Hadronizace a Lundský fragmentační model

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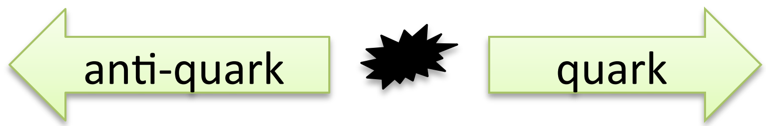
Tufts University,Medford, USA(+)

- ***Stručný úvod do strunového fragmentačního modelu***
- ***Intrinsic p_T (příčná hybnost)***
- ***Helix (model se spirální strunou)***
- ***… a pozorovatelné :***
  - ***inkluzivní p_T spectra***
  - ***azimutální uspořádání***
  - ***2-částicové korelace***
  - ***(asymetrie v kombinaci nábojů)***
- ***Helix versus Bose-Einsteinova symetrizace***
- ***Další vývoj modelu***
  prahová hodnota pT a Q , spektra hmot
  (kvantizace struny)

* since (+ till)1/4/2013

Brief introduction into string fragmentation model

B. Andersson *et al., "Parton* fragmentation *and string dynamics," Phys. Rept.* ***97, 31 (1983)391***
B. Andersson , *" The Lund Model " , Cambridge University Press 1998*



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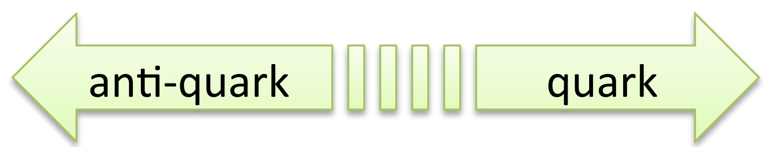
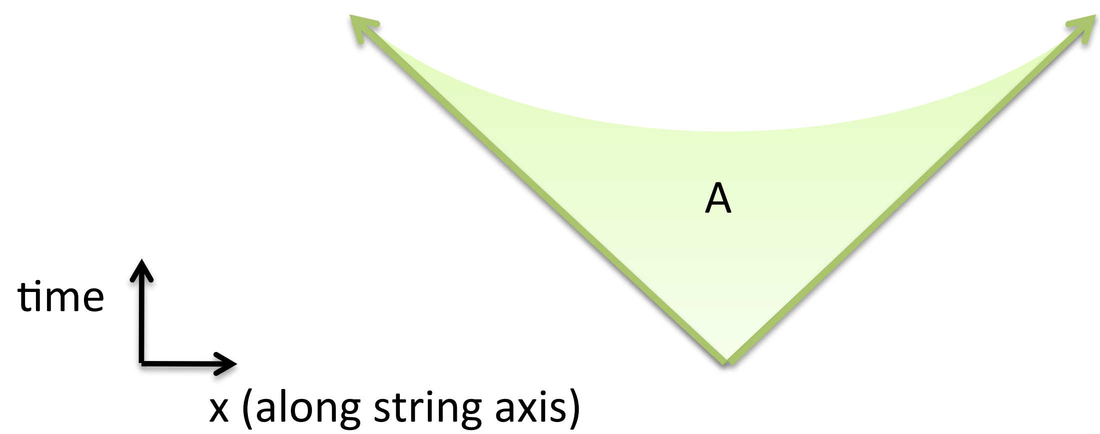


Partons loose
(κ ~ 1GeV/ fm)
through gluon emission
(-> confinment)
κ string tension



<u>String area A</u> : the area spanned by the string in the space-time diagram

<u>Probability</u> of break-up of the string ~ exp(-b A)

Brief introduction into string fragmentation model

String break-up occurs via so-called "tunneling effect" : a new qq~ pair is created from 'vacuum' (g->qq~)

Two adjacent string break-ups define a HADRON with

$$p_l = \kappa\,(t_1 - t_2)$$
$$E = \kappa\,(x_1 - x_2)$$

(meson ⇧ or baryon ⇩)

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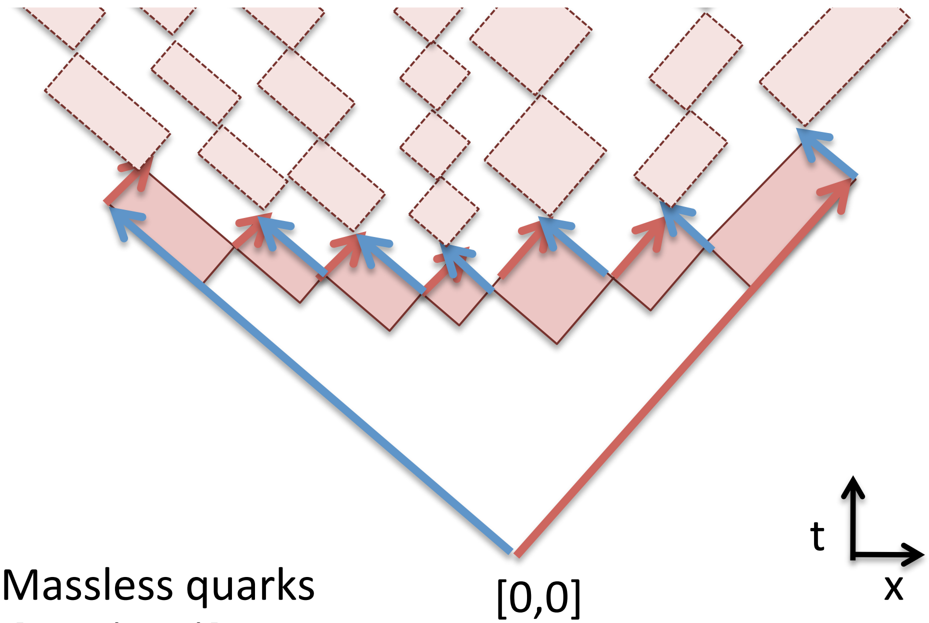
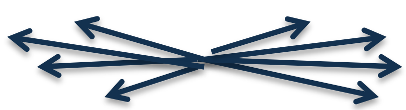


Massless quarks
[E, ± (p=E)]



Hadrons can be regarded as a pulsating string pieces (yo-yo effect of constant transfer of E/p between the parton and the field)

IMPORTANT: hadrons ALLWAYS carry a mixture of momenta of BOTH color partners

⇒ JET – PARTON correspondence is ill defined (only colour singlets are meaningful)

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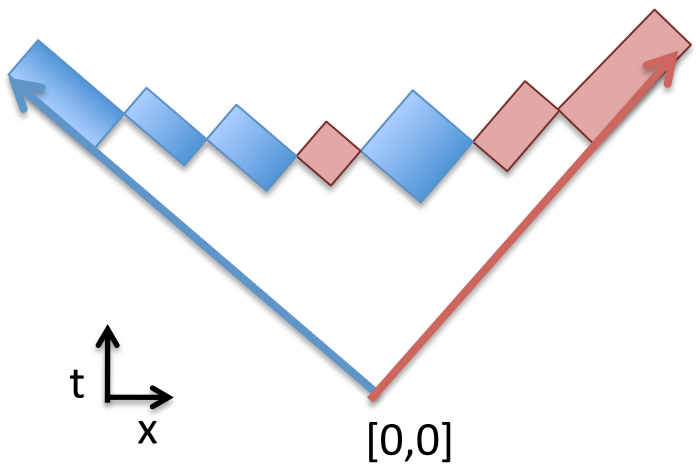
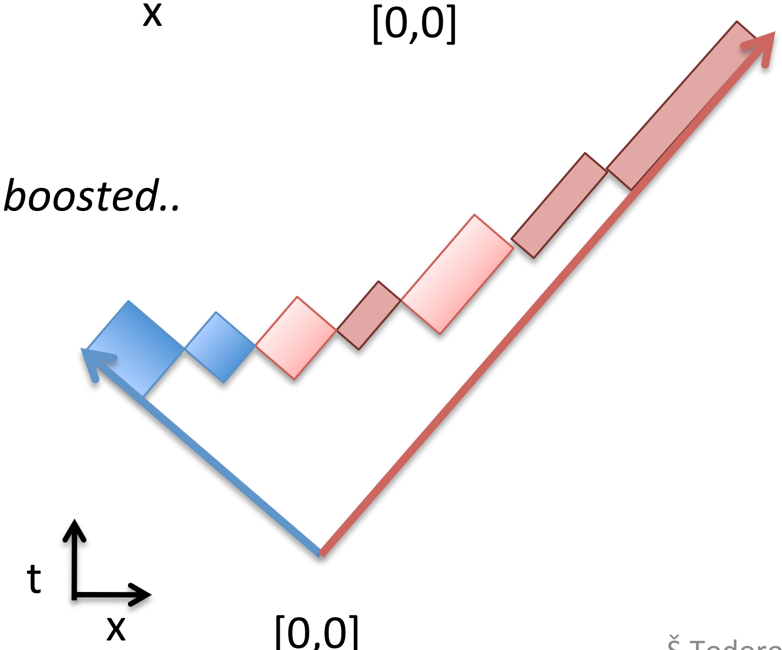


IMPORTANT: jets are NOT Lorentz invariant quantities !

Longitudinal boost affects composition of the jet !

..boosted..



The string fragmentation model is our PRINCIPAL tool for modelling of hadronisation (and jet shape) (JETSET -> PYTHIA)

Cluster model (HERWIG) – the only alternative - does not describe data as well

Brief introduction into string fragmentation model

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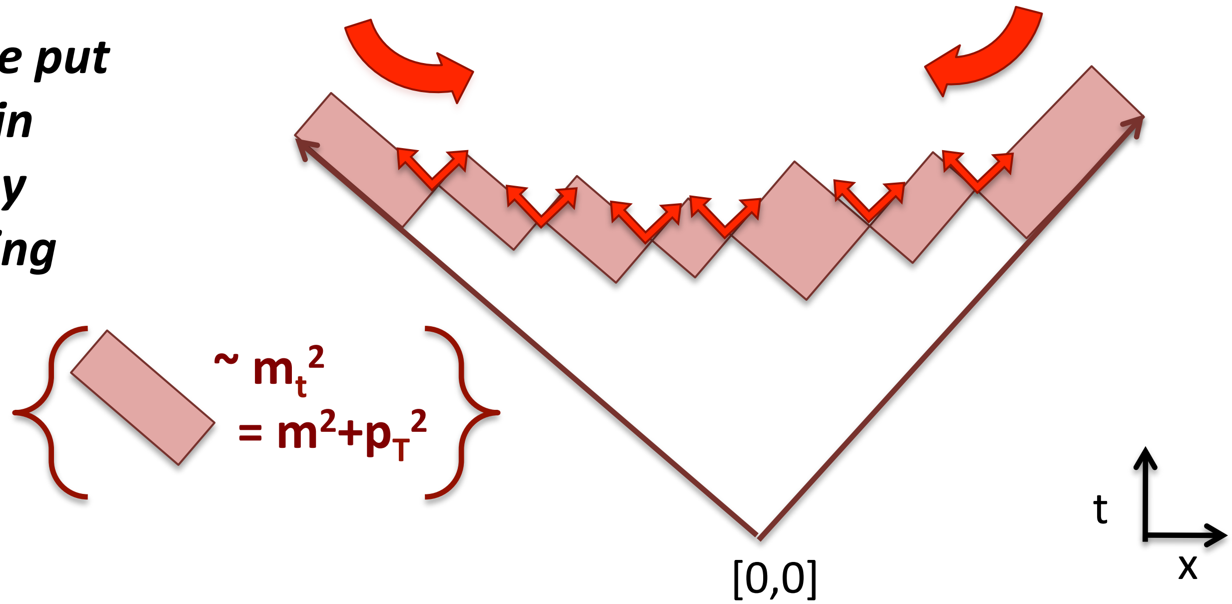
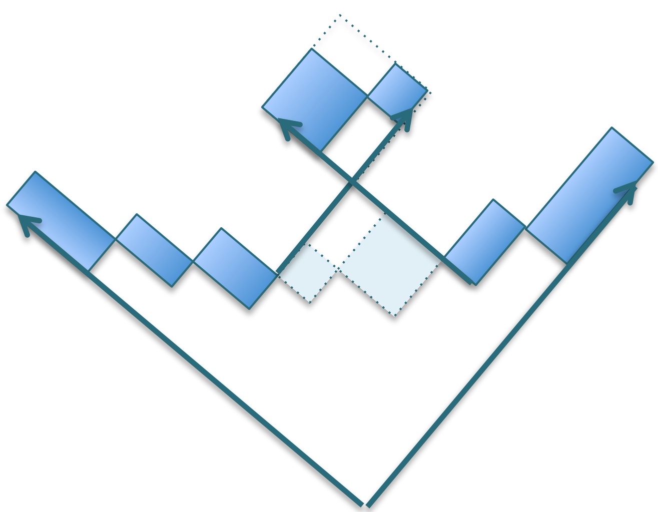
In PYTHIA, hadrons are put on-shell one by one, in 'outside-in' manner, by simple ordering of string break-ups

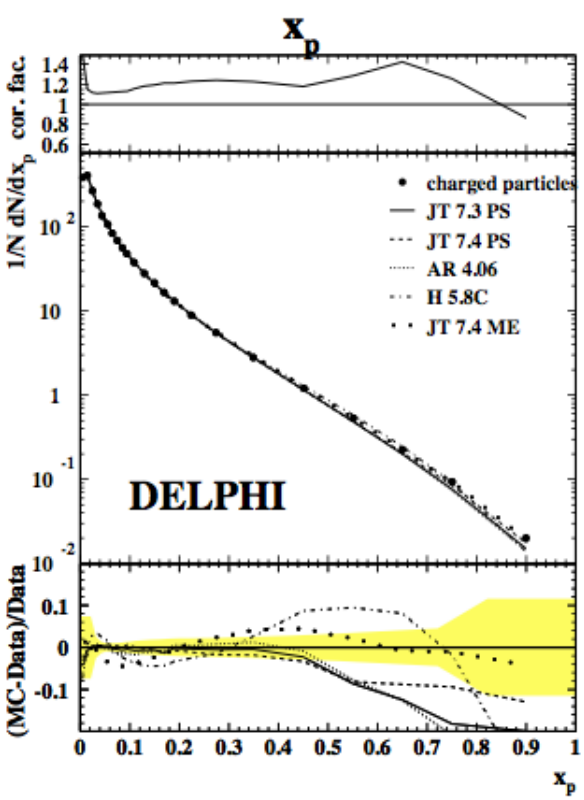


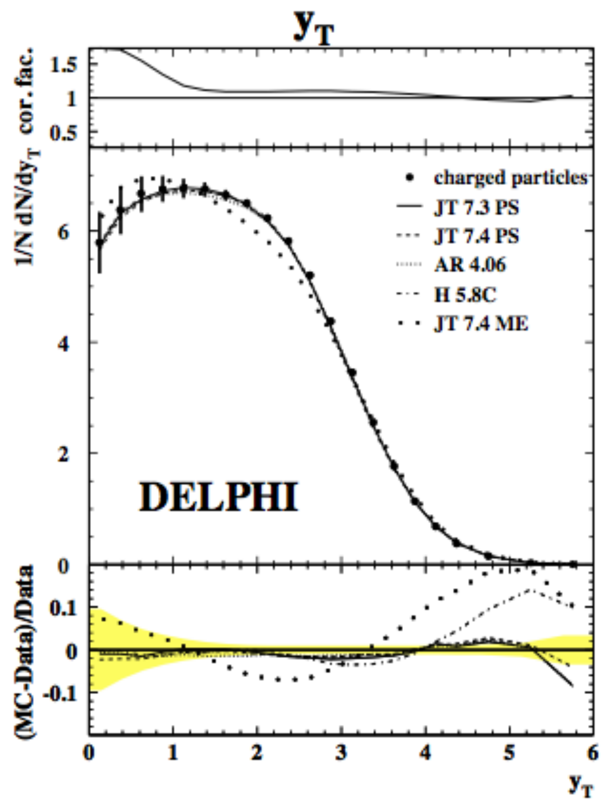


Fluctuations possible, but not simulated, because final state indistinguishable from 'base' configuration

Brief introduction into string fragmentation model

A wildly successful model – the JETSET/PYTHIA among top cited HEP references



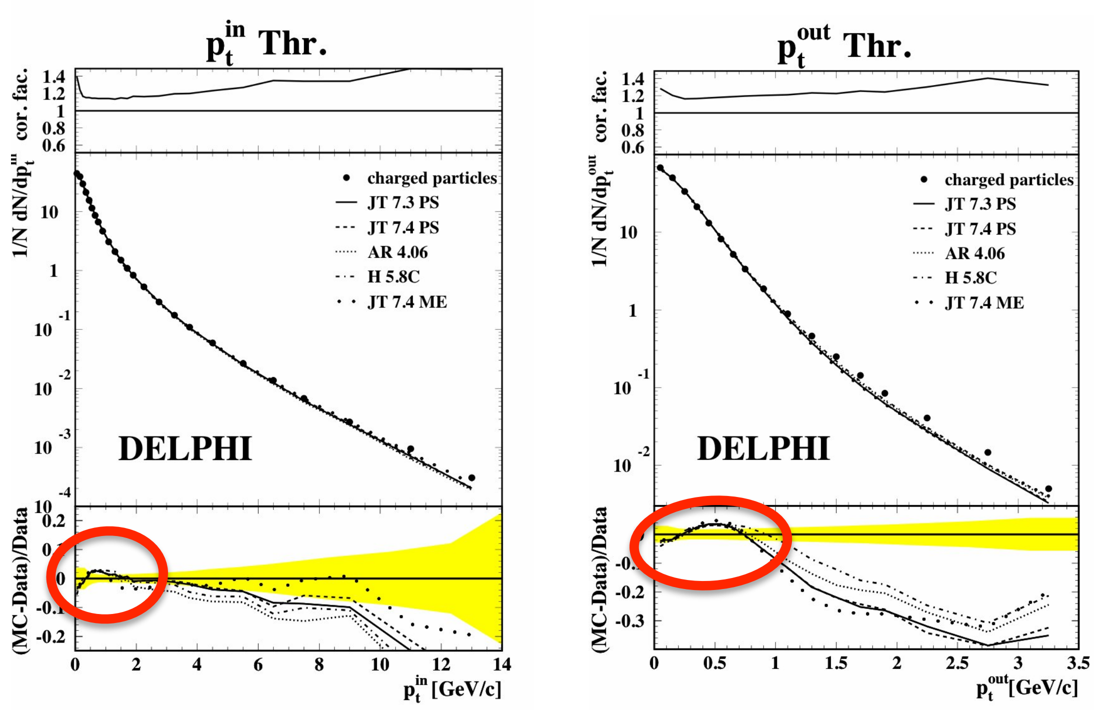


[DELPHI, Zeit. Phys. C73 (1996) 11]

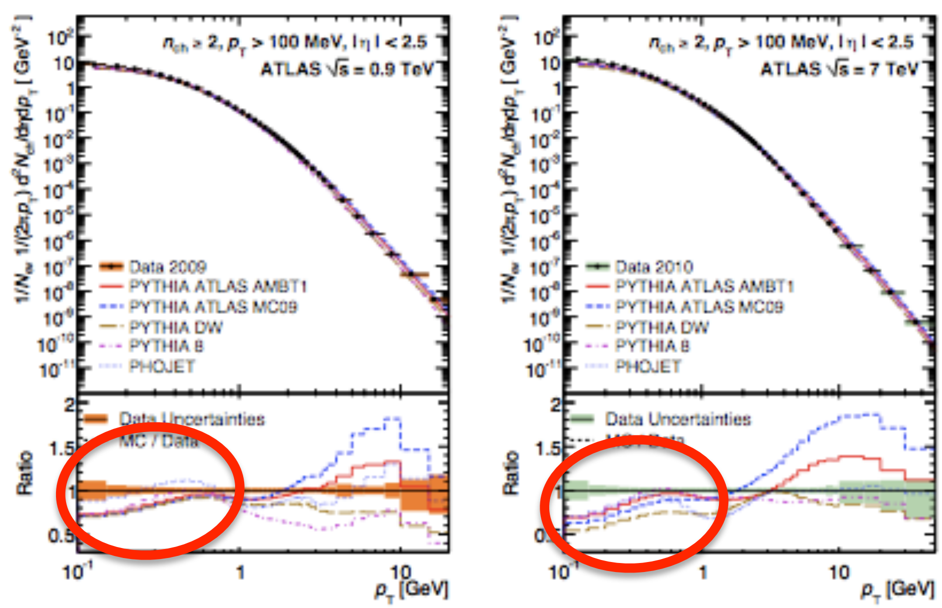
Good description of longitudinal fragmentation function

However: the model had allways some trouble to describe the transverse momenta

DELPHI data
[Z.Phys.C73(1996) 11.]



Similar discrepancy observed in ATLAS data
[New J.Phys.13(2011)053033]



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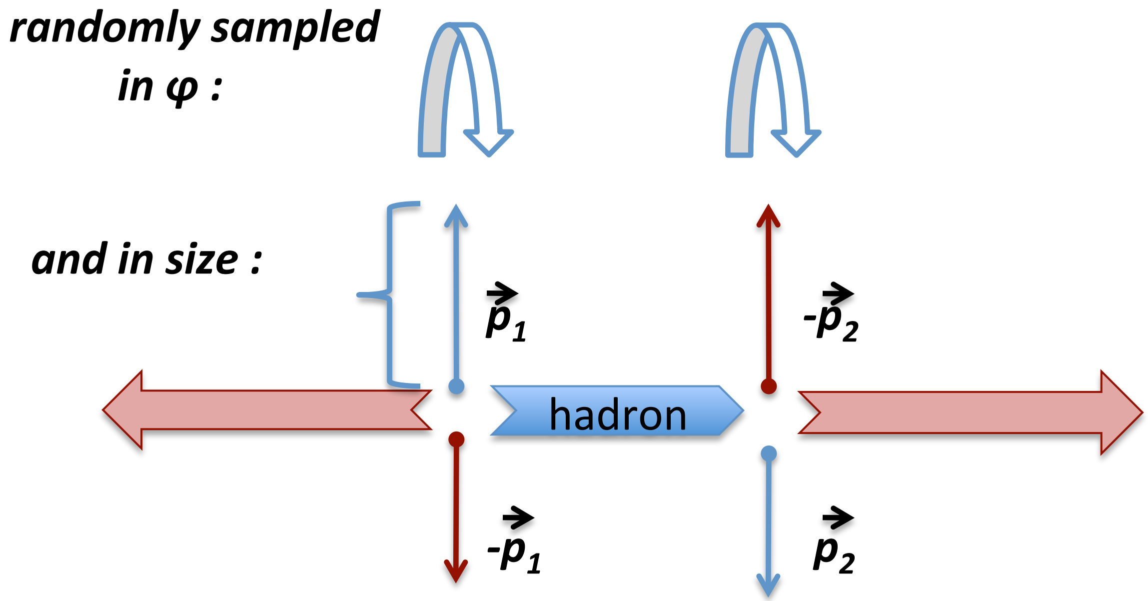
String break-up occurs via so-called "tunneling effect" : a new qq~ pair is created from 'vacuum' and assigned a certain transverse momentum



Two adjacent string break-ups define a HADRON with $\vec{p}_T = \vec{p}_1 + \vec{p}_2$

$$p_l = \kappa\,(t_1 - t_2)$$

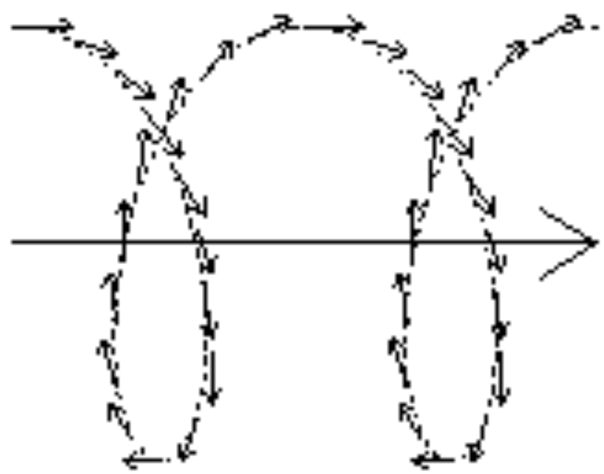
$$E = \kappa\,(x_1 - x_2)$$

HELIX string model

JHEP09(1998)014 , B.Anderson et al: "Is there a screwiness at the end of hadronic cascade?"

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

(helicity conservation rules forbid collinear emission of gluons)

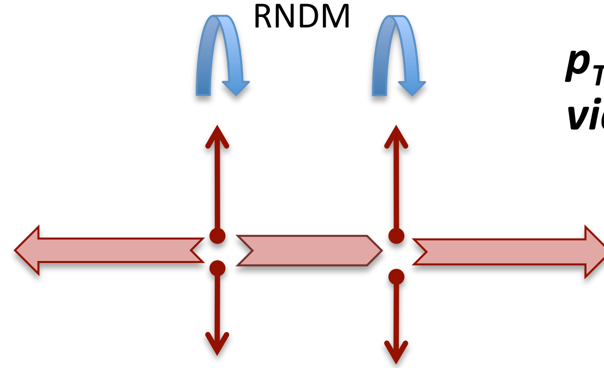


Alternative modelling of intrinsic p_T of direct hadrons

Replace the standard Lund string

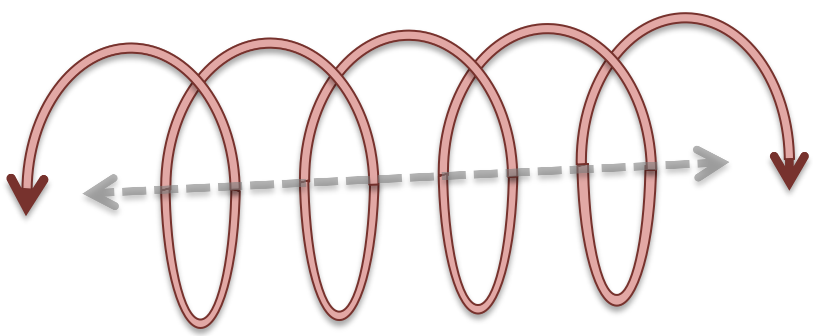
string tension κ ≈ 1 GeV/fm
(longitudinal)

+



p_T generation via tunneling effect

with a helix-like ordered gluon chain & suppress p_T in the tunneling :



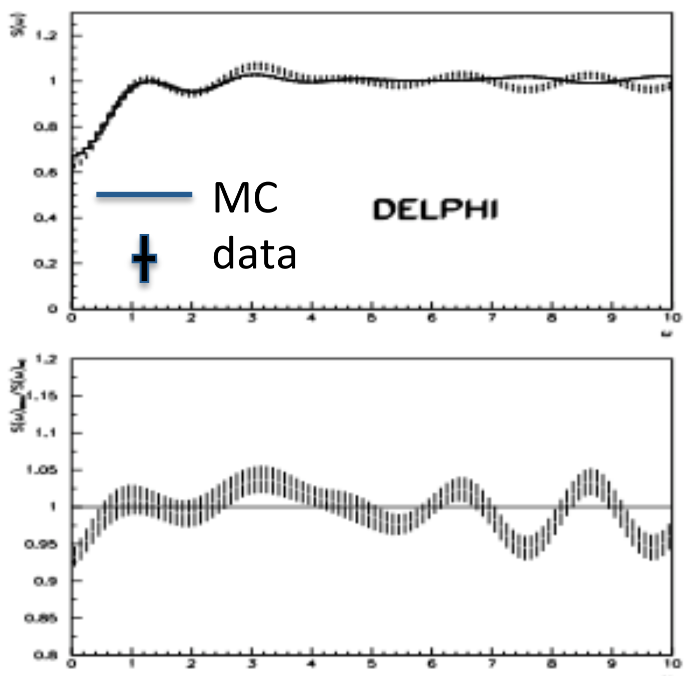
transverse momentum of a direct hadron ENTIRELY constrained by the spiral structure of the QCD string (2 degrees of freedom removed from the modelling)

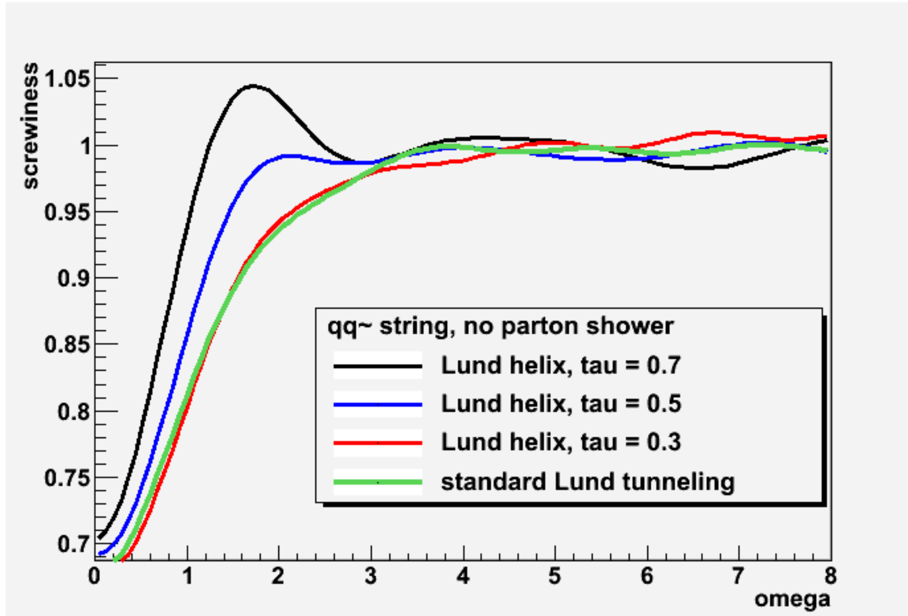
Helix string model (cont.)

'Screwiness' should be observable

$$S(\omega) = \Sigma_{ev} P_{ev} \, |\Sigma_i \exp(i(\omega y_i - \phi_i)|^2$$

- y *rapidity of hadron*
- ϕ *azimuthal angle of hadron*
- ω (=1/τ) *parameter*
- P_{ev} *normalization factor*





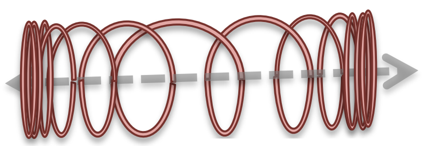
Immediately tested
(DELPHI 98-156 PHYS 799),
no signal found (τ ≤ 0.3)

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

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

[Š.T., arXiv:1101.2407]

$\delta\varphi$ neglected :



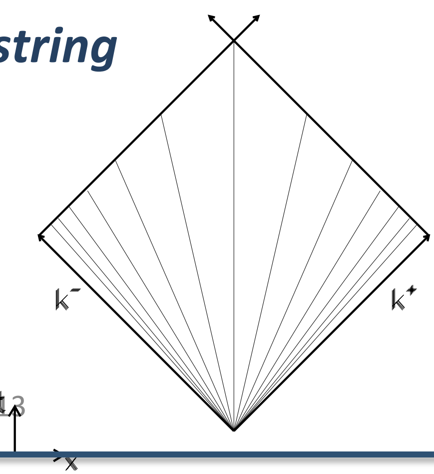
$$\Delta\Phi = \frac{\Delta y}{\tau}, \qquad \Delta y = 0.5 \ln\left(\frac{k_i^+ k_j^-}{k_i^- k_j^+}\right),$$

-> singularity at the endpoint

-> only for simple qq~ string

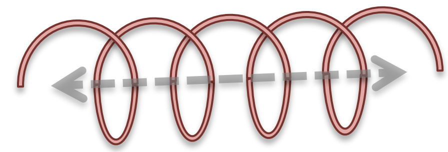
(Pythia sets endpoint quark p_T=0)

-> helix phase "running" along the string



(k stands for the fraction of the parton momentum at the origin)

δy neglected :

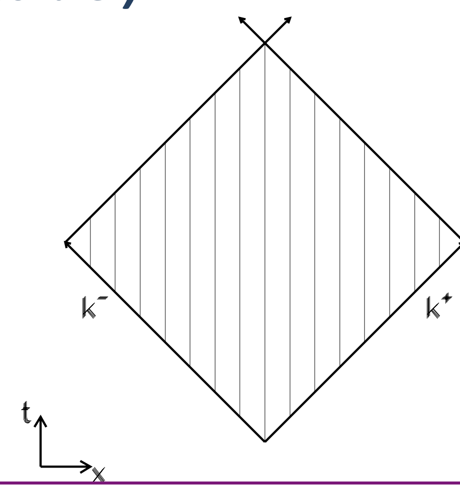


$$\Delta\Phi = \mathscr{S}\,(\Delta k^+ + \Delta k^-)\, M_0/2,$$

-> static helix structure

-> singularity removed

(arbitrary string configuration possible)

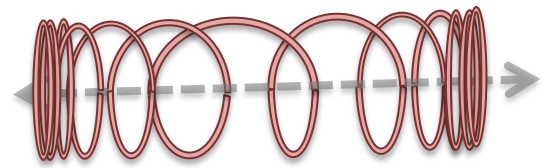


Helix re-parametrization

Original Lund helix parametrization : $\Delta\Phi = \Delta y / \tau$

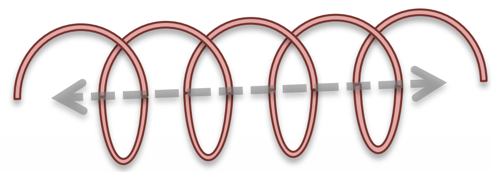
- non-homogenous string field

- contains endpoint singularity

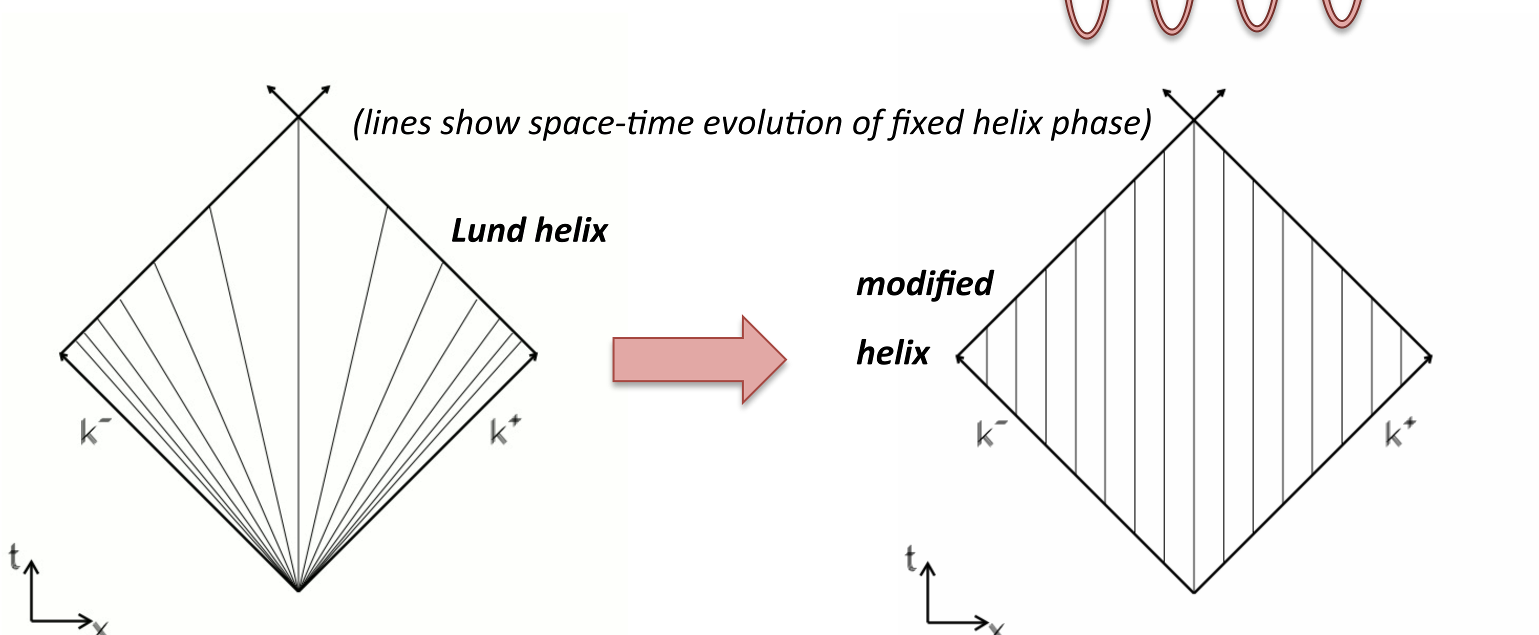


Simplified/modified helix parametrization : $\Delta\Phi = S\,\kappa\,\Delta l = S\,E$

- regular, static helix structure



(lines show space-time evolution of fixed helix phase)

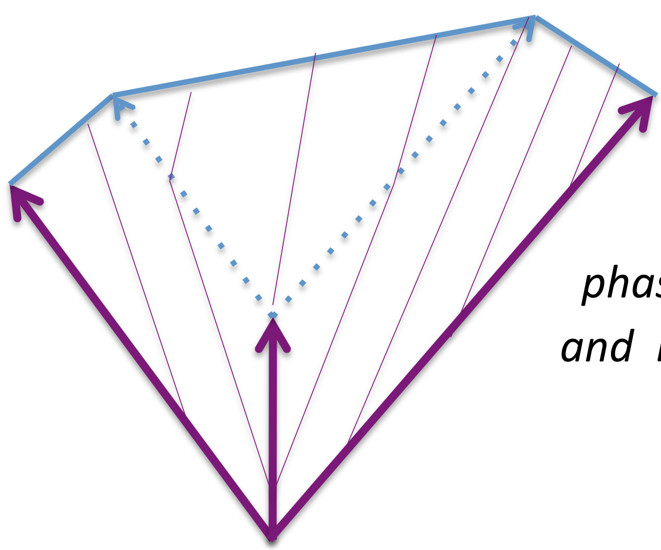


$\Delta\Phi = \Delta y/\tau$
$= 0.5 \ln (k_i^+ k_j^- / k_i^- k_j^+)$

$\Delta\Phi = 0.5\, S\, | k_i^+ + k_j^- - k_i^+ - k_j^+ |\, M$
$= 0.5\, S\, \kappa\, \Delta l$

Modified helix: implementation

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



helix phase difference between qq~ endpoints

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

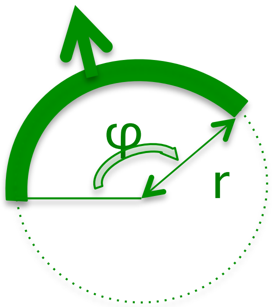
sum runs over all string pieces(*)

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

RE-implemented in Pythia 8 : HelixStringFragmentation class

[Code available at : http://projects.hepforge.org/helix]

Helix string model : phenomenology

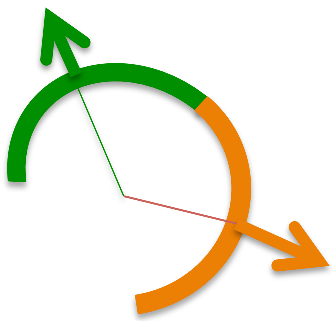


***Size** of the hadron' transverse momentum*

$$|\vec{p}_T| = 2r \sin(\Delta\phi/2)$$

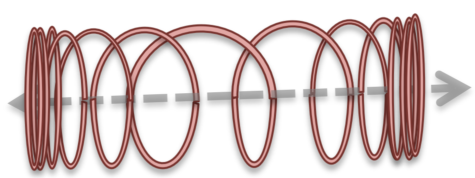
r helix radius
ϕ helix phase

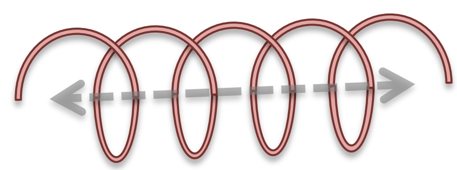
***Direction** follows helix phase in the middle of the string piece*



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

Helix : Δφ ~ longitudinal separation along the string
2 "extreme" scenarios on the market :





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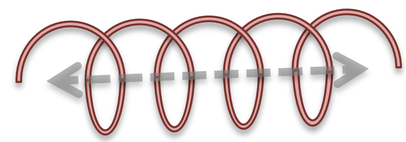
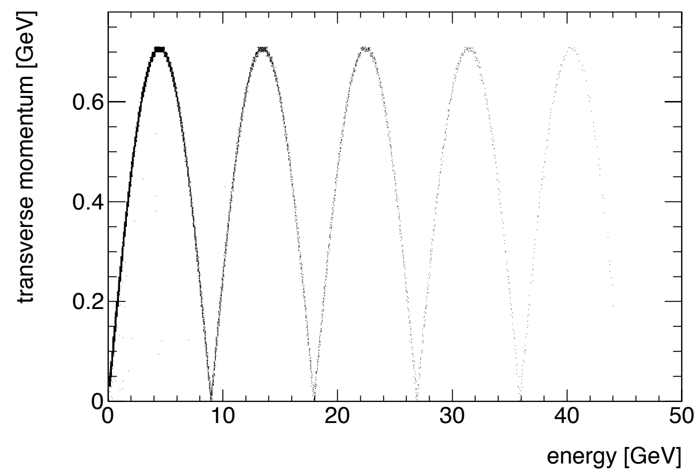
$$\Delta\Phi = \mathscr{S}\,(\Delta k^+ + \Delta k^-)\, M_0/2,$$

[arXiv:1101.2407]

Observables (inclusive spectra)



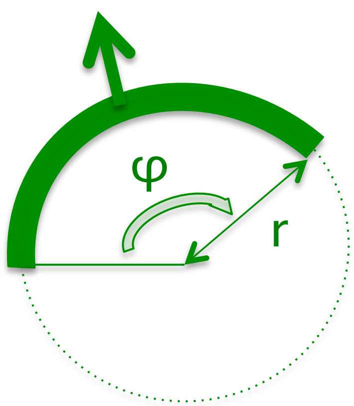
The (modified) helix structure constraint implies :



-> strong correlations between hadron p_T and energy (in the rest frame of the string)

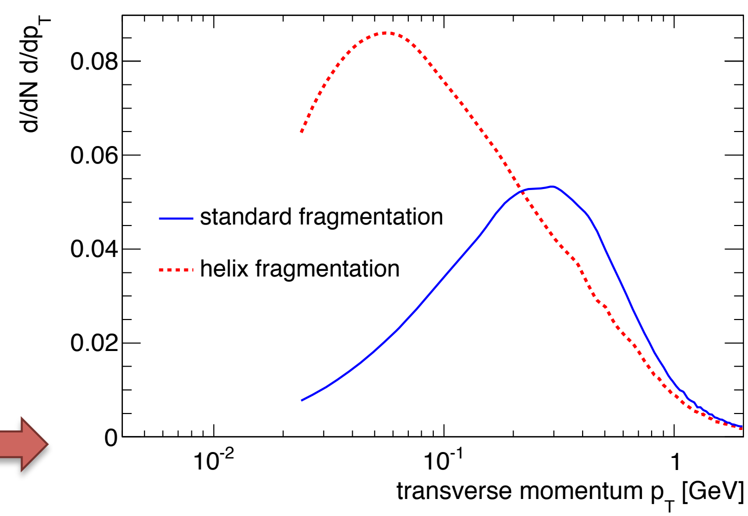
$$p_T^2 \approx 4\, r^2 \sin^2 (0.5{*}S{*}E)$$

(r radius of helix, S parameter)



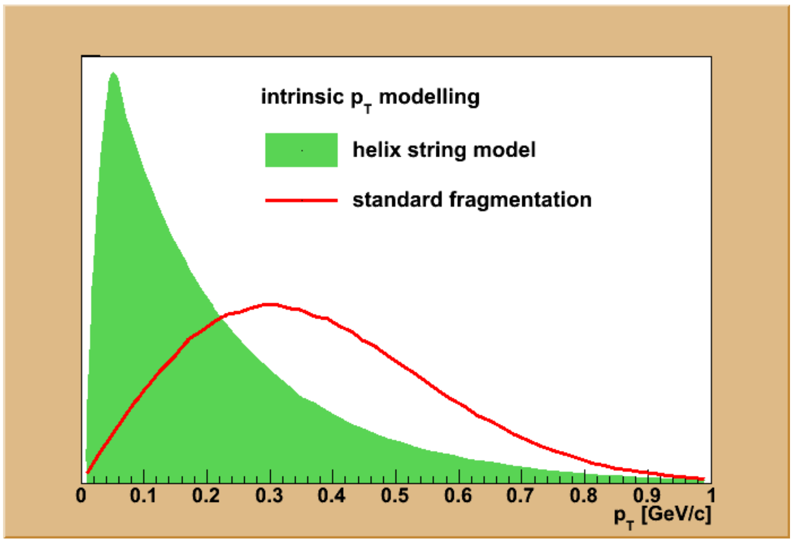
helix structure not directly observable (smeared by parton shower) ....

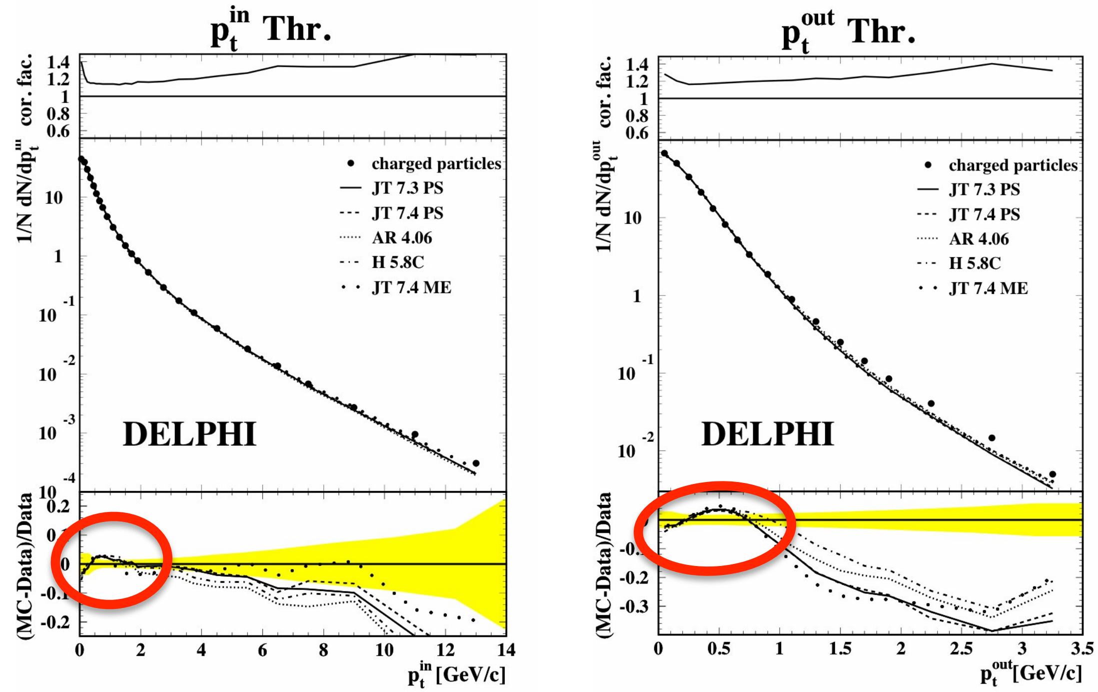
.... but visible trace left in the inclusive p_T distribution



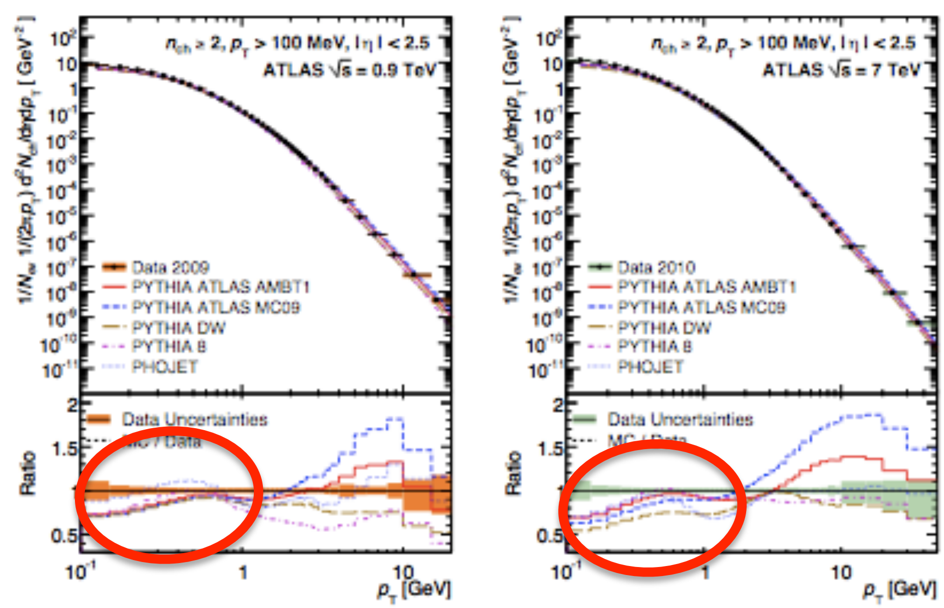
Indirect evidence: Inclusive pT spectra

DELPHI data
[Z.Phys.C73(1996) 11.]





Similar discrepancy observed in ATLAS data [New J.Phys.13(2011)053033]



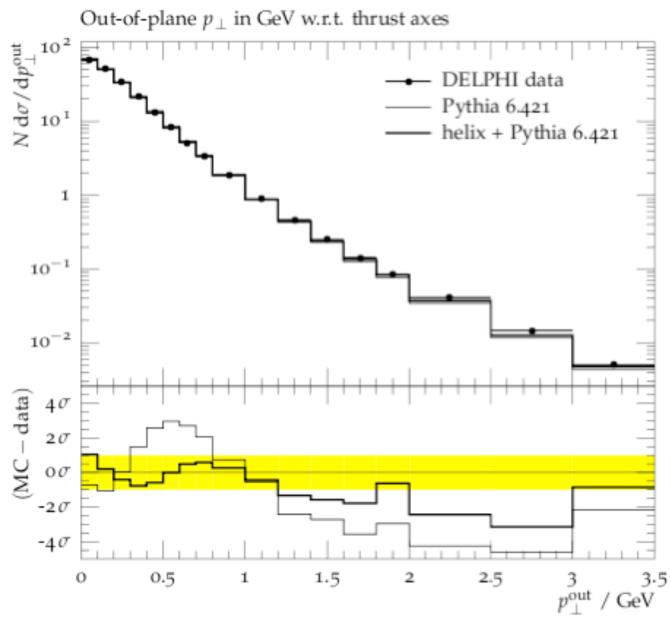
Tuning of the helix string model on Z^0 data

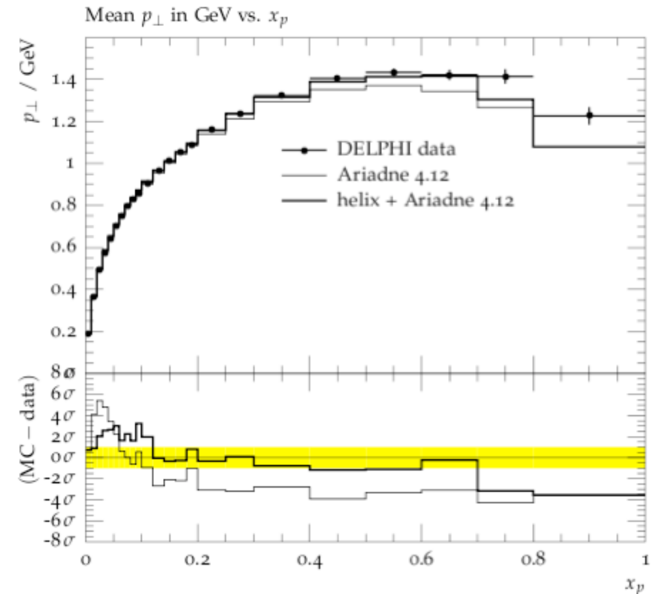
Thanks to Rivet & Professor projects !

Z^0 data: helix model describes better:

-> low p_T region

-> $\langle p_T \rangle$ vs x_p

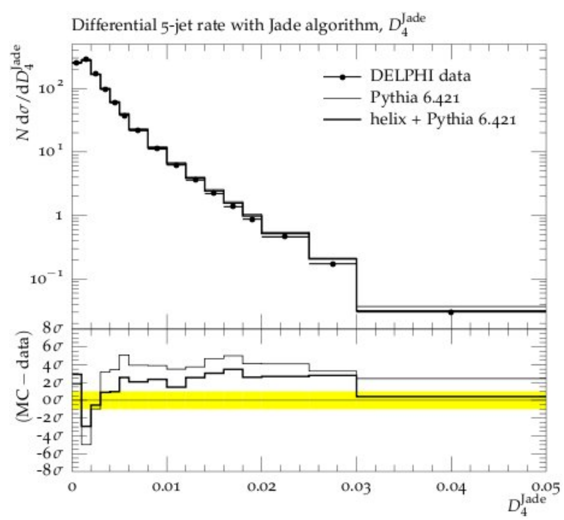


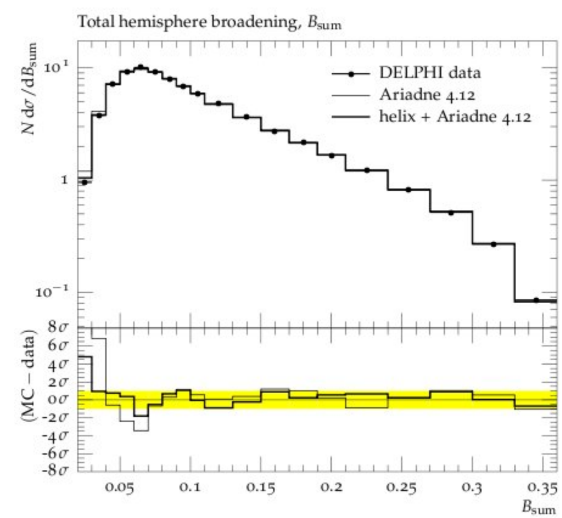


Also event shapes !

(interplay between non-perturbative & perturbative region !)

Š.T., arXiv:1012.5778 [hep-ph]



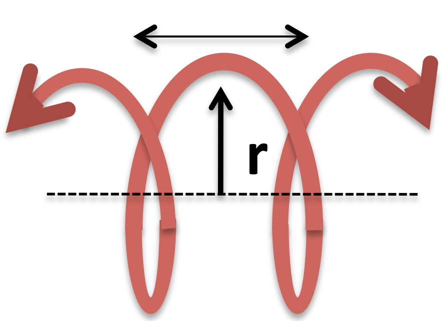


Significant improvement in description of data (arXiv:1012.5778 [hep-ph])

Data set	Pythia [10]	helix + Pythia	Ariadne	helix + Ariadne
inclusive spectra + event shapes $N_{bin} = 619$	4075 →	2453	2453 →	1489
ident.part.rates + b-fragmentation $N_{bin} = 47$	444	669(*)	614(*)	586(*)

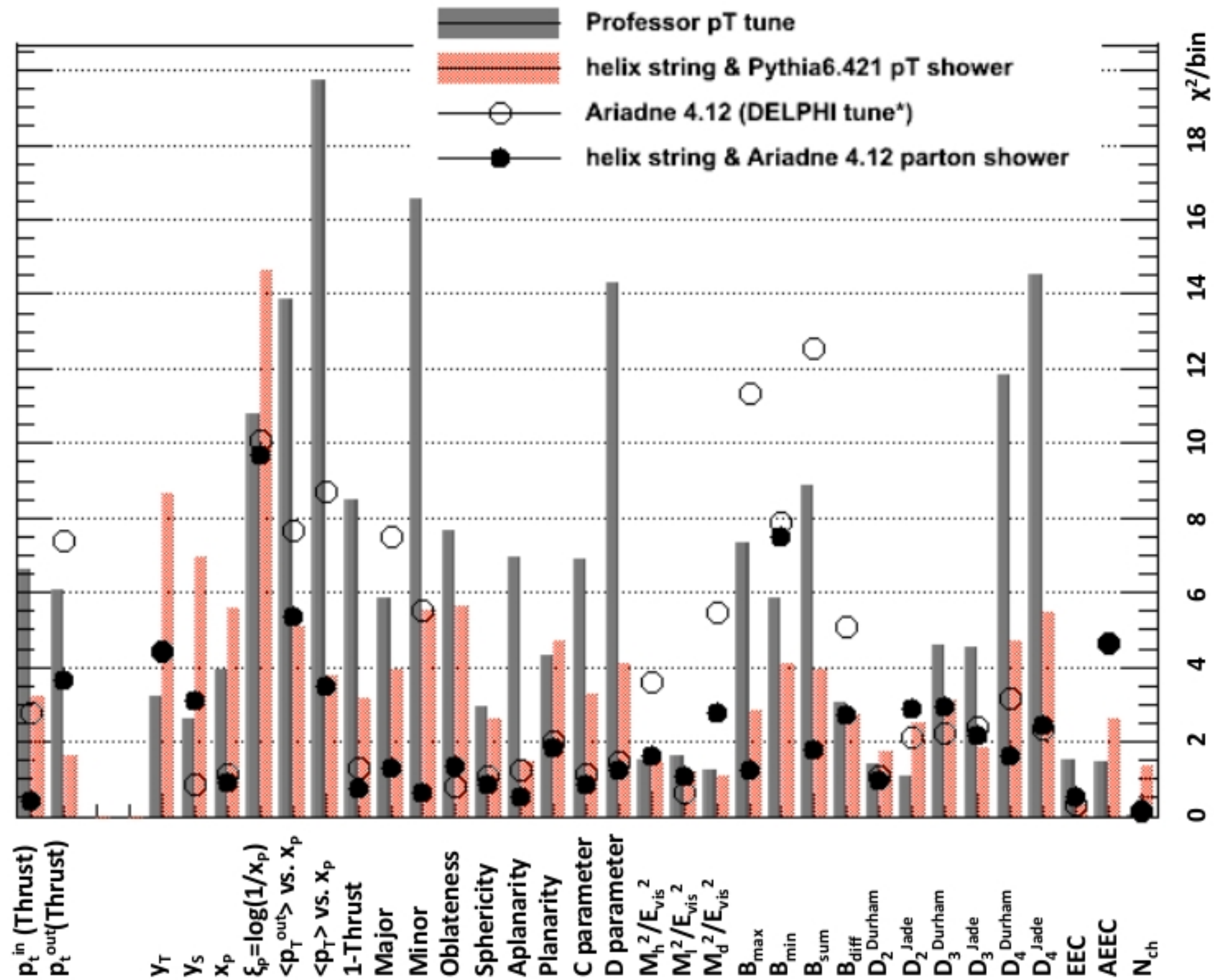
Table 1: Sum (over all bins) of χ^2 difference between data and models. The 'Pythia/Ariadne' labels distinguish between Pythia 6.421 pT-ordered parton shower, and Ariadne 4.12 parton shower. (*) distributions not included in the tune.

S=ΔΦ/(κ Δl)



Tuned values : (Δr fixed to 0.1 for simplicity)

		Ariadne	Pythia p_T-ord. shower
r [GeV/c]	=	0.43 ± 0.03	(0.36 ± 0.03)
S [rad/GeV]	=	0.68 ± 0.17	(0.5 ± 0.2)


Professor pT tune
helix string & Pythia6.421 pT shower
Ariadne 4.12 (DELPHI tune*)
helix string & Ariadne 4.12 parton shower
χ^2/bin
0
2
4
6
8
10
12
14
16
18
p_t^{in}(Thrust)
p_t^{out}(Thrust)
y_T
y_S
x_p
$\xi_p=\log(1/x_p)$
$<p_T^{out}>$ vs. x_p
$<p_T>$ vs. x_p
1-Thrust
Major
Minor
Oblateness
Sphericity
Aplanarity
Planarity
C parameter
D parameter
M_h^2/E_{vis}^2
M_l^2/E_{vis}^2
M_d^2/E_{vis}^2
B_{max}
B_{min}
B_{sum}
B_{diff}
D_2^{Durham}
D_2^{Jade}
D_3^{Durham}
D_3^{Jade}
D_4^{Durham}
D_4^{Jade}
EEC
AEEC
N_{ch}

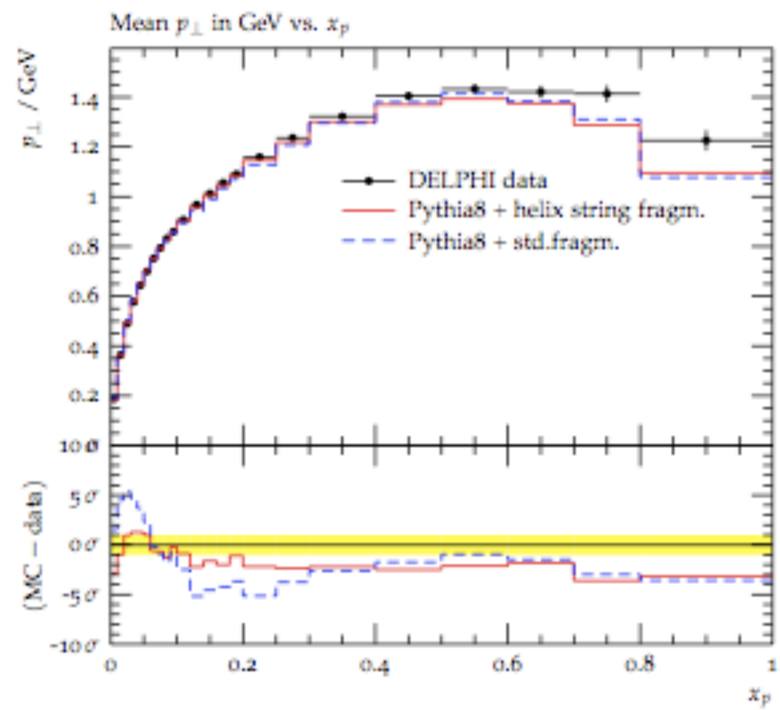
Tuning of the helix string model at Z^0 (shown already at ISMD2010)

Replay of an earlier tuning study [arXiv:1012.5778] with new re-implementation of the helix model (Pythia8 compatible)

Tuned parameter	Input data set	
Pythia 8 Tuned (std.fragm.)	Event shapes & incl.particle spectra	Inclusive particle spectra only
StringPT:sigma	0.276(1)	0.264(3)
StringZ:aLund	0.315(4)	0.262(9)
StringZ:bLund	0.689(6)	0.60(2)
TimeShower:alphaSvalue	0.1418(1)	0.1452(2)
TimeShower:pTmin	0.662(8)	0.73(3)
χ^2/N_{dof}	3.72	3.87
Pythia 8 +HELIX [6]	Event shapes & incl.particle spectra	Inclusive particle spectra only
HSF:screwiness	0.918(4)	0.54(1)
HSF:helixRadius	0.405(2)	0.53(2)
HSF:sigmaHelixRadius	0.063(1)	0.07(1)
StringZ:aLund	0.513(3)	0.51(6)
StringZ:bLund	0.443(5)	0.22(2)
TimeShower:alphaSvalue	0.1386(1)	0.1382(4)
TimeShower:pTmin	0.767(5)	0.74(3)
χ^2/N_{dof}	2.93	2.07

TABLE I. Results of the tuning study using the DELPHI data [16].

Improvement most visible in <p_T> vs. x_p (scaled momentum)



Š.T.,Phys.Rev.D86,034001(2012)

Azimuthal ordering … can it be measured ?

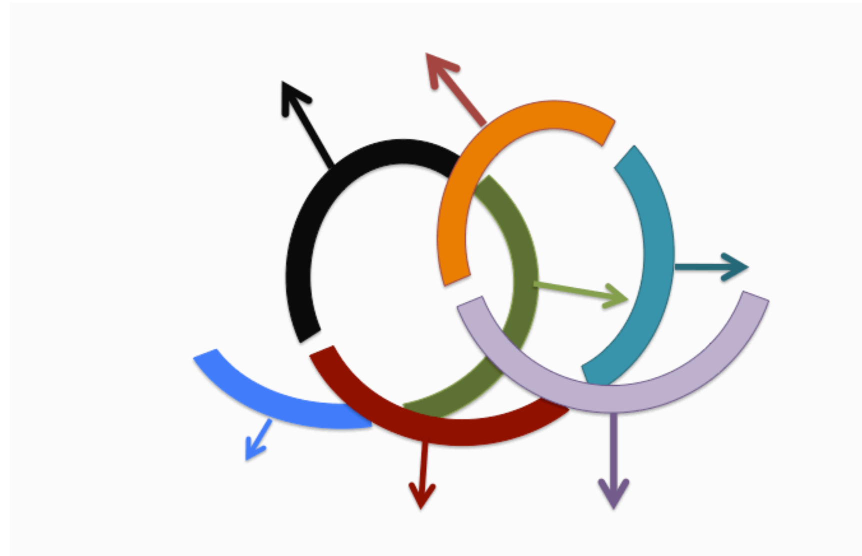
Azimuthal angle difference between direct hadrons is

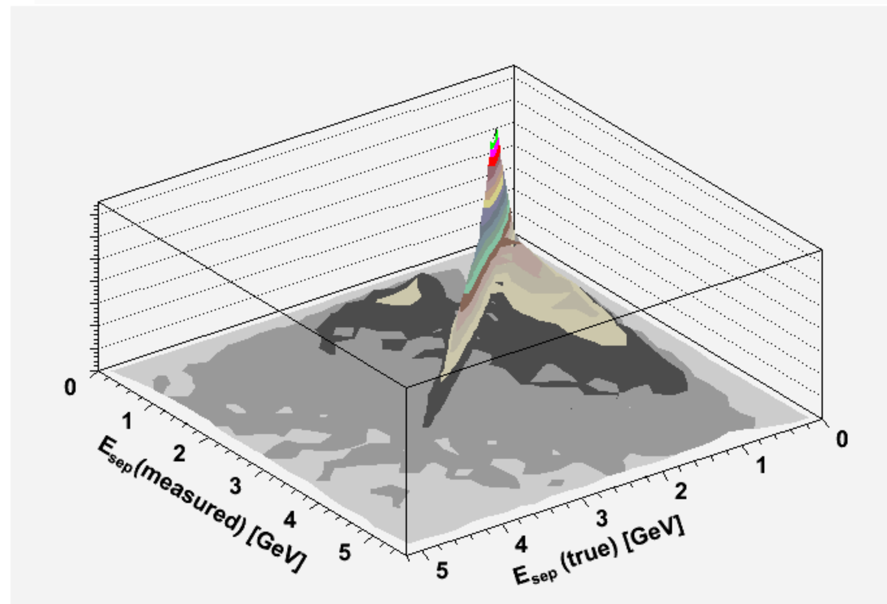
$$\Delta\phi_{ij} = S\,\kappa\,\Delta l_{ij} = S\,[\,0.5*(E_i+E_j) + \Sigma_k\,E_k\,]$$

l is the distance separating hadrons
κ is string energy density
sum runs over direct hadrons i<k<j

The distance between hadrons along the string can be approximated by sum of energies of (η,p_z) ordered final (charged) hadrons

Many effects contributing:
multiple strings, string boost, missing neutrals …





Pythia minbias , charged final tracks ordered in η , $max(p_T) < 1$ GeV/c

Azimuthal ordering: HOW TO measure it

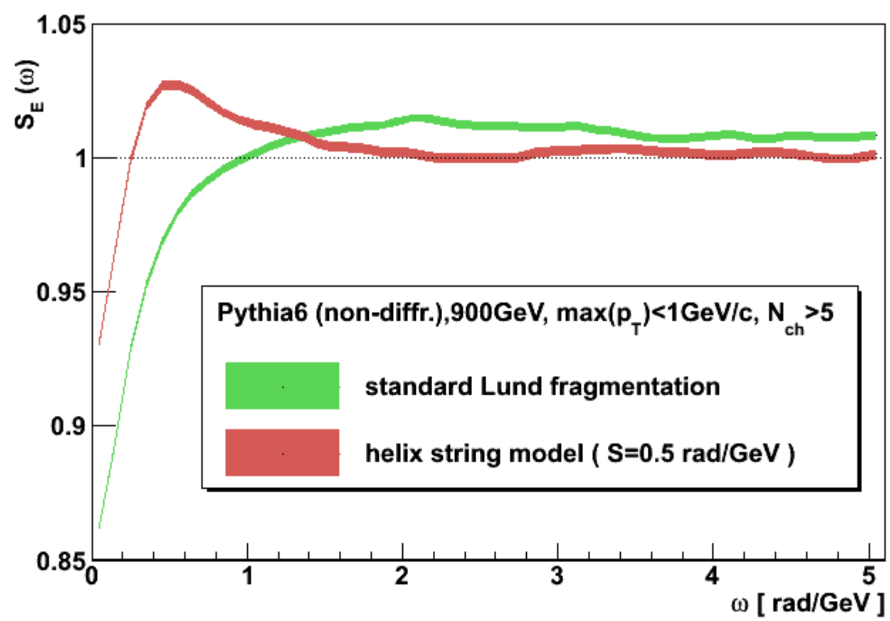
-> take minimum bias sample, remove all events with high p_T activity
(require $\max(p_T) < 1$ GeV/c)
-> order charged particles in pseudorapidity -> "hadron chain"
(particle defined by : azimuthal angle ϕ_i
position along the chain $X_i = 0.5*E_i + \Sigma_{k<i} E_k$)
-> calculate the power spectrum

$$S_E(\omega) = 1/N_{ev} \Sigma_{ev} 1/N_{had} \mid \Sigma_{had} \exp[i(\omega X_i - \Phi_j)] \mid^2$$

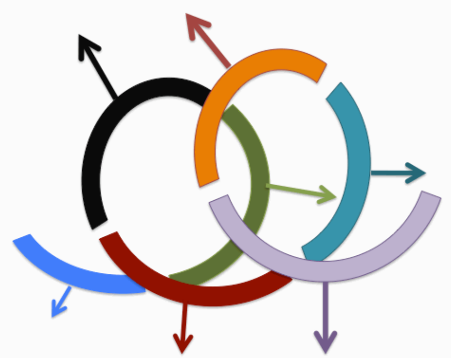
A peak expected at $\omega \sim S$

If observed :

this would be the first DIRECT evidence in favour of helix structure of the QCD string



Azimuthal ordering of hadrons [Phys.Rev.D86,052005 (2012)]



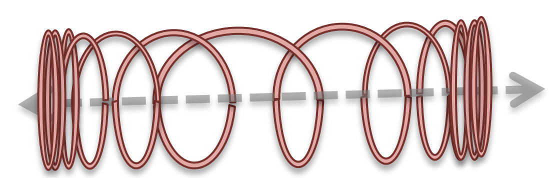
The helix-like shape structure of the QCD field should be visible in the azimuthal ordering of hadrons along the string

The exact form of the helix structure not predicted.

With the help of power spectra, we test two (weakly correlated) hypotheses

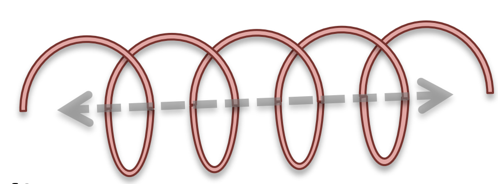
A/ ΔΦ ~ Δη

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



B/ ΔΦ ~ ΔX (energy-distance - amount of energy stored in the string/ ordered hadron chain - experimentally : ordered in pseudorapidity)

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

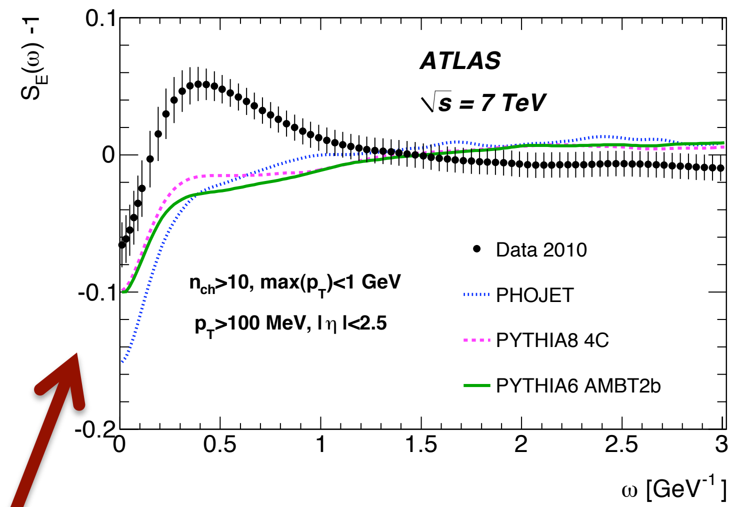


Search for resonant behaviour -> density of helix winding

Azimuthal ordering of hadrons

Phys.Rev.D86, 052005 (2012)

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

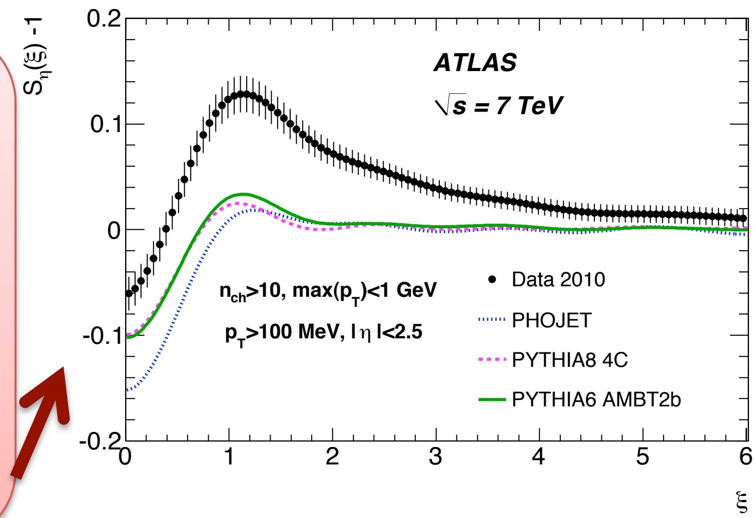


NOT DESCRIBED BY CONVENTIONAL MODELLING

Correlations STRONGER than expected

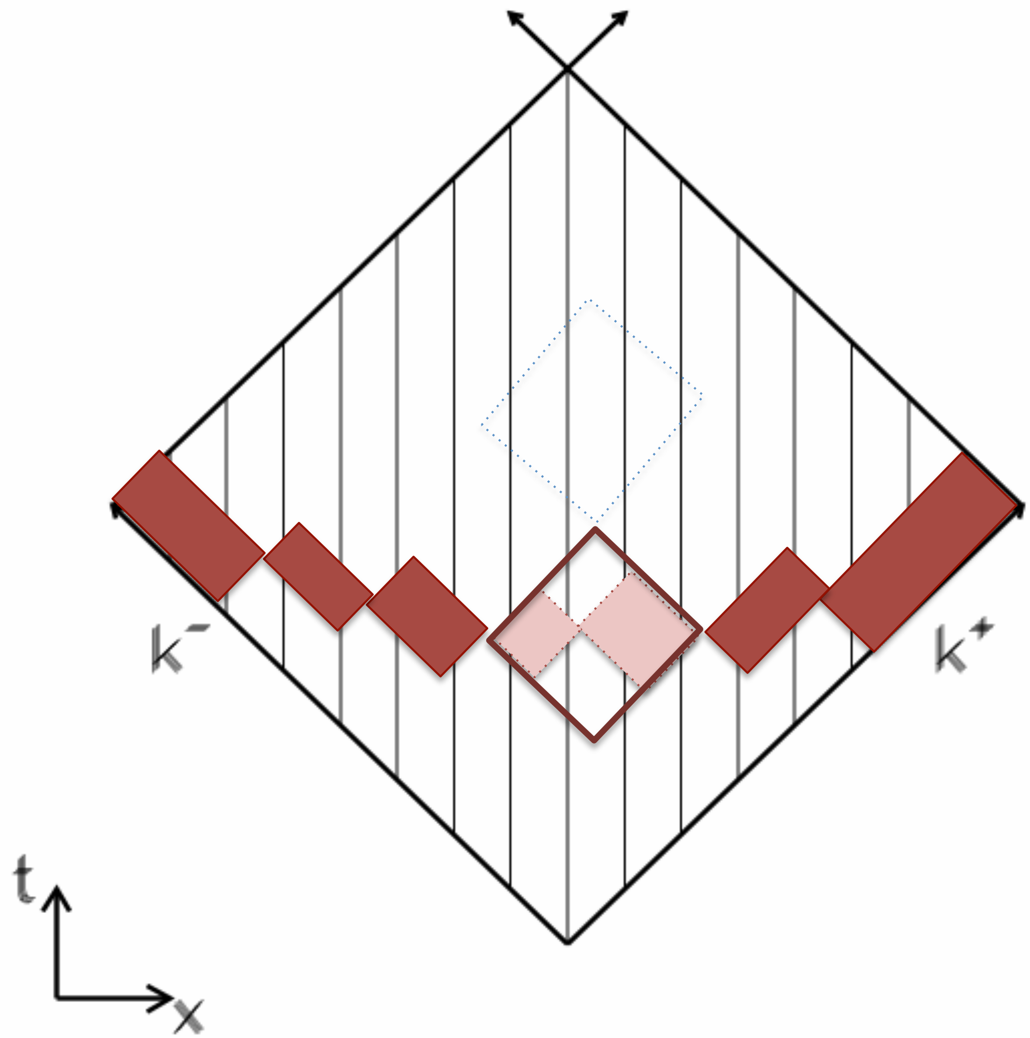
To describe the data, we need to extend the helix string model to cover the decays of short lived resonances (i.e. resonance decay treated as a smooth continuation of the fragmentation of the helix-shaped string)

SIGNIFICANT AMOUNT OF CORRELATIONS WHERE EXPECTED (and where not expected)



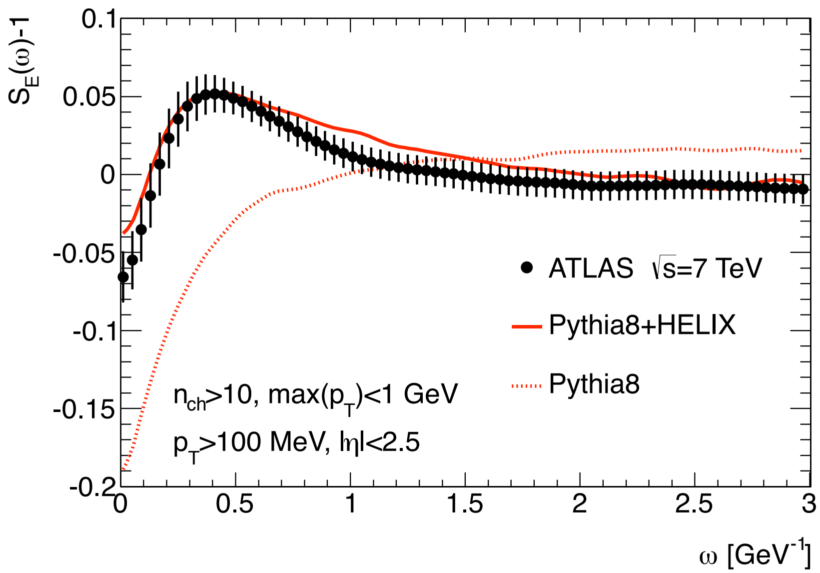
Resonance decay according to the helix string structure

resonance decay treated as a continuation of the helix string fragmentation

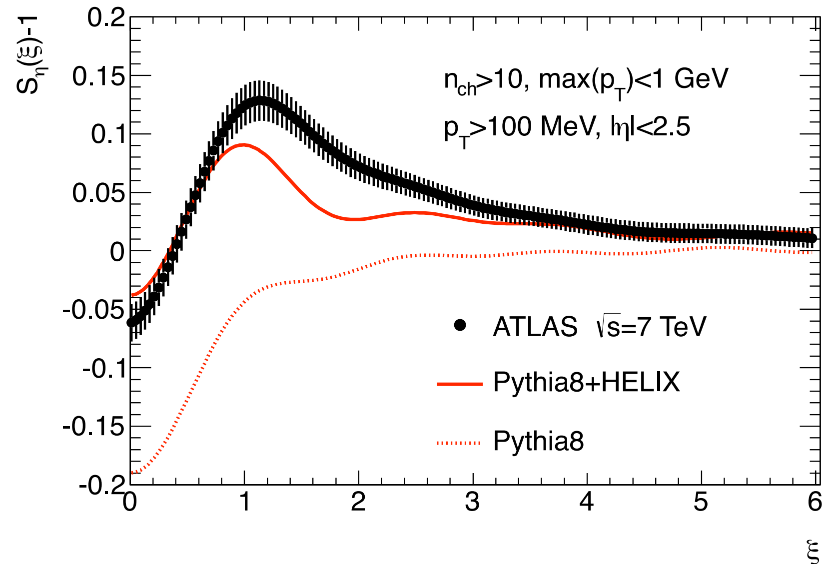


"Prediction" for the low-p_T enhanced region

Not too bad.



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

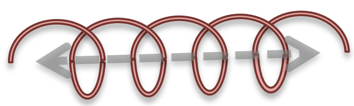


Dashed spectra : standard fragmentation with the same parameter setup
- for illustration of the possible size of the effect due to the helix-like ordering
(The non-helix simulation alone can be retuned to give a somewhat better description of the data !)

Phys.Rev.D86,034001(2012)

What did we learn so far …

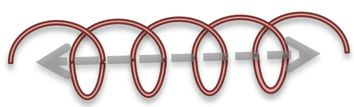
- **Existence of correlations between longitudinal and transverse component of hadron momentum supported by the LEP data**

(HELIX model  *S ~ 0.5-1. rad/ GeV*
r ~ 0.4-0.5 GeV)

91.2GeV e^+e^-

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

7TeV pp

(HELIX model  *S ~ 0.6 rad/GeV*
r ~ 0.5 GeV)

[Š.T., Phys.Rev.D86,034001(2012)]

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)

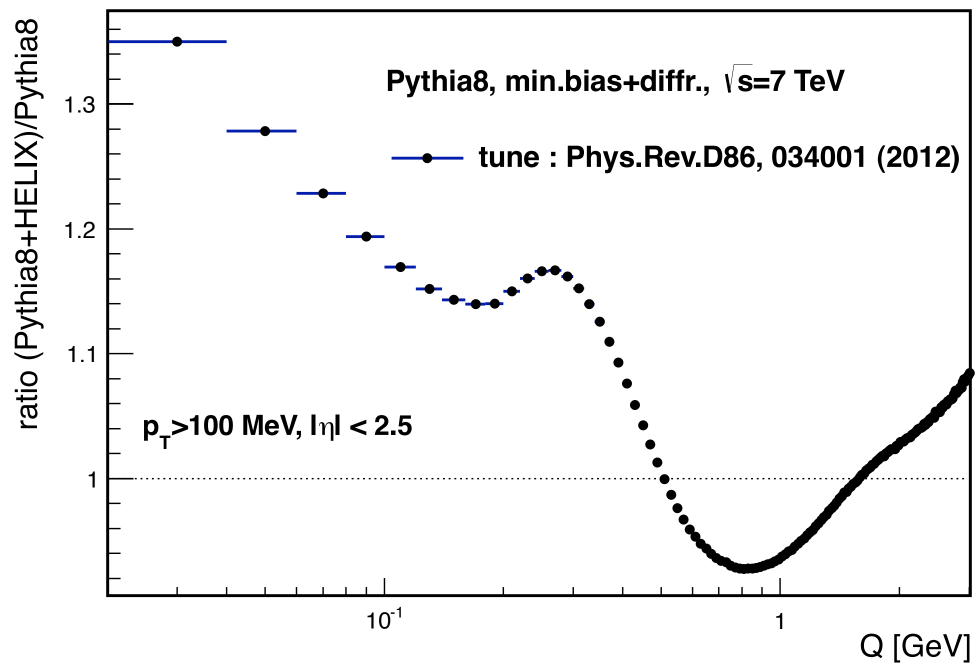
Done ? Actually, the most interesting is still to come …

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

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

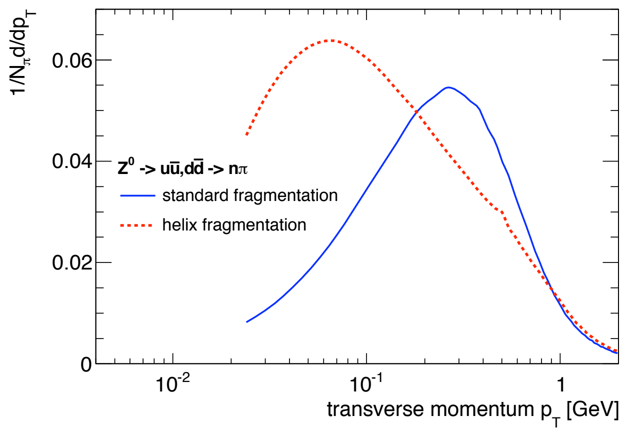
Is the prediction consistent with the data ?

proton-proton



For ATLAS colleagues : data can be found in ATL-COM-PHYS-2012-1305 to be published in the frame of BE analysis (draft ATL-COM-PHYS-2013-295)

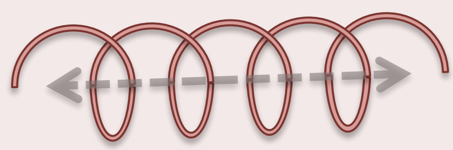
Where the difference comes from ? TOY MODEL : Z^0->direct pions



Helix vs. standard fragmentation:

p_T spectrum wider,

more exponential than gaussian



(plots with 'static' helix scenario)

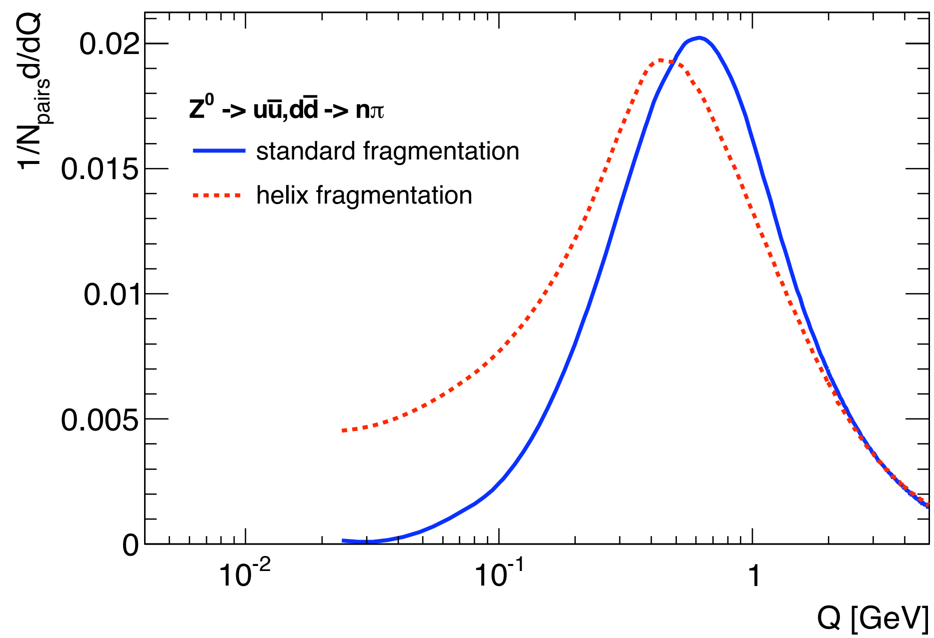
Helix vs. standard fragmentation:

Q spectrum wider,

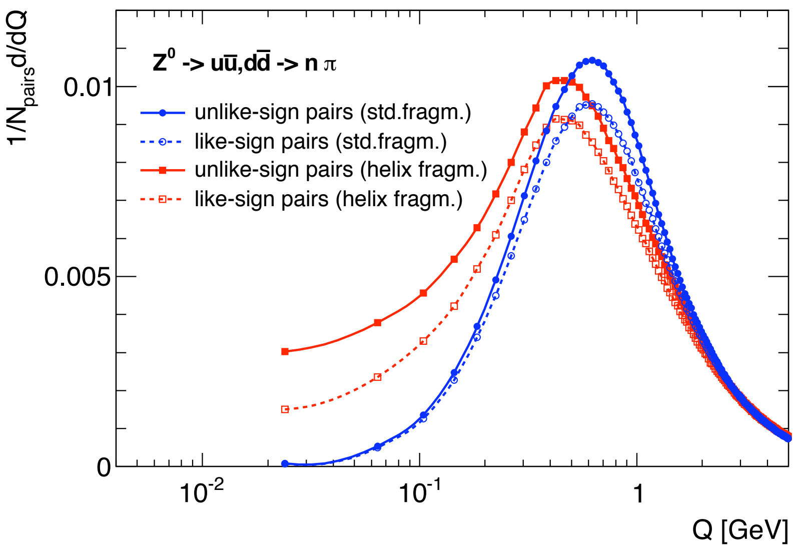
shifted to lower values

-> bump at Q ~ 0.3 GeV

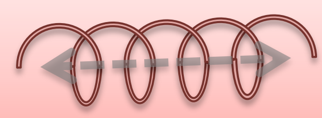
-> enhancement at low Q



Charge combination asymmetry ? Most amazing :



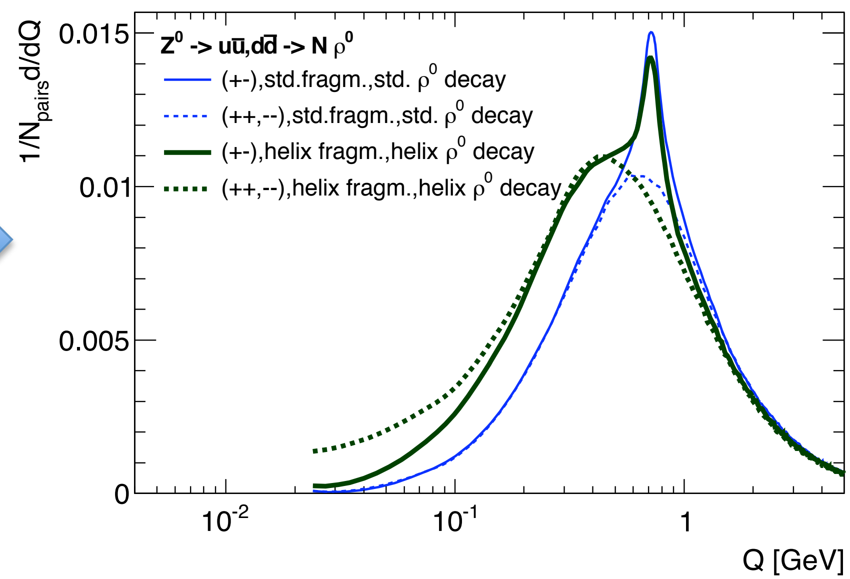
Helix model in the base scenario
(for direct hadrons only)
predicts larger enhancement
for unlike-sign pair combinations
(adjacent hadrons dominating)



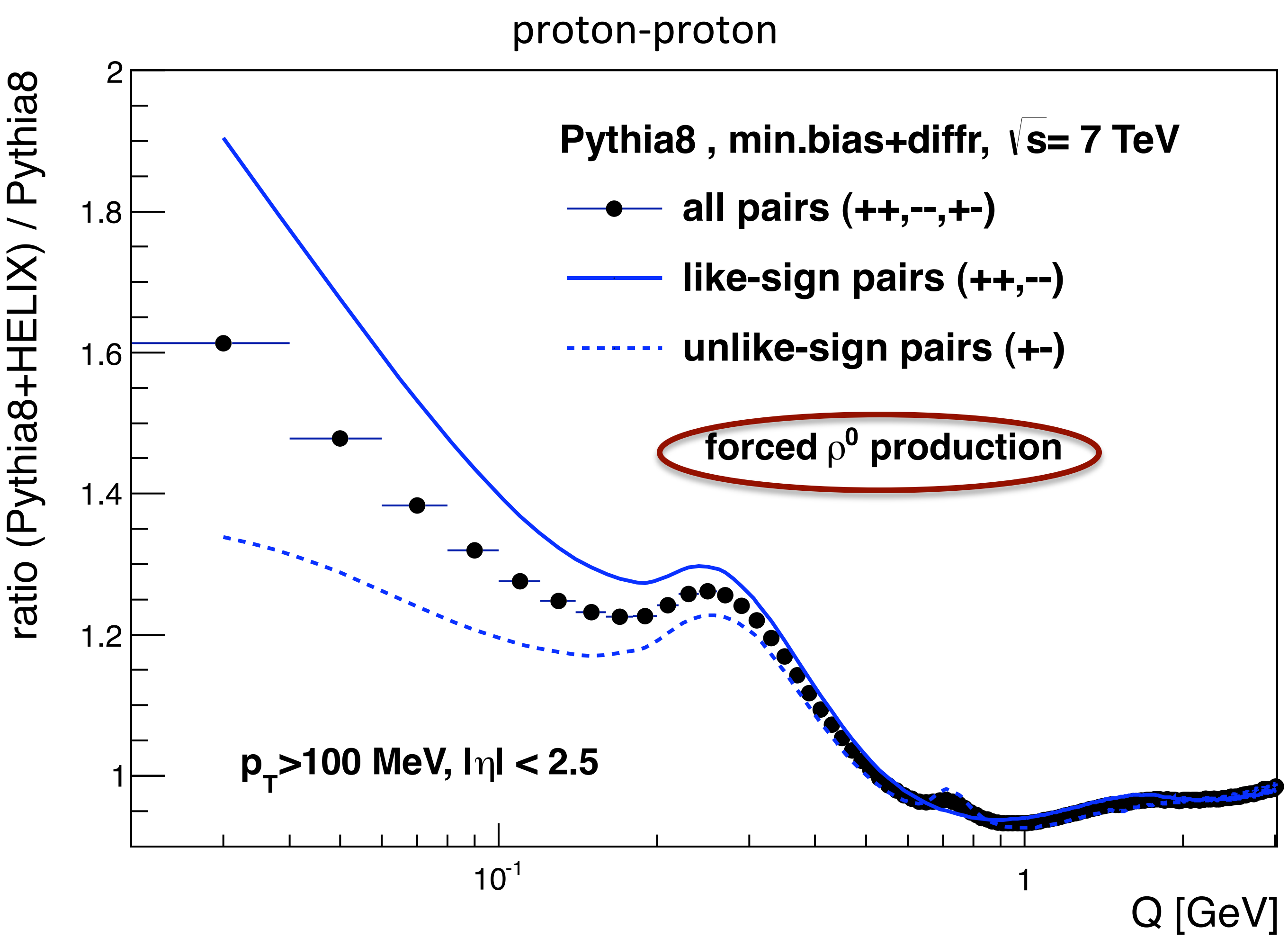
"static" helix
scenario

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

"Bose-Einstein"-like correlations arise NATURALLY in the helix string 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)

Delicate situation: HELIX versus Bose-Einstein interference

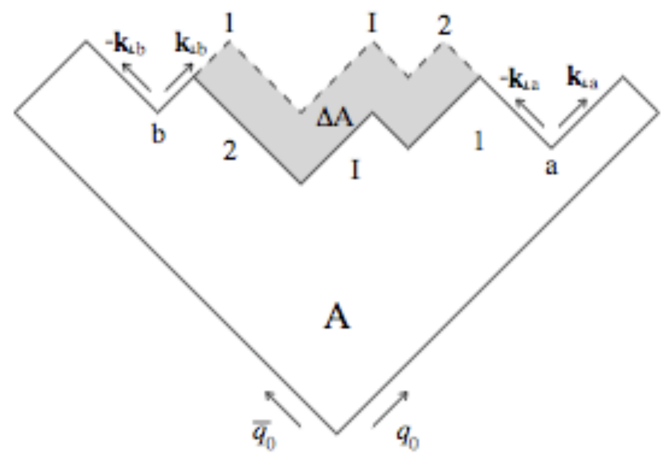
- ***The Bose-Einstein effect in the hadronic data was NEVER fully understood (formalism corresponds to incoherent particle protection, Hanbury-Brown-Twiss (HBT) effect, while we treat the hadronization as a coherent particle production)***

2 problems :

[I] B-E symmetrization weights calculated from the first principles in the Lund model <u>underestimate</u> the size of observed correlations (need to neglect the existence of resonances to describe the data)

$$\mathcal{M} \sim \exp(\, i\, \xi A\,)\ ,\quad \xi = 0.5\,(\,\kappa + ib\,)$$

A = string area ~ string action



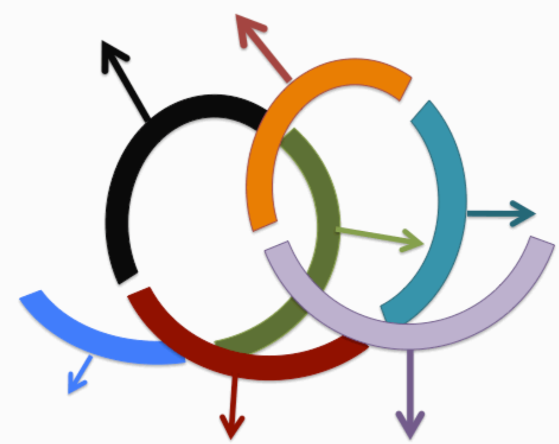
"genuine" Bose-Einstein symmetrization of the string diagram (Bo Andersson et al.) Phys.Lett.B421(1998)283

Delicate situation: HELIX versus Bose-Einstein interference

[II] The presence of helix string underlines a short-coming of the Lund model of BE symmetrization : the change of hadron ordering not possible unless $\Delta\varphi = n\, 2\pi$ (n=0,1,…) (otherwise non-identical final states)

In summary:

- ***helix string model is slowly emerging as an alternative explanation for (part of?) 2-particle correlations usually attributed to BE effect***
- ***the helix model is not yet describing the charge combination asymmetry -> further investigation needed***



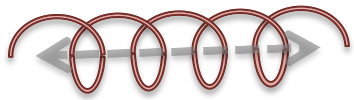
What about phase difference In the transverse plane ??

ATLAS is last to publish the BE analysis but the only collaboration which shall include the corrected Q spectra to allow a study of alternative models

What did we learn so far …

- ***Existence of correlations between longitudinal and transverse component of hadron momentum supported by the LEP data***

(HELIX model



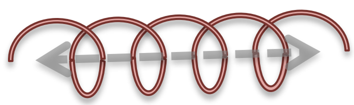
S ~ 0.5-1. rad/ GeV
r ~ 0.4-0.5 GeV)

91.2GeV e^+e^-

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

7TeV pp

(HELIX model



S ~ 0.6 rad/GeV
r ~ 0.5 GeV)

[Phys.Rev.D86,034001(2012)]

- ***Correlations similar to those usually attributed to the Bose Einstein effect arise naturally in the helix string model***

corrected Q spectra in preparation (ATLAS)

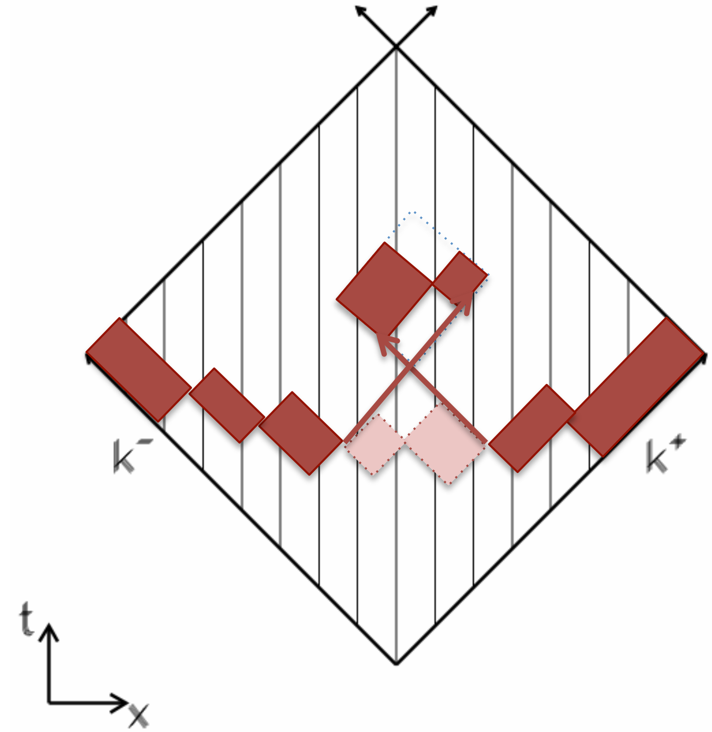
In all these cases, the helix string model provides explanation for poorly understood features in the real data while using FEW free parameters
(on the contrary – zillions of random numbers removed from the simulation)

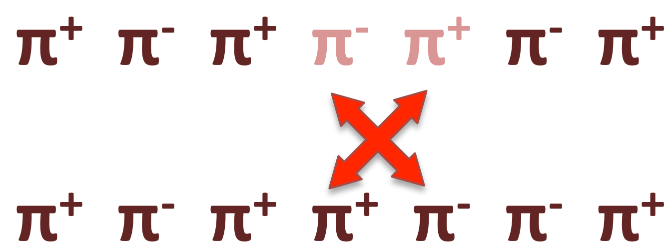
FURTHER STUDIES & MODEL DEVELOPMENT

Charged assymetry – possible explanation

The ambiguity in the time ordering of string breakups no longer apply in case of azimuthally ordered hadron chain !

Fluctuations in string breakup effectively rearrange hadrons along the chain
-> correlated (adjacent) ++,-- pairs appear
(which do not exist in the 'base' configuration)

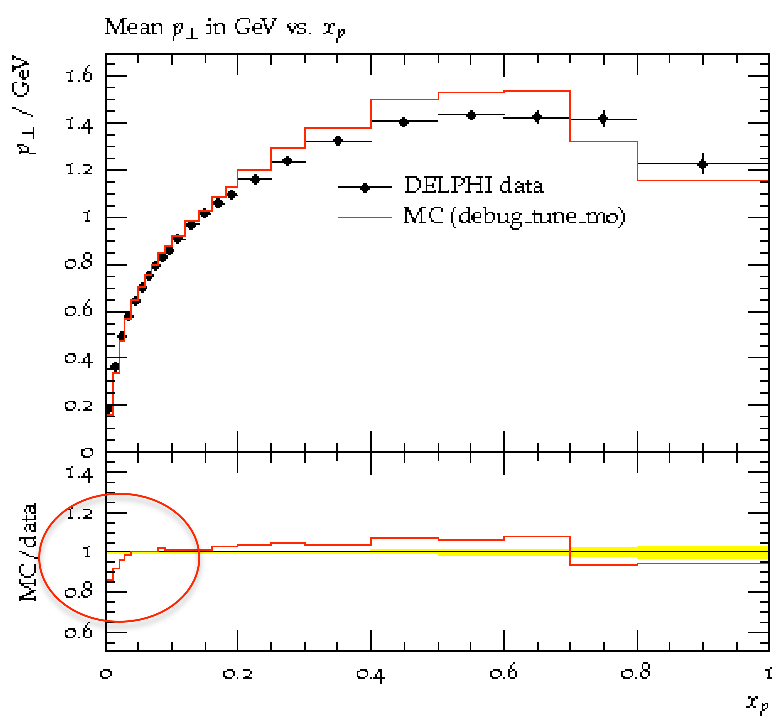


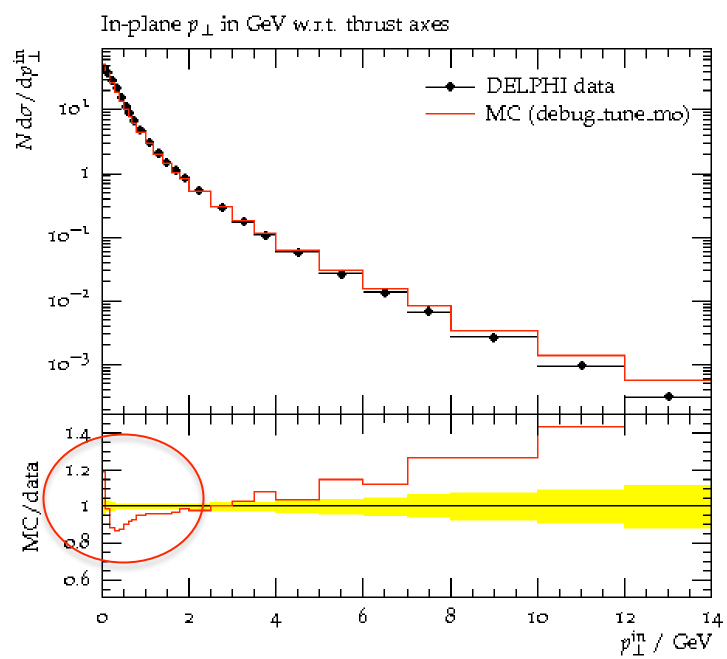


Helix field is pulling adjacent hadrons closer and fluctuations in string breaking create close like-sign pairs
- qualitatively, that's what we see
Detailed understanding needs much more work still

Infrared regularization

- ***With the extension of the helix string to resonance decay, too many soft particles produced (study with Z^0 data, also observed in LHC data)***





… is this a quantum effect ?

Quantization of the QCD string

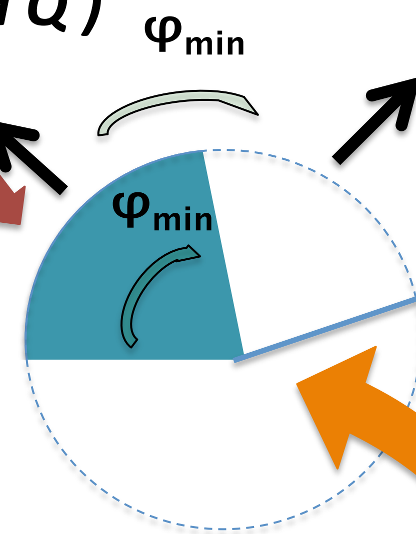
Open issues in the modelling all point towards quantization :

- ***-> infrared regularization (threshold on p_T and Q)***
- ***-> resonances***

The transverse string area proportional to the angular momentum:

-> ħ -> φ_{min}

-> $p_{Tmin} \sim 2\, r \sin(\varphi_{min}/2)$

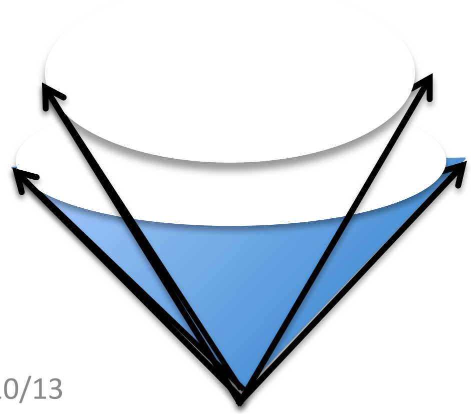


The helix string concept changes the properties of the Lund model significantly:

light-cone coordinates are gone !

The minimal distance (Q) between adjacent hadrons :

$-Q_{min} \sim 2\, p_{Tmin} \sin(\varphi_{min}/2)$



Quantization of the QCD string

The helix string concept changes the properties of the Lund model significantly:

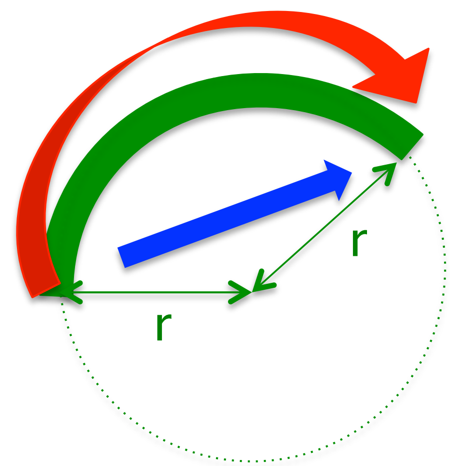
… with helix string structure, the model allows time-like distance between the adjacent break-up vertices !!!!!

Several possibilities :

1/ the parton triggers next vertex break-up as it passes by

$$m_{hadron} \sim R \sqrt{\Delta\varphi^2 - 4 \sin^2 \Delta\varphi/2}$$

2/ the information about the breakup passes outside "vortex" and triggers the next one



This resolves one outstanding puzzle
("how the hell the hadron appears on the mass shell ?")

… and pushing further still …

How the helix comes into being ?

several options : 1/ gluons are emitted chaotically, rearrange themselves in subsequent interactions

2/ gluons are emitted along the helix pattern

If (2) :

- ***the angular momentum associated with the φ ordered gluon emission is of the order of ~ ħ : do we see the quark spin ?***

- ***The recoil of gluon emission is generating an effective parton mass – consistent with 'constituent' quark mass - what if quark mass is purely dynamical quantity resulting from interaction with field quanta ?***

What comes next ?

Experiment: ***plenty of observable effects to check***

ALL hadronic data carry some information

helix model easy to kill if wrong – few free parameters

-> charge combination asymmetry in correlations

-> polarized short-lived resonance decay

The ball is on the THEORY side of the field :

? How the (effective?) helix shape comes into being ?

? Under assumption the helix is there at the moment of hadronization, what does it say about "initial conditions" – the primary parton emission pattern – does it have a dominant helical component, too ?

Shrnutí

- *Rostoucí experimentální evidence ve prospěch SPIRÁLNÍHO STRUNOVÉHO MODELU (VELMI zajímavá idea !)*
- *Studie azimutálních korelací hadronů zřetelně poukazuje na nedostatky současných hadronizačních modelů*
- *Vývoj modelů v oblasti fragmentace ustrnul přestože máme k dispozici spoustu dat ověřujících různé aspekty modelování*
- *Je zapotřebí systematicky studovat zejména korelační data, pokud chceme dosáhnout lepšího porozumění dynamiky hadronizace*

Vřelé díky za Vaši pozornost !

back-up slides

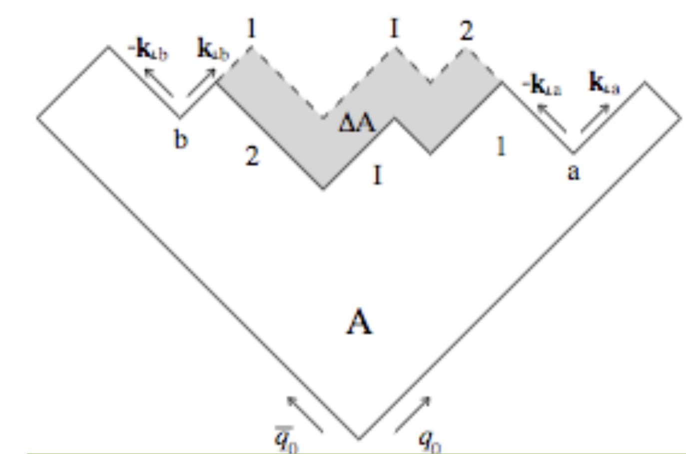
Documentation

- ***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]***
- ***Š.Todorova, arXiv:1101.2407 [hep-ph]*** ***[modeling]***
- ***http://projects.hepforge.org/helix/*** ***[PYTHIA-compatible code]***

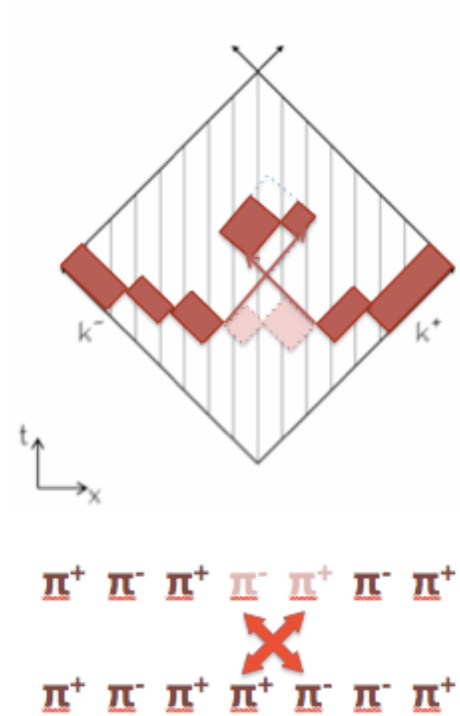
BE or not BE ?

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

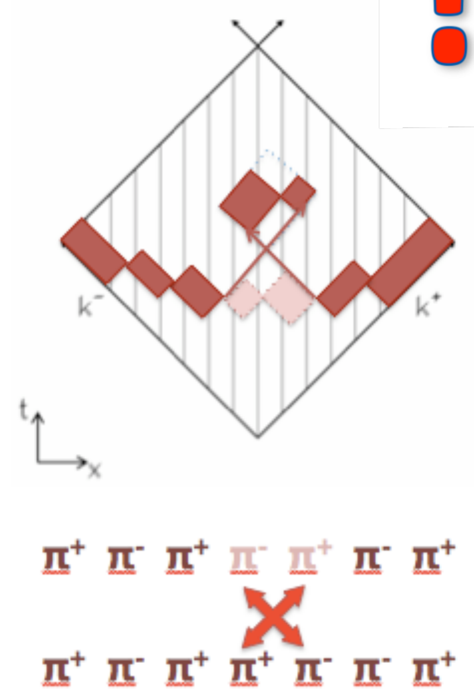
What about phase difference ??

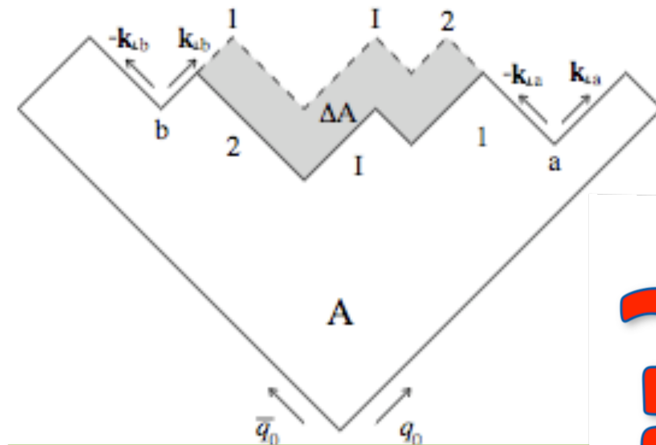
BE or not BE ?

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

What about phase difference ??

Indirect experimental evidence: tuning on Z^0 data

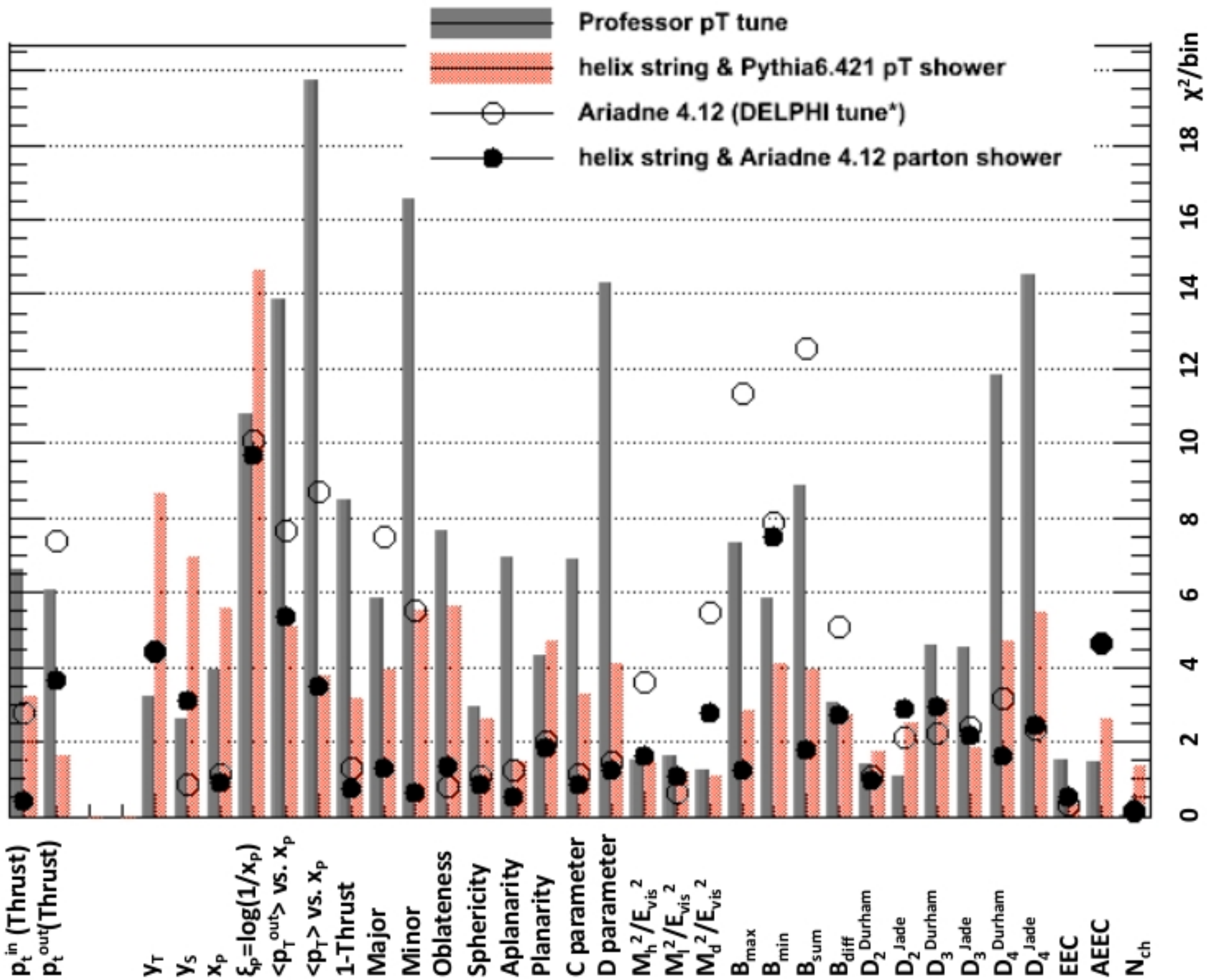
(DELPHI_1996_S3430090)

arXiv:1012.5578 [hep-ph]

Helix string fragmentation improves "goodness of fit" (χ^2/N_{dof})

6.6 -> 4.0
(Pythia 6 DELPHI 1996 tune)

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

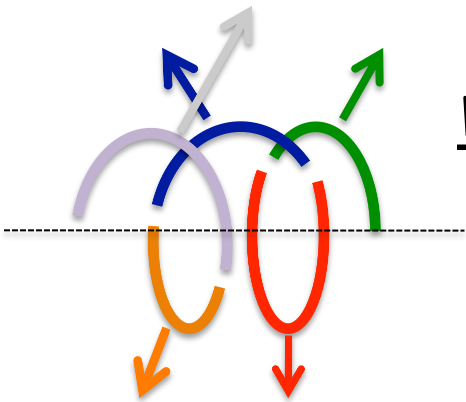


Best fit depends on the choice of input data
Pythia8 + HELIX (DELPHI_1996_S3430090)

•	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

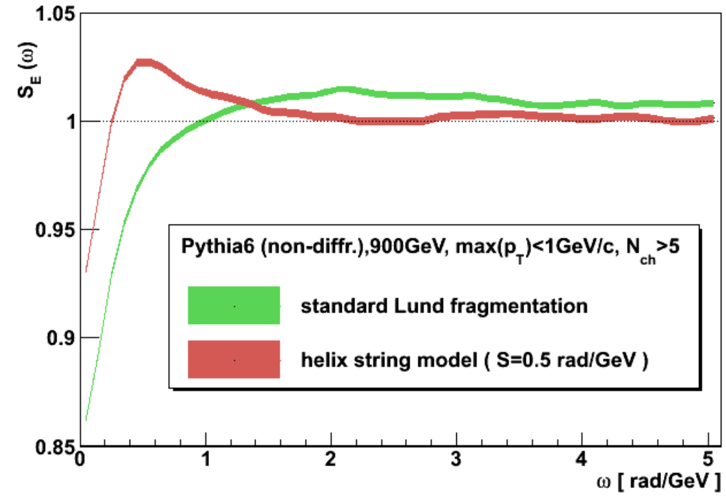
Fixed in the following
to simplify LHC tunes

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



What else do we expect to see ?

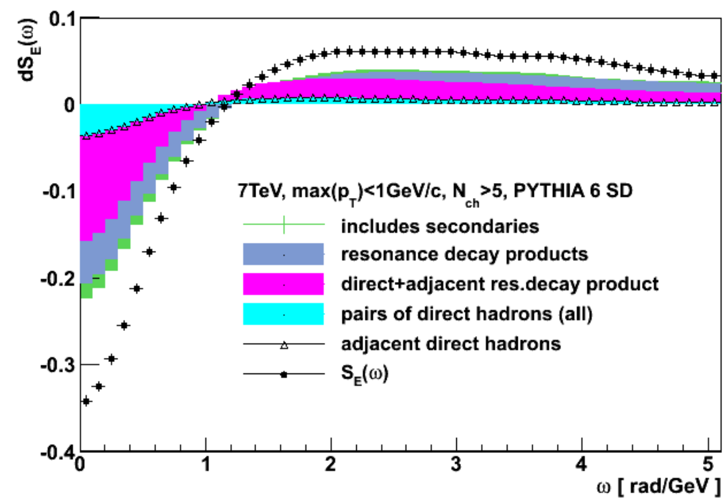
[Moriond 2011]



In the low-p_T region : helix string signature (a peak/enhancement in the power spectrum)

Power spectra sensitive also to :

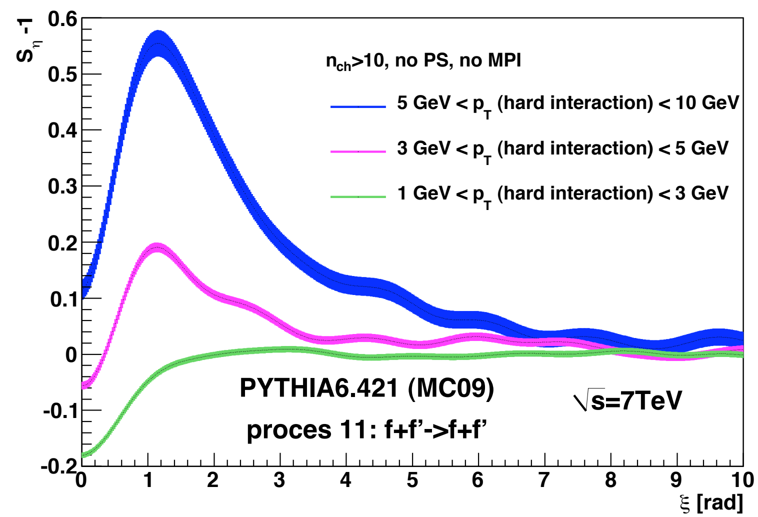
- ***local p_T conservation for adjacent hadrons***
- ***acollinear activity***



Azimuthal angle defined in the detector frame !

What do we expect to see ?

<u>In ‘hard’ p_T region :</u> ***dominated by the hard parton interaction (acollinear jets) -> peak structure in the power spectrum***

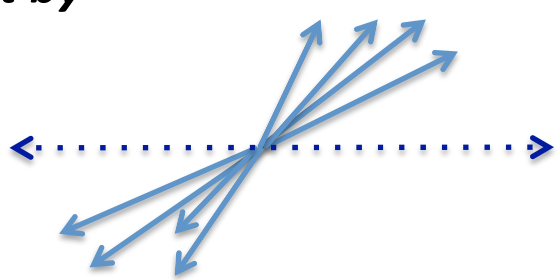


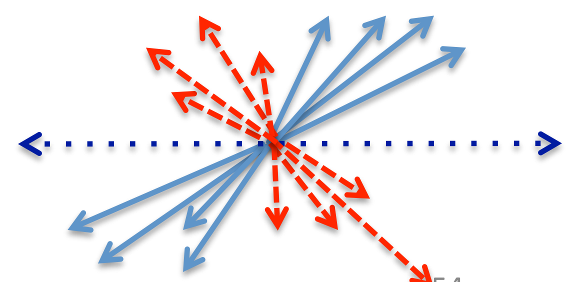
Sensitive to :

- properties of hard interaction

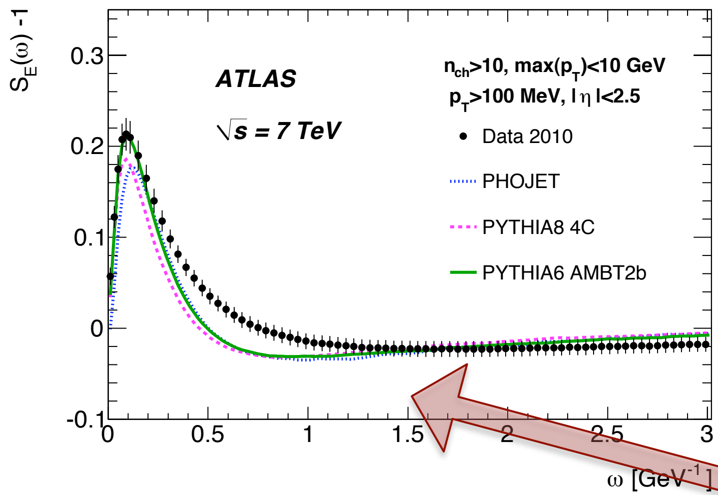
- ‘dilution’ of the hard interaction by : multiple parton interactions, parton shower, ISR

- ‘hardening’ of the event by colour reconnection



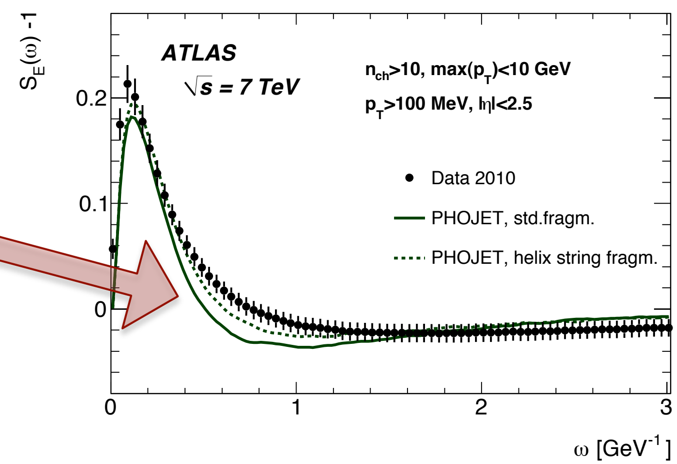


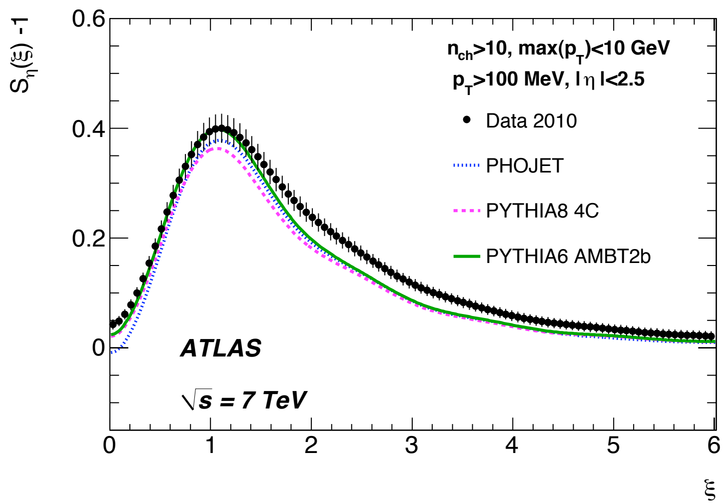
Azimuthal ordering of hadrons *PRD 86, 052005 (2012)*



Minimum bias : inclusive event selection

a discrepancy observed where expected (from Z0 data)



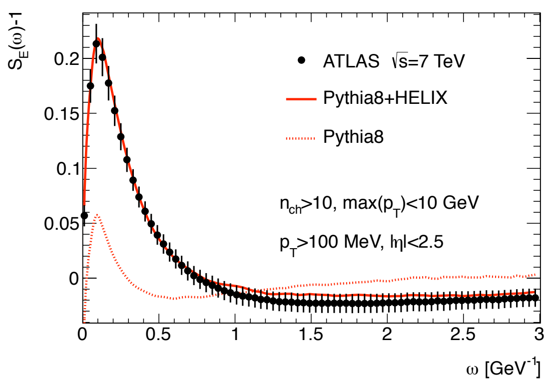


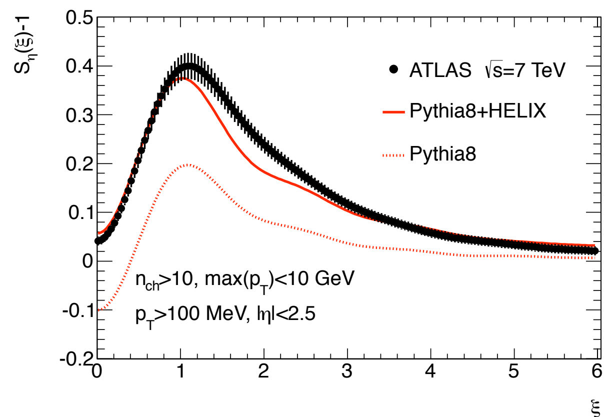
... but only small effect on top of high p_T background (acollinear jets)
=> impose cut on max p_T

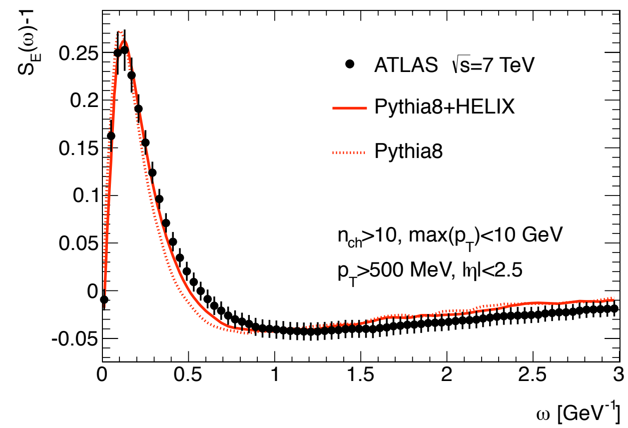
Tuning of the helix string model using ATLAS data

Fix fragmentation parameters to values found in Z^0 study

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

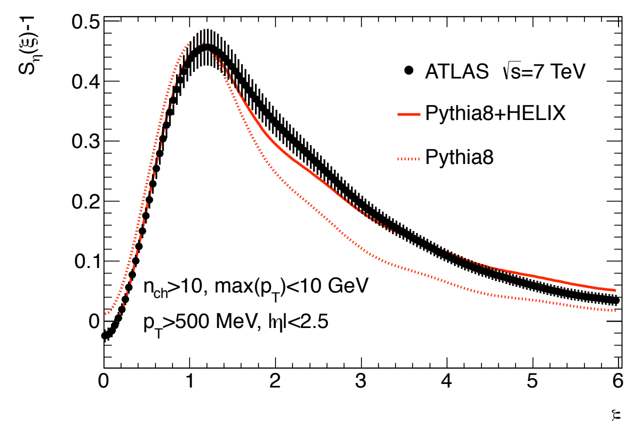






Tuned parameter	Input data set
Pythia8 4C +HELIX [6]	ATLAS_2012_I1091481 inclusive + low-p_T depleted
HSF:screwiness	0.61(2)
HSF:helixRadius	0.460(5)
MultipartonInteractions:expPow	3.7(1)
MultipartonInteractions:pT0Ref	2.09(3)
SpaceShower:pT0Ref	1.81(4)
BeamRemnants:reconnectRange	0.[F]
χ^2/N_{dof}	581/443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

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



PRD86,034001(2012)

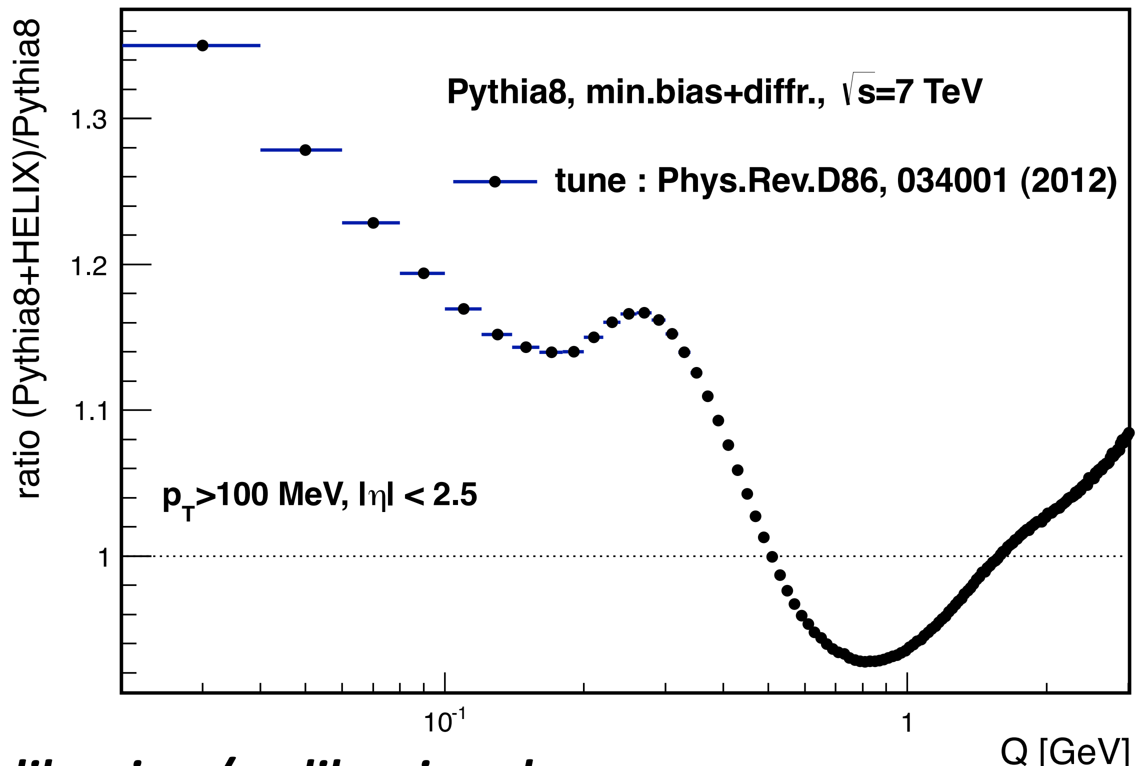
Use 'tuned' helix model to check expected effect on 'generic' 2-particle correlations

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 ?

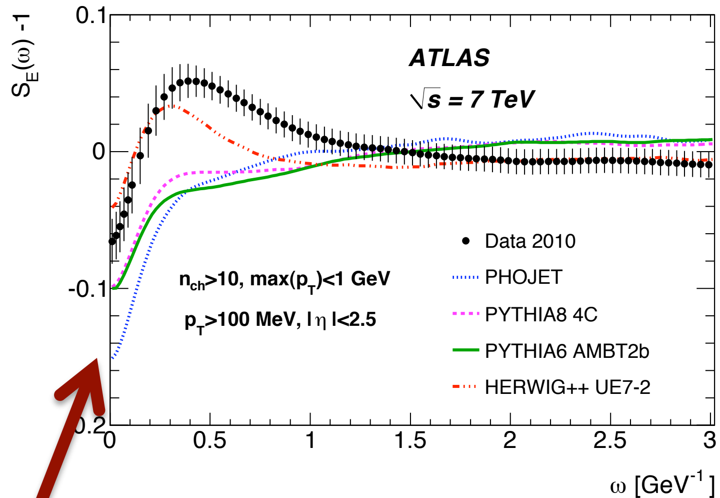
proton-proton

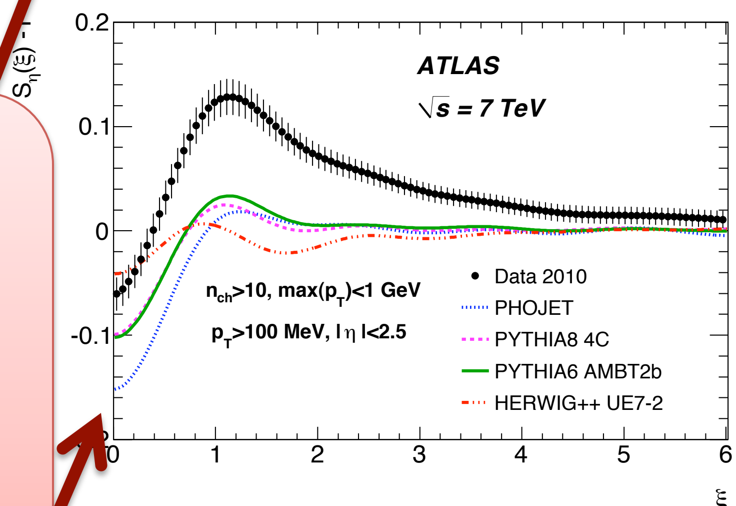


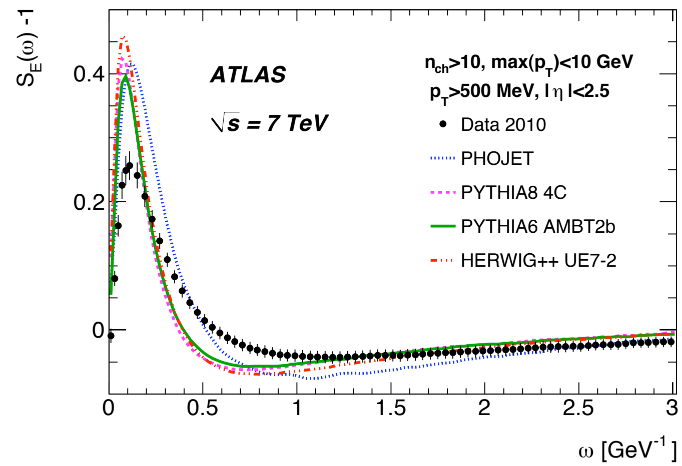
What about the prediction for like-sign / unlike-sign charge combination ?

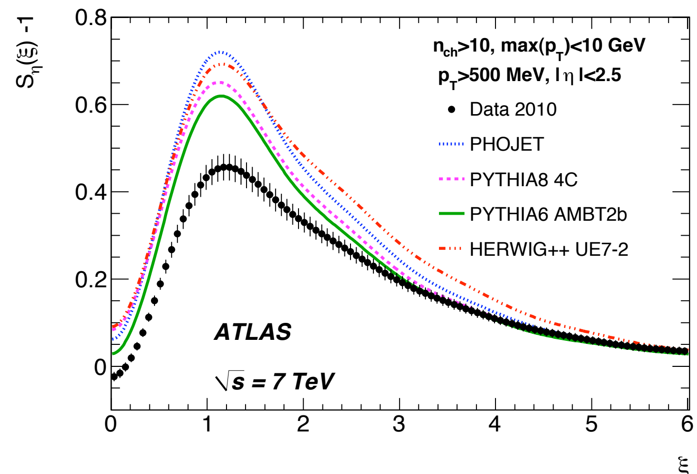
Direct evidence: Azimuthal ordering of hadrons [arXiv:1203.0419]

Soft selection
max(pT) < 1 GeV
-> sensitive to
fragmentation
effects







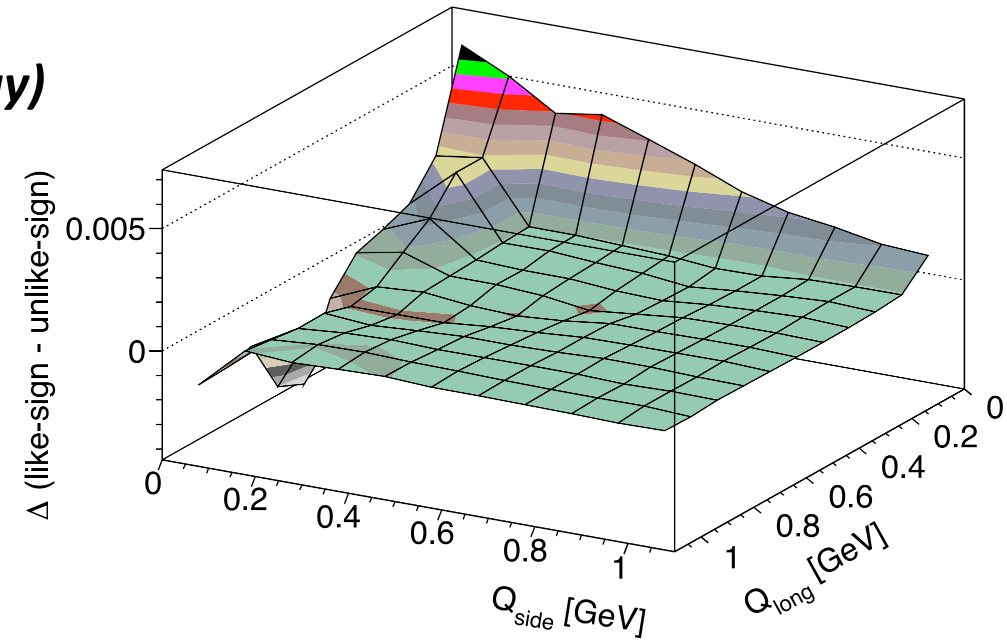


SIGNIFICANT AMOUNT OF CORRELATIONS WHERE EXPECTED (and where not expected)

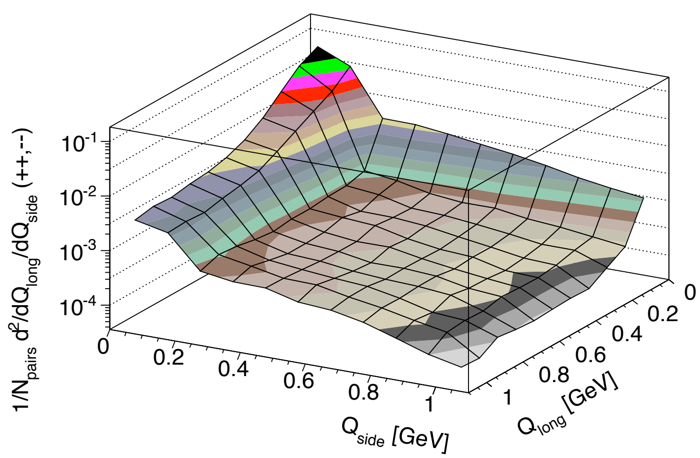
And HUGE overestimate of data in "hard" region - dominated by acollinear jets

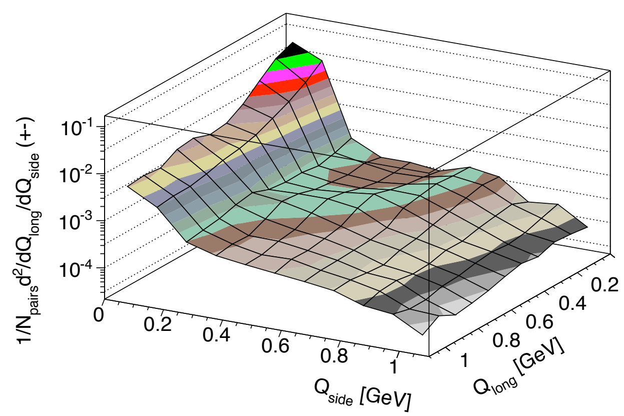
The model also hints on the 'elongation' of source:

Z^0->uu',dd'-> N ρ   (helix-string decay)

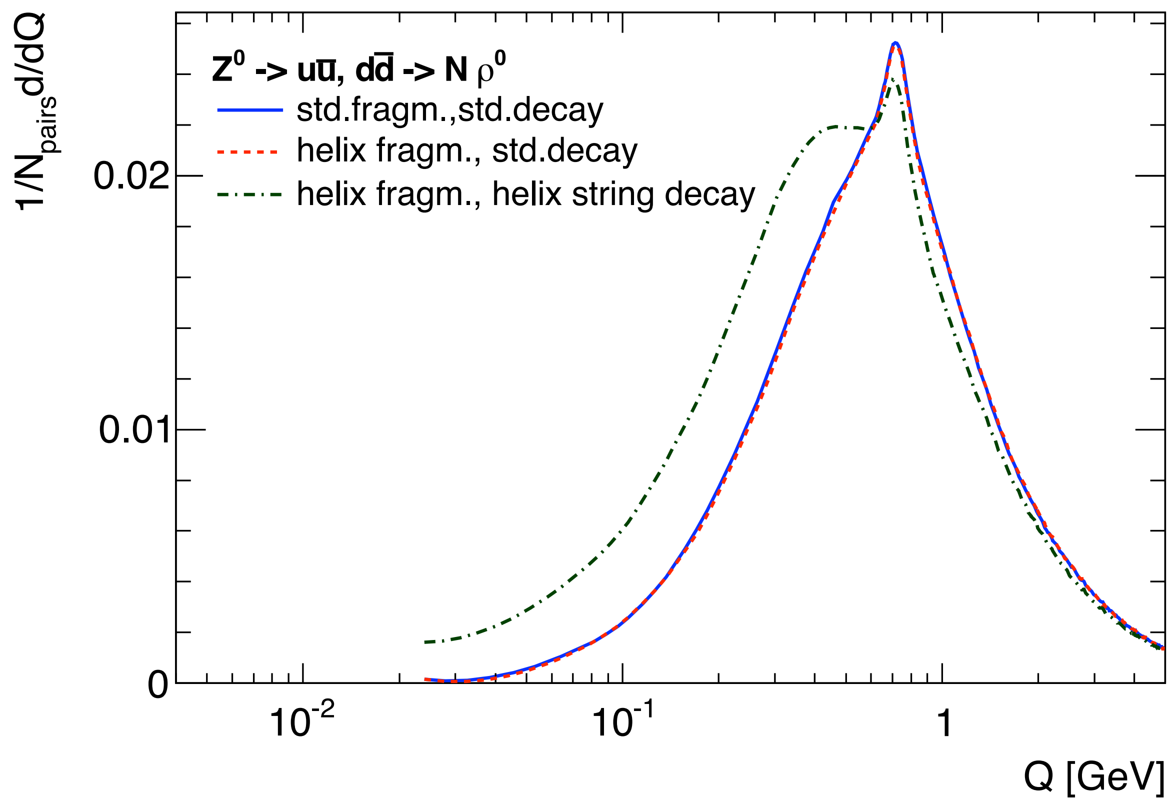


Parton shower switched off
Using longitudinal CMS for each pair
Q_{long} || Thrust (string axis)
Q_{out} < 240 MeV as in L3 measurement Phys.Lett.B458(1999)517



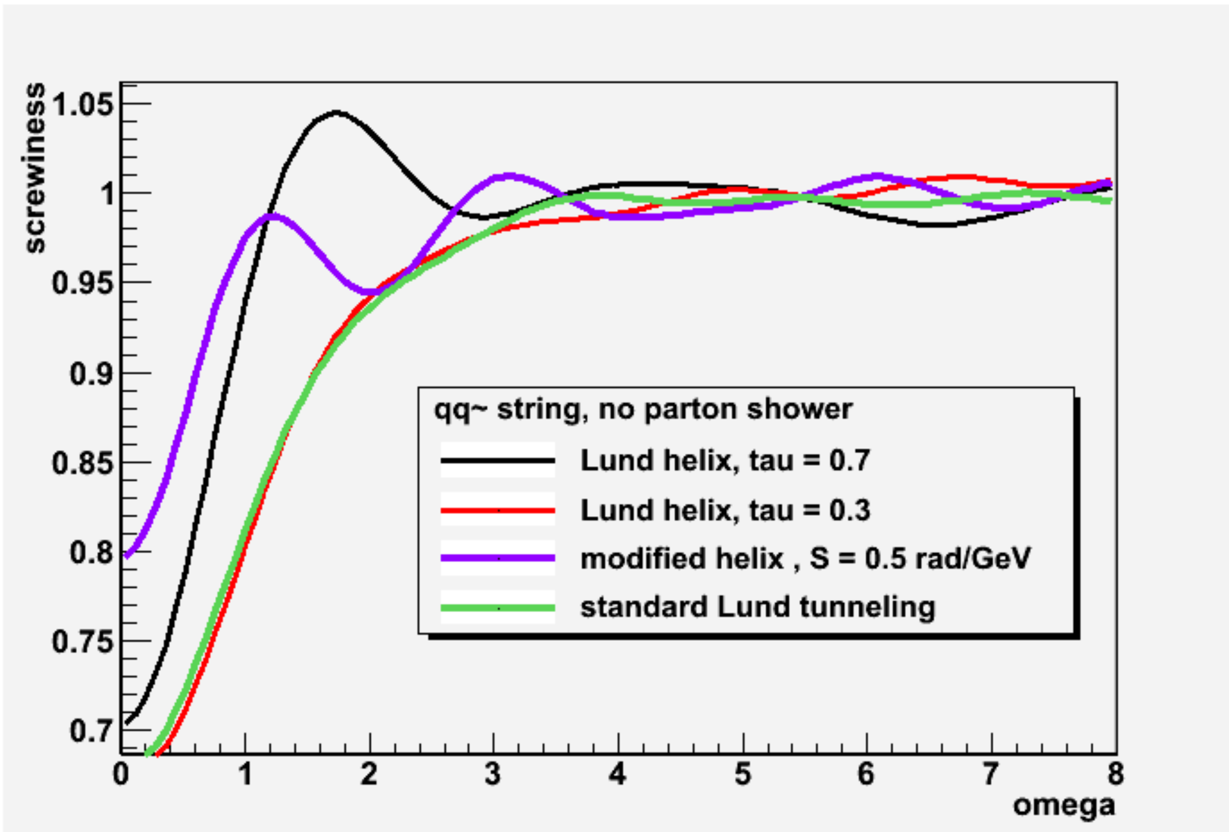


Combination of helix string fragmentation AND helix-like resonance decay necessary : 'ordinary' resonance decays destroy the helix string signature

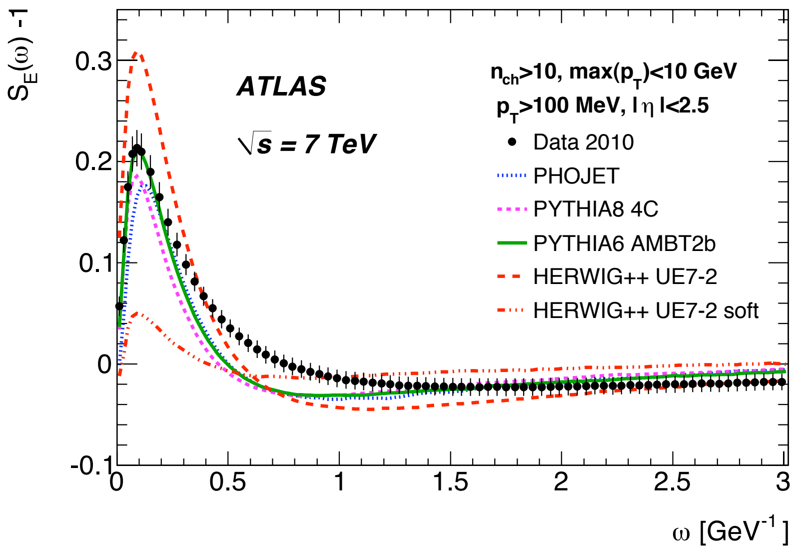


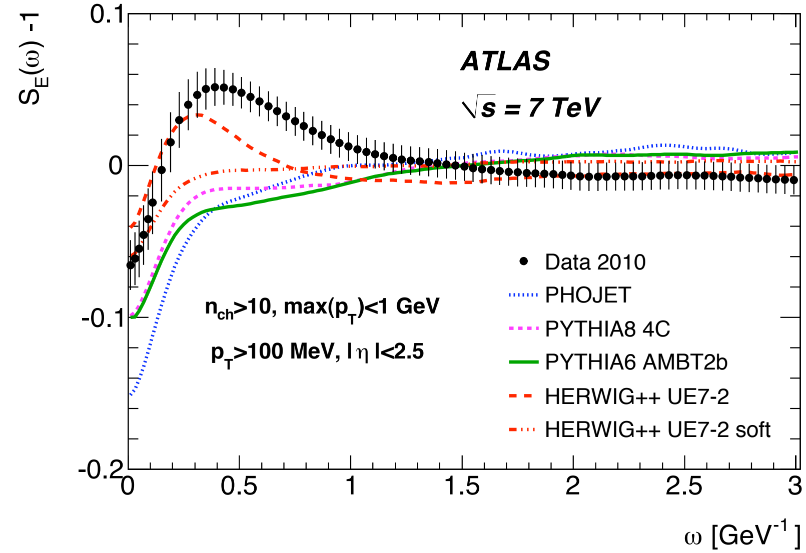
The search of the azimuthal ordering signal has been performed early on by DELPHI [DELPHI 98-156 CONF], unsuccesfully

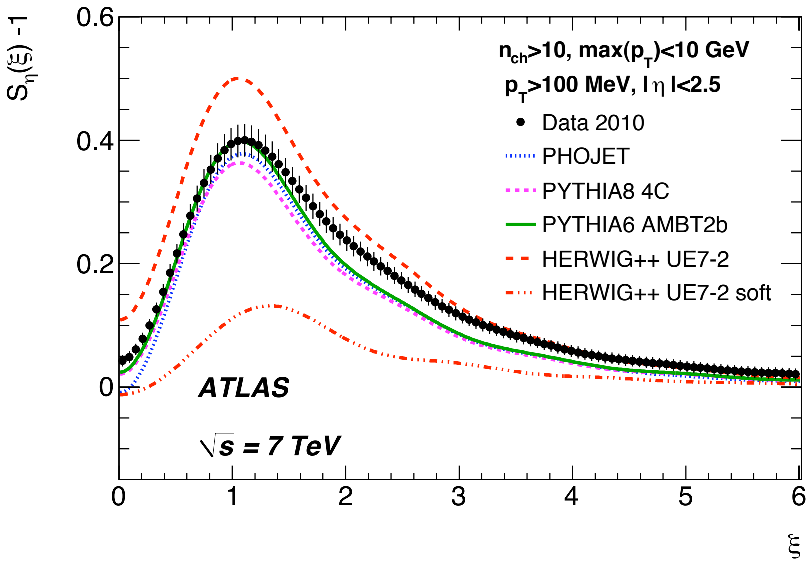
Was this related to the difference between helix models ?

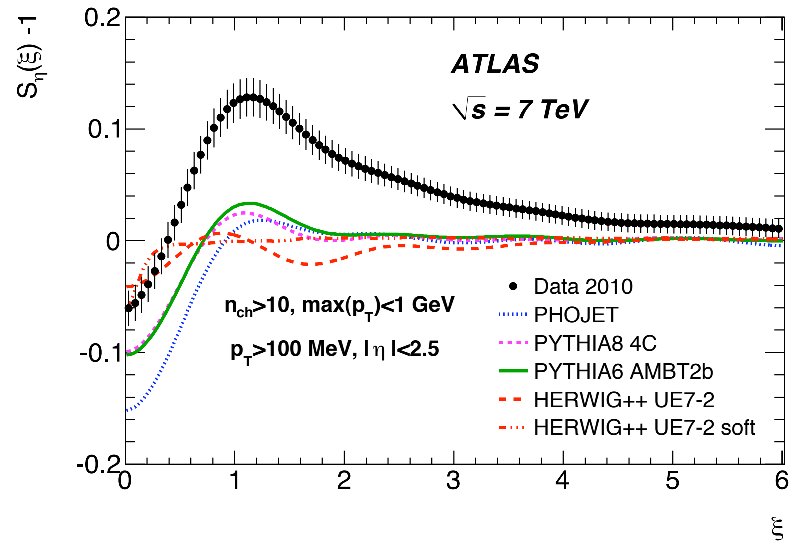


String model versus clusterization model

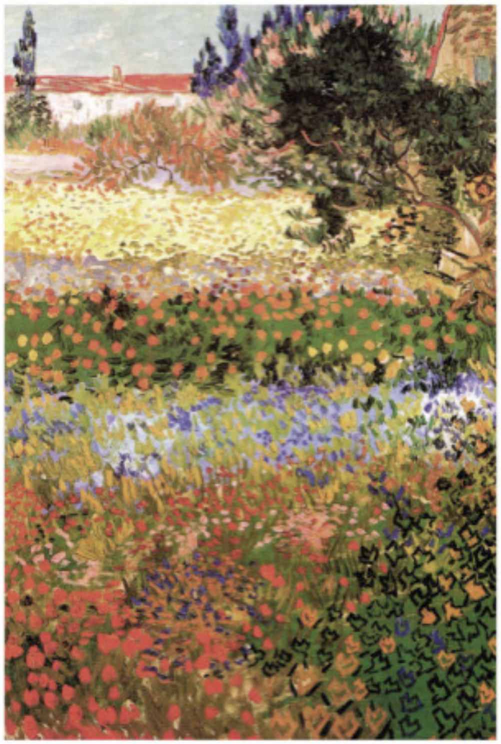




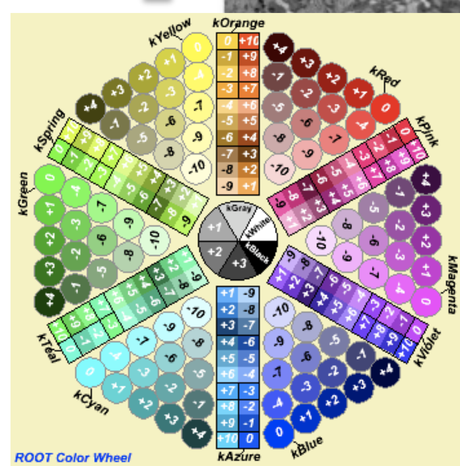




To measure inclusive spectra without correlations is like to look at paintings with shapes and colors separately ..

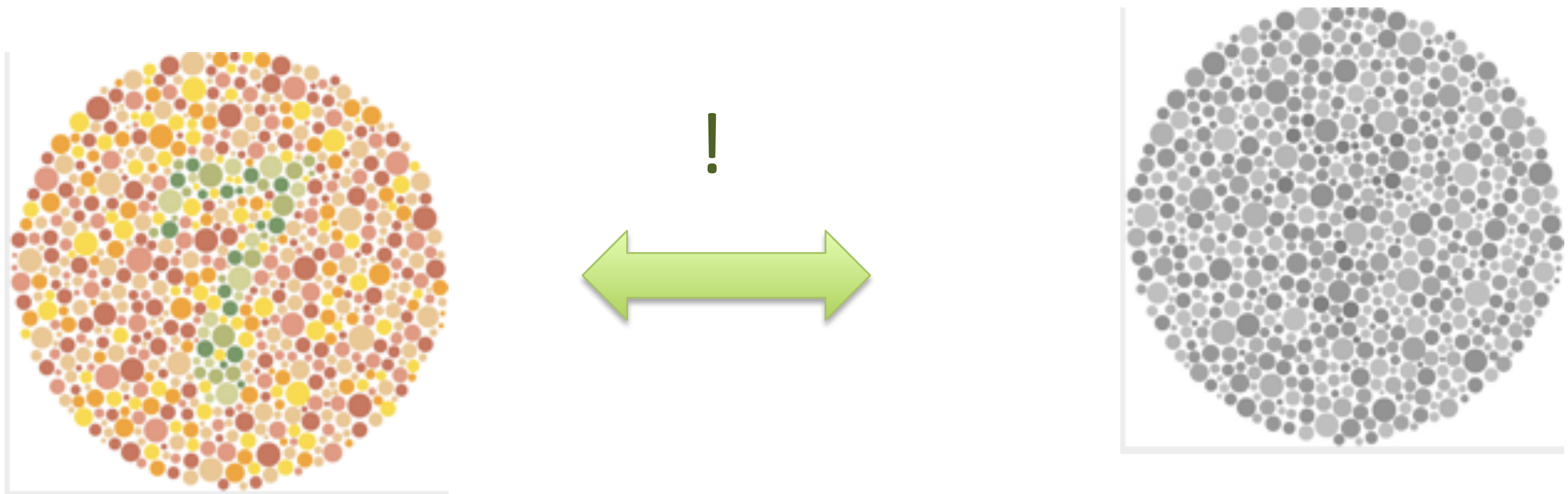


?



Sometimes, we may figure it out …

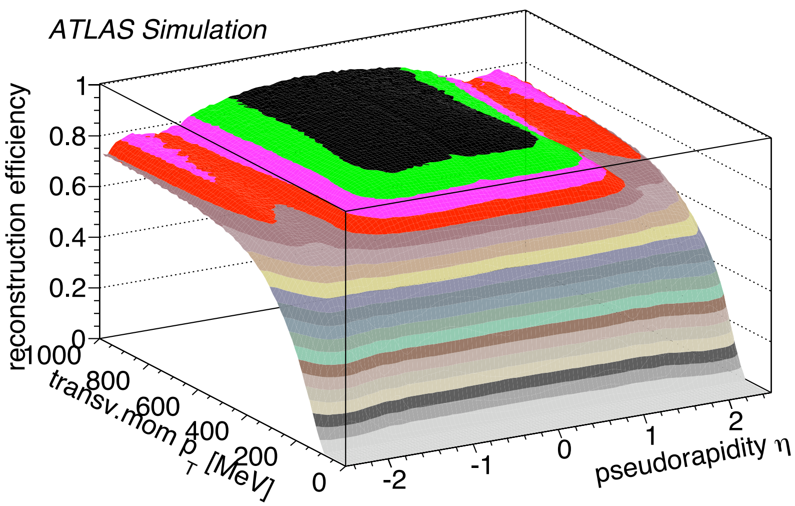
To measure inclusive spectra without correlations is like to look at paintings with shapes and colors separately ..



…and sometimes, we may stay clueless !

Correction procedure (unfolding) for the measurement of the azimuthal ordering
OR
How to correct the data when we cannot rely on MC models

Data markedly different from MC : the correction procedure needs to be model independent.
(A must : reliable detector simulation !)

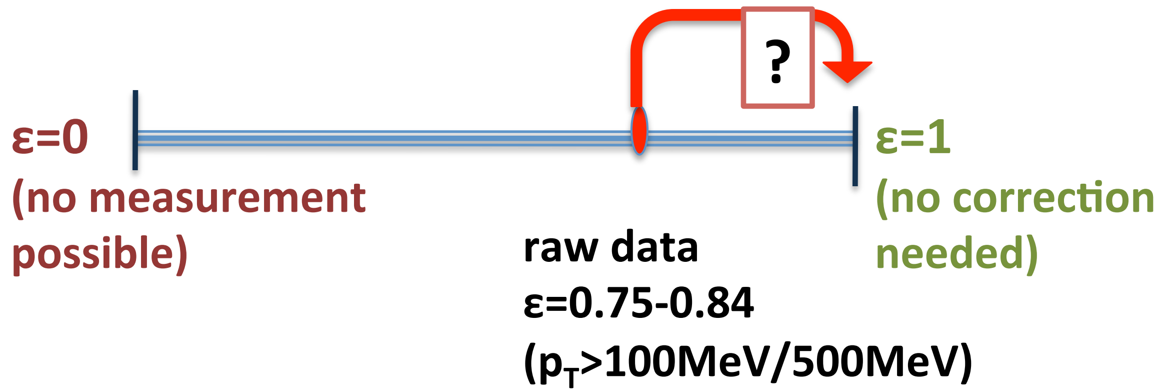


Simple solution : weight with (inverse) of track reconstruction efficiency

BUT this does not work for renormalized samples

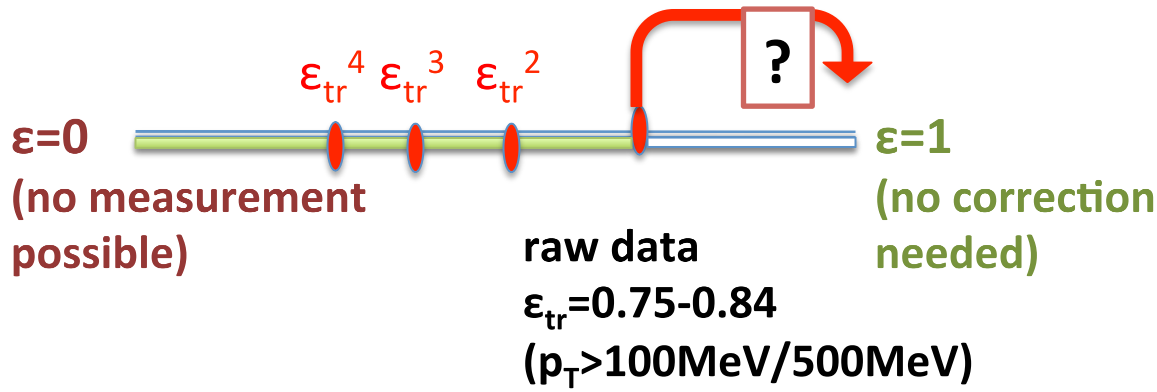
Correction procedure (unfolding)

Effective track reconstruction rate

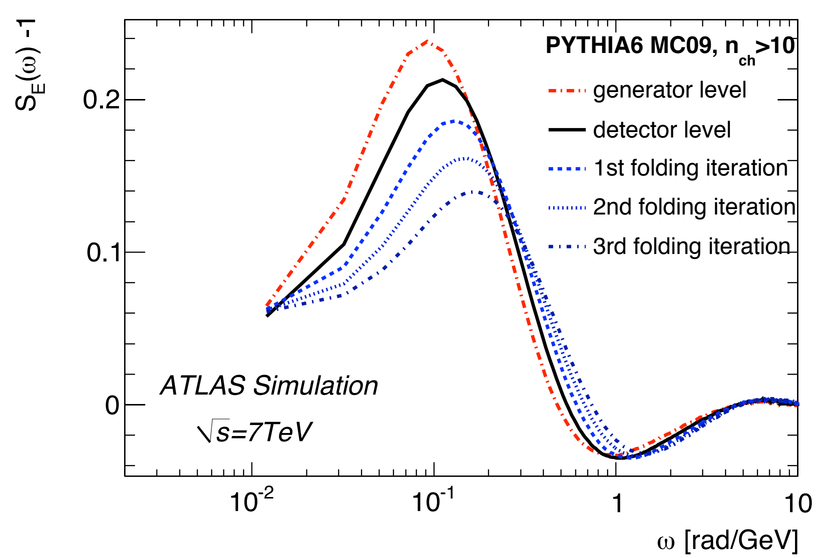


Correction procedure (unfolding)

Effective track reconstruction rate



Folding iterations allow to study the dependence on the effective track reconstruction rate



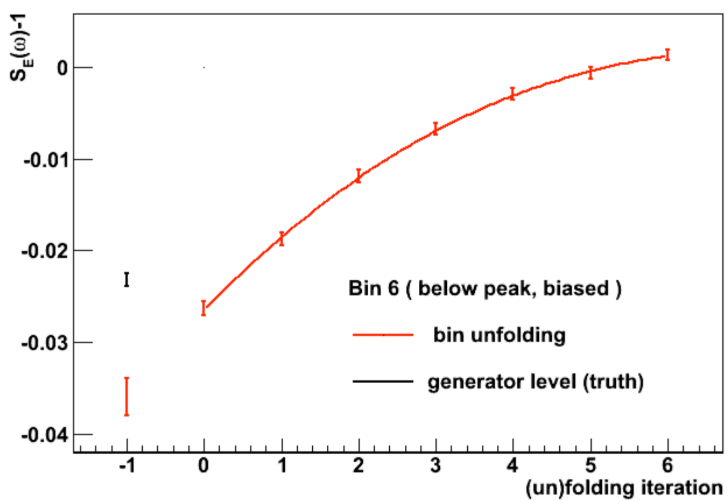
-> extrapolation to ε_{tr} = 1.

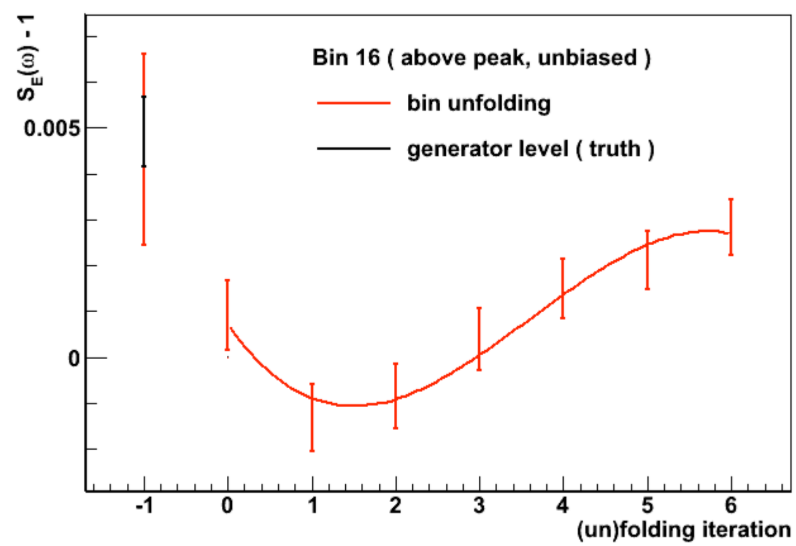
Various methods :

- ***-> bin-per-bin fit***
- ***-> scaling***
- ***-> … ?***

Correction procedure (unfolding)

The choice of the optimal technique depends on the observable …





In case of 'moving' peaks, the bin-per-bin extrapolation fails to capture the 'arrival' of the peak (->relatively large systematics)

Correction procedure (unfolding)

The choice of the optimal technique depends on the observable …

Power spectra exhibit a linear dependence on the track reconstruction efficiency and can be corrected with help of a couple of scaling factors

$$S_E^{(i-1)}(\omega)-1 = [\, S_e^{i}(\omega/f_\omega) - 1] / f_S$$

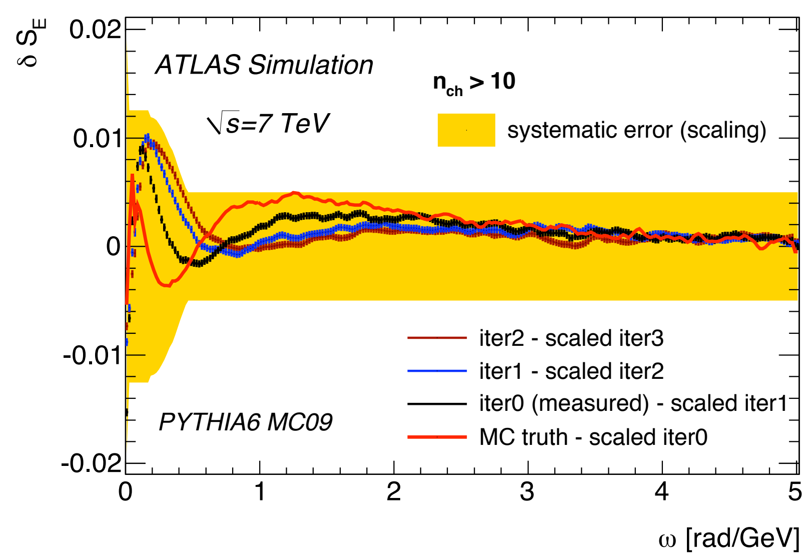
Very neat :

-> model independent

-> scaling factors (2-3 numbers) found from 1st folding iteration

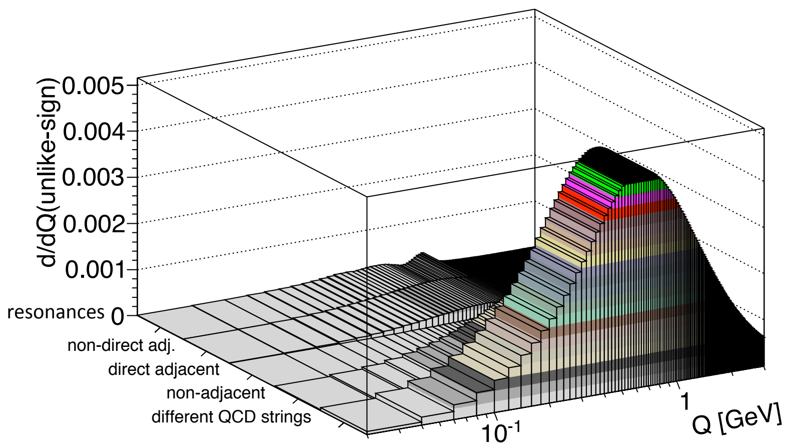
-> stability and precision of the scaling verified on 2nd and 3rd folding iteration

(-> systematic uncertainty)



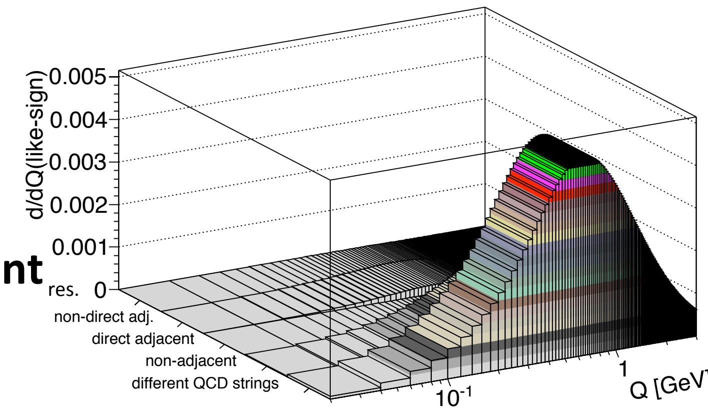
Charge-combination asymmetry of correlations : a unique tool for fragmentation studies: subtraction (unlike-sign pairs – like-sign pairs) very efficiently extracts "close"(adjacent) pairs from the combinatorial background

Unlike-sign pairs vs. source

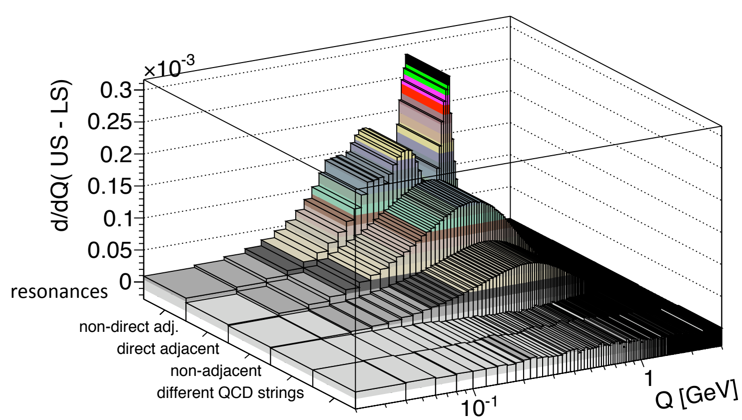


Q spectra dominated by non-adjacent hadron pairs

Like-sign pairs vs. source



Difference (unlike-sign – like-sign) driven by adjacent hadron pairs



(consequence of local charge conservation in the string breakup)