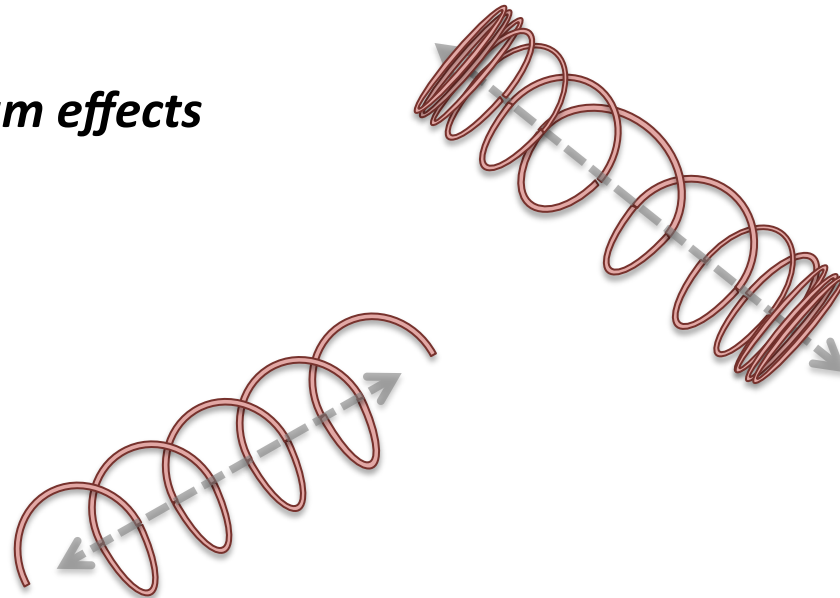# Study of the helix model
## (Šárka Todorova-Nová, MFF UK Prague)

➢ **Introduction : the idea & the experimental evidence**
-> inclusive $(p_T)$ spectra
-> azimuthal ordering of hadrons

➢ **Model development : quantum effects**
-> meson spectra
-> $p_T$ threshold
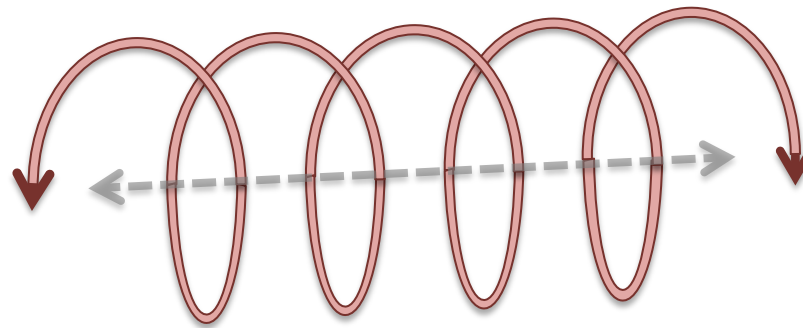-> 2-particle correlations

➢ **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 κ ≈ 1 GeV/fm  )**
**( = fragmentation method in Jetset/Pythia)**
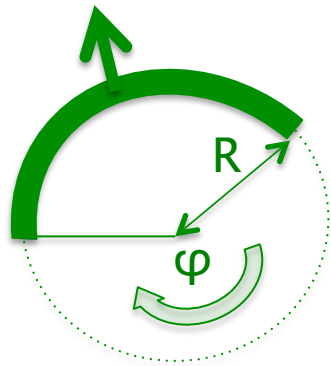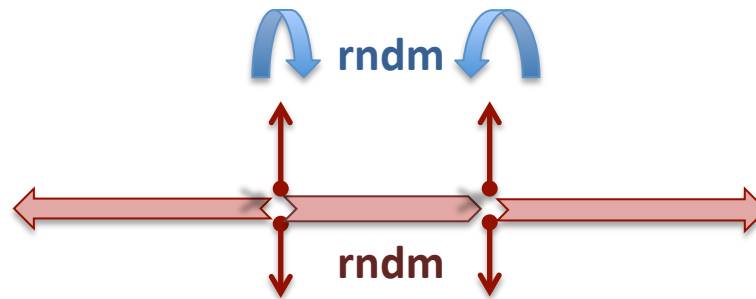
q ⟵————————————————⟶ q̄

**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*
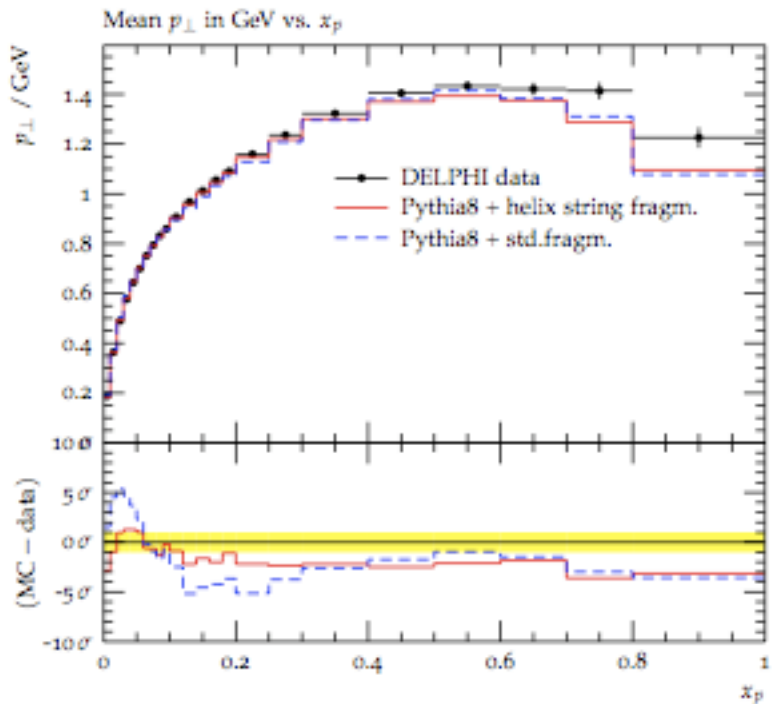*at each breakup vertex )….*

**rndm**

**rndm**

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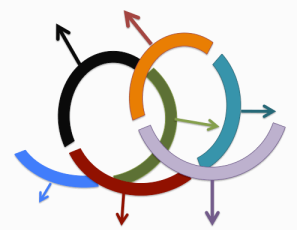*by the helical structure of the string*

R

φ

**| $p_T$ | = 2R sin (Δφ/2)**

R   helix radius
φ   helix phase

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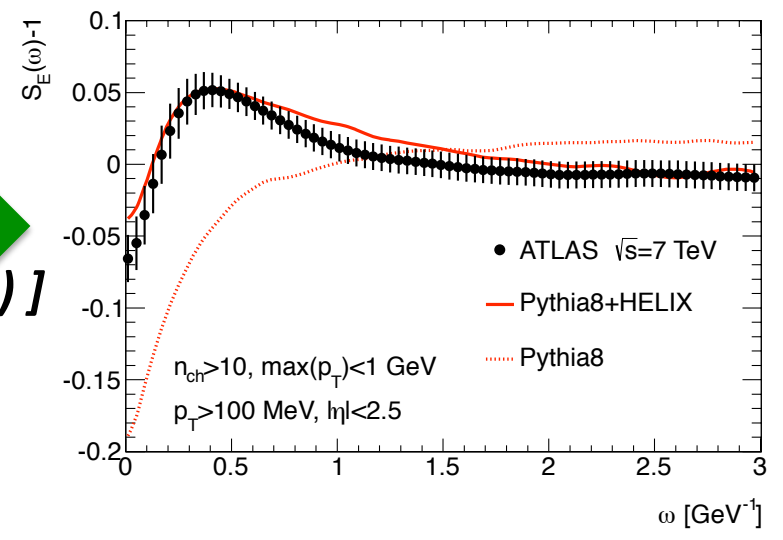
## Experimental evidence

*Mean $p_\perp$ in GeV vs. $x_p$*

*The removal of 2 degrees of freedom associated with the intrinsic pT generation leads to <u>significant</u> improvement in the description of hadronic Z0 data ( in particular, for $\langle p_T \rangle$ vs. $x_p$ )*

*The model predicts azimuthal ordering of hadrons [ Phys.Rev.D86, 052005 (2012) ]*

**The model drastically reduces "randomness" in the intrinsic pT sector yet describes the relevant hadronic data better over large span of energies ….**
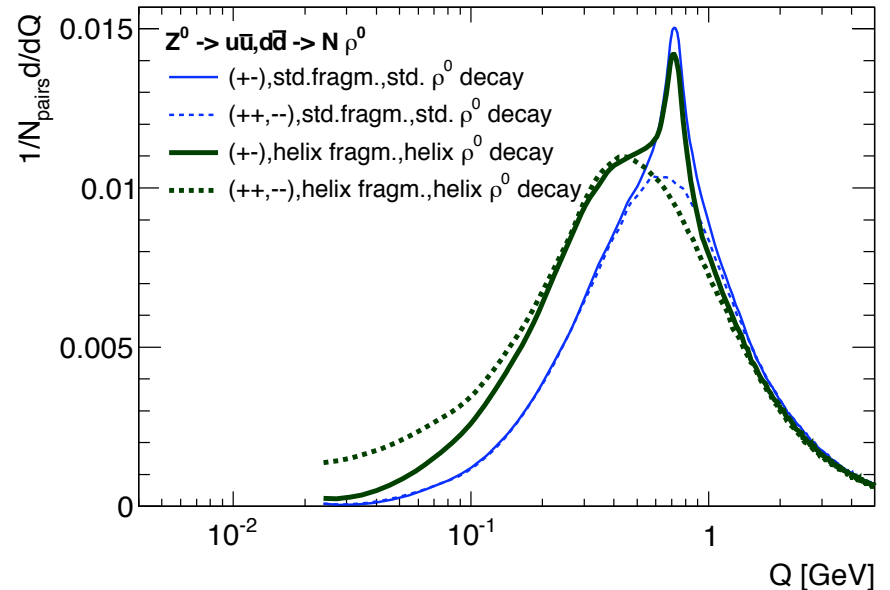
Comparison with model in Phys.Rev.D86,034001(2012)

*However, the model is not complete ...*

In-plane $p_\perp$ in GeV w.r.t. thrust axes



*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 ( $Z^0$ data no longer so well described )*

*A strong presence of resonances needed to reproduce the correct charged asymmetry pattern in 2-particle correlations*



$Z^0 \rightarrow u\bar{u}, d\bar{d} \rightarrow N \rho^0$
— (+-),std.fragm.,std. $\rho^0$ decay
---- (++,--),std.fragm.,std. $\rho^0$ decay
— (+-),helix fragm.,helix $\rho^0$ decay
···· (++,--),helix fragm.,helix $\rho^0$ decay

*However, the model is not complete …*

In-plane $p_\perp$ in GeV w.r.t. thrust axes



**$p_T$ threshold needed ?**

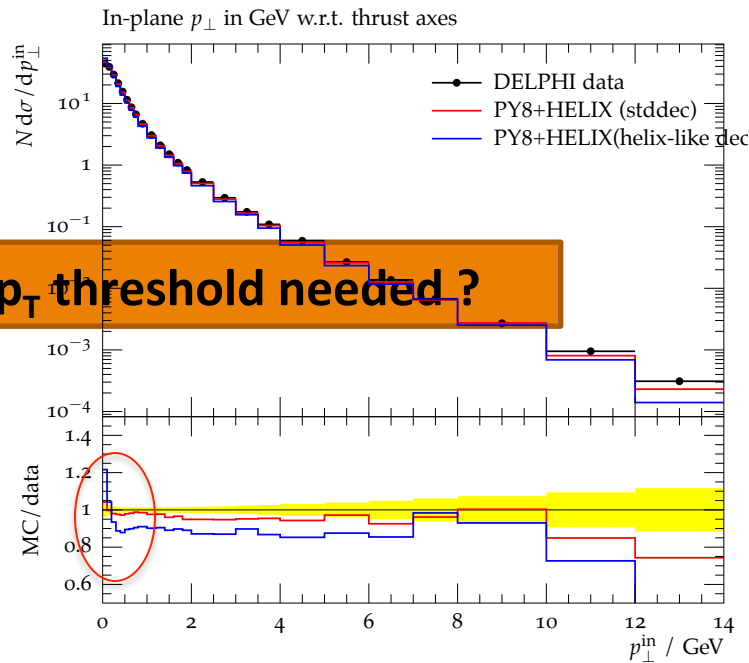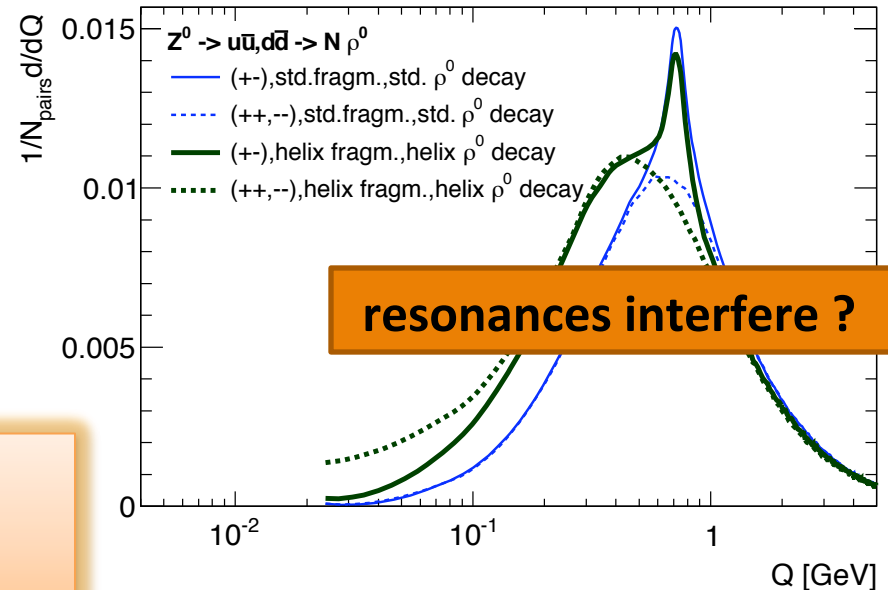*A strong presence of resonances needed to reproduce the correct charged asymmetry pattern in 2-particle correlations*

**Quantum effects better be taken into account explicitly ?**

*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 ( $Z^0$ data no longer so well described )*
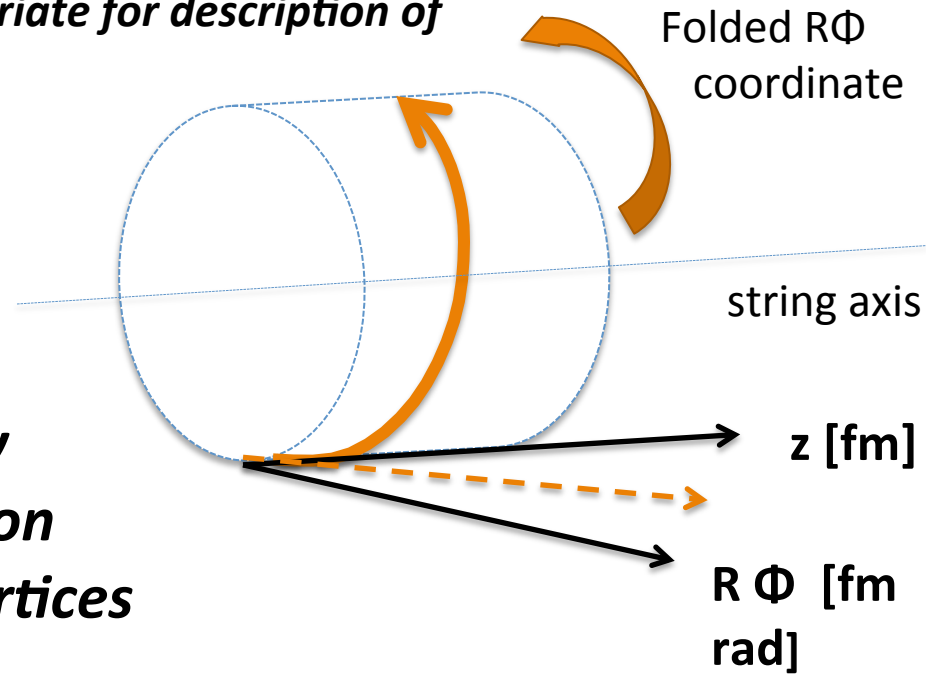


**resonances interfere ?**
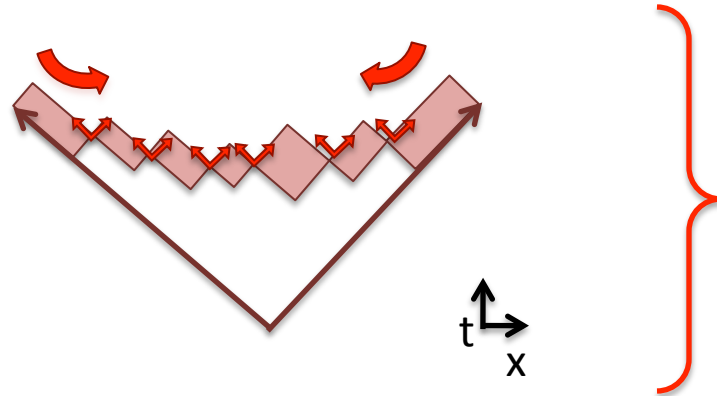
# Helix model in space-time coordinates

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

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

Folded RΦ coordinate

string axis

z [fm]

R Φ  [fm rad]

**… 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 allways space-like !*

t
x

# What happens if we IMPOSE TIME-LIKE DISTANCE between string breakup vertices which define the final hadron ?

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

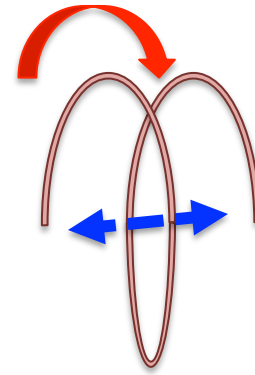**A/ information travels along string only**

$\rightarrow (X_i-X_j)^2 = 0$

( 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**

$(X_i-X_j)^2 > 0$

$m_S \leq m_c \leq m_S \sqrt{1+\beta^2}$

$\beta = v/c$  ( longitudinal )

It is sufficient to quantize $R\Phi$ to obtain discrete hadron spectra …

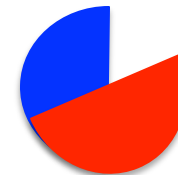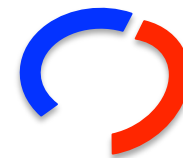# What happens if we IMPOSE TIME-LIKE DISTANCE between string breakup vertices which define the final hadron ?

**Quantization of RΦ leads to a discrete spectrum**

**RΦ ->  n R ΔΦ**    ( 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  $J \sim \kappa R^2 \Delta\Phi \sim m_T^2 / \kappa$
( -> Regge trajectories )

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

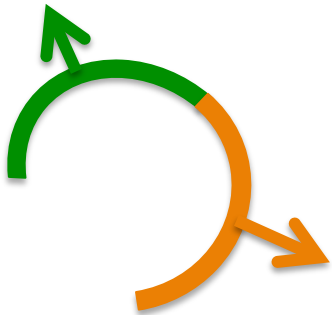**Can we figure out the properties of a "QCD quantum" ?**

Let's consider light pseudoscalar mesons :  π(140), η(547), η'(948)

- π  ground state (lightest hadron)        $R, \Delta\Phi$ ?    $m_T (n=1,3,5) = n \kappa R \Delta\Phi$

- η - > 3 π  ;  η' -> 5 π                              $p_T = 2 \kappa R \mid sin( 0.5 n \Delta\Phi) \mid$

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

$\xi = \kappa R \Delta\Phi \approx$ 0.192 GeV

$\Delta\Phi \approx 2.8$   ( constrained by
               π  mass )

R ≈ 0.07 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 ~ 0.14 GeV*

✔ *( data seem to suggest $p_T$(threshold) < 0.2 GeV )*
*Just about what is needed to "regularize" the soft particle production*
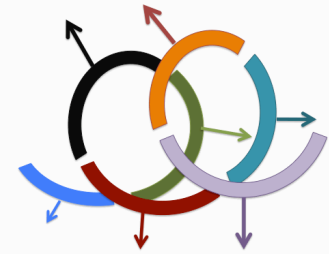*in the helix string model ?*

-> *intrinsic Q threshold at ~ 0.28 GeV for adjacent hadrons*
*( ground state pions ) -> direct impact on the correlation pattern*

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

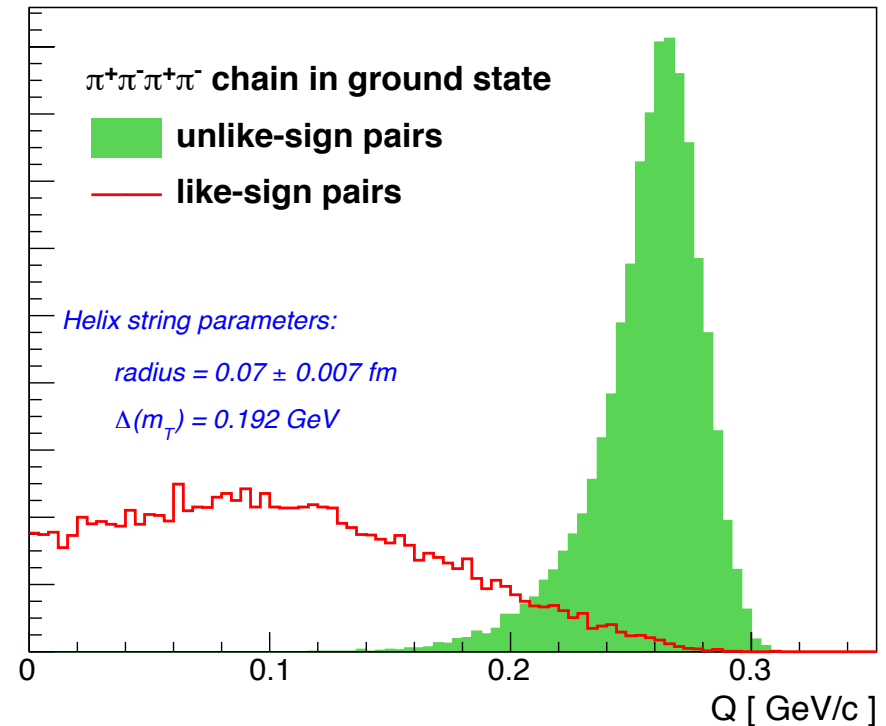$$Q \approx 2\, p_T \, \sin ( \Delta\Phi/2 )$$

# *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~0.2 GeV*

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



$\pi^+\pi^-\pi^+\pi^-$ chain in ground state
- unlike-sign pairs
- like-sign pairs

Helix string parameters:
radius = 0.07 ± 0.007 fm
$\Delta(m_T)$ = 0.192 GeV

Q [ GeV/c ]

*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 )*
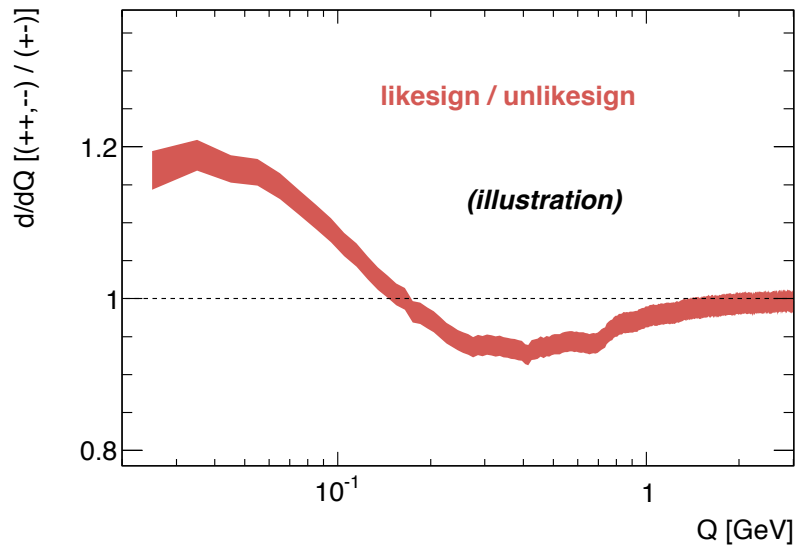
# *Here we hit upon an old unresolved problem :*

- *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*

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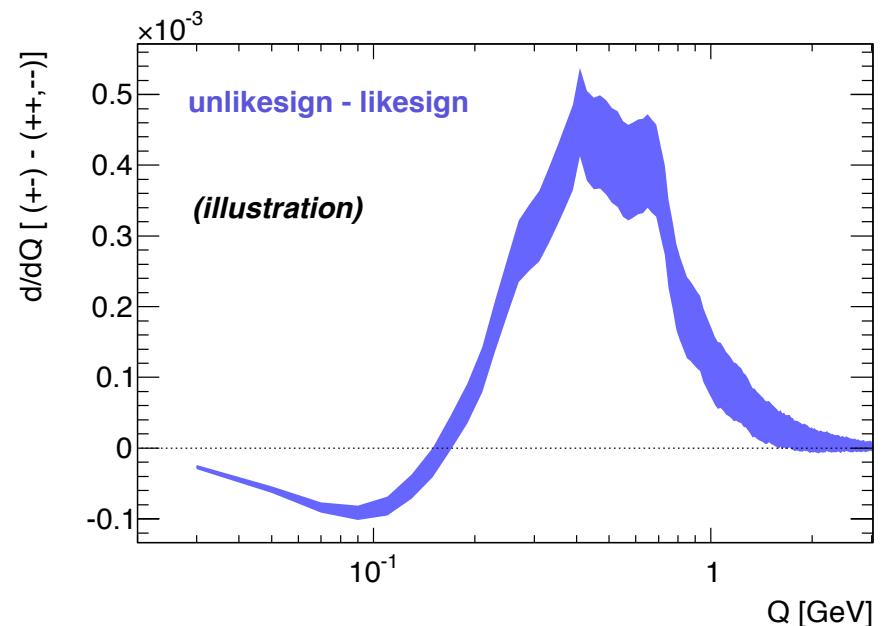
*assume INCOHERENT (chaotic) particle production study Bose-Einstein interference*

*assume COHERENT (correlated) particle production study  FRAGMENTATION*

likesign / unlikesign

(illustration)

y-axis: d/dQ [(++,--) / (+-)]

x-axis: Q [GeV]

**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*



unlikesign - likesign

(illustration)

y-axis: d/dQ [ (+-) - (++,--) ]

x-axis: Q [GeV]

# *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 ( NOVELTY 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' )*

# Next steps ?

- *Incorporate basic quantization ( $p_T$ threshold ) in the model,
propagate to the resonance decay, retune on data
( -> 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*


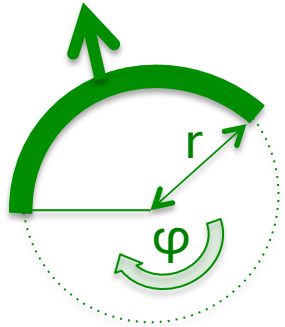  *( FRAGMENTATION or BOSE-EINSTEIN SYMMETRIZATION ? )*


- *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]*
- *ATLAS Coll., Phys.Rev.D86, 052005 (2012)*        *[azimuthal ordering]*
- *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

$$| \vec{p}_T | = 2r \sin (\Delta\phi/2) \qquad\qquad r \quad \text{helix radius}$$
$$\phi \quad \text{helix phase}$$

*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 : $\Delta\varphi$ ~ longitudinal separation along the string
2 "extreme" scenarios on the market :

$$\Delta\Phi = \frac{\Delta y}{\tau}, \qquad \Delta y = 0.5 \ln\left(\frac{k_i^+ k_j^-}{k_i^- k_j^+}\right), \qquad\qquad \Delta\Phi = \mathscr{S}\left(\Delta k^+ + \Delta k^-\right) M_0/2,$$

[ arXiv:1101.2407]

# *Helix shape* *corresponds to the optimal packing of soft gluons in the phase space*

## *Distance between gluons* $\sim \sqrt{(\delta y)^2 + (\delta \varphi)^2}$

**δφ neglected :**

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

-> singularity at the endpoint

-> works for simple qq~ string

(Pythia sets endpoint quark $p_T$=0)
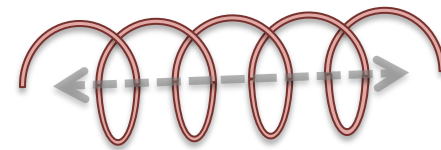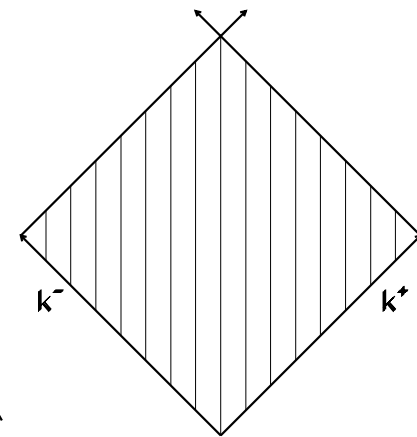
-> helix phase "running" along

 the string

**δy neglected :**

$$\Delta \Phi = \mathscr{S} \left(\Delta k^+ + \Delta k^-\right) M_0/2,$$

-> static helix structure

-> 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 ?*

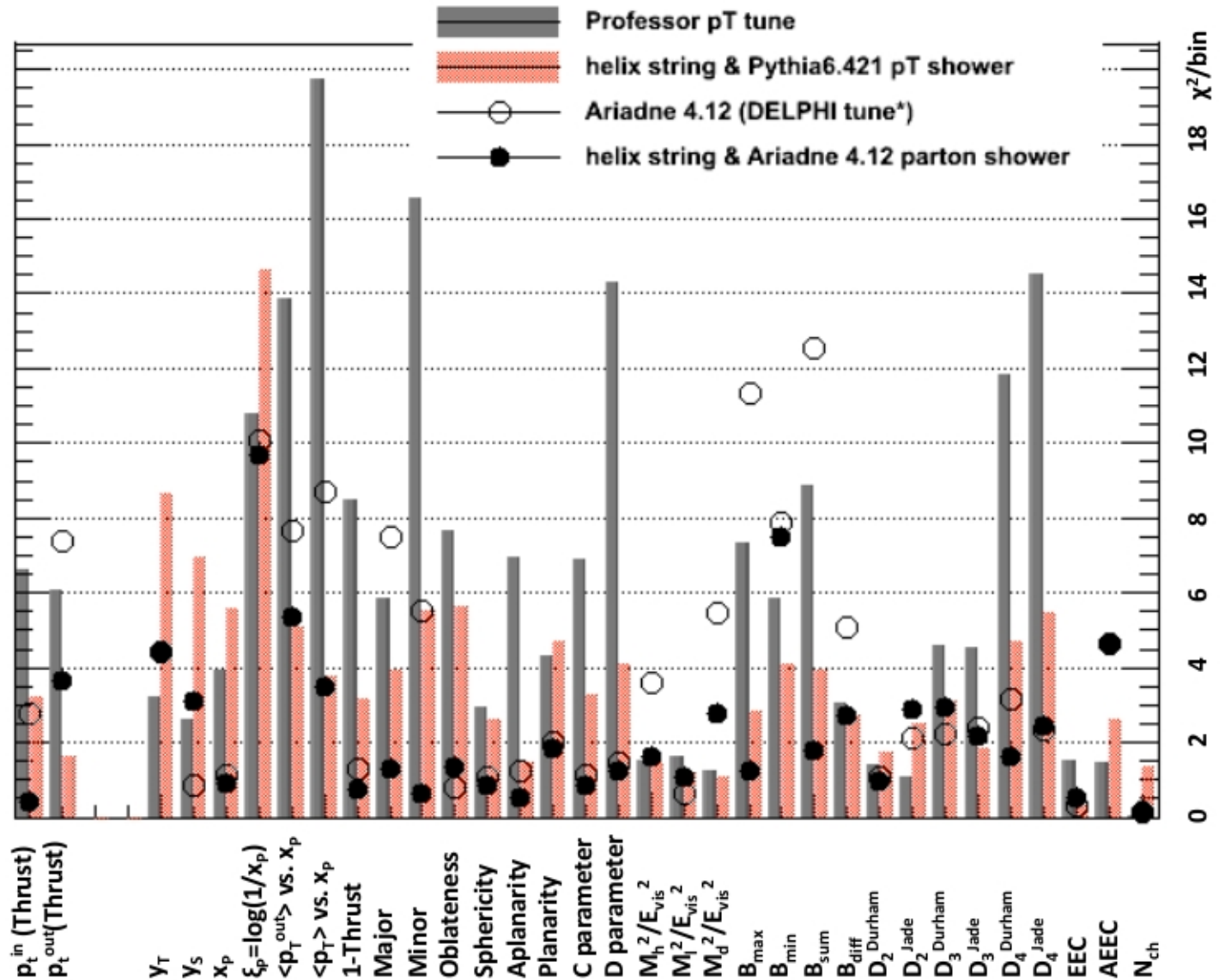# Indirect experimental evidence: tuning on $Z^0$ data
## ( DELPHI_1996_S3430090)

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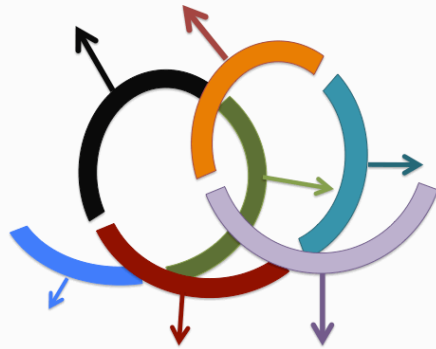
**4.0 -> 2.4 (Pythia 6 with ARIADNE parton shower )**

17/09/2013

## Best fit depends on the choice of input data
## Pythia8 + HELIX ( DELPHI_1996_S3430090 )

| • | Evshapes+Incl. | Evshapes | Inclusive | PT-only |
|---|---|---|---|---|
| HSF:screwiness | 0.92 | 0.91 | 0.54 | 0.72 |
| HSF:helixRadius | 0.41 | 0.39 | 0.54 | 0.30 |
| HSF:sigmaHelixRadius | 0.07 | 0.07 | 0.07 | 0.14 |
| TimeShower:pTmin | 0.77 | 0.72 | 0.74 | 1.04 |
| TimeShower:alphaSvalue | 0.139 | 0.138 | 0.138 | 0.141 |
| StringZ:aLund | 0.51 | 0.54 | 0.51 | 0.39 |
| StringZ:bLund | 0.44 | 0.48 | 0.22 | 0.47 |

Fixed in the following
to simplify LHC tunes

HelixStringFragmentation:screwiness ~ (0.5 – 1.0) [rad/GeV]
HelixStringFragmentation:helixRadius ~ (0.4 – 0.5) [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._

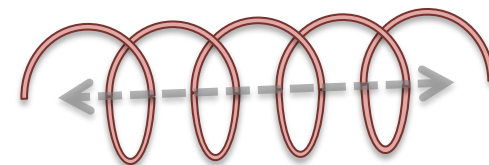**_With the help of power spectra, we test two (weakly correlated) hypotheses_**

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

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

B/ $\Delta\Phi \sim \Delta X$ _(energy-distance - amount of energy stored in the string/ ordered hadron chain - experimentally : ordered in pseudorapidity )_
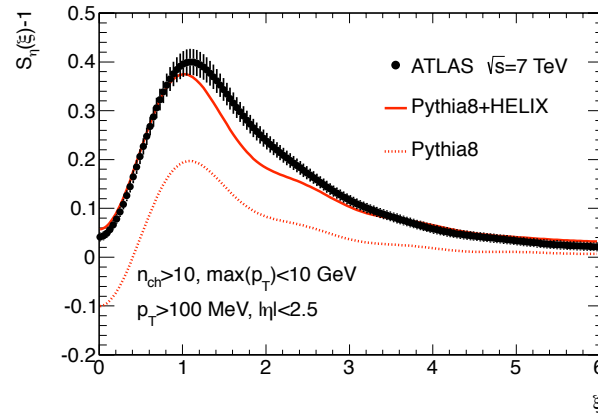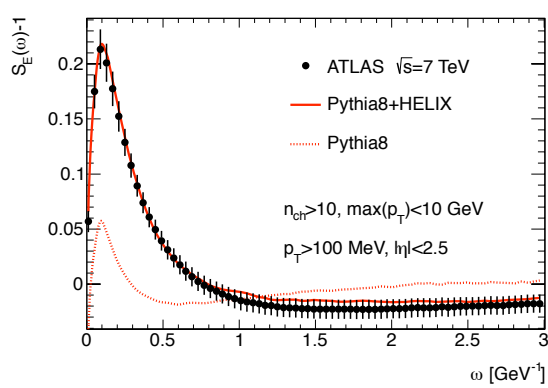
$$S_E(\omega) = \frac{1}{N_{ev}} \sum_{event} \frac{1}{n_{ch}} \left| \sum_j \exp(i(\omega X_j - \phi_j)) \right|^2$$

_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 ).*



| Tuned parameter | Input data set |
|---|---|
| Pythia8 4C +HELIX [6] | ATLAS_2012_I1091481 inclusive + low-$p_T$ depleted |
| HSF:screwiness | 0.61(2) |
| HSF:helixRadius | 0.460(5) |
| MultipartonInteractions:expPow | 3.7(1) |
| MultipartonInteractions:pT0Ref | 2.09(3) |
| SpaceShower:pT0Ref | 1.81(4) |
| BeamRemnants:reconnectRange | 0.[F] |
| $\chi^2/N_{dof}$ | 581/443 = 1.3 |

TABLE II. Results of the tuning study using the ATLAS data [7]
collected at $\sqrt{s}$=7 TeV.

**PRD86,034001(2012)**

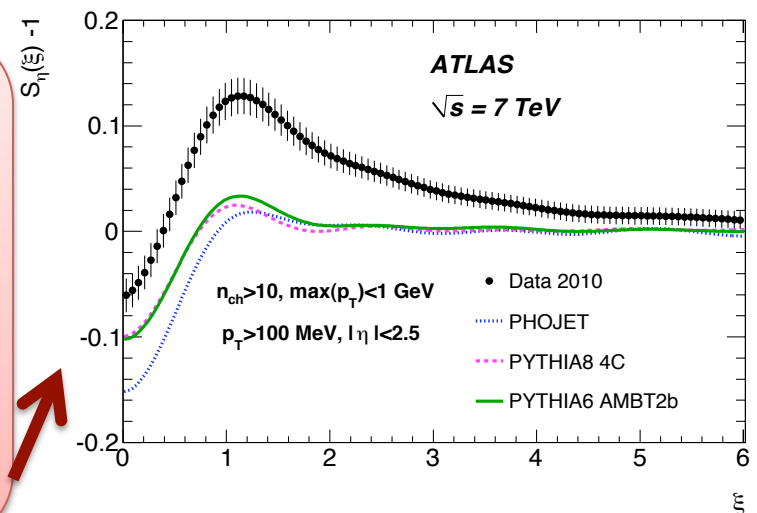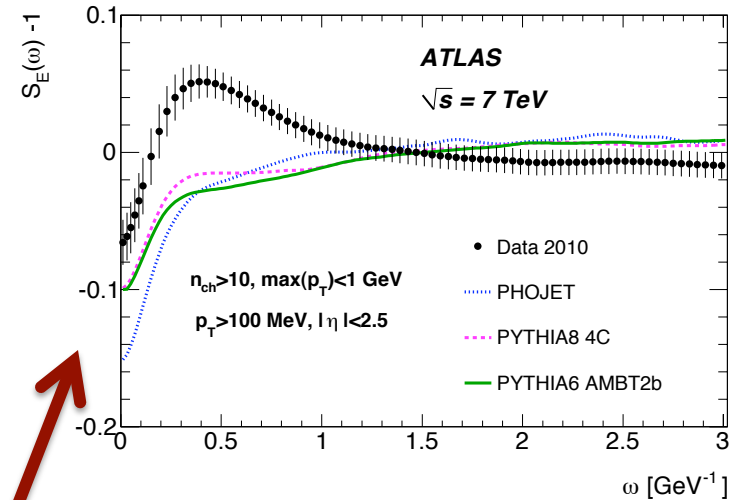# Azimuthal ordering of hadrons   *PRD86, 052005 (2012)*

*"Low $p_T$ enhanced" event selection*
*max($p_T$) < 1 GeV   (more sensitive to*
*fragmentation effects)*

**NOT DESCRIBED BY CONVENTIONAL MODELLING**

*Correlations  <u>STRONGER</u>  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
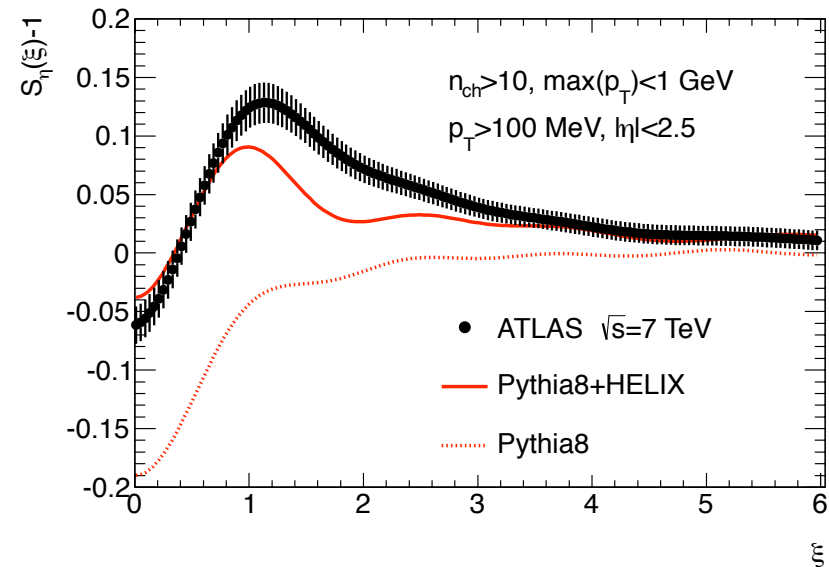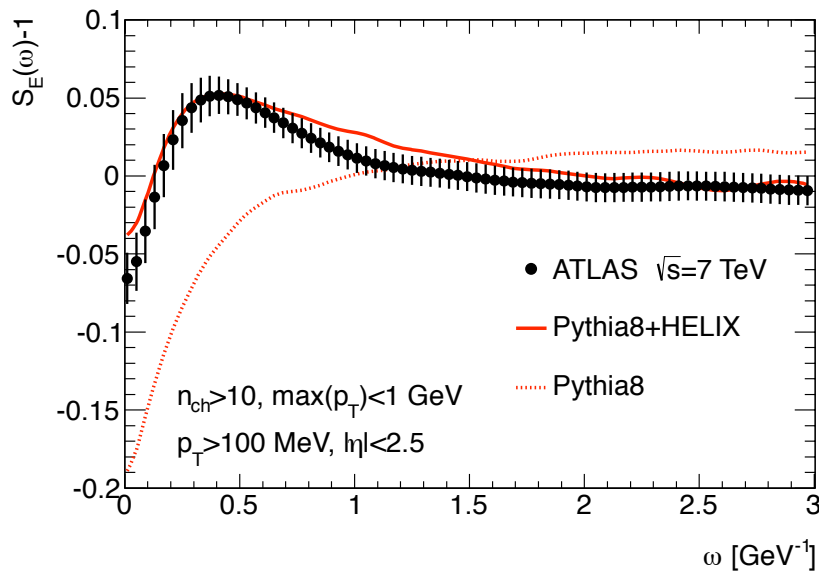 continuation of the
 fragmentation of the
 helix-shaped string )**



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*
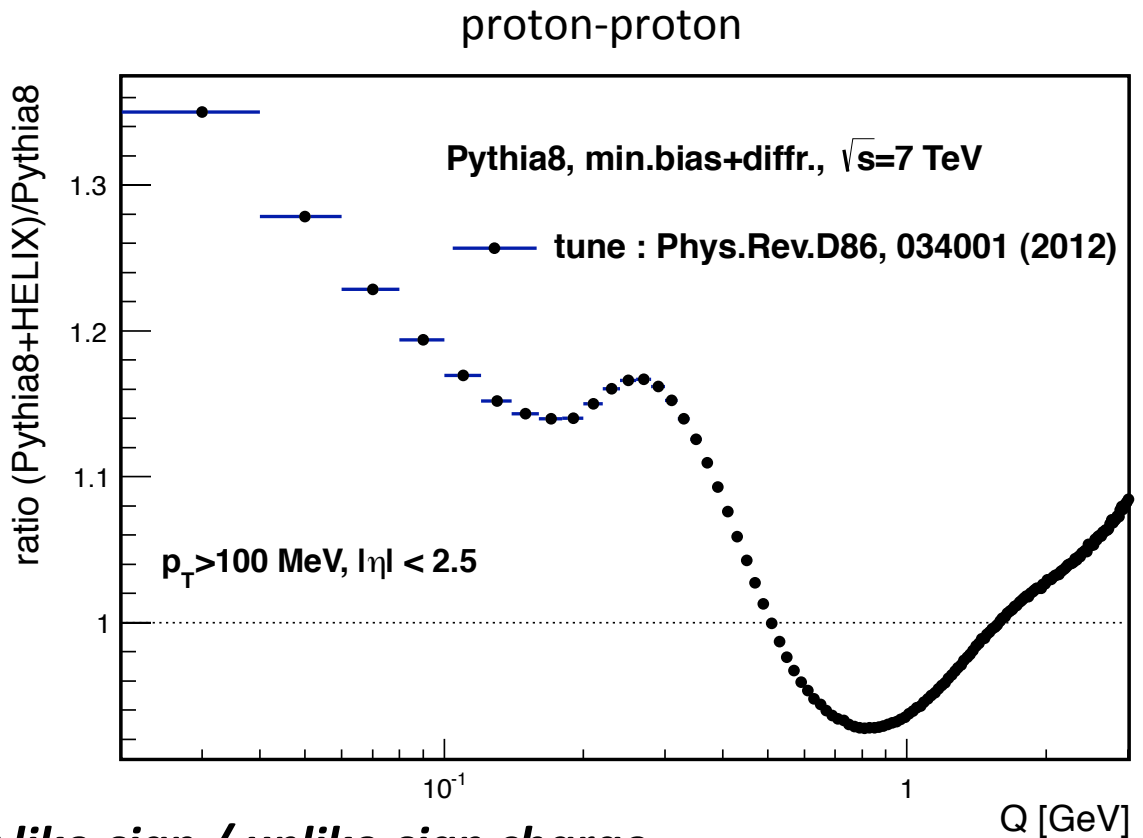*  of the data ! )*

**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*
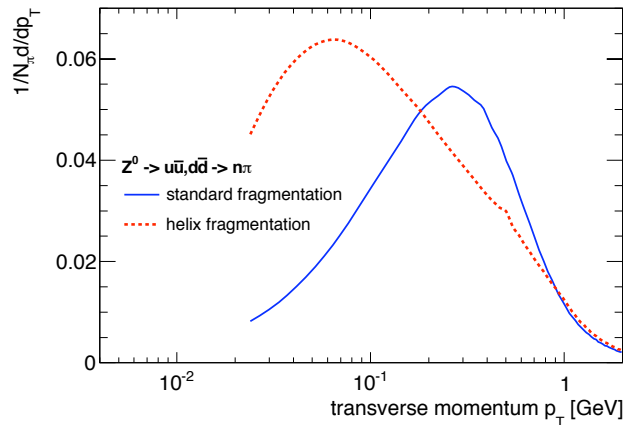
$$Q = \sqrt{-(p_1 - p_2)^2}$$
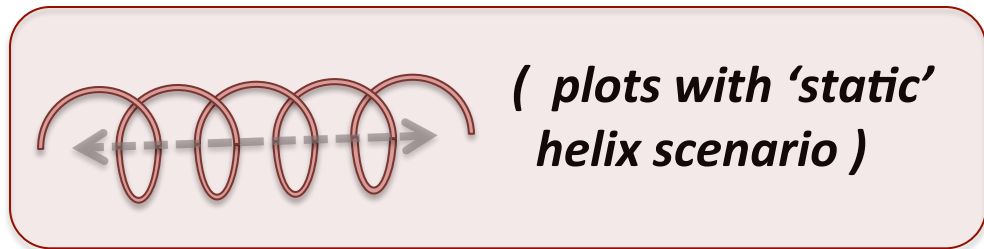
*Is the prediction consistent with the data ?*

proton-proton



Pythia8, min.bias+diffr., $\sqrt{s}$=7 TeV

tune : Phys.Rev.D86, 034001 (2012)

$p_T$>100 MeV, |$\eta$| < 2.5

ratio (Pythia8+HELIX)/Pythia8

Q [GeV]

*What about the prediction for like-sign / unlike-sign charge combination ?*

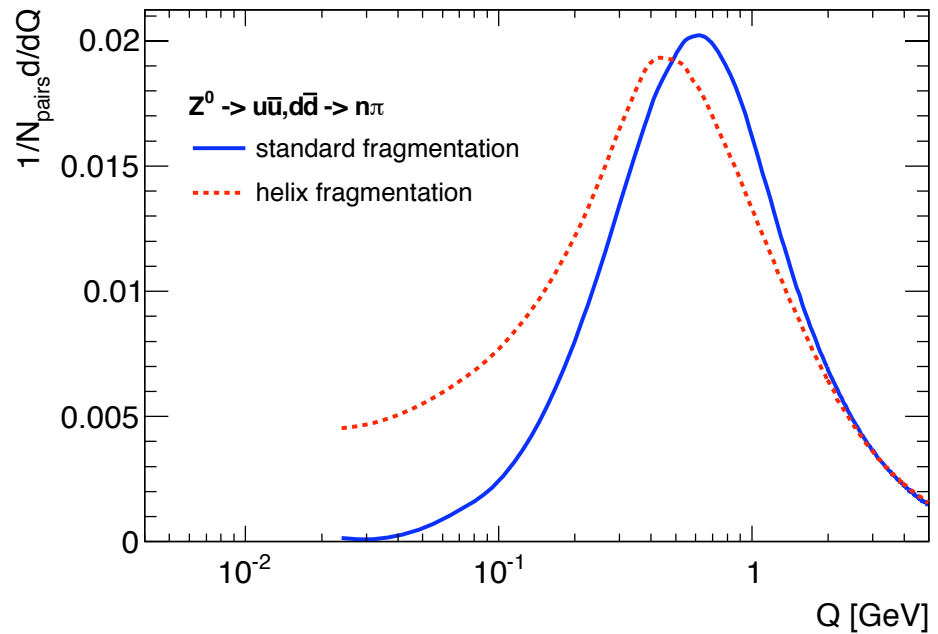# *Where the difference comes from ?* *TOY MODEL : $Z^0$ ->direct pions*



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

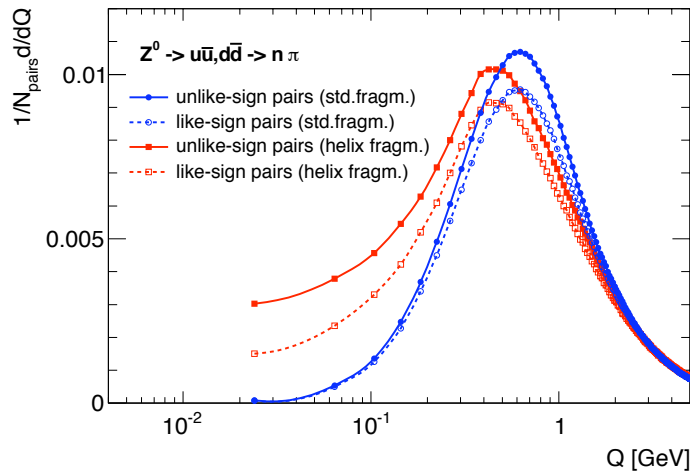*( plots with 'static' helix scenario )*

*Helix vs. standard fragmentation:*
*Q spectrum wider,*
*shifted to lower values*

*-> bump at Q ~ 0.3 GeV*
*-> enhancement at low Q*

# *Charge combination asymmetry ?  Most amazing :*



$Z^0 \to u\bar{u}, d\bar{d} \to n\pi$

- unlike-sign pairs (std.fragm.)
- like-sign pairs (std.fragm.)
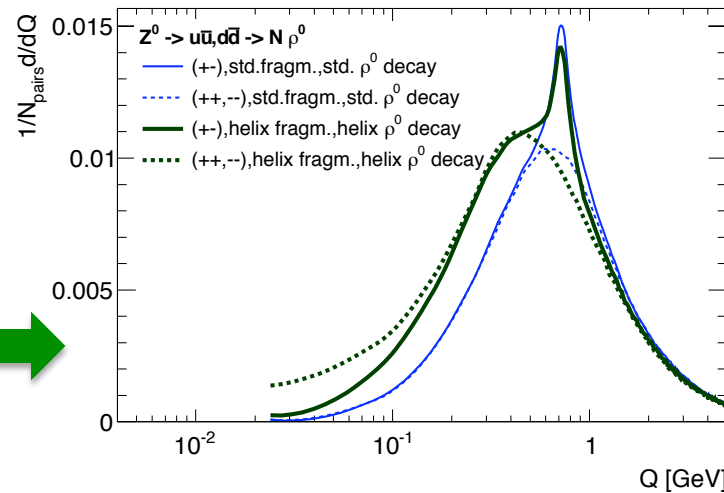- unlike-sign pairs (helix fragm.)
- like-sign pairs (helix fragm.)

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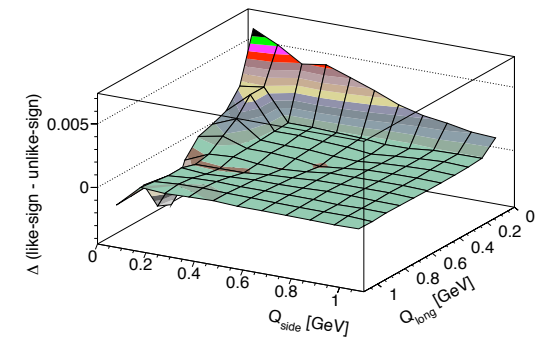
"static" helix scenario

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

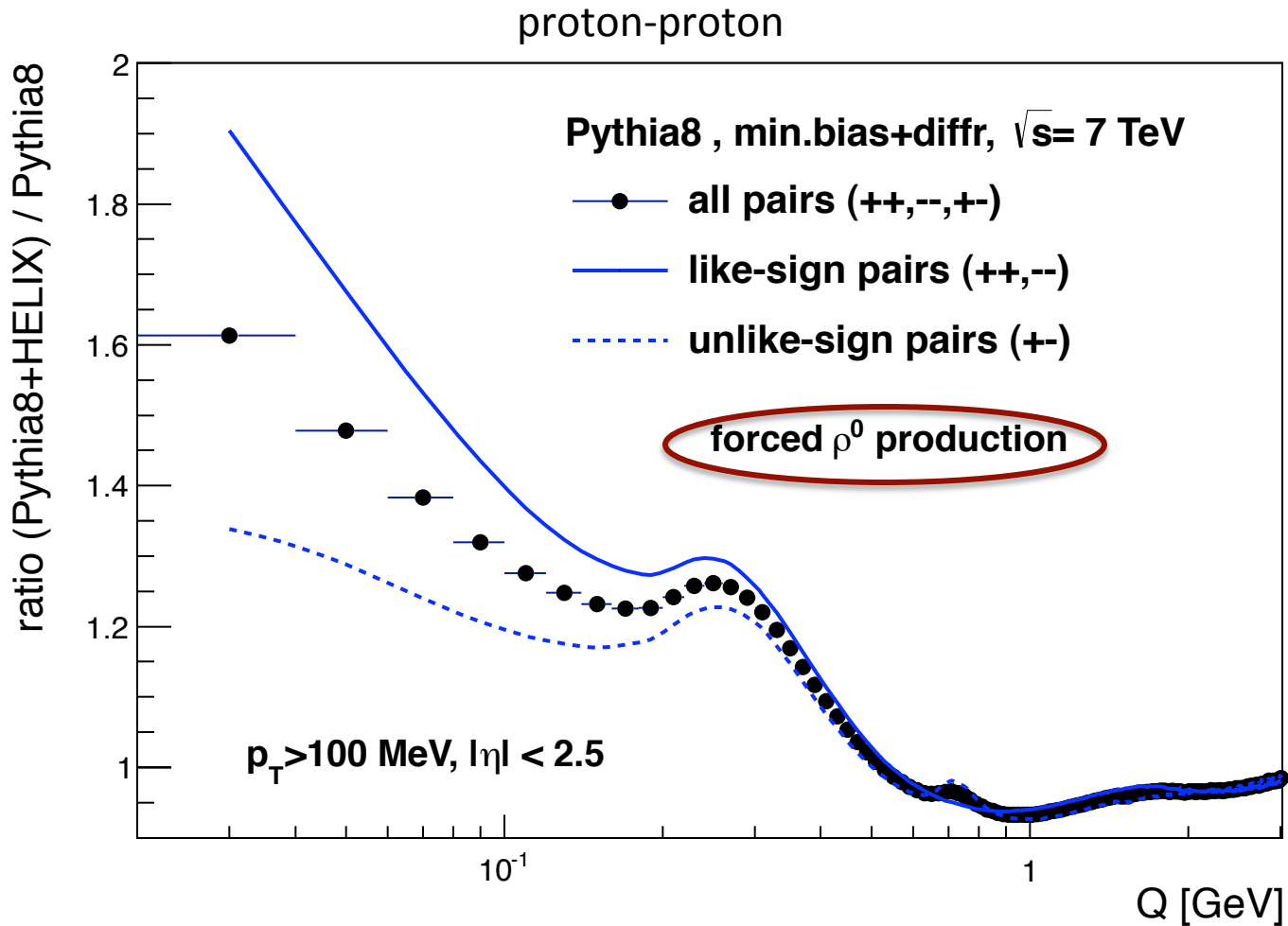*Bose-Einstein-like correlations arise NATURALLY in the helix string model !!!*



$Z^0 \to u\bar{u}, d\bar{d} \to N\rho^0$

- (+-),std.fragm.,std. $\rho^0$ decay
- (++,--),std.fragm.,std. $\rho^0$ decay
- (+-),helix fragm.,helix $\rho^0$ decay
- (++,--),helix fragm.,helix $\rho^0$ decay

*Also :  the phenomenon known as 'enhancement of the source' (in BE terminology) is  qualitatively reproduced by the model*

## *The expected effect very similar for Z⁰ hadronic decay and the LHC minimum bias:*
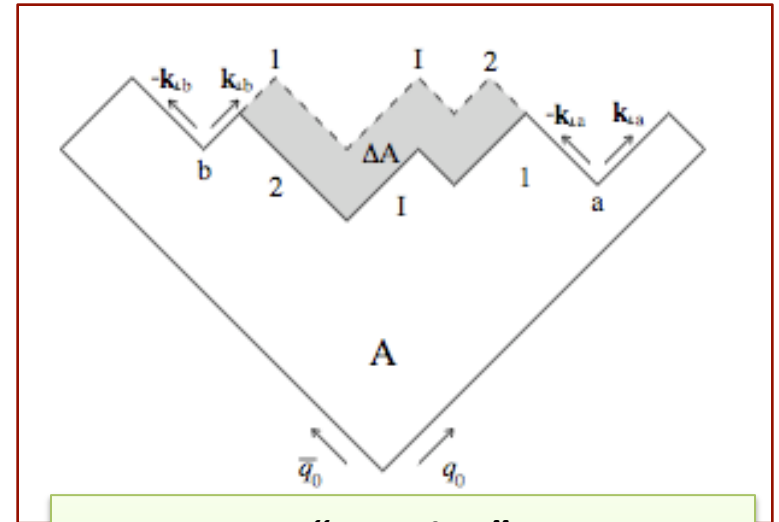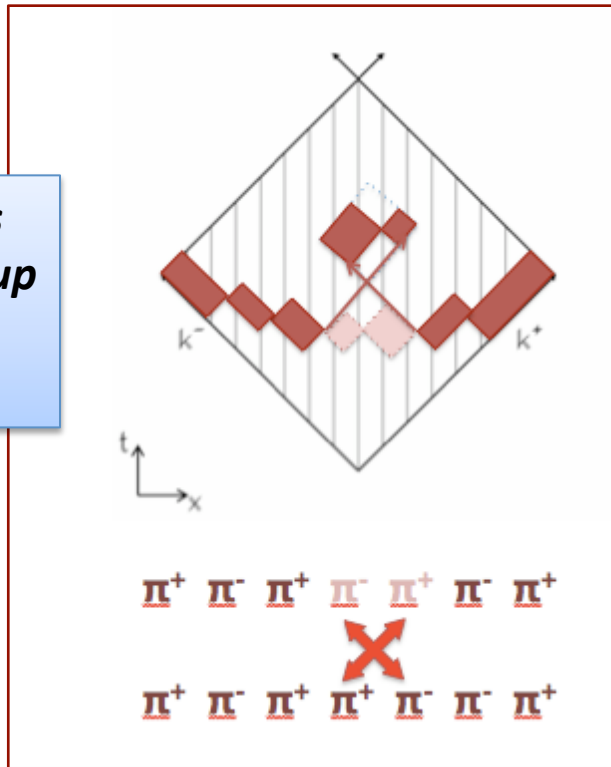
proton-proton



*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
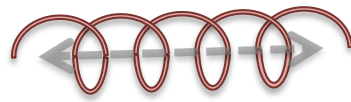> in the string break-up
> history affecting
> color flow



> HELIX + "genuine"
> Bose-Einstein symmetrization
> of the string diagram
> (Bo Andersson et al. )
> Phys.Lett.B421(1998)283

# *Tuned helix parameter summary*

❑ **Existence of correlations between longitudinal and transverse component of hadron momentum supported by the LEP data**
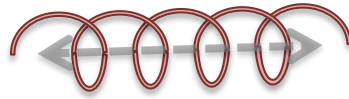
*( HELIX model*

$S \sim$ 0.5-1. rad/ GeV
$r \sim$ 0.4-0.5 GeV    )

91.2GeV $e^+e^-$

❑ **Existence of azimuthal ordering of hadrons supported by the LHC data**

*( HELIX model*

$S \sim$ 0.6 rad/GeV
$r \sim$ 0.5 GeV   )

7TeV pp

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

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