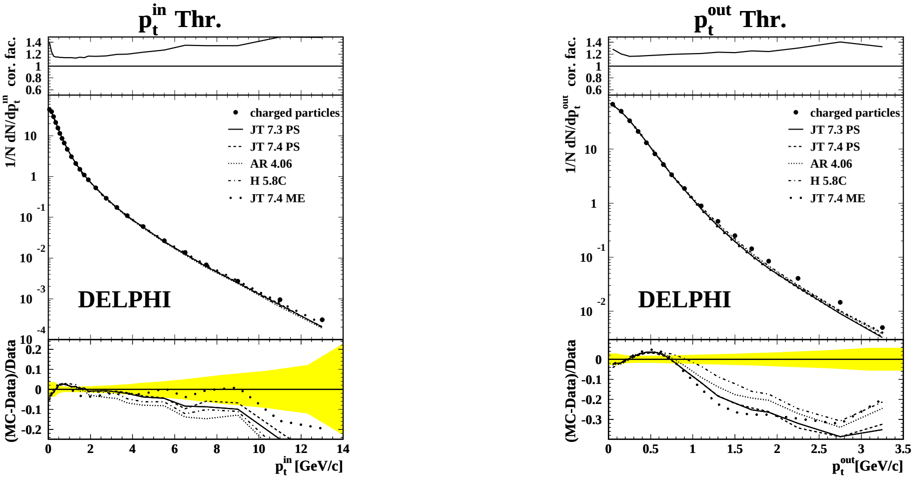


Figure 1: Inclusive charged particle transverse momentum spectra in hadronic $Z^0$ events as measured by DELPHI Coll. compared to predictions of tuned models [3].

## 2 Modelling of transverse momentum in Lund string model

In the Lund string model [1], direct hadrons (hadrons created by string fragmentation) acquire transverse momentum via so-called ‘tunneling’ effect: the string break-up is realized by creation of a quark-antiquark pair out of vacuum, and partons are assigned a non-zero transverse momentum. In the standard Pythia implementation of the model [6], the size of transverse momentum is sampled from a gaussian distribution with adjustable width. The transverse momentum of a direct hadron is defined by the vector sum of transverse momenta of partons created in the adjacent string break-ups. There is no correlation between the longitudinal and transverse components of the hadron momentum in the model.

### 2.1 Ordered gluon field

An alternative model of string breaking, and of intrinsic transverse momentum modelling, was proposed in [4]. On the basis of study of optimal packing of soft gluons in the phase space, and constraints imposed on gluon emission by helicity conservation, it was shown that at the end of gluon emission cascade, a helix-ordered gluon field may emerge (see Fig. 2). In this variant of the fragmentation model, direct hadrons would acquire their transverse momenta by *integration* over soft gluons momenta along the field:

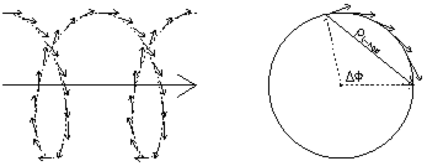


Figure 2: Helix-like ordering of soft gluons at the end of parton cascade (left) and direct hadron transverse momentum (right).

$$|\vec{p_T}| = 2r|sin\frac{\Delta\Phi}{2}| \tag{1}$$

where $\vec{p_T}$ is the transverse momentum of the hadron, $r$ stands for the radius of the helix, and $\Delta\Phi$ is the difference of the helix phase between the string break-ups which define the hadron.

Contrary to the standard Lund string, a helix-ordered string produces hadrons with *correlated* transverse and longitudinal momentum components. The exact form of the correlation will depend on the actual parametrization of the helix string.

## 2.2 Parametrizations of helix string

In [4], the helix string was parametrized in terms of rapidity difference between string breakups, which can be expressed in terms of endpoint-quark momentum (dimensionless) fraction $k^{\pm}$

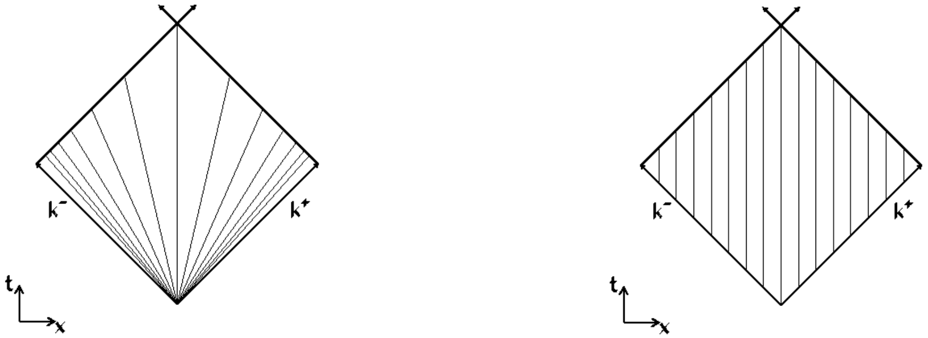
$$\Delta\Phi = \frac{\Delta y}{\tau} = \frac{1}{2\tau}\ln\frac{k_i^+ k_j^-}{k_j^+ k_i^-} \tag{2}$$

where $\tau$ is a parameter, and $k_i, k_j$ define breakup points. Fig. 3a) shows the corresponding map of helix phase in a space-time diagram of string evolution.

Since it can be argued that such a parametrization does not satisfy the assumption of the homogenity of the string field, we also consider an alternative parametrization where the difference in the helix phase is proportional to the energy density stored in the string

$$\Delta\Phi = \frac{SM}{2}|k_i^+ - k_j^+ + k_j^- - k_i^-| \tag{3}$$

where $M$ stands for the string mass, and $S$ is a parameter. Equation 3 describes, in the rest frame of the string, a static helix with a constant pitch (Fig. 3b).



a) b)

Figure 3: Space-time diagram of string evolution with mapping of helix phase (lines inside string diagram connect points with equal helix phase). Left: Lund helix parametrization (Eq. 2). Right: Modified helix parametrization (Eq. 3) .

# 3 Observables

Helix string existence in the form described by Eq.2 can be revealed by correlation between hadron rapidity and azimuthal angle. A variable called *screwiness* was introduced in [4] and experimentally studied by DELPHI [5], but no helix signature was found. The modified helix parametrization (Eq.3), on the other hand, strongly influences the *size* of transverse momentum, and it may well be at origin of the discrepancy mentioned in the introduction. The comparison of the standard Lund fragmentation model with helix string models, on screwiness measure and for inclusive transverse momentum, is shown in Fig.4, for a model case of simple $q\bar{q}$ string. The modified helix parametrization (Eq.3) shows only moderate signal in screwiness measure, while the helix parametrization of Eq.2 has far less impact on the transverse momentum distribution.

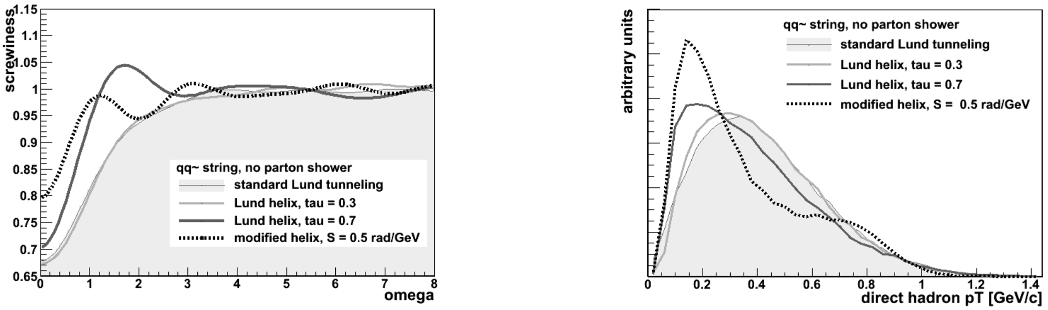


Figure 4: Impact of helix string on properties of direct hadrons. Simple $q\bar{q}$ string without parton shower ($E_{cms} = 91.2GeV$). Left: screwiness measure. Right: inclusive $p_T$ distribution.

# 4 Helix model and multiparton string topology

In order to allow comparison of model tuning with real data, the modified helix model was implemented also for string topologies with hard gluon emission (Fig. 5). The space-time evolution of the string defines the helix phase difference between arbitrary breaking points along the string. The calculations are relatively simple due to the fact that the modified helix model coresponds to a static form of helix field. The model is available as a private version of Pythia PYSTRF routine [7]. In the Pythia implementation, the helix string is described by 3 parameters: helix radius and its variance [GeV/c], and the parameter $S$ corresponding to helix pitch [rad/GeV].

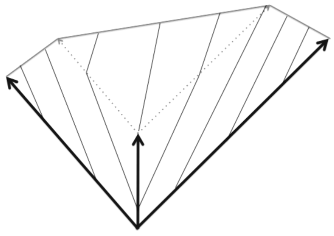


Figure 5: Evolution of the modified (Eq.3) helix phase over hard gluon kink.

# 5 Comparison with data and model tuning

The modified helix model was tuned on DELPHI data [3] with the help of Rivet [8] and Professor [9] tools. A six parameter tune was performed simultaneously fitting helix radius and pitch, Lund parameters a and b, parton shower cut-off $Q_0$ and coupling constant $\Lambda_{QCD}$. The variance of helix radius was set to 0.1 GeV/c. The values of other Pythia parameters correspond to the Professor tune of fragmentation parameters [10]. The goodness of the fit is reported in Table 1 and compared with a recent update of the Professor tune [11]. A significant improvement in the description of data is observed not only for inclusive charged spectra as expected, but also for the ensemble of event shape distributions. Fig. 6 shows the comparison of tuned Pythia predictions and the DELPHI data. Please note that in both tunings, the new shower scheme of Pythia (so-called $p_T$-*ordered shower* [6]) was used.

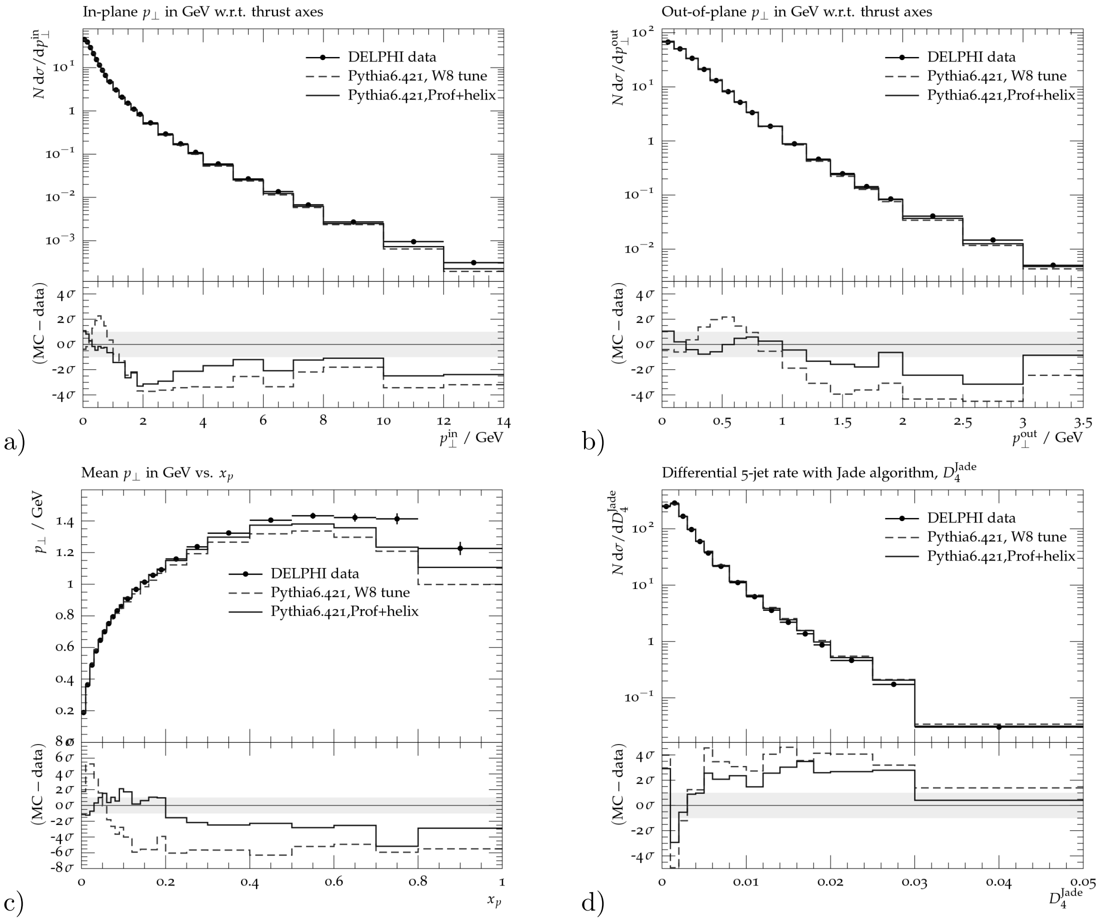


Figure 6: Comparison of tuned MC predictions with measured DELPHI hadronic $Z^0$ data, showing: inclusive transverse momentum measured in Thrust-Major(a) and Thrust-minor(b) direction, average transverse momentum w.r.t. scaled momentum (c), and differential 5-jet rate $D_4^{Jade}$ (d).

| Model | inclusive spectra and event shapes | | inclusive $p_T$ spectra only | | event shapes only | |
|---|---|---|---|---|---|---|
| | $\chi^2$ | Ndof | $\chi^2$ | Ndof | $\chi^2$ | Ndof |
| Professor(W8) tune/standard fragm. [11] | 4191 | 754 | 1430 | 124 | 2119 | 457 |
| Professor(W8) tune/modified helix | 2713 | 754 | 436 | 124 | 1340 | 457 |

Table 1: Goodness of fit of Pythia 6.421 tune to the DELPHI data [3], with and without helix string model included. The comparison is done for combined inclusive spectra and event shapes (column 2-3), a subset including $p_T$ spectra only (column 4-5), and collection of event shape distributions (column 6-7).

# 6 Summary

Despite the fact that helix string model appeared more than 10 years ago, there has been little activity on the subject after an unsuccessful search for helix string signature. In this paper, we present a modification of the helix string model which is supported by data. The evidence is so far indirect only, nevertheless the improvement in the description of data is quite significant. Moreover, the introduction of the helix string model helps to remove some of the most notorious discrepancies between MC and data from the LEP era.

In addition to features described above, the helix-ordered gluon field also implies azimuthal ordering of direct hadrons which may be observable in a study of 2-particle correlations. This may well be a way to find a direct evidence of the existence of a helix gluon field. Unfortunately, the expected signal is very weak, at best at a per cent level compared to the background.

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