Quantized fragmentation of 3-dim QCD string

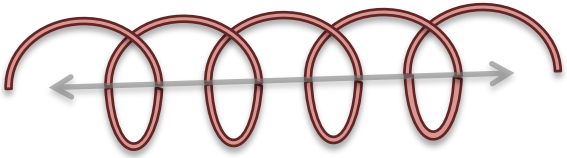
(Šárka Todorova-Nová, Charles University, Prague)

- ***follow-up of my talk at ISMD 2015***

- ***replacing 1-dim Lund string (PYTHIA/JETSET,) by a helix***

B.Andersson et al.: "Is there a screwiness at the end of partons showers ?

Phys. Rept. ***97, 31 (1983)391***



JHEP09(1998)14

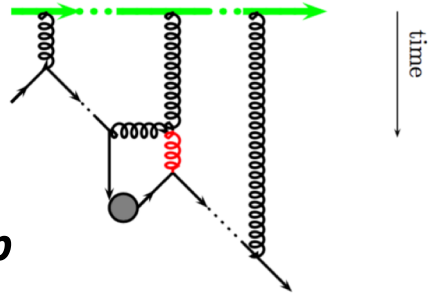
Common points :

- ***confinement modeled by (tangential) string tension κ (~1GeV/fm)***
- ***string breaks via g -> $q\bar{q}$***

Differences :

- ***intrinsic p_T added « by-hand » for 1-dim string***
- ***breakup points defining hadron in 1-dim string scheme are - by construction – causally disconnected <-> hadron masses are external parameters of the model***

3-dim string allows to establish a causal link between breakups



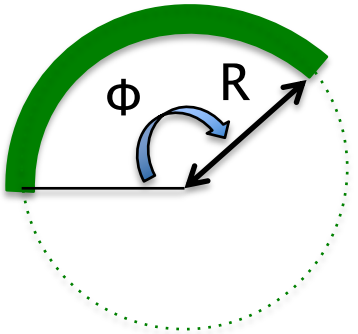
Case A : information about string breakup propagates along the string

-> (massless) quark propagating along the string triggers the next breakup

-> transverse and longitudinal momentum components decouple

$$\vec{p}_T = \kappa R \int_A^B \exp i(\Phi \pm \pi/2) d\Phi$$
$$= 2\kappa R \sin\frac{\Phi_B - \Phi_A}{2} \exp i(\frac{\Phi_A + \Phi_B \pm \pi}{2}),$$
$$m_{AB} = \kappa R \sqrt{(\Phi_B - \Phi_A)^2 - (2\sin\frac{\Phi_B - \Phi_A}{2})^2}.$$

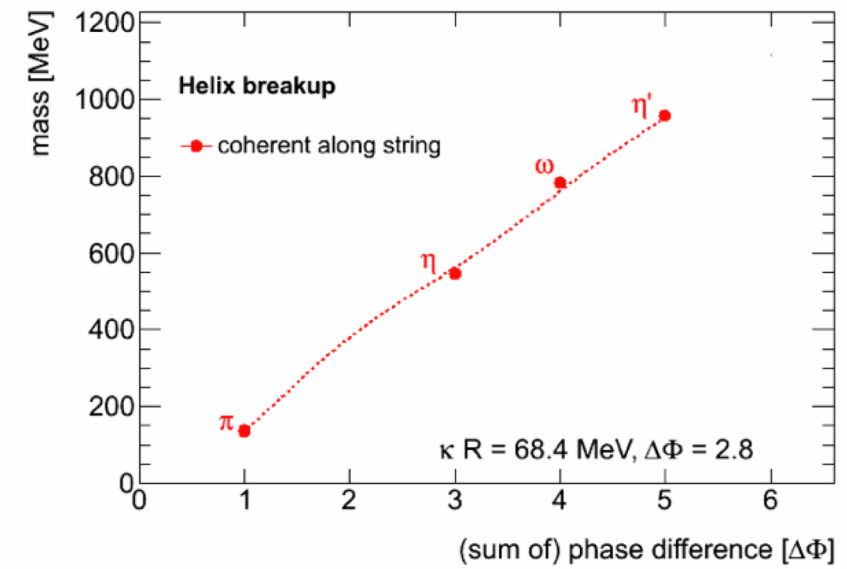
helical string parametrized by radius R and phase Φ



Hadron mass driven by
the string topology in the transverse plane
- derived quantity, no longer a parameter

Deployment of the causal constraint
reveals the quantized nature
of hadron formation Φ_{AB} -> n $\Delta\Phi$

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



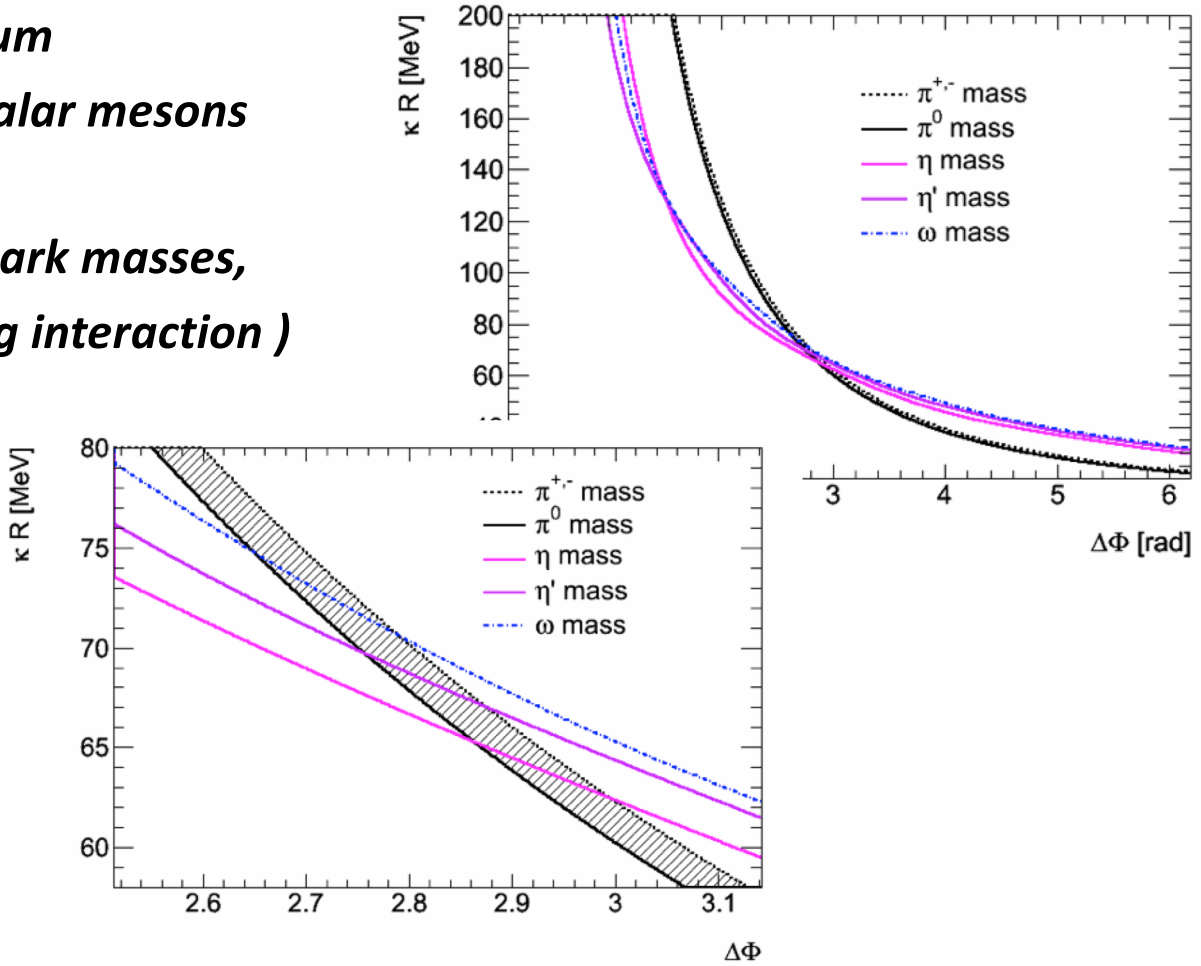
Phys.Rev.D89(2014) 015002

3-dim string allows to establish a causal link between breakups

Case A : information about string breakup propagates along the string

String parameters (κR , $\Delta\Phi$)
constrained by mass spectrum
of - for example – pseudoscalar mesons

Model not complete (no quark masses,
no detailed description of qg interaction)
-> intrinsic precision ~ 3 %



κR ~ 0.07 GeV
$\Delta\Phi$ ~ 2.8 rad

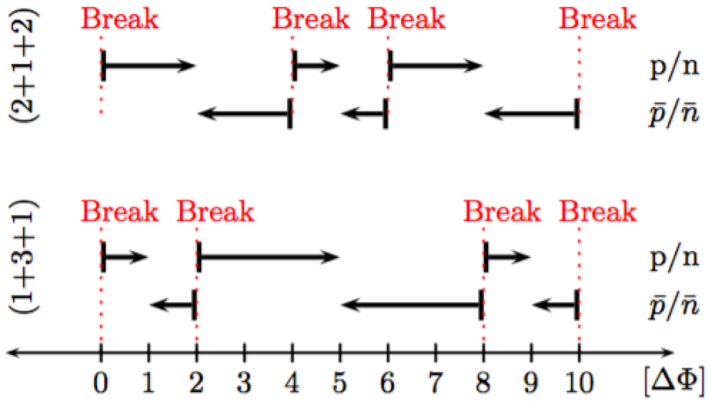
3-dim string allows to establish a causal link between breakups

Case B : information about string breakup propagates across string loops

-> baryon formation

arXiv:2103.05269[hep-ph]

Nucleons (p,n) are n=5 states



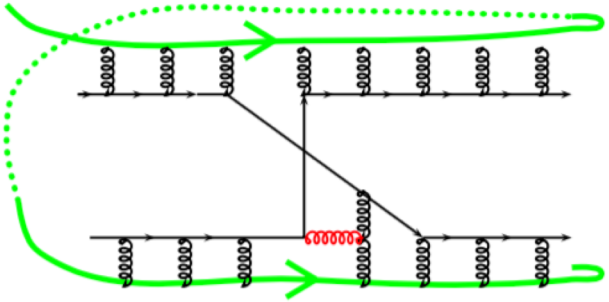
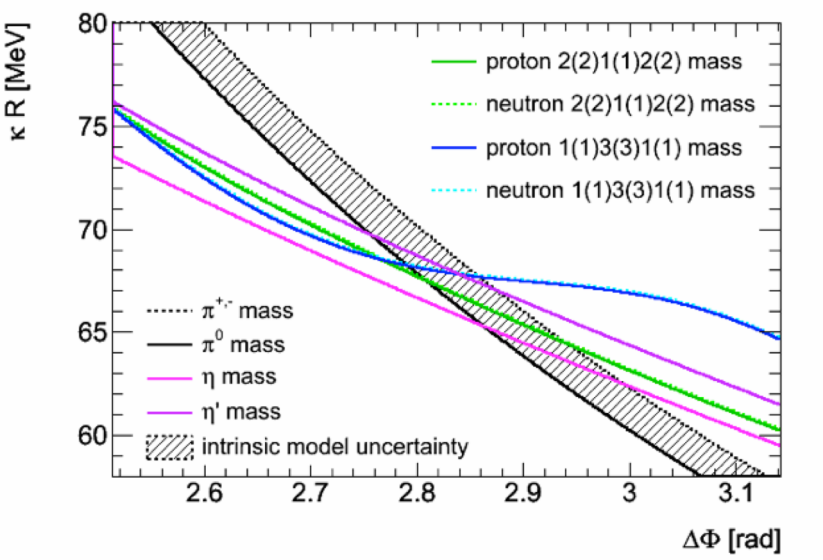


FIG. 3. Schema of correlated(induced) string breakup across string loops. Green band indicates the color flow ordering of the gluon ladder. Excited gluon – which splits promptly into a $Q\bar{Q}$ pair – is marked in red.

Nucleons naturally fit in the model of quantized fragmentation of helical QCD string when cross-talk between string loops allowed



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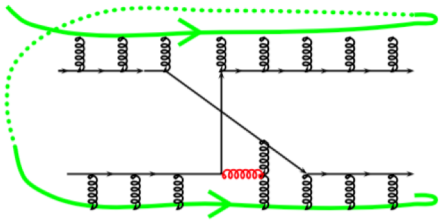

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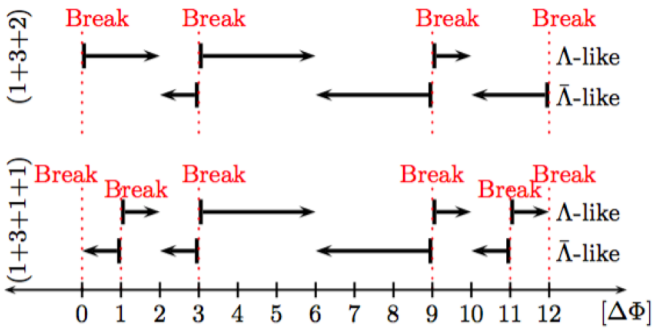
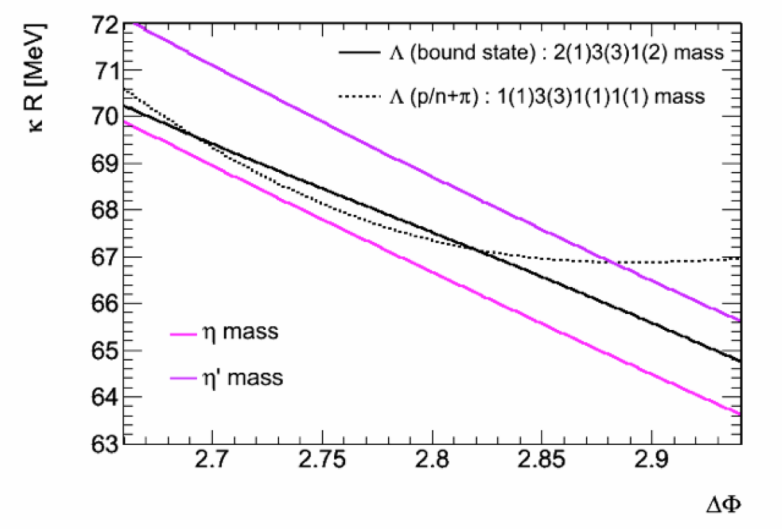
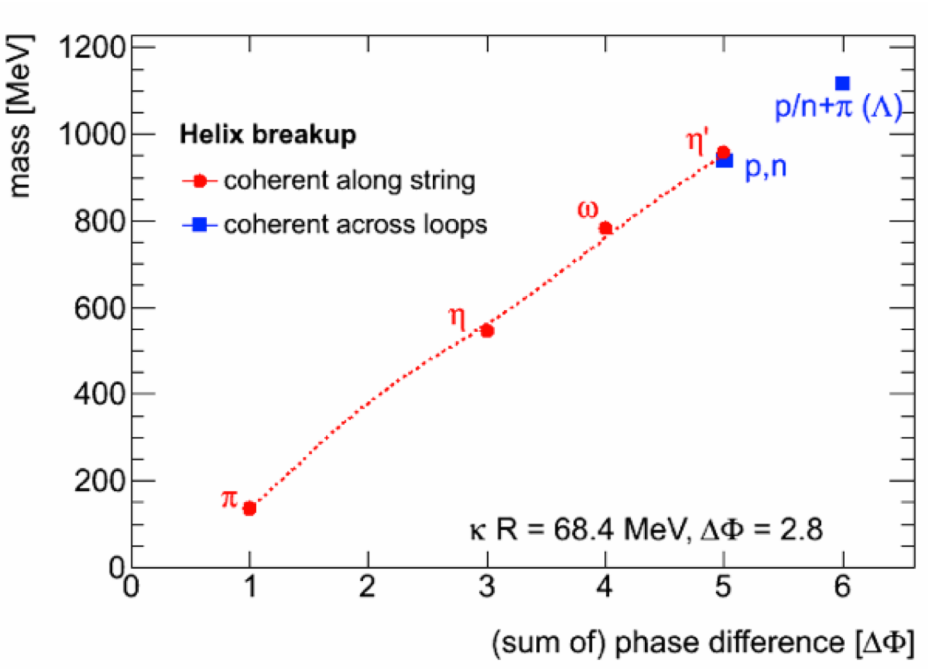
Case B : information about string breakup propagates across string loops -> baryon formation

Idem for Λ – like state n = 6

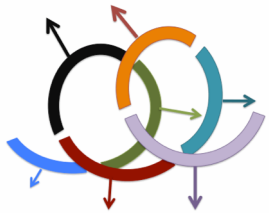




both bound and unbound state (p+n) fits well the quantization scheme within 3% precision allowance (no s-quark involved)



Model of helical string overconstrained , plenty of observables …



… hadron masses, intrinsic p_T, correlations between adjacent hadrons ….

Predicted momentum difference between (colour ordered) direct pions, for helical string with constant pitch

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

-> threshold-like correlation between adjacent (opposite-sign,OS) pion pairs

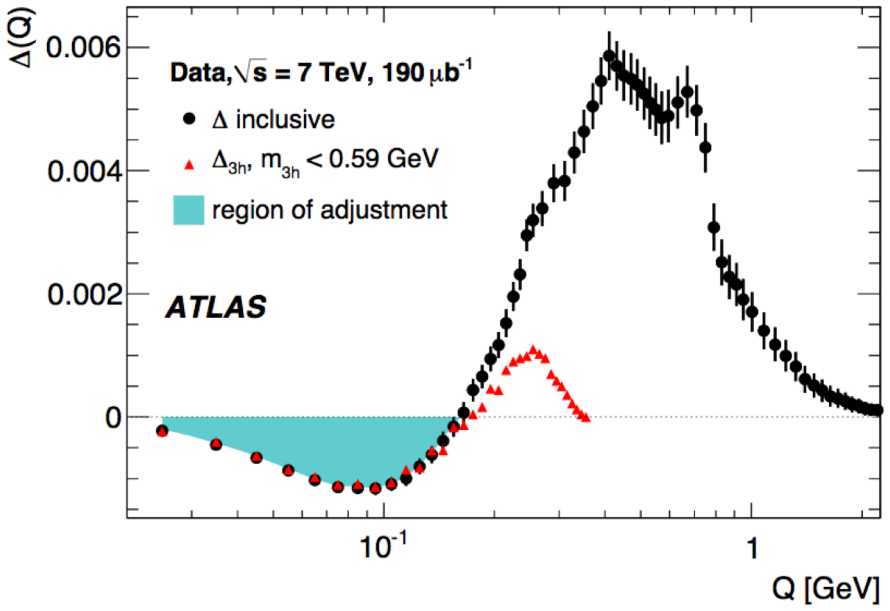
-> low Q dominated by rank 2 (like-sign,LS) pion pairs ?

Phys.Rev.D96(2017) 092008

Studied by ATLAS with help of difference between OS and LS spectra

$$\Delta(Q) = \frac{1}{N_{ch}} [\, N(Q)^{OS} - N(Q)^{LS} \,]$$

Source of anomalous production of close LS pairs isolated by selecting charge-ordered hadron chains (+-+,-+-) via mass minimization (Δ_{3h} , see backup)



In Rivet: ATLAS_ 2017_I1624693

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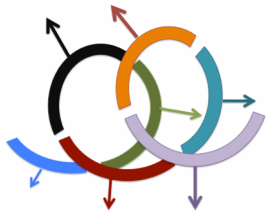

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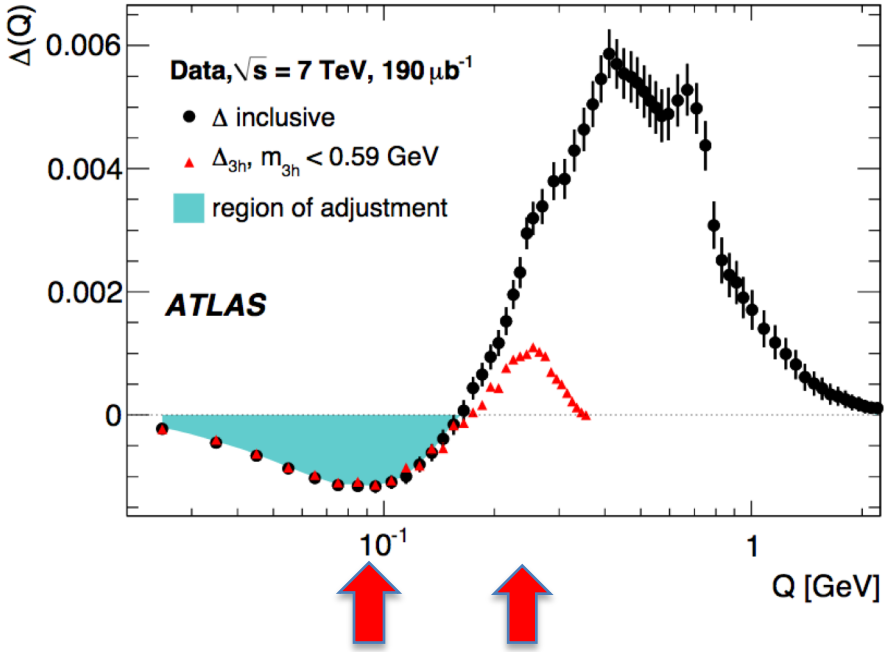

$Q(r) = 4\kappa R \sin(\Delta\Phi/2)\, |\sin(r\Delta\Phi/2)|$

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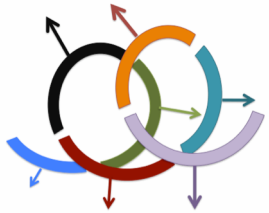
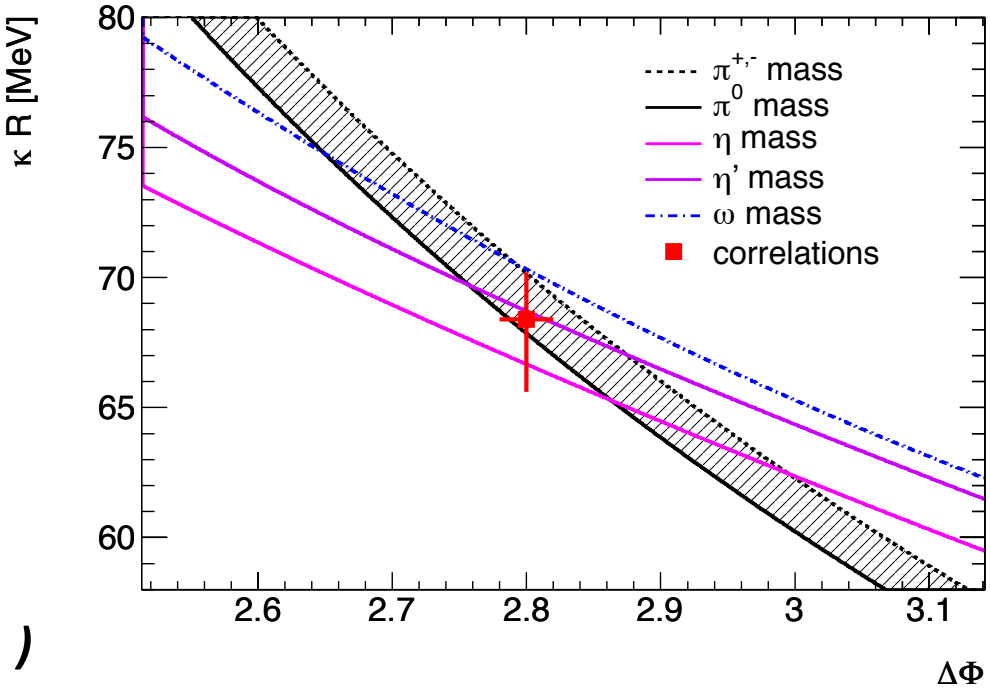


Study of ordered hadron chains provides an independent measurement of string parameters.

ΔΦ measured with precision of 1%

Quantized fragmentation explains the entire anomalous production of close LS pairs, (previously incorrectly attributed to BEC)



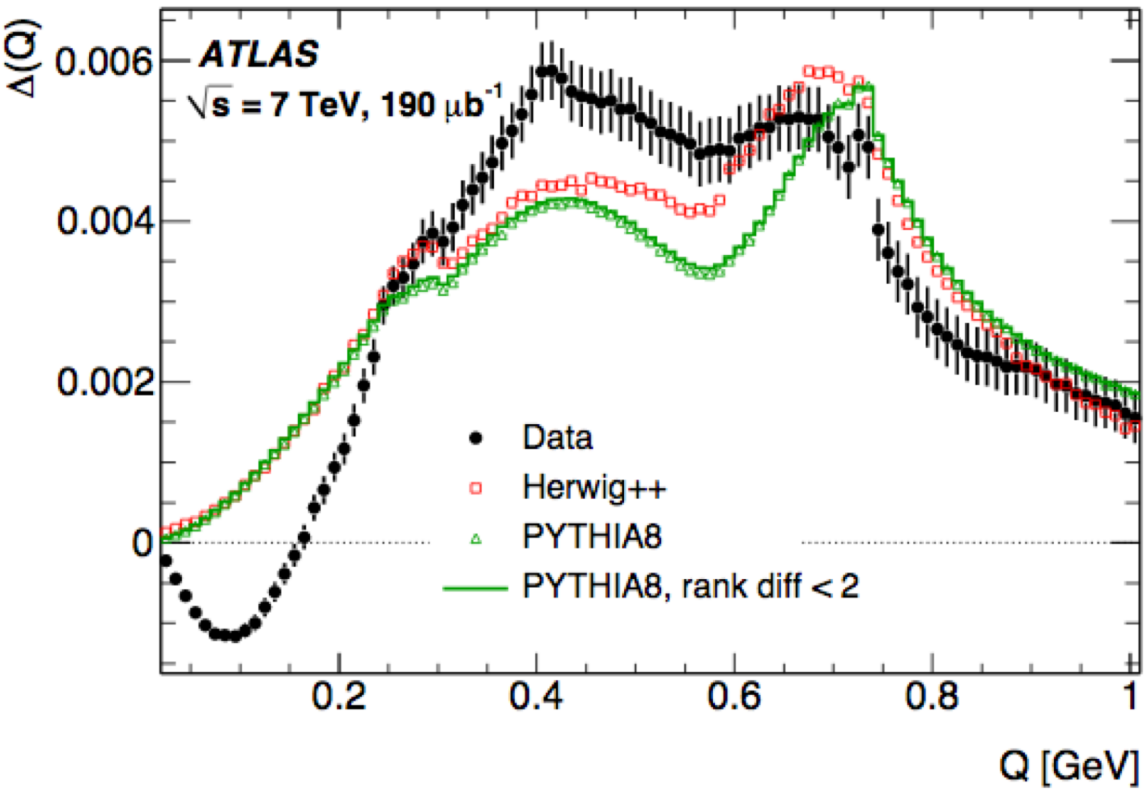
More results coming soon from the analysis of Run2 data in ATLAS (pp & HI).

It's not just BEC we have a problem with…..

Phys.Rev.D96(2017) 092008

Δ observable is an ideal candidate for a benchmark evaluation of hadronization models : provides (inclusively) the same information we would obtain from colour-adjacent hadrons with a perfect knowledge of colour flow in the event (about jet substructure, among other).

Very poorly described by conventional models (string & clusters alike). Worse still, models converge between themselves, far from data – we have no tool to properly estimate the hadronization systematics.



The absence of correlations between adjacent hadrons is possibly the dominant source of discrepancies here. 3-dim QCD string allows to address the issue.

Model of helical QCD string alive and kicking : a lot of material to process both in the experiment and in the phenomenology

Hadron content & production mechanism
- **intrinsic p_T & correlations**

Parton shower & fragmentation function
- **jet & inclusive spectra**

long ordered hadron chains
<-> long range corrrelations

heavy quarks & glueballs

implications for QFT

The most natural explanation for the quantization is a limited number of gluons in the field (as few as two per $\Delta\Phi$?)

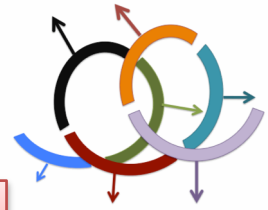
- ✓ ***quantized fragmentation wipes away the sea of non-perturbative gluons***
- ✓ ***QCD vacuum becomes sparsely populated and well ordered***

THIS WAS THE GOAL OF « SCREWINESS » PAPER, at the origin of helical string

- full parton shower without collinear divergencies
- dynamic model of proton (as system of 3 quarks + 8(9) gluons) } ***feasible ?***

backup slides

Source of « Bose-Einstein correlations « (BEC)

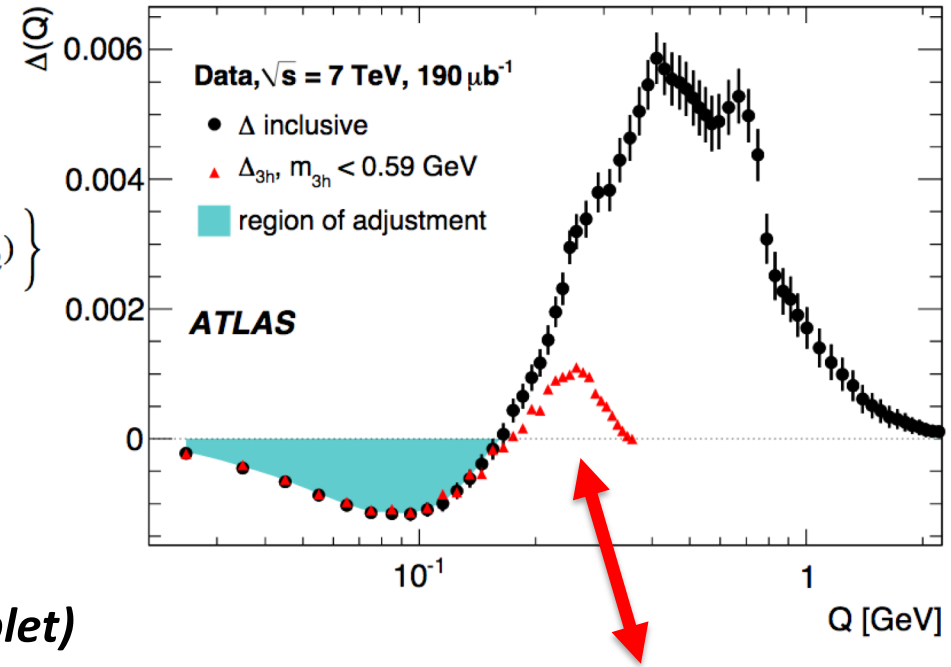


Phys.Rev.D96(2017) 092008

Rivet: ATLAS_ 2017_I1624693

- *excess of close LS pairs correlates with the presence of correlated +-+, -+- triplets consistent with chains of adjacent direct pions*

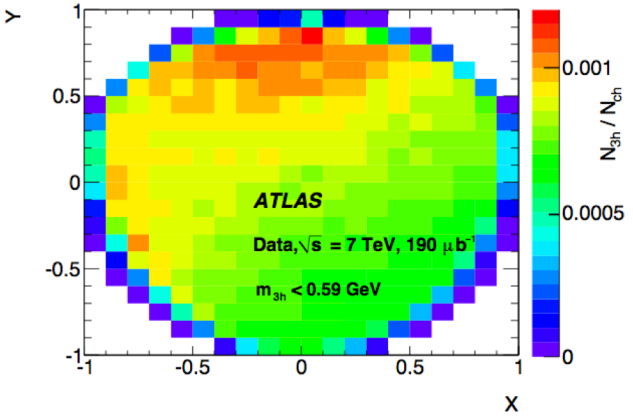
$$\Delta_{3h}(Q) = \frac{1}{N_{ch}} \sum_{k=1}^{N_{ev}} \sum_{i=1}^{n_{ch}^k} w_i \left\{ \frac{1}{2}\,\delta(Q - Q_{01}^i) + \frac{1}{2}\,\delta(Q - Q_{12}^i) - \delta(Q - Q_{02}^i) \right\}$$

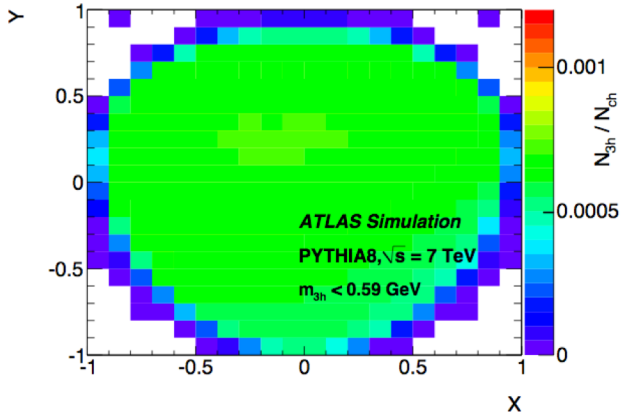


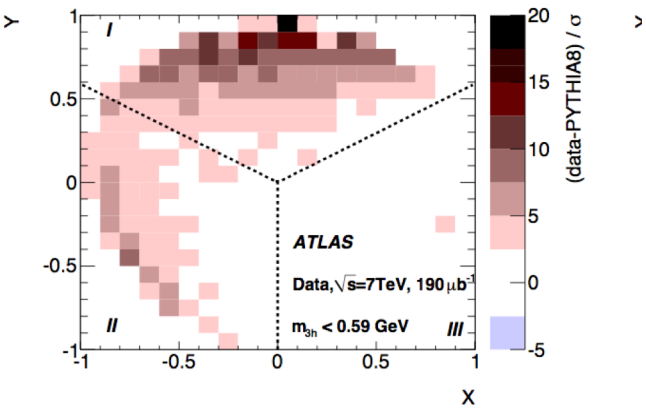
Measured also via Dalitz plot

$$X = \sqrt{3}\,\frac{T_0 - T_2}{\Sigma_{i=0}^2 T_i}, \qquad Y = \frac{3T_1}{\Sigma_{i=0}^2 T_i} - 1,$$

(T_i kinetic energy in the rest frame of triplet)







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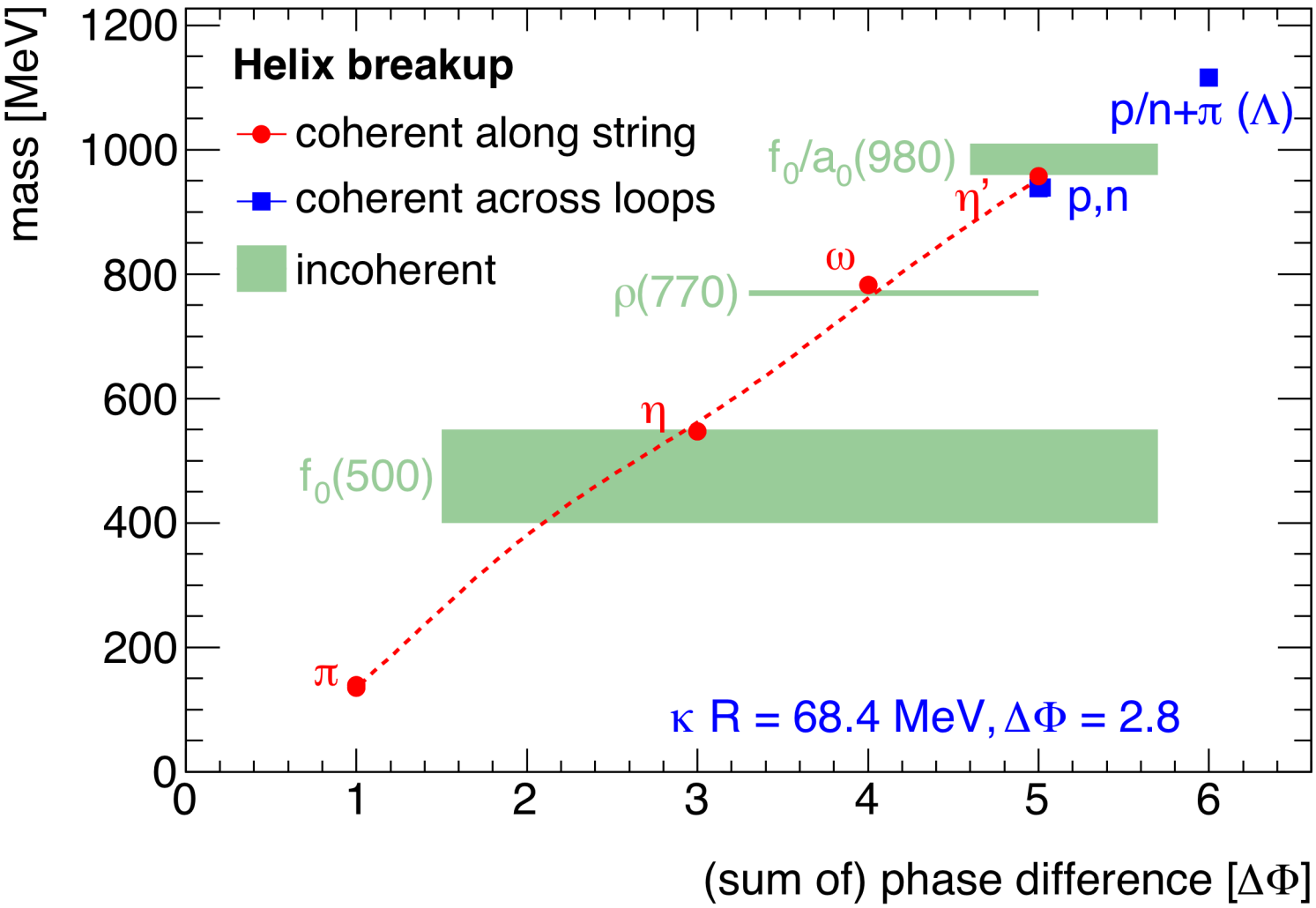

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Possibility to further cross-check model predictions and/or distinguish different production modes.

Requires knowledge of string direction
(LEP : pencil-like events
LHC : soft minimum bias events)

TABLE I. Model prediction for intrinsic transverse momentum of direct hadrons, for measured (Appendix A) string parameters.

hadron	production mode	quantized content [$\Delta\Phi$]	p_T [MeV]
π	induced, light-front	1	135 (+4,-6)
η	induced, light-front	3	119 (+3,-5)
ω	induced, light-front	4	86 (+2,-4)
η'	induced, light-front	5	90 (+3,-4)
p,n	induced, across loop	1+2+2	206 (+6,-9)
p,n	induced, across loop	2+1+2	135 (+4,-6)
p,n	induced, across loop	1+3+1	172 (+5,-7)
Λ	induced, across loop	1+3+2	208 (+6,-9)

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