Modelling of low transverse momentum in hadronic interactions

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- **motivation**: characteristic data/MC discrepancies observed in LEP->LHC data

- low pT region (< 1 GeV) dominated by ‘intrinsic’ hadron pT (acquired in the fragmentation process)

- alternative models of fragmentation of the Lund string

- observables & model tuning
**Intrinsic charged particle $p_T$ in LEP data**


Characteristic ‘bump’ around $p_T \sim 0.5$ GeV/c

$\rightarrow$ fragmentation

Tails not well described $\rightarrow$ parton shower

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Intrinsic charged particle $p_T$ in LEP data

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Intrinsic charged particle $p_T$ in LHC data

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complex picture: diffractive physics,
multiple interactions, proton structure

technically demanding: low $p_T$ tracking, not trivial

low $p_T$ ‘bump’
much like the one known from LEP data

$\frac{1}{N_{ev}} \frac{d^2N_{ch}}{dp_T}$ [GeV$^{-2}$]

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S.Todorova, ISMD2010
Transverse momentum generation in Lund string fragmentation

- Standard Lund model: tunneling effect (at every breaking point, newly created quark/antiquark is assigned $+p_t/-p_t$):
  - $\rightarrow$ size sampled from gaussian
  - $\rightarrow$ azimuthal direction random
Alternative model


-> optimal packing of soft gluons at the end of parton cascade HELIX-LIKE

Hadron gets its transverse momentum by integration over momenta of soft gluons forming the corresponding string piece:

\[ p_T = 2 \, r \, |\sin(0.5 \, \Delta \phi)| \]
\[ r \, [\text{GeV/c}] \, , \, \Delta \phi \, \text{difference of helix phase} \]

An observable proposed:

\[ \text{screwiness } S(\omega) = \Sigma_{ev} P_{ev} \left| \Sigma_i \exp(i(\omega y_i - \phi_i)) \right|^2 \]
\[ y \, \text{rapidity of hadron} \]
\[ \phi \, \text{azimuthal angle of hadron} \]
\[ \omega \, \text{parameter} \]

The model was immediately tested (DELPHI 98-156 PHYS 799), no signal found (\( \tau \leq 0.3 \))
Proposal: modification of the helix-string model

Helix-like string maintained, but parametrized differently:
(lines show space-time evolution of fixed helix phase)

ΔΦ = Δy/τ
= 0.5/τ ln ( k_i^+ k_j^- / k_i^- k_j^+ )

ΔΦ = 0.5 S |k_i^+ k_j^- - k_i^- k_j^+| M
= 0.5 S κ Δl

M ... mass of the string
κ ... string tension
Proposal: modification of the helix-string model

Helix-like string maintained, but parametrized differently:
(lines show space-time evolution of fixed helix phase)

\[ \Delta \Phi = \Delta y/\tau = 0.5/\tau \ln \left( k_i^+k_j^-/k_i^-k_j^+ \right) \]

\[ \Delta \Phi = 0.5 \ S |k_i^+ + k_j^- - k_i^+ - k_j^+| M = 0.5 \ S \ \kappa \ \Delta l \]

BOTH VARIANTS REMOVE THE AZIMUTHAL DEGREE OF FREEDOM
helix phase fixed by parametrization
Helix parametrization introduces correlations

azimuthal direction – rapidity

(transverse momentum - energy)

(Lund helix)

modified helix

qq~ string, no parton shower

Lund helix, tau = 0.7

energy of primary hadron [GeV]

pl of primary hadron [GeV]
**Helix: phenomenology**

Not much effect expected in the screwiness measure for modified helix string .... ?  
(further diluted by parton shower)

**Inclusive pT spectra :**  
- bump at \( pT \sim 0.5 \text{ GeV} \) expected !  
  (ex.: helix radius \( 0.4 \pm 0.1 \) GeV/c, helix winding \( 0.5 \text{ rad/GeV} \))

Lund helix shows similar tendency  
( in already excluded region ..? )
**Modified helix: implementation**

*E-pT correlation implemented in PYSTRF routine (Pythia6*) on iteration basis. The real difficulty resides in treatment of hard gluon kink:*

helix phase difference between $qq\sim$ endpoints

$$\Delta \phi = S \Sigma M_{ij}$$

sum runs over all string pieces(*)

phase at a given point given by initial conditions and $E_L/E_R$ fraction in corresponding string piece

*This is not feasible in case of original Lund helix: gluon kink represents a singularity in helix phase – how to deal with it?*
Modified helix: comparison with data (tuning)

The modified helix model in combination with ‘pT-ordered’ parton shower provides much better description of LEP inclusive pT:

Best fit to pT inclusive (more info in backup slides)

This should translate into better description of a jet profile, as well.
Modified helix: other observables?

Genuine azimuthal angle correlations are present in the model:

\[ \psi_1 - \psi_2 = 0.5 (\phi_{i+2} - \phi_i) \]
\[ = 0.5 \ast S \ast (E_1 + E_2) \]

in c.m.s. of the string

Strongly diluted by combinatorial background:

There is some hope to observe these correlations in case short-lived resonances ‘remember’ the gluon field structure

... under investigation
Modified helix parametrization: theory

Is the re-parametrized helix model compatible with theoretical arguments behind the introduction of the helix string?

YES! The modified model corresponds to a color ordered stream of gluons with constant \( k_T \) and \( \Delta y = 0 \). The gluons ‘go apart’ in the transverse plane (to satisfy the requirement of helicity conservation). The resulting chain of gluon dipoles (with similar mass) forms a regularly spiralling colour field with constant energy density (see next slide for numerical estimates).
Modified helix parametrization: theory

(Based on JHEP09(1998)014., eq.(7))

Minimal mass of di-gluon dipole allowed to emit additional gluon
\[ s = \Lambda^2 e^c = \Lambda^2 e^{11/6} \approx 0.56 \text{ GeV}^2 \Rightarrow M \sim 0.75 \text{ GeV} \]
(helicity conservation)
Mass of the resulting dipoles (after the last emission)
\[ s' \approx 0.19 \text{ GeV}^2 \Rightarrow m \sim 0.44 \text{ GeV} \]

Tuning of modified parametrization suggests \( \Delta \phi \approx 0.5 \text{ rad/GeV} \)

Mass of dipoles for 1 GeV gluons emitted with azimuthal distance 0.45 rad:
\[ \sim 0.45 \text{ GeV} \]
Summary

This is an attempt to highlight some less understood features of fragmentation model, and to resuscitate the idea of helix-like ordered string color field.

A modification of a helix string model [JHEP09(1998)14] predicts observable effects compatible with LEP data. (LHC data under investigation)

Modified helix model successfully tuned to LEP (DELPHI) data. This is a non-trivial result – the helix model effectively removes one degree of freedom from the fragmentation process!

Observables (pT spectra, 2-particle correlations, jet shapes, ...) : indirect evidence?

Possible extension to resonance region? Under investigation ... in the absence of convincing theoretical picture, a lot of speculation involved.

Theoretical picture: possible reconciliation of the different helix parametrizations?

Acknowledgements to the Rivet/Professor project – a very useful tools!
BACK-UP slides
Helix on top of DELPHI tune

-> fixes low pT region
   (>90% of tracks below 1 GeV)
-> retuning not necessary – very
   little impact on other observables

These plots done with:
  helix radius  0.4±0.1 GeV/c
  winding       0.5 rad/GeV
**pT ordered shower tune**
*(H.Schulz, ALEPH/DELPHI/OPAL/JADE data)*

vs. DELPHI tune

- **pT—in/out equally underestimated**
- **scaled momentum worse ...(!)**
- **Try ARIADNE ? (not available for LHC)**
**Helix + pT ordered shower tune**  
(6 parameters Professor tune, DELPHI data)  
vs. DELPHI tune

Almost perfect tune of pT  
*but scaled momentum worse ... mostly due to parton shower ...*  
Quite some improvement in event shapes, too:

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**Helix + pT ordered shower tune**  
*(6 parameters Professor tune, DELPHI data)*

**Tuned parameters :**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>inclusive spectra</th>
<th>pT inclusive</th>
<th>event shapes</th>
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<tbody>
<tr>
<td></td>
<td>+event shapes</td>
<td></td>
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<tr>
<td>$r$ PARJ(102)</td>
<td>0.36 $\pm$ 0.1</td>
<td>0.28 $\pm$ 0.1</td>
<td>0.42$\pm$ 0.1</td>
</tr>
<tr>
<td>$d r$ PARJ(103)</td>
<td>fixed (0.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S$ PARJ(104)</td>
<td>0.5 $\pm$ 0.5</td>
<td>0.59 $\pm$ 0.6</td>
<td>0.38$\pm$ 0.6</td>
</tr>
<tr>
<td>Lund a PARJ(41)</td>
<td>0.08 $\pm$ 0.7</td>
<td>0. $\pm$ 0.6</td>
<td>0.6$\pm$ 0.9</td>
</tr>
<tr>
<td>Lund b PARJ(42)</td>
<td>0.37 $\pm$ 1.</td>
<td>0.77 $\pm$ 0.8</td>
<td>0.9$\pm$ 0.9</td>
</tr>
<tr>
<td>$L_{QCD}$ PARJ(81)</td>
<td>0.237$\pm$ 0.005</td>
<td>0.297$\pm$ 0.056</td>
<td>0.23$\pm$ 0.05</td>
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<tr>
<td>$Q_0$ PARJ(82)</td>
<td>0.65 $\pm$ 0.8</td>
<td>0.41$\pm$ 0.5</td>
<td>0.63$\pm$ 0.9</td>
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**Goodness of fit**

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<td>1.8</td>
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<td>754</td>
<td>124</td>
<td>457</td>
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</tbody>
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*Only helix ‘radius’ and Lambda$_{QCD}$ realy constrained => another iteration needed to study softer dependence ( S, Lund a,b , ... )*
Helix string & short lived resonances

Some hope to discover genuine, helix-string induced, azimuthal angle correlation, in case the short-lived resonances ‘remember’ gluon field structure

-> enhanced signal ( primary + decay products )
-> polarized decay ? ( 2 degrees of freedom removed from 1-> 2 body decay )

Rho resonance enhanced helix signal in pT
( 900 GeV pp non-diffractive minimum bias)