Measurements of correlated hadron production with the ATLAS detector

Šárka Todorova-Nová, LAPP Annecy

7TeV minimum bias data analysed for

- *study of Bose-Einstein interference*

and

- *study of correlated hadronization*

The talk illustrates how our assumptions influence the choice of observables and the interpretation of results.

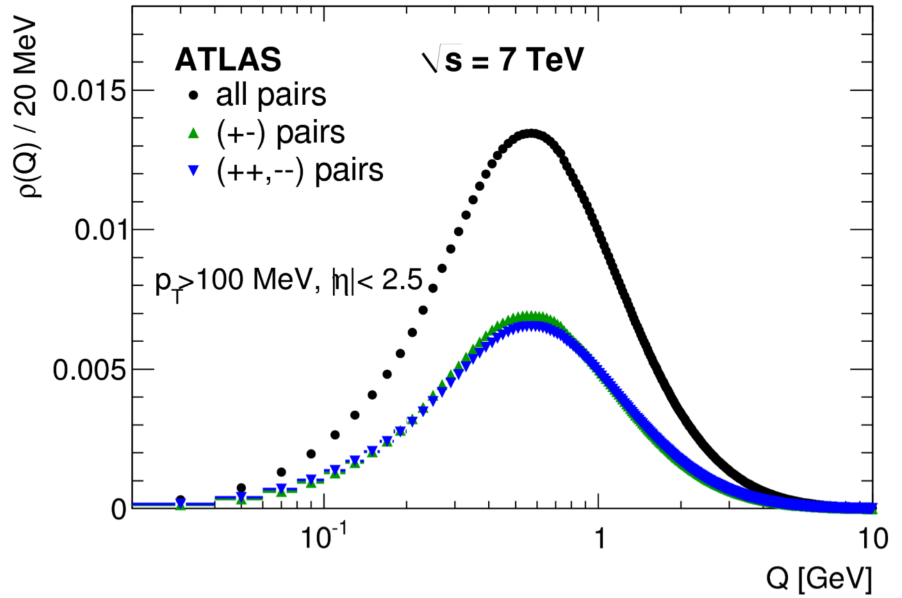
MPI@LHC , Perugia 2018

Introduction

Excess of close pairs of same-sign hadrons observed in hadronic data.
Traditionally, the effect is interpreted as a signature of Bose-Einstein interference operating on superposition of wave-functions of identical bosons
(in close analogy with stellar interferometry, Hanbury-Brown-Twiss effect)

Experimentally, the effect is studied by comparing the like-sign (LS/++,--) and opposite-sign (OS/+-) pair spectra as a function of the (4)-momentum difference

$$Q_{ij} = \sqrt{-(p_i - p_j)^2}$$



This talk contains only non-identified spectra ,
all particles have the pion mass assigned (MC indicates ~70% purity for $\pi\pi$)

Traditional approach (BE driven) : study the ratio (LS/OS)

correlation function

$$C_2(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)}$$

ρ pair density, ρ_0 reference sample
(OS pairs in this analysis)

Observable corrected for non-BE correlations with help of MC samples

$$R_2(Q) = \frac{C_2(Q)}{C_2^{\mathrm{MC}}(Q)}$$

Fit with exponential function

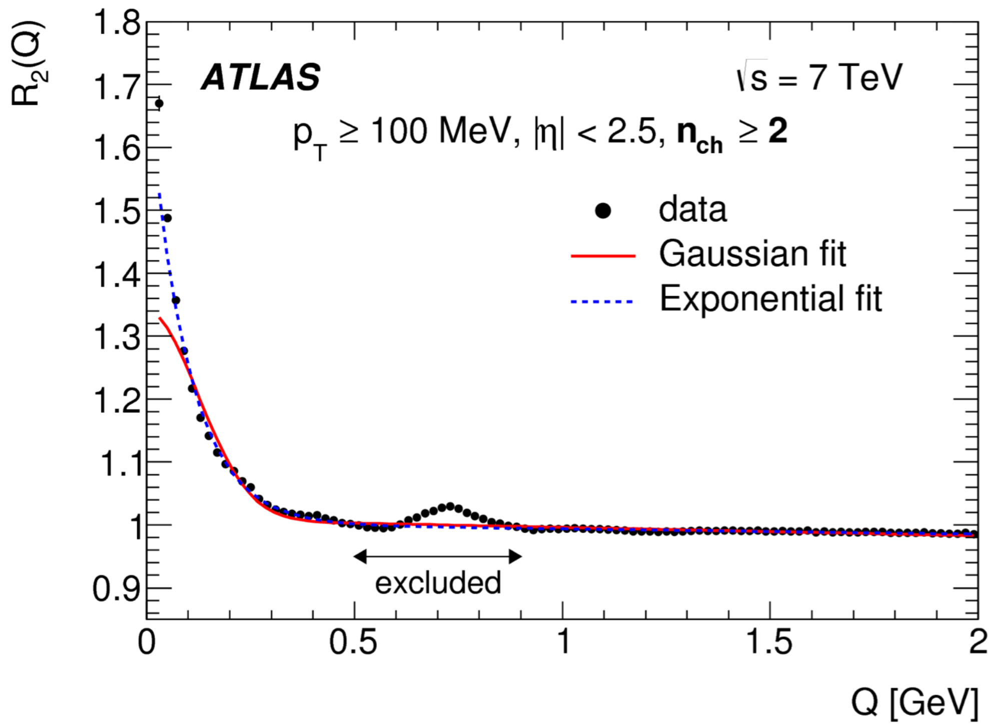
$$\Omega = \lambda \cdot \exp(-RQ)$$

Eur. Phys. J. C75 (2015) 466

Minimum bias trigger, samples corrected for track and vertex reconstruction efficiency, Coulomb correction applied

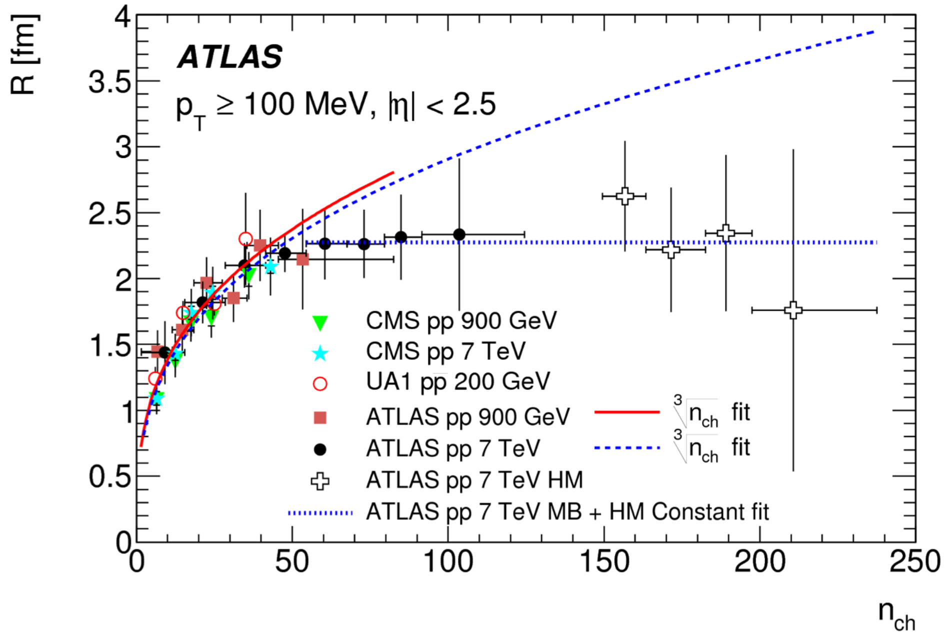
$$\rho_{\mathrm{corr}}(Q) = \frac{\rho(Q)}{G(Q)} \quad , \quad G(Q) = \frac{2\pi\zeta}{e^{2\pi\zeta} - 1}$$

$$\zeta = \pm\frac{\alpha m_{\pi}}{Q}$$

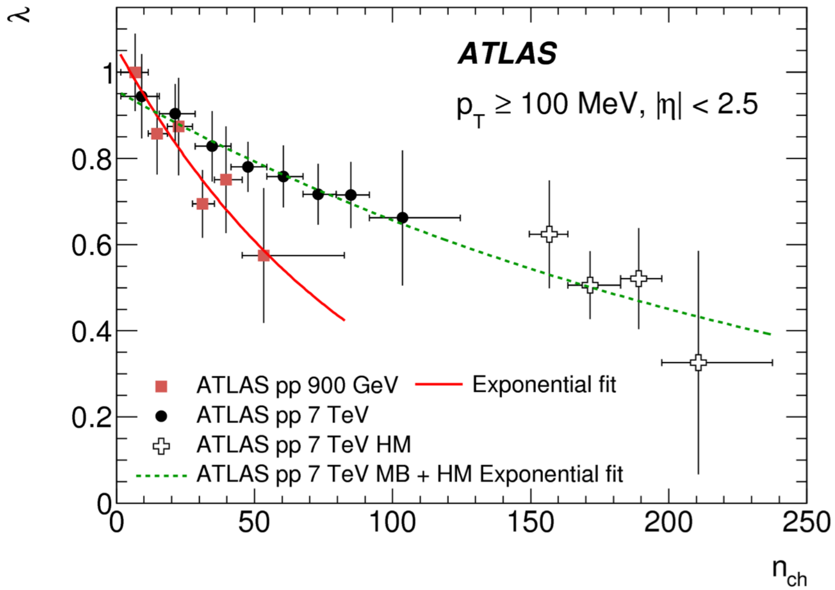


Traditional approach (BE driven) : study the ratio (LS/OS)

[Eur. Phys. J. C75 (2015) 466]()



Measurement of the (corrected) event multiplicity dependence of the fitted parameters



R interpreted as a characteristic size of the source

Increasing with the event multiplicity, ATLAS measurement shows flattening around $n_{ch} \gtrsim 50$

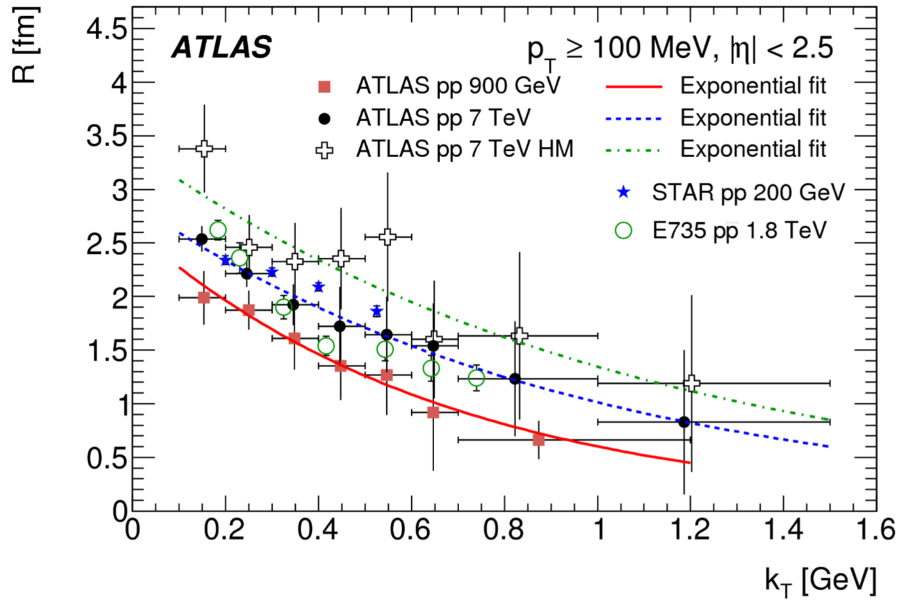
Traditional approach (BE driven) : study the ratio (LS/OS)

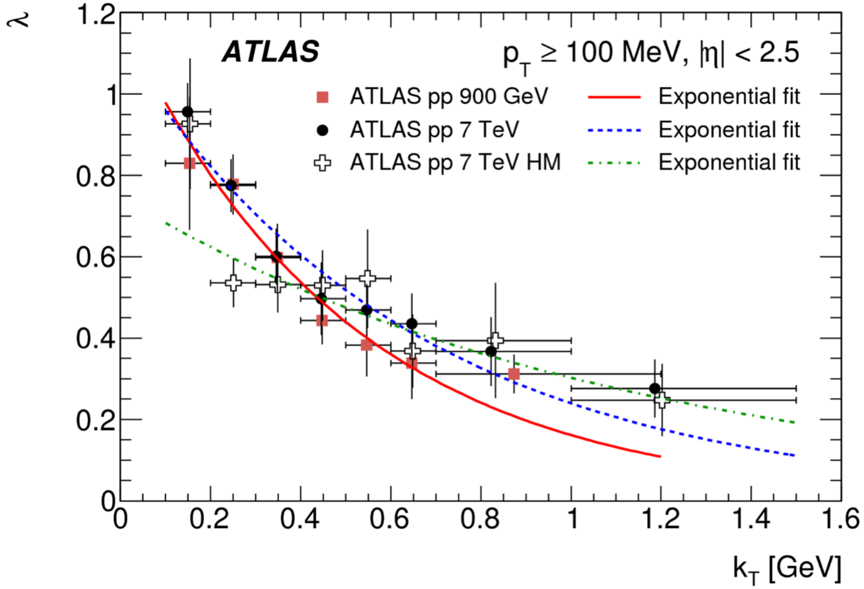
Eur. Phys. J. C75 (2015) 466

Measurement of the k_T dependence

$$k_{\mathrm{T}} = |\mathbf{p}_{\mathrm{T},1} + \mathbf{p}_{\mathrm{T},2}|/2.$$

(average vector sum of transverse momenta)





R interpreted as the characteristic size of the source

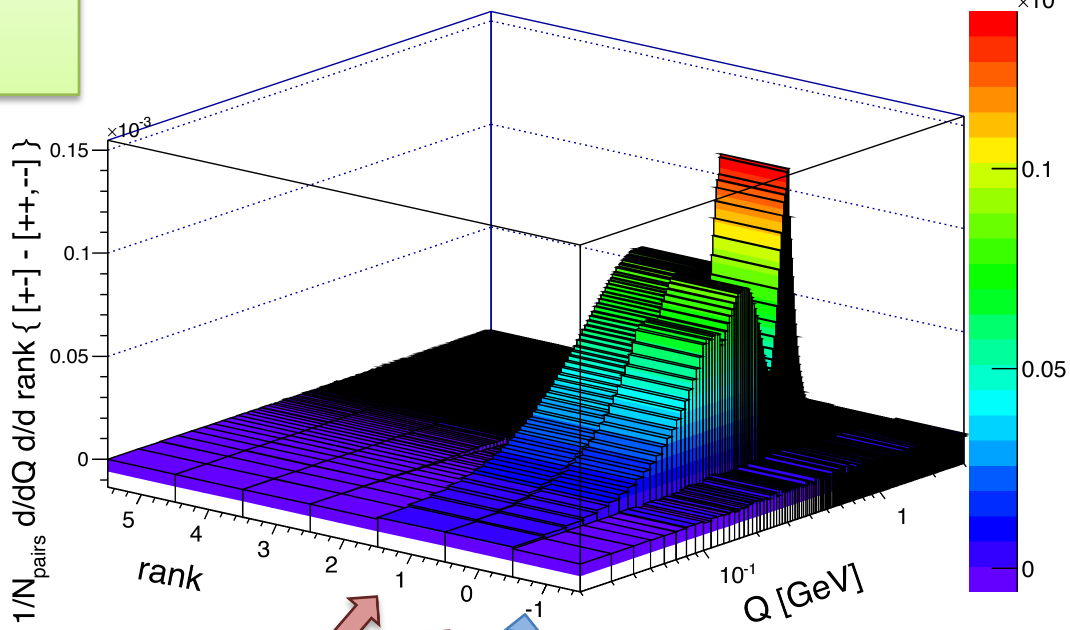
Inversely proportional to k_T

Alternative approach (hadronization) : study the difference (OS-LS)

$$\Delta(Q) = 1/N_{ch} \, [\; N^{+-}(Q) \; - \; N^{++,--}(Q) \;]$$

MC truth (PYTHIA8) :
nearly perfect subtraction of
non-adjacent pair contribution

rank>1 : non-adjacent
(subtracted)



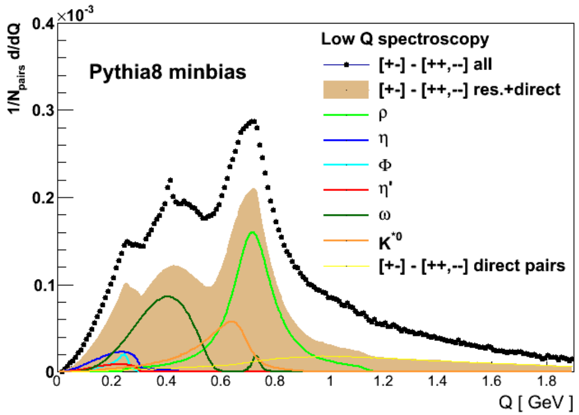
rank=1 : adjacent

rank=0 :
common direct
mother (decays)

rank=-1 : different strings
(random, subtracted)

Rank refers to the ordering
of hadrons according to color flow,
adjacent hadrons share breakup vertex

Lund string fragmentation: 1-dim string,
local charge and momentum
conservation in string breakup,
no cross-talk between breakup vertices
(breaking points causally disconnected)



Alternative approach (hadronization) : study the difference (OS-LS)

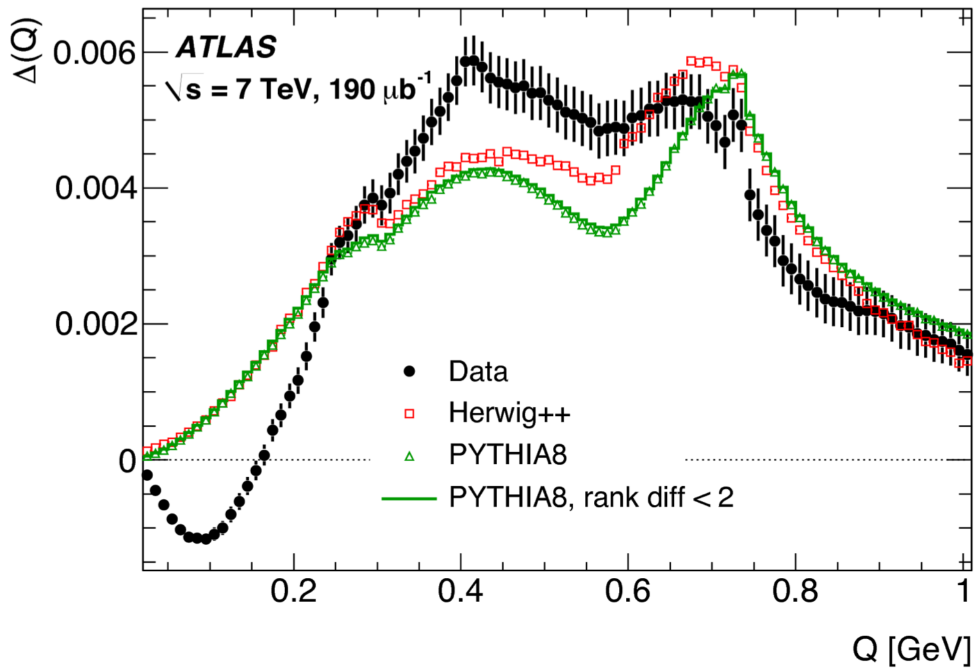
[*Phys. Rev. D 96 (2017) 092008*]

$$\Delta(Q) = 1/N_{ch} [N^{+-}(Q) - N^{++,--}(Q)]$$

Observable not described by any of our hadronization algorithms

Poor agreement not only in the region of BE correlations (the dip) but also at higher Q .

We need to change some of our assumptions … let's try a correlated fragmentation scenario.



Like-sign pairs cannot be produced as adjacent hadrons (forbidden by local charge conservation). There has to be at least one (OS) hadron produced in between them (the ordering follows the colour flow)

Select triplets (particle + closest like-sign partner + closest unlike-sign partner) -> charge-ordered chains [+-+] and [-+-]

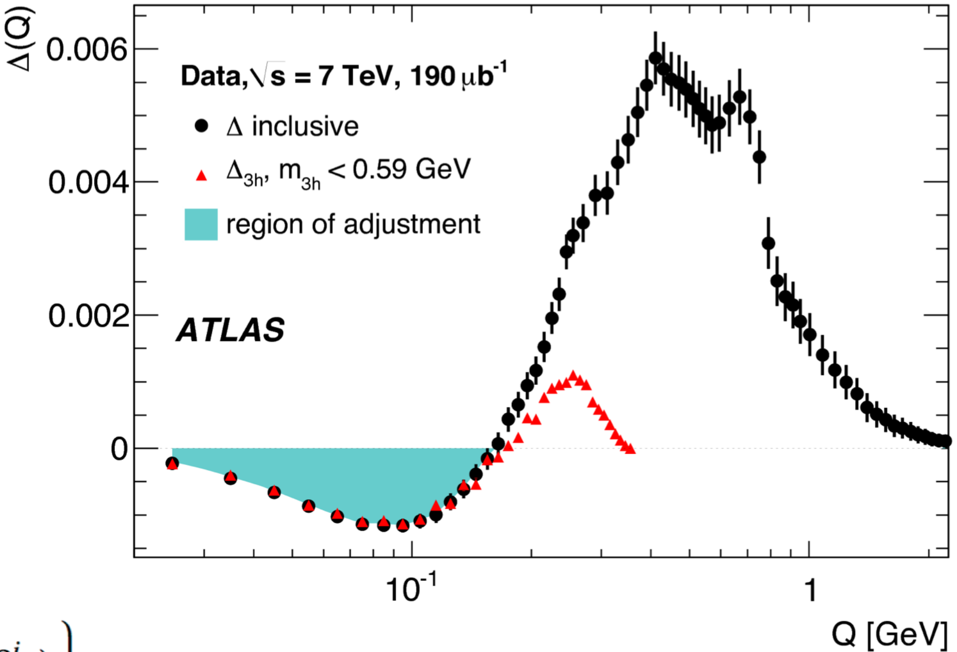
Alternative approach (hadronization) : study the difference (OS-LS)

[Phys. Rev. D 96 (2017) 092008]

$\Delta(Q) = 1/N_{ch}\ [\ N^{+-}(Q) - N^{++,--}(Q)\ ]$

Compare selected triplets with the inclusive signal as function of triplet mass

Since there are 2 pairs with opposite -sign and only 1 pair with like-sign charge in each triplet, the contribution from OS pairs is scaled by 0.5, to allow the cancellation of the combinatorial background.



$$\Delta_{3h}(Q) = \frac{1}{N_{ch}} \sum_{k=1}^{N_{ev}} \sum_{i=1}^{n^k_{ch}} w_i \left\{ \frac{1}{2}\,\delta(Q - Q^i_{01}) + \frac{1}{2}\,\delta(Q - Q^i_{12})\ - \delta(Q - Q^i_{02}) \right\}$$

The low-Q shape of correlations is reproduced by closely packed triplets with mass below 0.6 GeV, i.e. comparable with the lowest mass of known 3π decays (η , K)

This looks like a fully coherent/correlated particle production …. compatible with η' decay

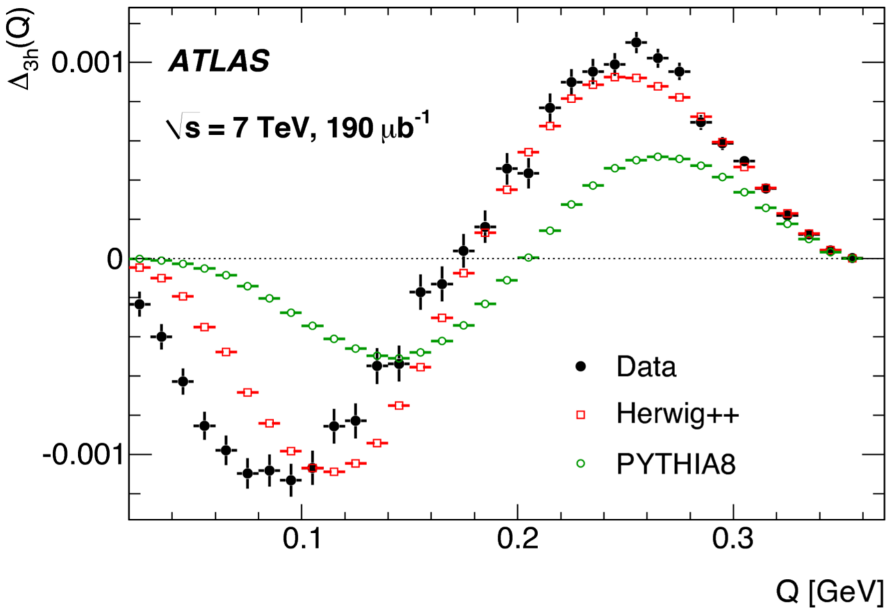
Alternative approach (hadronization) : study the difference (OS-LS)

[**Phys. Rev. D 96 (2017) 092008**](#)

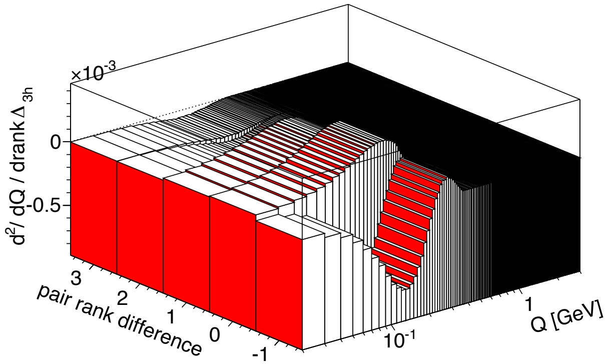
$$\Delta_{3h}(Q) = \frac{1}{N_{ch}} \sum_{k=1}^{N_{ev}} \sum_{i=1}^{n_{ch}^k} w_i \left\{ \frac{1}{2}\,\delta(Q - Q_{01}^i) + \frac{1}{2}\,\delta(Q - Q_{12}^i) \; - \delta(Q - Q_{02}^i) \right\}$$

We need to be careful not to jump to the conclusions hastily …

… Δ_{3h} remains an inclusive observable, obtained by subtraction .. the agreement can be just accidental ..



.. and indeed, the MC shows a similar signal even though there are no true low-mass chains simulated : the MC truth info indicates these are combinations of a real adjacent (OS) pair with a random close track



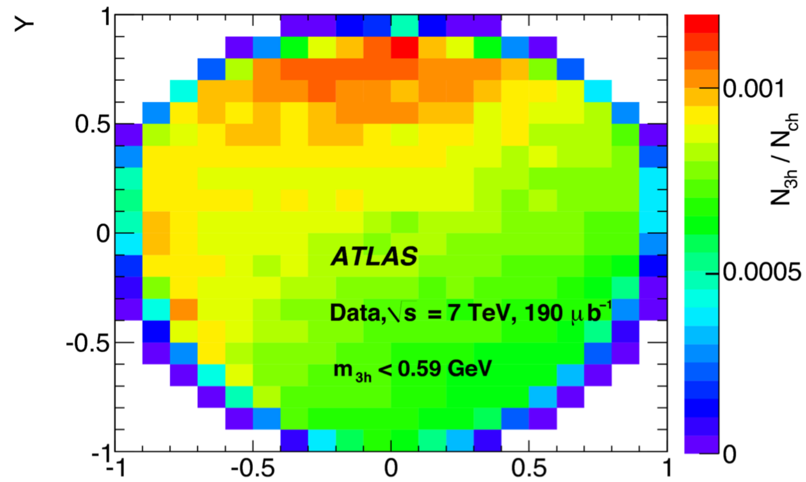
We need additional measurement to find out if there are « real » chains present in the data

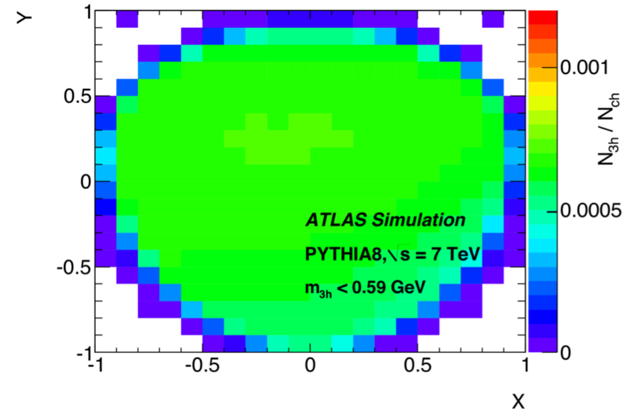
Alternative approach (hadronization) : study the difference (OS-LS)

3-body decay / Dalitz plot

T_i kinetic energy (E-m)

$$X = \sqrt{3}\frac{T_0 - T_2}{\Sigma T};\ Y = \frac{3T_1}{\Sigma T} - 1;$$

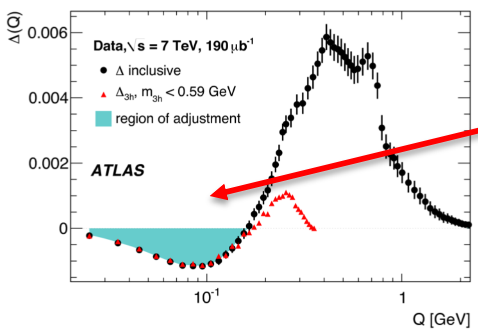


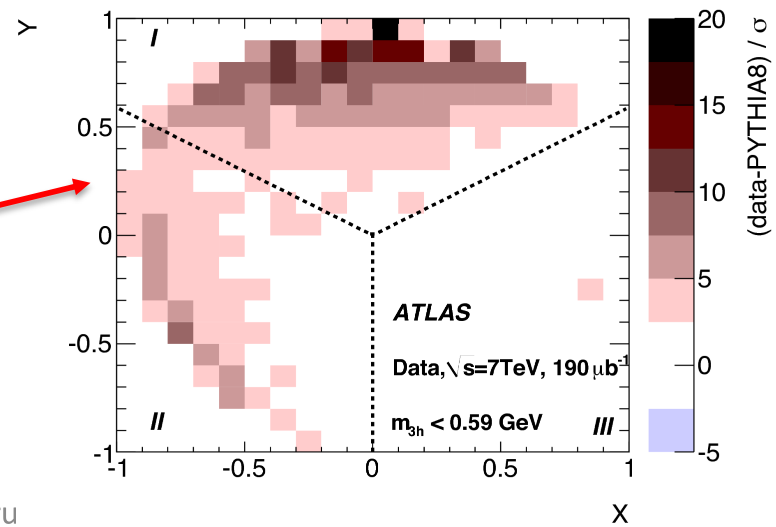


The excess of selected triplets is confirmed by the study of 3-body decay kinematics.

The integrated excess in the signal region (I+II) corresponds to the measured rate of correlated like-sign pairs (selected triplet chains) of 1.1 % per charged track.

We may start to be reasonably confident about the hadronization scenario …

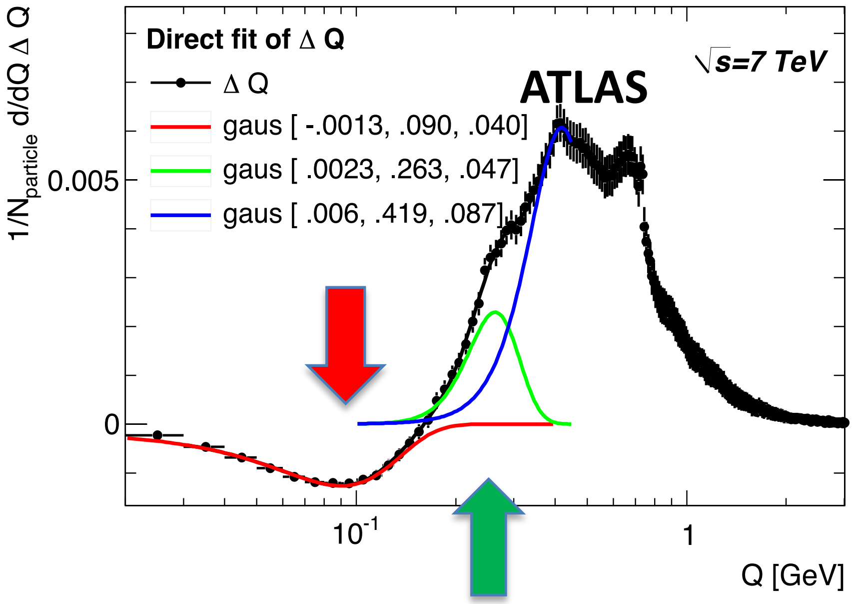


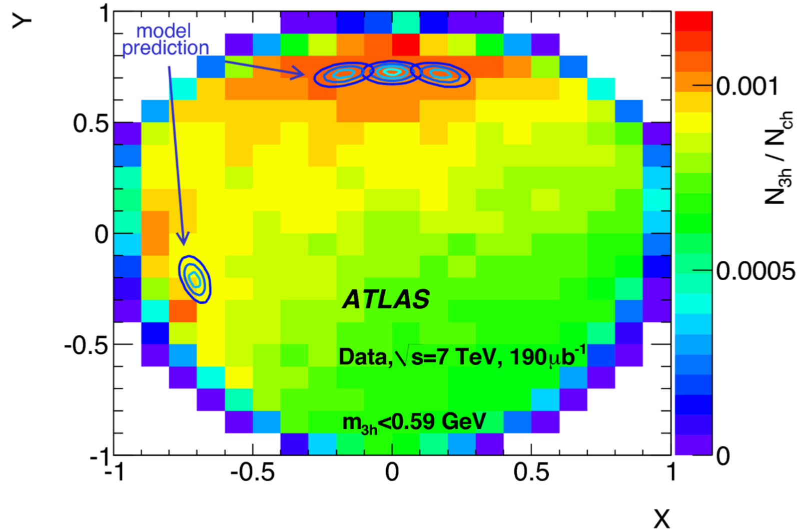


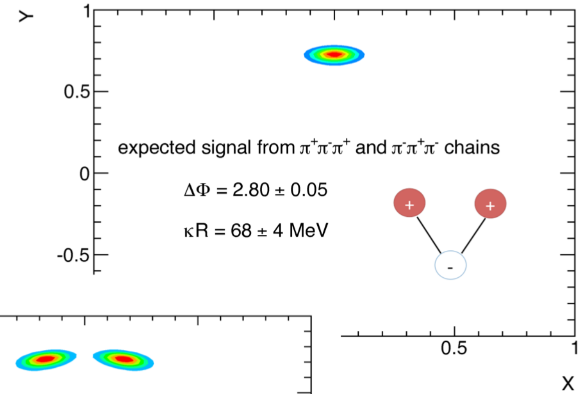
Alternative approach (hadronization) : study the difference (OS-LS)

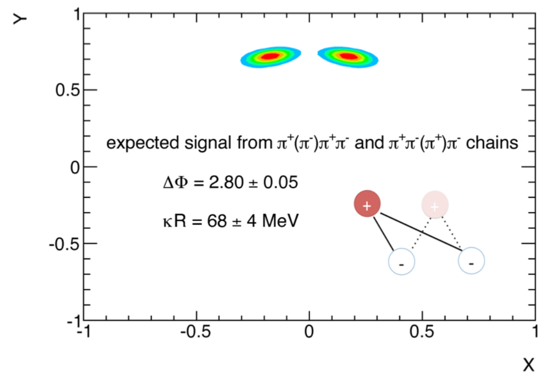
… even more so, since the effect is actually predicted by the model of a quantized fragmentation of a helical QCD string
[Phys.Rev.D89,015002(2014)]

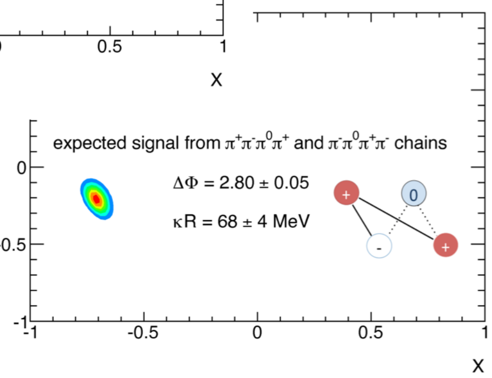
Pair rank difference r	1	2	3	4	5
Q expected [MeV]	266 ± 8	91 ± 3	236 ± 7	171 ± 5	178 ± 5





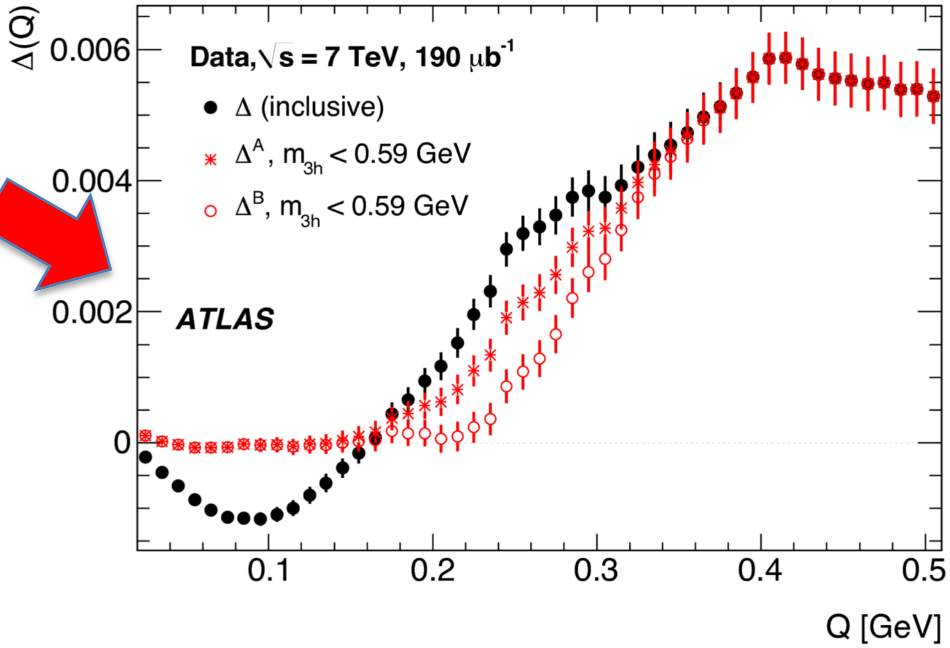


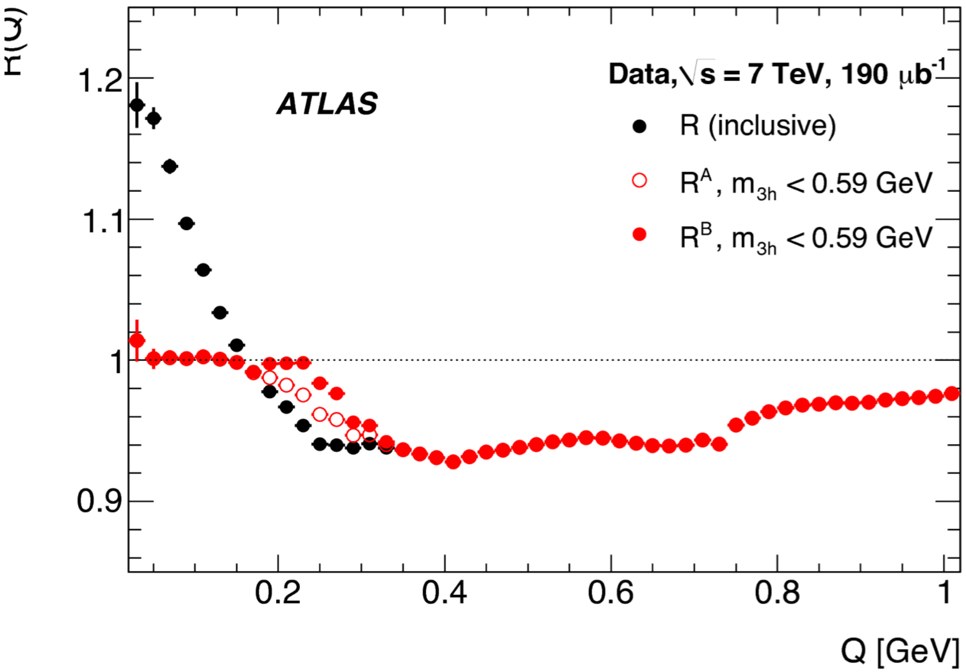




Observables after subtraction of low-mass triplets/removal of source of correlations

The model of the quantized fragmentation suggests we are looking at the quantum threshold in the production of adjacent hadrons (minimal momentum difference of adjacent pairs around 0.26 MeV) and that the enhanced production of LS pairs is rather a secondary effect of quantization.





Indeed after the removal of the triplet chain selection (inclusive!) , the BE-like effect is gone in ratio of LS/OS spectra

$R^{A,B}$,$\mathbf{\Delta}^{A,B}$ indicate inclusive observables without contribution from selected chains Scenario B includes the rescaling of content of OS pairs in triplet chains.

Summary, outlook

- ***two analyses of (charge-combination dependent) 2-particle correlations presented***

  -> traditional (Bose-Einstein interference)

  -> emerging (correlated hadronization effects)

- ***corrected data available for further phenomenological studies***

  (Rivet: ATLAS_2017_I1624693 / hadronic chains)

- ***Additional observables predicted by model of quantized helical QCD string***
  (which serves as a useful working hypothesis), measurements ongoing

  -> p_T dependence : the ground-state pions should be produced with an intrinsic transverse momentum of about 130 MeV

  -> approximately linear rise of correlation yield with the number of particles in the sample expected

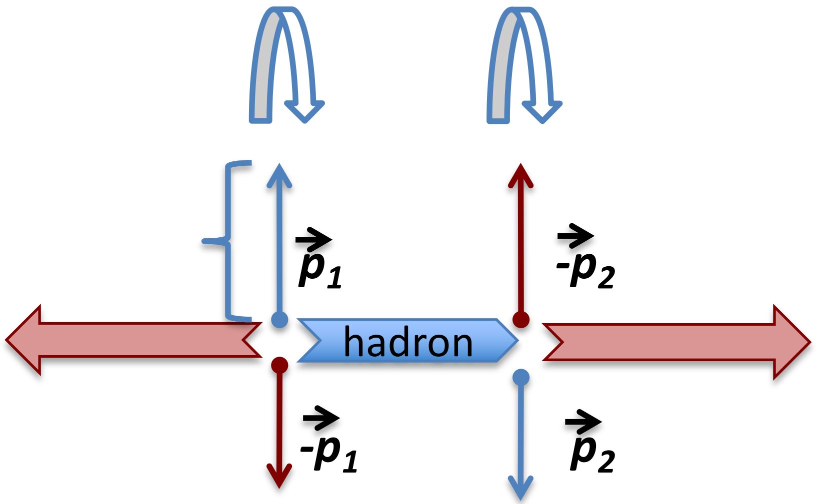
  -> effect qualitatively and quantitatively stable in all hadronic data

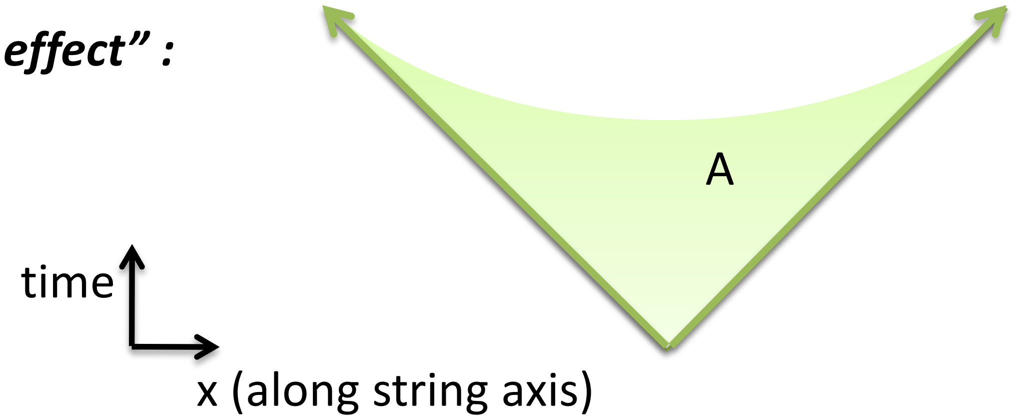
back-up slides

Hadron formation in the string fragmentation model

Lund model [Phys. Rept. 97, 31 (1983)391]

String breakup occurs via so-called "tunneling effect" :
a new qq~ pair is created from 'vacuum' and
assigned a certain transverse momentum
randomly sampled in size & azimuthal angle:





Semi-classical model :
- confinement modeled by relativistic massless string with constant string tension (κ~1 GeV/fm)

- massless partons moving in light-cone coordinates

- the area span of the string (A) corresponds to the action

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

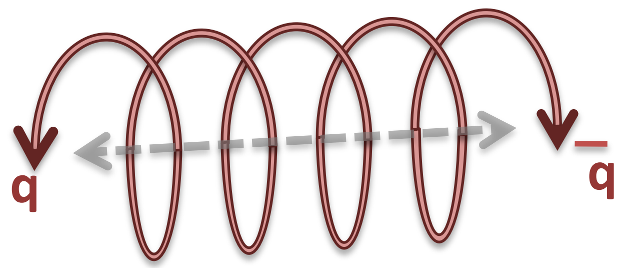
$$p_{||} = \kappa\,(t_1 - t_2)$$
$$E = \kappa\,(x_1 - x_2)$$

Causally disconnected breakups

Hadron masses are external parameters of the model

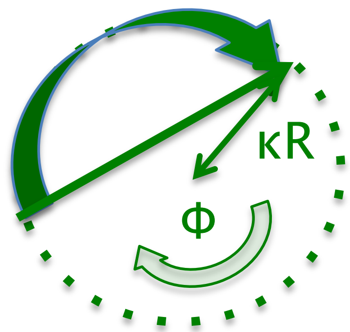
Helix string concept *[JHEP09(1998)14.]*

- *introduced to stabilize the end of parton shower*
- *optimal packing of soft gluons for helicity preserving emissions*



3-dim string: the string tension operates in the transverse plane and the hadron acquires transverse momentum p_T

The removal of 2 degrees of freedom associated with the intrinsic pT generation leads to a <u>significant</u> improvement in the description of hadronic Z0 data [arXiv:1012.5778]



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

κR helix radius
φ helix phase

3-dim string allows to maintain causal relations between breakup vertices

i.e., we can IMPOSE time-like distance (⇔ cross-talk) between breakup vertices

QCD field (string tension) transforms

into : longitudinal quark momentum

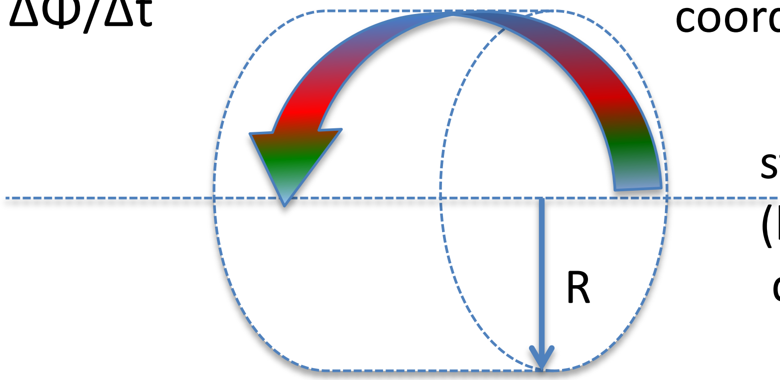
$p_{II} = \kappa\, \beta\, c\, \Delta t$; $\beta^2 = 1 - (R\omega/c)^2$; $\omega = \Delta\Phi/\Delta t$

+ transverse quark momentum

$|p_T| = 2\, \kappa R \sin (\Delta\Phi/2)$

+ effective quark mass

$m_T = \sqrt{(m^2+p_T^2)} = \kappa R\, \Delta\Phi$



<u>If we let the</u> information about breakup travel along string together with the quark

(propagating quark "triggers" the next breakup & creation of hadron)

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

-> mass of the hadron depends on the TRANSVERSE shape of string only

(the longitudinal momentum and transverse mass decouple)

-> narrow resonant states ?

Mass spectra of light hadrons (π, $\eta(547)$, $\eta'(948)$ ..) can be reproduced by fragmenting the helical string in regular intervals $\Delta\Phi$:

- ***π ground state (lightest hadron) ; $\eta \to 3\,\pi$; $\eta' \to 5\,\pi$***
- ***effective quantization:*** $E_T\,(n=1,3,5) = n\,\kappa\,R\,\Delta\Phi$

  $p_T\,(n=1,3,5) = 2\,\kappa\,R\,|\,\sin(\,n\,\Delta\Phi/2\,)\,|$

  $m = \mathrm{sqrt}\,(\,E_T^2 - p_T^2\,)$

2 parameters to constrain :

κR, $\Delta\Phi$

Best fit of the pion ground state properties in the quantized helix string model

Phys.Rev.D89,015002(2014)
arXiv:1309.6761

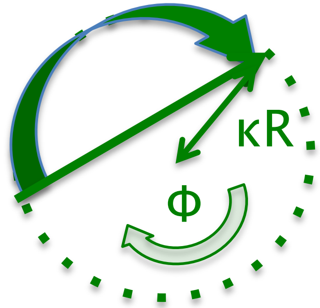
$\kappa\xi$ [MeV]	κ R [MeV]	$\Delta\Phi$
192.5 ± 0.5	68 ± 2	2.82 ± 0.06

meson	PDG mass [MeV]	model estimate [MeV]
π	135 - 140	137
η	548	565
η'	958	958

TABLE I. Best fit of the parameters of the pion ground state obtained from the mass spectrum of light pseudoscalar mesons. The η mass is reproduced within a 3% margin which serves as the base of uncertainty for $R, \Delta\Phi$ parameters.

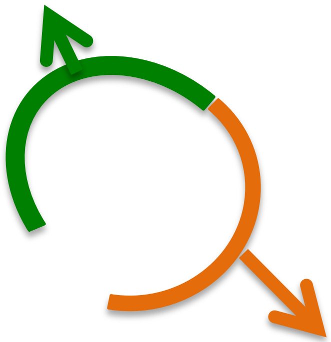
Model predictions for
κR ≈ 68 MeV
ΔΦ ≈ 2.8 rad

I/ lightest hadron/ground state pion :



$$|\, p_T \,|_{n=1} = 2\kappa R \sin(\Delta\phi/2) \sim 134 \text{ MeV}$$
$$m_T = \kappa R\, \Delta\Phi \sim 192 \text{ MeV}$$

II/ pion chains : correlations in the transverse plane



adjacent direct pions $Q = \sqrt{-(p_i - p_{i+1})^2} \approx |\, p_{Ti} - p_{Ti+1} \,|$
$\approx 2\, p_T^{n=1}\, |\sin(\Delta\Phi/2)| \sim 266 \text{ MeV}$

-> ***<u>a threshold momentum difference for adjacent pions</u>***

pions with rank difference r=2 :
$Q = p_T^{n=1}\, |\sin(r\,\Delta\Phi/2)| \sim 91 \text{ MeV}$

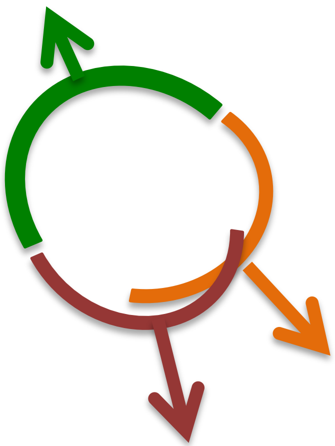


Table 1: The expected momentum difference between hadrons formed by fragmentation of a homogeneous string into a chain of ground-state pions, in the quantized helix string model (see Appendix A). The 3% uncertainty is derived from the precision of the fit of the mass spectrum of light pseudoscalar mesons (π, η, η') [2].

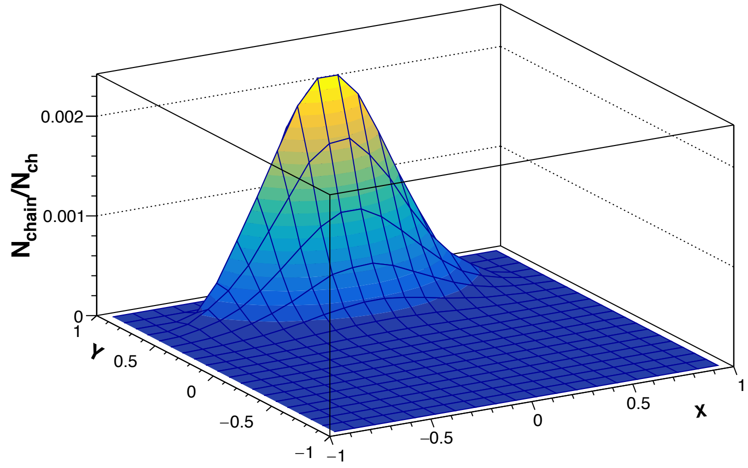
Pair rank difference r	1	2	3	4	5
Q expected [MeV]	266 ± 8	91 ± 3	236 ± 7	171 ± 5	178 ± 5

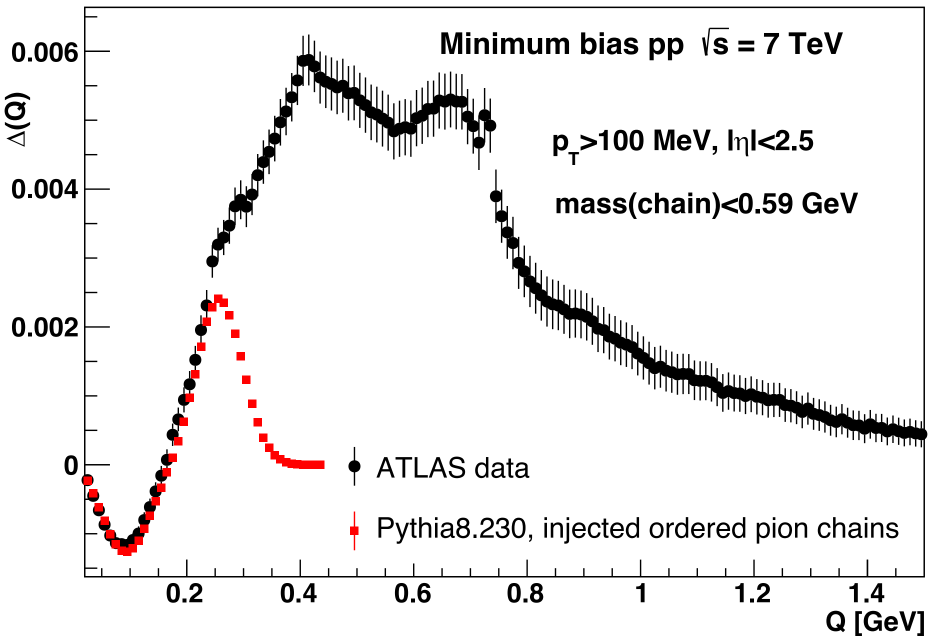
Modelling of quantum effects

arXiv:1801.10232 [hep-ph]

2 ingredients:

- ***correlated pion chains***
- ***enforce Q threshold for adjacent hadrons***





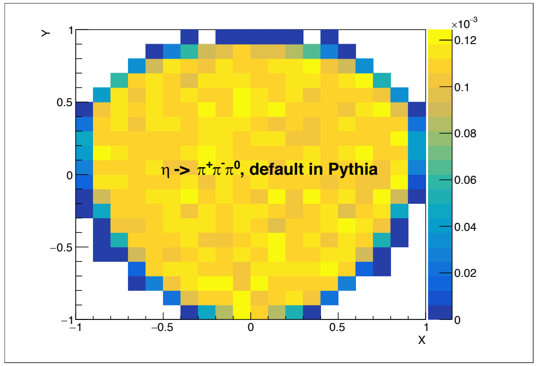
Injection of correlated pion chains trivial

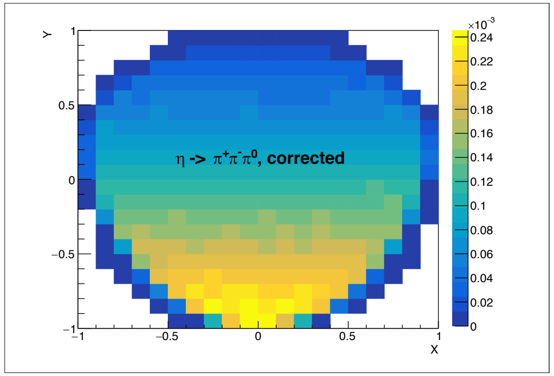
- ***parametrize measured correlated triplets (Dalitz plot)***
- ***inject in the Pythia fragmentation algorithm according to the measured rate***

(~ 0.01 per final charged particle)

Modelling of quantum effects

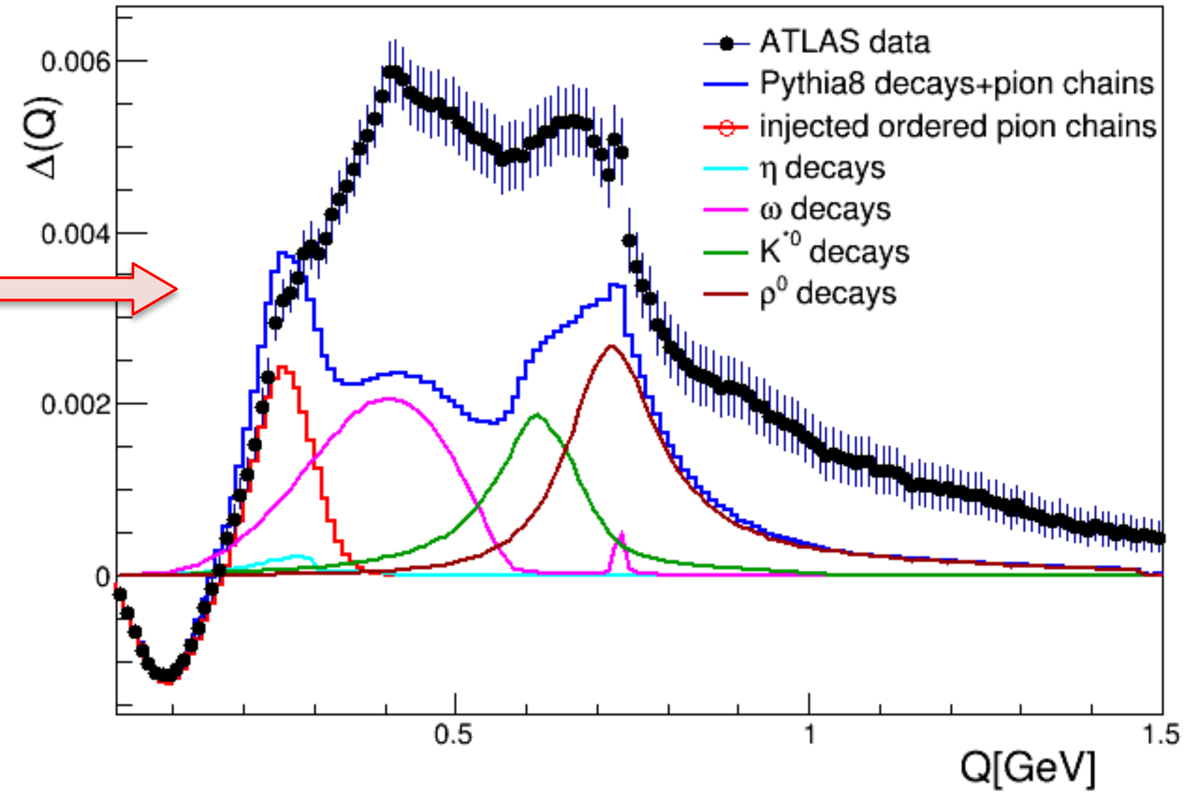
corrected : $\eta \to \pi^+\pi^-\pi^0$ decay   JHEP 05, 006 (2008)





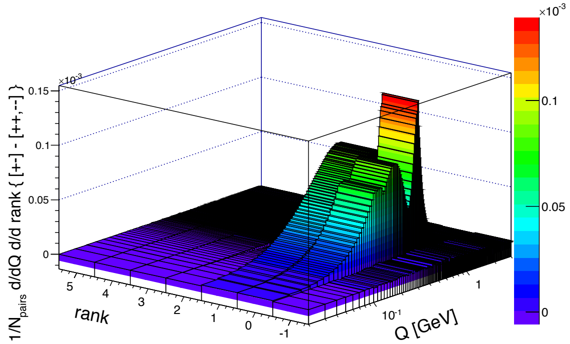
Chains of direct pions

+ decays of unstable hadrons (rank 0 pairs)



Double–counting of $\pi^+\pi^-$ pairs in chains and η/ω decay ?

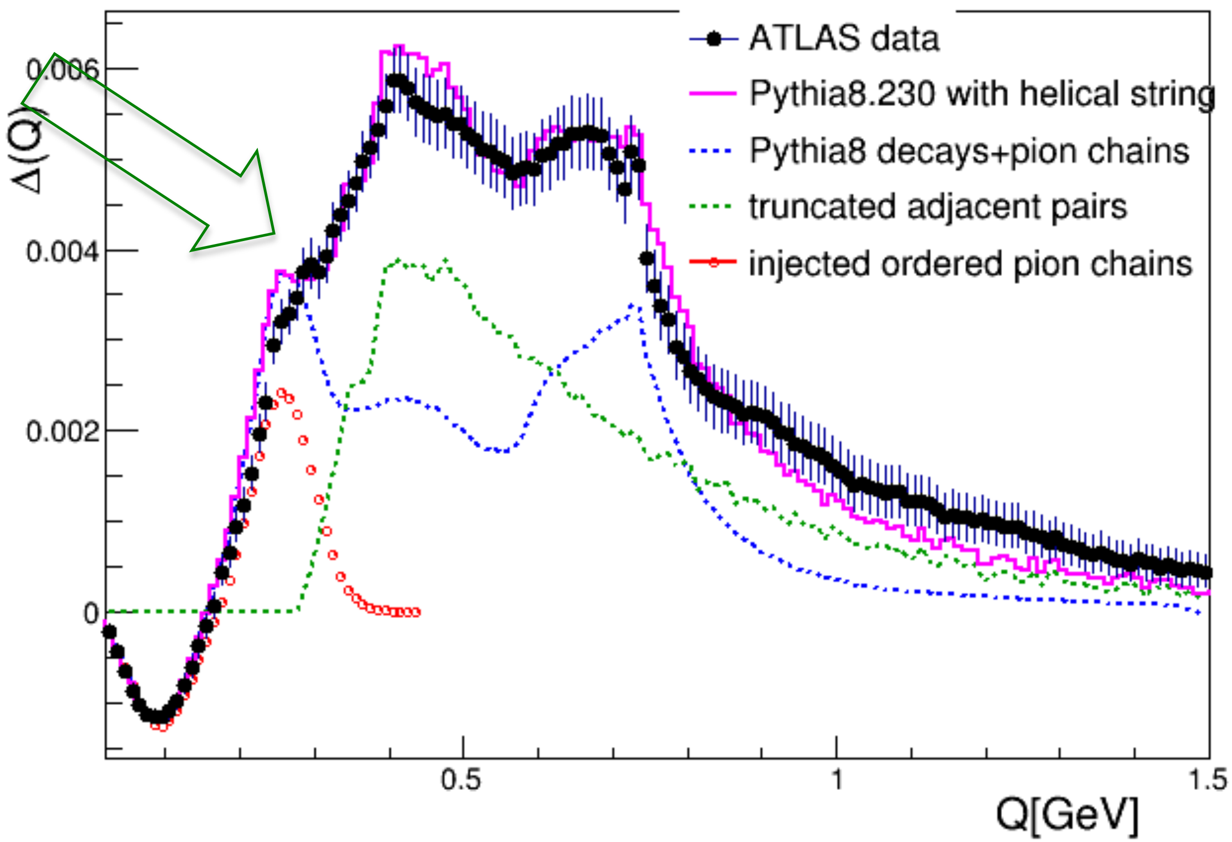
Modelling of quantum effects



Chains of direct pions + decays of unstable hadrons (rank 0 pairs)
+ adjacent hadrons (rank 1 pairs)

Q threshold applied (veto)
Driven by polarization effects in decay of charged unstable hadrons ($\rho^{+,-}$, K^*) ?

Here adjusted "by hand" but in principle, everything can be measured independently - no additional free parameters

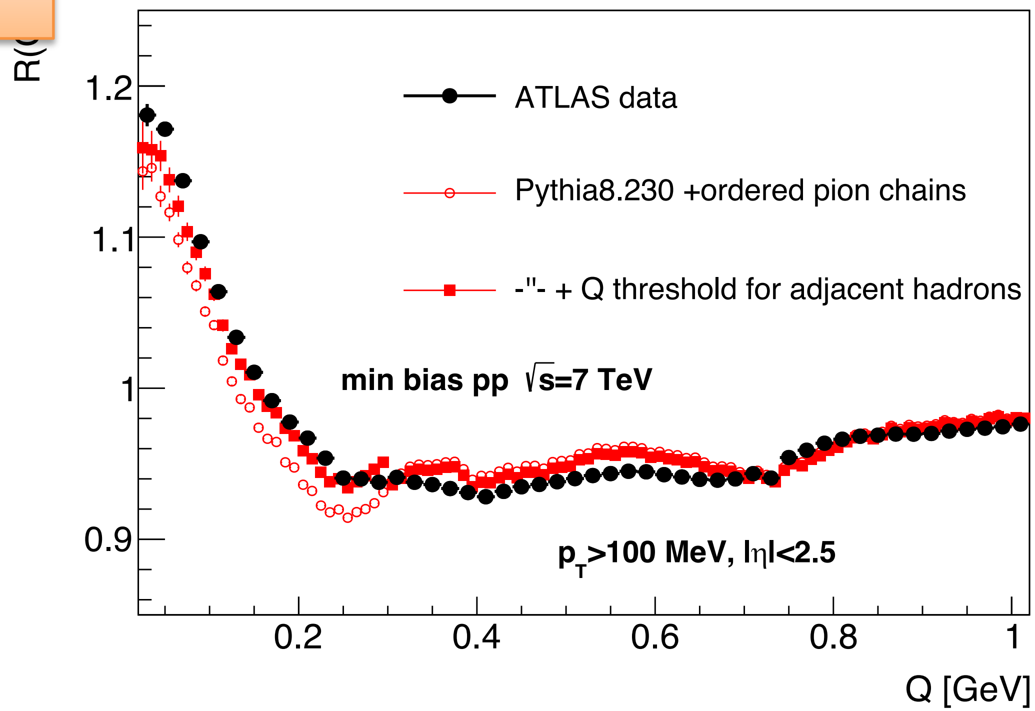


Modelling of quantum effects

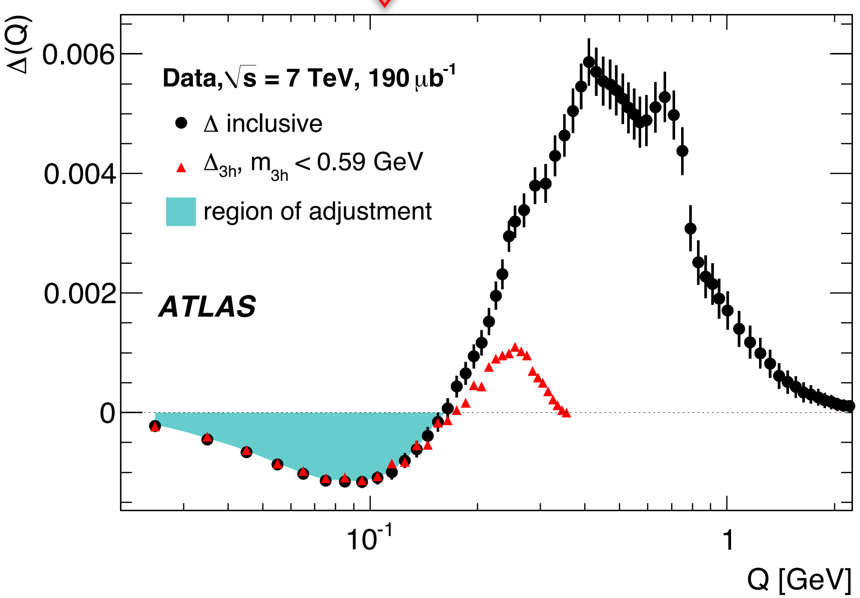
"Bose-Einstein effect" simulated :

the traditional correlation function

$R(Q) = N^{++,--}(Q) / N^{+-}(Q)$



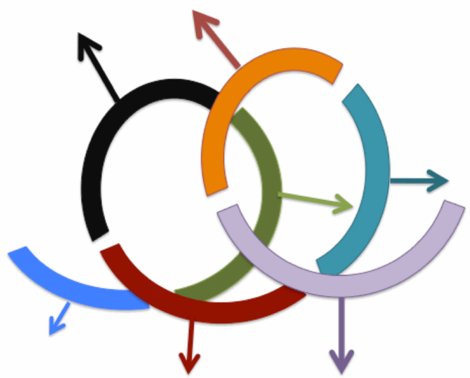
the input 2-particle spectra are identical



... but as a side effect of correlations between adjacent pions

... fully described by the quantized fragmentation of the helical QCD string. No free parameters needed.

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



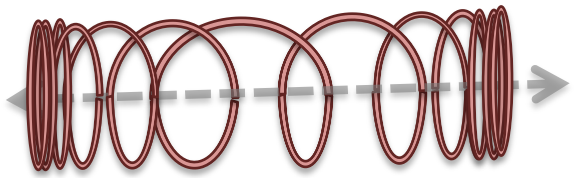
The helix-like shape structure of the QCD field should be visible in the azimuthal ordering of hadrons along the string

The exact form of the helix structure not predicted.

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

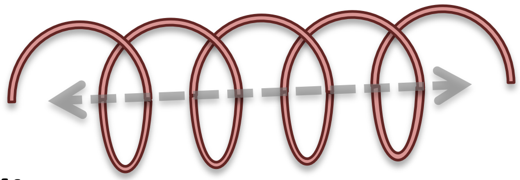
A/ ΔΦ ~ Δη

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



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

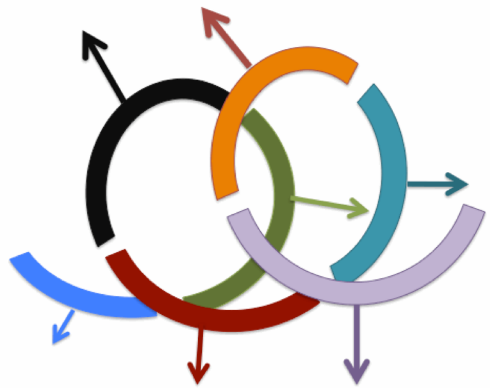
$$S_E(\omega) = \frac{1}{N_{ev}} \sum_{event} \frac{1}{n_{ch}} \left| \sum_j \exp(i(\omega X_j - \phi_j)) \right|^2$$



Search for resonant behaviour -> density of helix winding

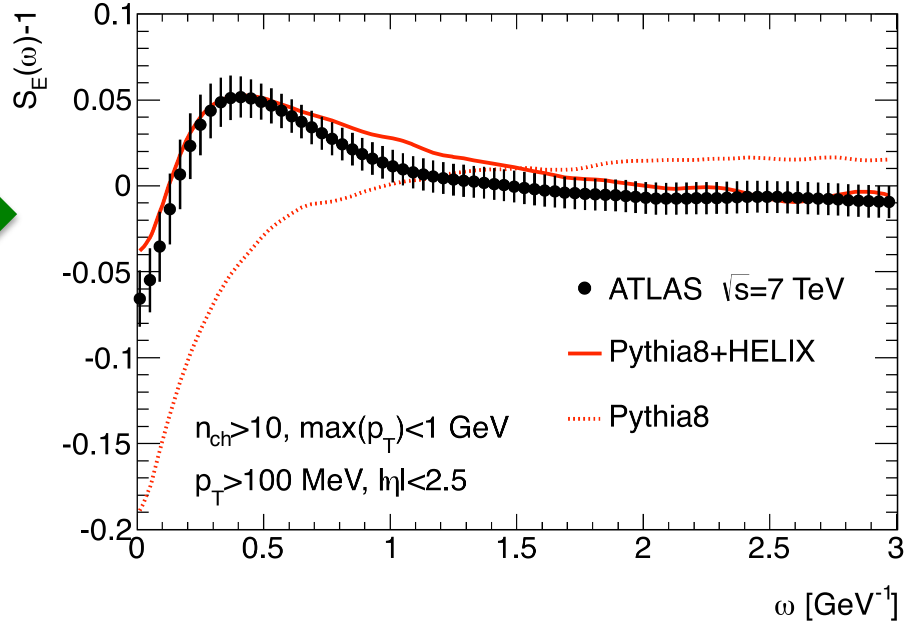
Azimuthal ordering

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



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

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



Comparison with model in Phys.Rev.D86,034001(2012)

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