Study of the helix model
(Šárka Todorova-Nová, MFF UK Prague)

- Introduction: the idea & the experimental evidence
  - inclusive \( p_T \) spectra
  - azimuthal ordering of hadrons

- Model development: quantum effects
  - meson spectra
  - \( p_T \) threshold
  - 2-particle correlations

- Summary
The idea of helix string [first proposed in JHEP09(1998)14.]
Bo Anderson et al.:”Is there a screwiness at the end of parton cascade ?”

Replace the standard Lund string ( string tension $\kappa \approx 1 \text{ GeV/fm} $)
( = fragmentation method in Jetset/Pythia)

with a helix-like ordered gluon chain :

- gluon emission from quark cannot be collinear -> transverse component
- helicity conservation & numerical consideration suggest helix-like shape
This affects in particular the generation of the intrinsic $p_T$:

Suppress the standard Lund string $p_T$ generation (associated with the tunneling effect
- 2 random numbers thrown at each breakup vertex )....

... and let the string tension operate in the transverse plane
=> the intrinsic $p_T$ ENTIRELY constrained by the helical structure of the string

$|p_T| = 2R \sin (\Delta \phi/2)$

R helix radius
$\phi$ helix phase

2 degrees of freedom removed from the modelling!
**Experimental evidence**

The removal of 2 degrees of freedom associated with the intrinsic $p_T$ generation leads to significant improvement in the description of hadronic $Z^0$ data (in particular, for $<p_T>$ vs. $x_p$)

The model predicts azimuthal ordering of hadrons

[Phys.Rev.D86, 052005 (2012)]

The model drastically reduces “randomness” in the intrinsic $p_T$ sector yet describes the relevant hadronic data better over large span of energies ....

However, the model is not complete ...

The azimuthal ordering is not well described if the helix model operates on direct hadrons only -> decay of short-lived resonances incorporated in the model

.. but the enhanced helix model produces way too many soft particles (Z⁰ data no longer so well described)

A strong presence of resonances needed to reproduce the correct charged asymmetry pattern in 2-particle correlations
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Quantum effects better be taken into account explicitly?
**Helix model in space-time coordinates**

Light-cone coordinates no longer appropriate for description of the string evolution …

( massless partons evolve with $v < c$ along string axis )

… but there is now a possibility to introduce CAUSALITY relation between adjacent breakup vertices

Reminder: in standard Lund model formulation, the distance between breakup points is always space-like!
What happens if we IMPOSE TIME-LIKE DISTANCE between string breakup vertices which define the final hadron?

**A/ information travels along string only**

-> \((X_i - X_j)^2 = 0\)

( propagating quark “triggers” the next breakup )

\[
m_S = \kappa R \sqrt{(\Delta \Phi)^2 - (2 \sin \Delta \Phi / 2)^2}.
\]

**The hadron mass depends on the transverse shape only – decouples from longitudinal momentum !**

**B/ information travels through the vortex**

\((X_i - X_j)^2 > 0\)

\[
m_s \leq m_c \leq m_s \sqrt{1+\beta^2}
\]

\[
\beta = \frac{v}{c} \quad (longitudinal)
\]

It is sufficient to quantize \(R\Phi\) to obtain discrete hadron spectra ...
What happens if we IMPOSE TIME-LIKE DISTANCE between string breakup vertices which define the final hadron?

Quantization of $R\Phi$ leads to a discrete spectrum

$$R\Phi \rightarrow n R \Delta\Phi \quad (\text{in ideal helix shape approximation})$$

Quantization can proceed in:

transverse mass $m_T = \sqrt{m^2 + p_T^2} = \kappa n R \Delta\Phi$

angular momentum $J \sim \kappa R^2 \Delta\Phi \sim m_T^2 / \kappa$

$(\rightarrow \text{Regge trajectories})$

(A) seems suitable for the description of narrow resonant states
(B) wider final states

Can we figure out the properties of a “QCD quantum”?
Let’s consider light pseudoscalar mesons: $\pi(140), \eta(547), \eta'(948)$

- $\pi$ ground state (lightest hadron) $R, \Delta \Phi \ ? \ m_T(n=1,3,5) = n \kappa R \Delta \Phi$
- $\eta \to 3 \pi$; $\eta' \to 5 \pi$

The system is overconstrained – but there is a solution which agrees with the experimental data (with precision of ~3%)

$$\xi = \kappa R \Delta \Phi \approx 0.192 \text{ GeV}$$

$$\Delta \Phi \approx 2.8 \text{ (constrained by } \pi \text{ mass)}$$

$R \approx 0.07 \text{ fm}$

This defines the ground state properties of pion in the quantized helix string model
Quantized helix properties, ground state

-> intrinsic $p_T$ threshold at $\sim 0.14$ GeV

✔ (data seem to suggest $p_T$(threshold) < 0.2 GeV)

Just about what is needed to “regularize” the soft particle production in the helix string model?

-> intrinsic $Q$ threshold at $\sim 0.28$ GeV for adjacent hadrons

(ground state pions) -> direct impact on the correlation pattern

$$ Q = \sqrt{- (p_i - p_{i+1})^2} \approx | p_{Ti} - p_{Ti+1} | $$

$$ Q \approx 2 \ p_T \sin (\Delta \Phi/2) $$

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**Quantized helix properties: correlation pattern**

-> correlation properties of the chain of pions in ground state (such as coming from the η’ decay)

**Neat enhancement of the** like-sign component in the momentum transfer, the unlike-sign combination pushed above $Q \sim 0.2$ GeV

**Very close to the observed correlation pattern** – the influence of η’ should be verified experimentally

**If significant contribution from ground state chain is found, it would be very simple to explain the so-called “source elongation” (in Bose-Einstein terminology)**
Here we hit upon an old unresolved problem:

- The study of particle correlations exhibiting charge-combination asymmetry (like-sign/ unlike-sign pairs) CRUCIAL for understanding of the fragmentation stage: local charge conservation forbids creation of adjacent like-sign hadron pairs
  
  \[ \rightarrow \text{unlike-sign pairs carry MORE information about the fragmentation than like-sign pairs} \]

There is an old discussion about “COHERENT” versus “INCOHERENT” particle emission which has a clear impact on the way the data are analysed:

- assume INCOHERENT (chaotic) particle production study Bose-Einstein interference

- assume COHERENT (correlated) particle production study FRAGMENTATION
**INCOHERENT approach:**
Bose-Einstein correlations
-> measure correlation function
  ( ratio like-sign/ unlike-sign )
-> extract ‘source’ dimension

**COHERENT approach:**
-> study fragmentation
concentrate on adjacent/close pairs
  ( better accessed via
unlike and like-sign pairs difference )
-> study resonance spectrum,
and Q threshold
Summary

• Various observations (excess of low pT particles, large impact of resonant hadronic states) point towards necessity to include quantum effects in the helix string model

• A possible way of STRING QUANTIZATION suggested – based on the requirement of causal relation between string breakup vertices (for the Lund model!) and the mass spectrum of light pseudoscalar mesons -> provides low pT threshold (regularization of the soft particle production) -> highlights the coherent contribution to the 2-particle correlations

Very down-to-earth approach to the quantization of QCD string, in line with the spirit of the helix model building:

Use the model (“educated guess”) to connect dots between various phenomena (experimental data) and to phase out free parameters from the model

• All model predictions are verifiable using hadronic data within our reach (although it may be a little tough to reconstruct the η’)

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Next steps?

• Incorporate basic quantization (\( p_T \) threshold) in the model, propagate to the resonance decay, retune on data
  (\( \rightarrow \) interplay with parton shower)

• Evaluate the contribution from coherent hadron chain to the observed \((2++)\) particle correlations – put into relation with the spectrum of resonant hadronic states

  (FRAGMENTATION or BOSE-EINSTEIN SYMMETRIZATION?)

• Test various options for the evolution of the helix phase along the string, combine with causality requirements for well-established resonant hadronic states – a vast program but here we talk about better understanding of the hadronization for everybody working in the particle physics field!
Documentation

- Bo Andersson et al., JHEP 09 (1998) 014. [phenomenology]
- Š. Todorova, Phys.Rev.D86, 034001 (2012) [phenomenology]
- Š. Todorova, arXiv:1012.5778 [hep-ph] [tune with LEP data]
- http://projects.hepforge.org/helix/ [PYTHIA-compatible code]
back-up slides
**Helix string model : phenomenology**

**Size** of the hadron' transverse momentum

\[ | \mathbf{p}_T | = 2r \sin (\Delta \phi / 2) \]

- \( r \) helix radius
- \( \phi \) helix phase

**Direction** follows helix phase in the middle of the string piece

**Azimuthal opening angle** between hadrons corresponds to the helix phase difference along the helix

*Helix : \( \Delta \phi \sim \) longitudinal separation along the string*

2 “extreme” scenarios on the market :

\[ \Delta \Phi = \frac{\Delta y}{\tau}, \quad \Delta y = 0.5 \ln \left( \frac{k_i^+ k_j^-}{k_i^- k_j^+} \right), \]

\[ \Delta \Phi = \mathcal{J} (\Delta k^+ + \Delta k^-) M_0 / 2, \]

[ arXiv:1101.2407]
**Helix shape** corresponds to the optimal packing of soft gluons in the phase space.

Distance between gluons \( \sim \sqrt{(\delta y)^2 + (\delta \phi)^2} \)

- \( \delta \phi \) neglected:
  \[
  \Delta \Phi = \frac{\Delta y}{\tau}, \quad \Delta y = 0.5 \ln\left(\frac{k_i^+ k_j^-}{k_i^- k_j^+}\right),
  \]
  - \( \rightarrow \) singularity at the endpoint
  - \( \rightarrow \) works for simple \( qq^\sim \) string
    (Pythia sets endpoint quark \( p_T=0 \))
  - \( \rightarrow \) helix phase “running” along the string

- \( \delta y \) neglected:
  \[
  \Delta \Phi = \mathcal{S} (\Delta k^+ + \Delta k^-) M_0/2,
  \]
  - \( \rightarrow \) static helix structure
  - \( \rightarrow \) fully functional MC
    (arbitrary string configuration)
The search of the azimuthal ordering signal has been performed early on by DELPHI [DELPHI 98-156 CONF], unsuccesfully.

Was this related to the difference between helix models?
Indirect experimental evidence: tuning on $Z^0$ data

(DELPHI_1996_S3430090)

arXiv:1012.5578 [hep-ph]

Helix string fragmentation improves “goodness of fit” ($\chi^2/N_{dof}$)

6.6 -> 4.0
(Pythia 6 DELPHI 1996 tune)

4.0 -> 2.4
(Pythia 6 with ARIADNE parton shower)

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**Best fit depends on the choice of input data**

**Pythia8 + HELIX (DELPHI_1996_S3430090)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Evshapes+Incl</th>
<th>Evshapes</th>
<th>Inclusive</th>
<th>PT-only</th>
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<tr>
<td>HSF:screwiness</td>
<td>0.92</td>
<td>0.91</td>
<td>0.54</td>
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<td>HSF:helixRadius</td>
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<td>TimeShower:pTmin</td>
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<tr>
<td>StringZ:aLund</td>
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<td>StringZ:bLund</td>
<td>0.44</td>
<td>0.48</td>
<td>0.22</td>
<td>0.47</td>
</tr>
</tbody>
</table>

*Fixed in the following to simplify LHC tunes*

HelixStringFragmentation:screwiness $\sim (0.5 - 1.0) \text{ [rad/GeV]}$

HelixStringFragmentation:helixRadius $\sim (0.4 - 0.5) \text{ [GeV]}$
Azimuthal ordering of hadrons [Phys.Rev.D86,052005 (2012)]

The helix-like shape structure of the QCD field should be visible in the azimuthal ordering of hadrons along the string.

The exact form of the helix structure not predicted. With the help of power spectra, we test two (weakly correlated) hypotheses

A/ $\Delta \Phi \sim \Delta \eta$

$$S_\eta(\xi) = \frac{1}{N_{ev \ event}} \sum_{n_{ch}} \frac{1}{|\sum_j \exp(i(\xi_n \eta_j - \phi_j))|^2}$$

B/ $\Delta \Phi \sim \Delta X$ (energy-distance - amount of energy stored in the string/ ordered hadron chain - experimentally: ordered in pseudorapidity)

$$S_E(\omega) = \frac{1}{N_{ev \ event}} \sum_{n_{ch}} \frac{1}{|\sum_j \exp(i(\omega \ X_j - \phi_j))|^2}$$

Search for resonant behaviour -> density of helix winding
**Tuning of the helix string model using ATLAS data**

Fix fragmentation parameters to values found in Z⁰ study

Use the measurement of the azimuthal ordering in the inclusive and low-pT depleted region (less sensitive to fragmentation effects).

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**Table II. Results of the tuning study using the ATLAS data [7] collected at \(\sqrt{s}=7\) TeV.**

<table>
<thead>
<tr>
<th>Tuned parameter</th>
<th>Input data set</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSF:screwing</td>
<td>0.61(2)</td>
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<td>HSF:helixRadius</td>
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<td>MultipartonInteractions:expPow</td>
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<td>SpaceShower:pT0Ref</td>
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<td>BeamRemnants:reconnectRange</td>
<td>0.0[F]</td>
</tr>
<tr>
<td>(\chi^2/N_{dof})</td>
<td>581/443 = 1.3</td>
</tr>
</tbody>
</table>

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PRD86,034001(2012)

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Azimuthal ordering of hadrons

PRD86, 052005 (2012)

“Low $p_T$ enhanced” event selection
$\text{max}(p_T) < 1 \text{ GeV}$ (more sensitive to fragmentation effects)

NOT DESCRIBED BY CONVENTIONAL MODELLING

Correlations **STRONGER** than expected

To describe the data, we need to extend the helix string model to cover the decays of short lived resonances (i.e. resonance decay treated as a smooth continuation of the fragmentation of the helix-shaped string)

SIGNIFICANT AMOUNT OF CORRELATIONS WHERE EXPECTED (and where not expected)
**“Prediction” for the low-$p_T$ enhanced region**

**Not too bad.**

**Missing spectral components?**
*(wavy structure persists in a sample with high statistics)*

**Dashed spectra : standard fragmentation with the same parameter setup**
- for illustration of the possible size of the effect due to the helix-like ordering
  *(The non-helix simulation alone can be retuned to give a somewhat better description of the data!)*

PRD86,034001(2012)
Use ‘tuned’ helix model to check expected effect on ‘generic’ 2-particle correlations

A significant effect predicted! In the low Q region usually associated with Bose-Einstein correlations .... with a very distinctive shape

\[ Q = \sqrt{-(p_1 - p_2)^2} \]

Is the prediction consistent with the data?

What about the prediction for like-sign / unlike-sign charge combination?
Where the difference comes from?  

TOY MODEL: $Z^0 \rightarrow \text{direct pions}$

Helix vs. standard fragmentation:
- $p_T$ spectrum wider,
- more exponential than gaussian

(plots with ‘static’ helix scenario)

Helix vs. standard fragmentation:
- $Q$ spectrum wider,
- shifted to lower values
- $\rightarrow$ bump at $Q \sim 0.3$ GeV
- $\rightarrow$ enhancement at low $Q$
Charge combination asymmetry? Most amazing:

Helix model in the base scenario (for direct hadrons only) predicts larger enhancement for unlike-sign pair combinations (adjacent hadrons dominating)

After extension of the model to the resonance decay, the like-sign pairs dominate the low Q region!!!

Bose-Einstein-like correlations arise NATURALLY in the helix string model!!!

Also: the phenomenon known as ‘enhancement of the source’ (in BE terminology) is qualitatively reproduced by the model
The expected effect very similar for $Z^0$ hadronic decay and the LHC minimum bias:

This is just an illustration: does not include neutrals and long-lived resonances (correlations overestimated)
BE or not BE?

Several possibilities:

HELIX ( + reordering of resonances ) sufficient to describe the data

HELIX + fluctuations in the string break-up history affecting color flow

HELIX + “genuine” Bose-Einstein symmetrization of the string diagram (Bo Andersson et al.)

Tuned helix parameter summary

- **Existence of correlations between longitudinal and transverse component of hadron momentum supported by the LEP data**
  
  \[ \text{(HELIX model)} \]

  \( S \approx 0.5-1. \text{ rad/GeV} \)

  \( r \approx 0.4-0.5 \text{ GeV} \)

- **Existence of azimuthal ordering of hadrons supported by the LHC data**
  
  \[ \text{(HELIX model)} \]

  \( S \approx 0.6 \text{ rad/GeV} \)

  \( r \approx 0.5 \text{ GeV} \)

- **The predicted 2-particle correlations qualitatively consistent with observations traditionally attributed to the Bose-Einstein interference**

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In all these cases, the helix string model provides explanation for poorly understood features in the real data while using FEW free parameters (on the contrary – zillions of random numbers removed from the simulation)
String model versus clusterization model

ATLAS
\( \sqrt{s} = 7 \text{ TeV} \)

- Data 2010
- PHOJET
- PYTHIA8 4C
- PYTHIA6 AMBT2b
- HERWIG++ UE7-2
- HERWIG++ UE7-2 soft

\( n_{\text{ch}}>10, \ max(p_T)<10 \text{ GeV} \)
\( p_T>100 \text{ MeV}, |\eta|<2.5 \)

\( n_{\text{ch}}>10, \ max(p_T)<1 \text{ GeV} \)
\( p_T>100 \text{ MeV}, |\eta|<2.5 \)

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