Helix string fragmentation
and
charged particle measurements with ATLAS

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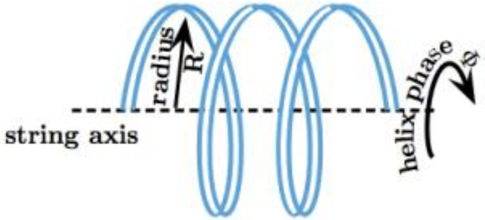
idea

the correlation between like-sign (LS) hadrons is consequence of coherent hadron emission
linked to attempt to understand the shape of a QCD string in 3d and stabilization of the end of the parton shower cascade: B. Andersson, G. Gustafson, J. Hakkinen, M. Ringner and P. Sutton, "Is there screwiness at the end of the QCD cascades?" **JHEP 09 (1998), p. 014**

it was deduced, on the basis of optimal packing of non-collinear gluon emissions, that the shape of the QCD string should be, at the end, helix-like



one dimensional string -> 3d string & quantum tunneling -> gluon splitting to quark-antiquark pair

fragmentation generates intrinsic transverse momentum that depends on the folding of the string and **implies azimuthal correlations between hadrons**

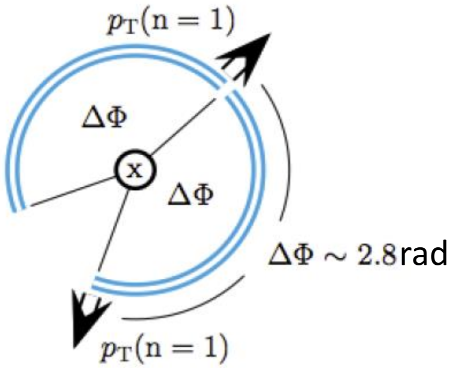
azimuthal correlations compatible with the helical shape of the QCD string have been observed by ATLAS **Phys. Rev. D 86, 052005, 2012**

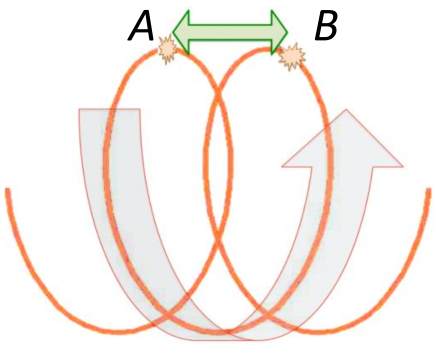
the helix model was refined in Š. Todorova-Nová, "Quantization of the QCD string with a helical structure", **Phys.Rev. D89902 (2014) 015002** & "Baryon production in the quantized fragmentation of helical QCD string", **Phys.Rev. D104 (2021) 034012**

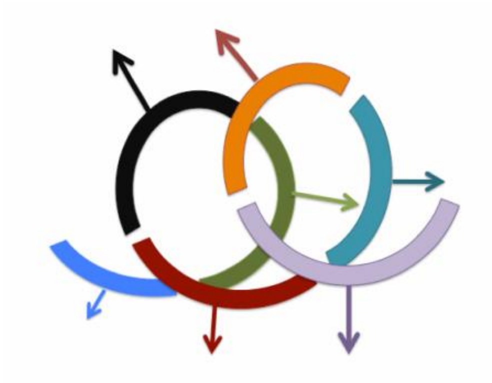
string fragmentation

Phys. Rev. D 89 (2014), p. 015002

3d fragmentation model enables cross talk between break-up vertices; causal constraints imposed on the fragmentation, the mass spectrum of light mesons is reproduced, if string breaks in **regular multiple of ΔΦ** intervals







a fit of mass spectrum **predicts** rather narrow radius of the helix, κR = 68±2 MeV, where κ ~ 1 GeV/fm is the string tension, and ΔΦ = 2.82±0.06 rad, i.e. almost back-to-back

$$m^{AB} = \kappa R \sqrt{(\Phi^B - \Phi^A)^2 - \left(2\sin\frac{\Phi^B - \Phi^A}{2}\right)^2}$$

$$= \kappa R \sqrt{(n\Delta\Phi)^2 - \left(2\sin\frac{n\Delta\Phi}{2}\right)^2}$$

$\kappa\xi$ [MeV]	κ R [MeV]	ΔΦ
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

for the definition od kinematics variables – see backup

rank and anomalous production of LS pairs

$$Q(p_i, p_j) = \sqrt{-(p_i - p_j)^2} = 2p_\mathrm{T}\left|\sin\frac{r\Delta\Phi}{2}\right|$$

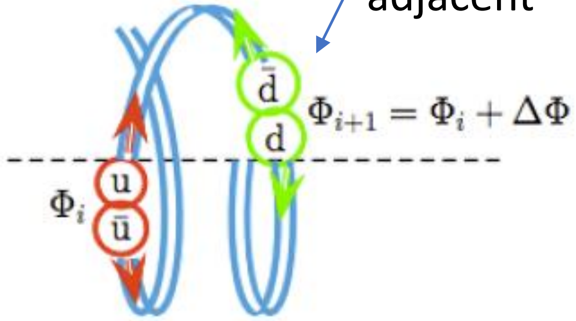
where p_i, p_j are 4-momenta of particles in the considered pair

rank variable ***r*** characterizes the relation, due to ordering within the helix, between products

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

calculated in the limit of locally homogeneous string field

adjacent



local charge conservation -> production of pairs of pions with

LS charge for ***r*** = 2, 4, …

and

OS for ***r*** = 1, 3, …

region Q < 100 MeV is occupied by pairs with *r* = 2 -> production of LS pairs – it is the prediction of the model

basic observables

$Q(p_i, p_j) = \sqrt{-(p_i - p_j)^2}$ already defined; note pion mass is assigned to all particles!

$$N^{OS}(Q) = \sum_{k=1}^{N_{ev}} \sum_{i,j=1,i>j}^{N_{ch}^{k}} \delta(q_i + q_j)\delta(Q - Q(p_i, p_j)),$$

$$N^{LS}(Q) = \sum_{k=1}^{N_{ev}} \sum_{i,j=1,i>j}^{N_{ch}^{k}} \delta(q_i - q_j)\delta(Q - Q(p_i, p_j)),$$

$$\delta(x) = 1 - sign^2(x)$$

$$N_{ch} = \sum_{k=1}^{N_{ev}} N_{ch}^{k}$$

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

in hadronic simulation samples generated with Pythia8:

$\Delta(Q)$ reproduces quite well (with precision of ~ 1%) the true distribution of pairs with rank (difference) 0 and 1!

observable sensitive to color flow

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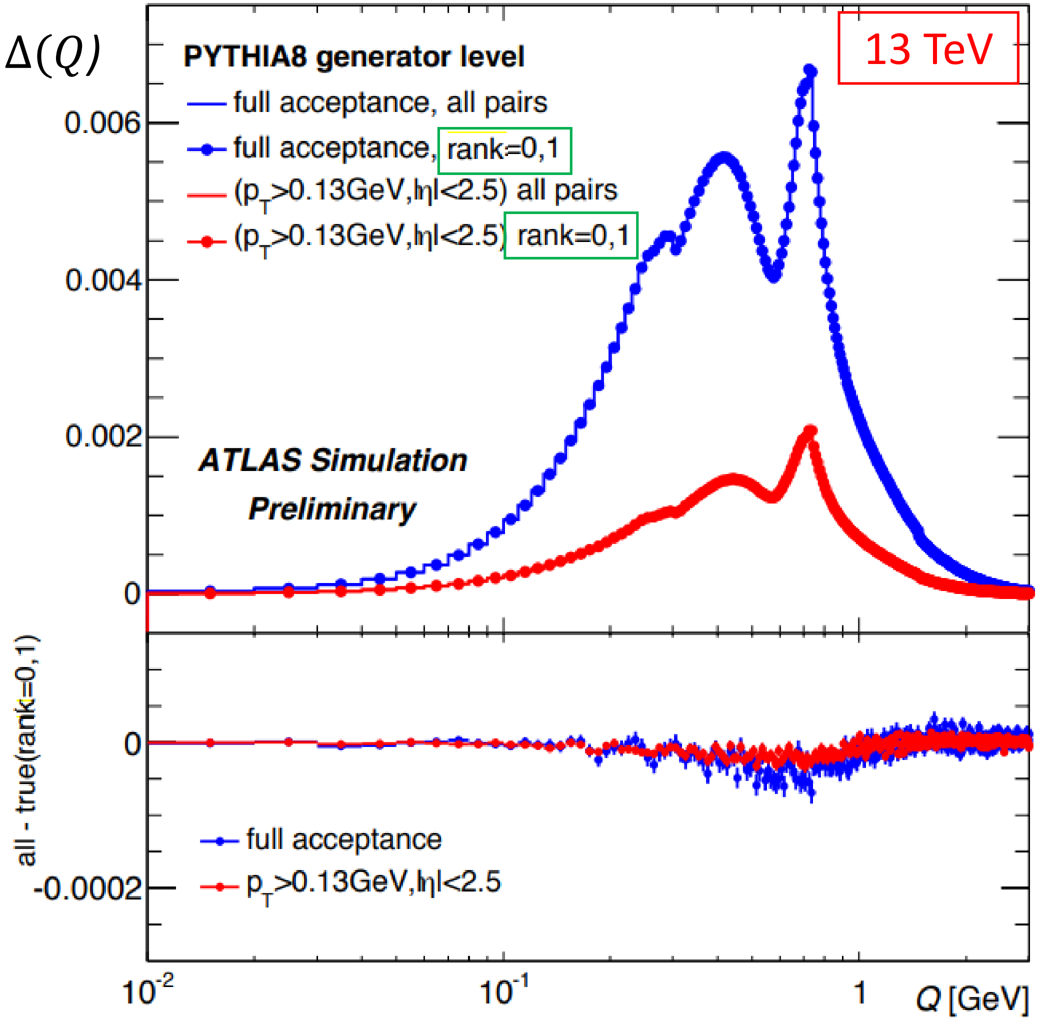
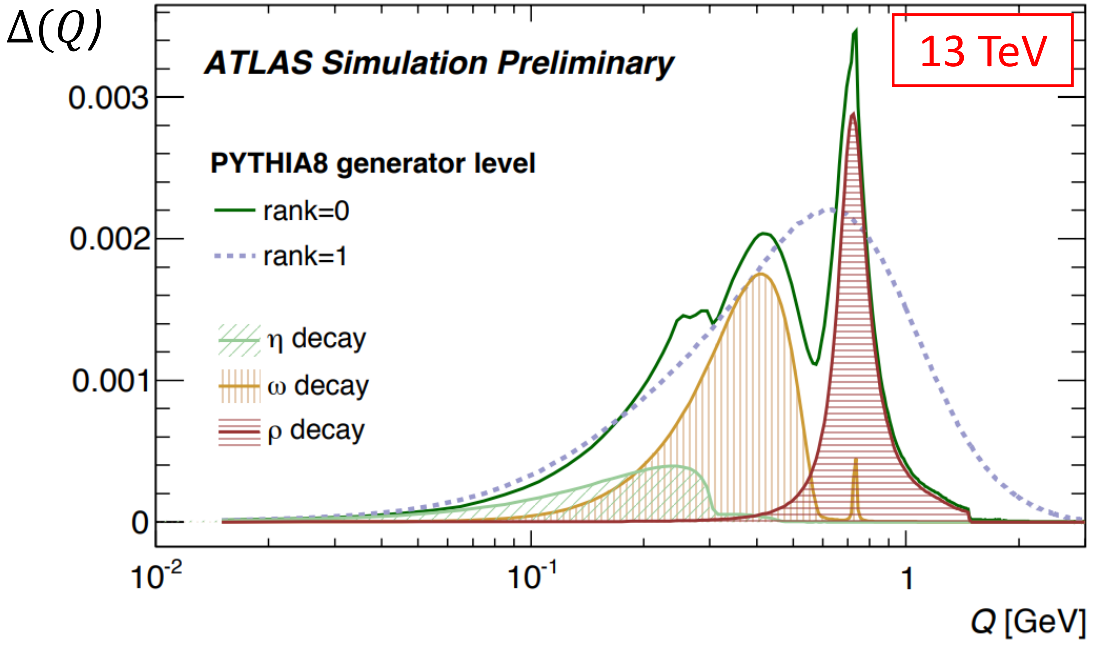




rank 0 describes production of resonances

data and event selection

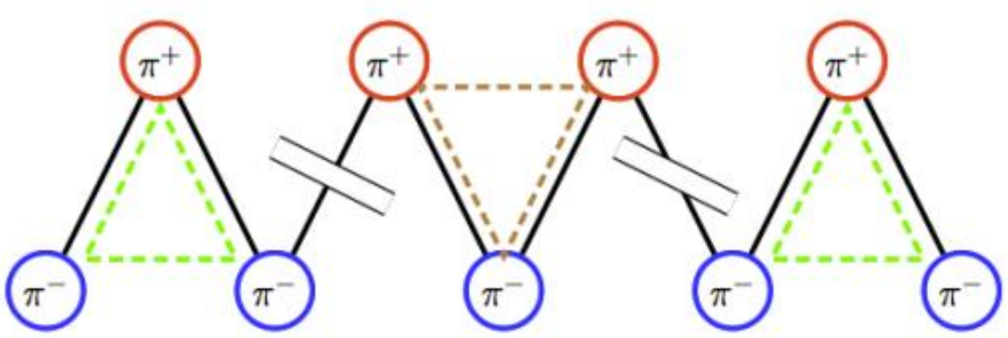
collision system	$\sqrt{s}$	integrated luminosity	$< \mu >$	number of events
pp	0.9 TeV	53.9 pb^{-1}	0.005	4.4×10^6
pp	5.02 TeV	31.4 nb^{-1}	0.47	8.2×10^6
pp	13 TeV	14.0 nb^{-1}	0.003 - 0.321	65.5×10^6
p+Pb	5.02 TeV	0.27 nb^{-1}	0.0002-0.005	18.7×10^6
Pb+Pb	5.02 TeV	19.3 pb^{-1}	0.002 - 0.003	9.3×10^6

- pass a single arm MBTS trigger (if *pp* or *p*+Pb collisions). Pb+Pb events are selected within peripheral collisions, which is defined by a ZDC coincidence at L1 in concurrence with a presence of a reconstructed track at the HLT, and for which a veto is applied on the maximal calorimeter energy deposit. Two complementary configurations are used in the analysis, one with a veto above 50 GeV, the other requiring a minimal deposit of 50 GeV and a veto above 600 GeV. The former reduces the average number of particles per event to value which is comparable with *pp*@13TeV sample.
- have a primary vertex reconstructed with at least two associated tracks,
- not have a second primary vertex reconstructed with more than three tracks,
- have at least three good tracks. for "good track" definition – see backup

definition of $\Delta_{3h,}$ 3h chains

$$\Delta_{3h}(Q) = \frac{1}{N_{ch}} \sum_{k=1}^{N_{ev}} \sum_{i=1}^{n_{ch}^{k}} w_i \left\{ \frac{1}{2}\,\delta(Q - Q_{01}^{i}) + \frac{1}{2}\,\delta(Q - Q_{12}^{i}) - \delta(Q - Q_{02}^{i}) \right\} \qquad w_i(=0,\tfrac{1}{2},1)$$

where each chain contributes with three entries: two for opposite-sign pairs at Q_{01}, Q_{12} and one for the like-sign pair at Q_{02} (the indexes reflect charge-ordering of particles in the chain). The w_i stand for the weight factor of the i-th chain in the event.



the algorithm for the calculation of Δ_{3h} is described in the backup

anomalous production of LS hadrons pairs

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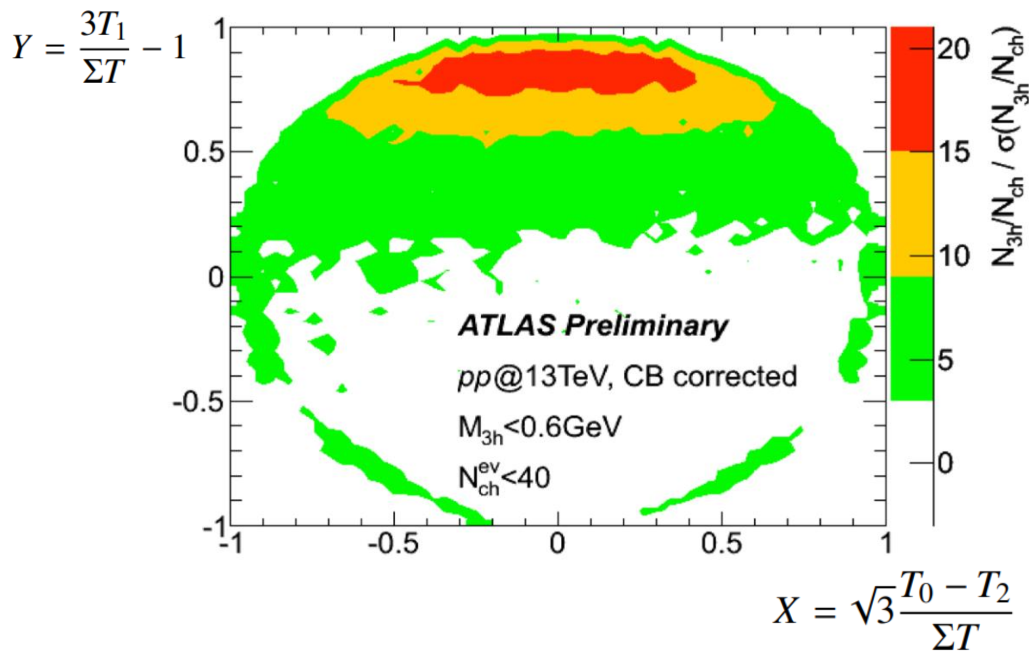

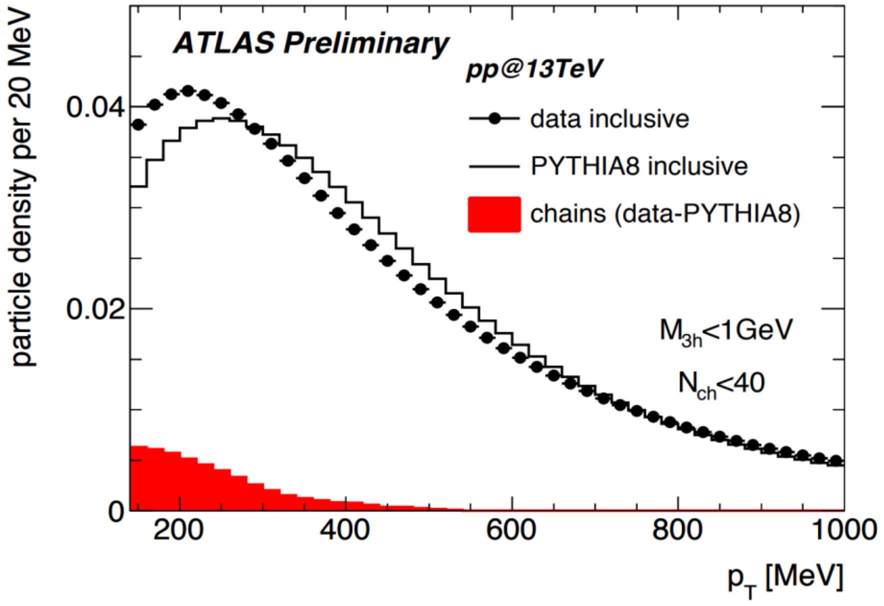

T_i stand for the kinetic energy of charge-ordered particles in the rest frame of the chain (particles 0 and 2 form the LS pair), ΣT runs over the three particles in the triplet; CB – combinatorial background

data consistent with model expectations:

- excess in mass-minimized charge ordered triplet chains observed (Dalitz plot)
- associated with the source of anomalous production of close LS pairs (Δ vs. Δ_{3h})
- associated with the modification of inclusive low p_T spectra (quantized fragmentation predicts intrinsic p_T of a direct pion ~130 MeV)

anomalous production of LS hadrons pairs II

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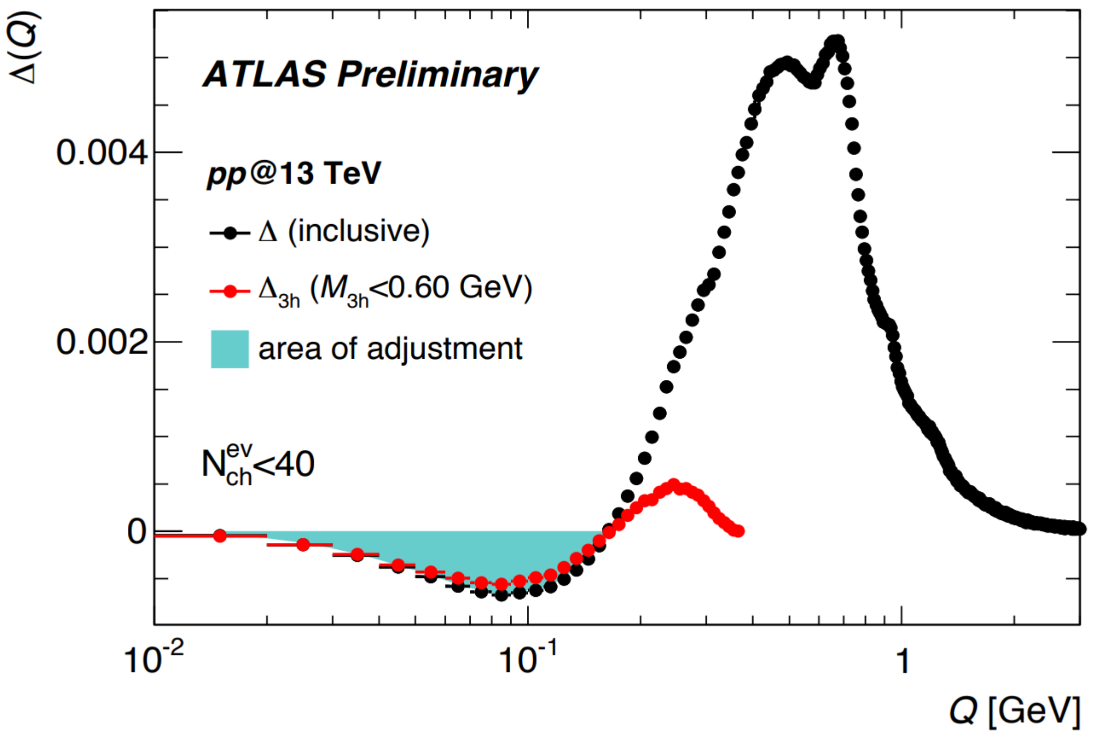
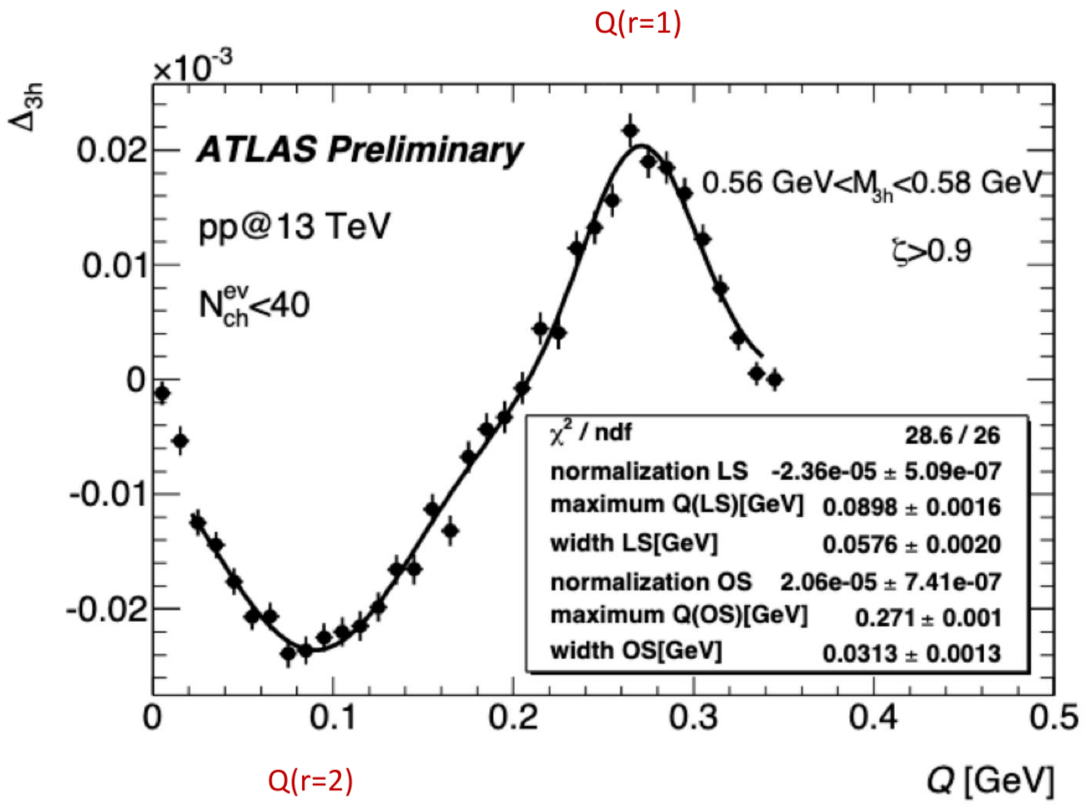
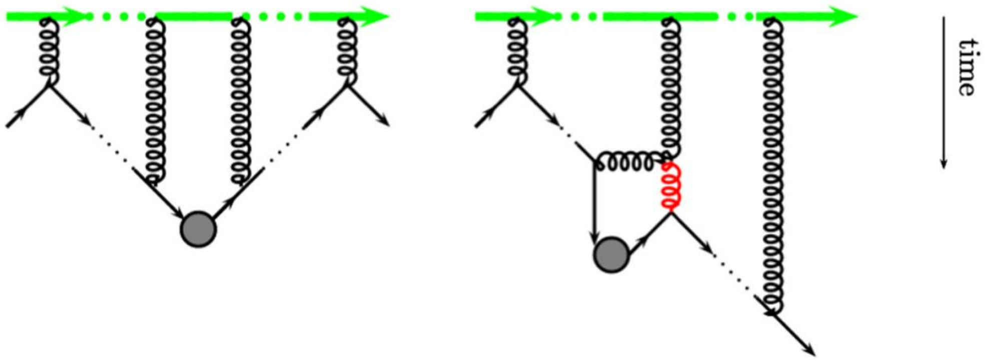




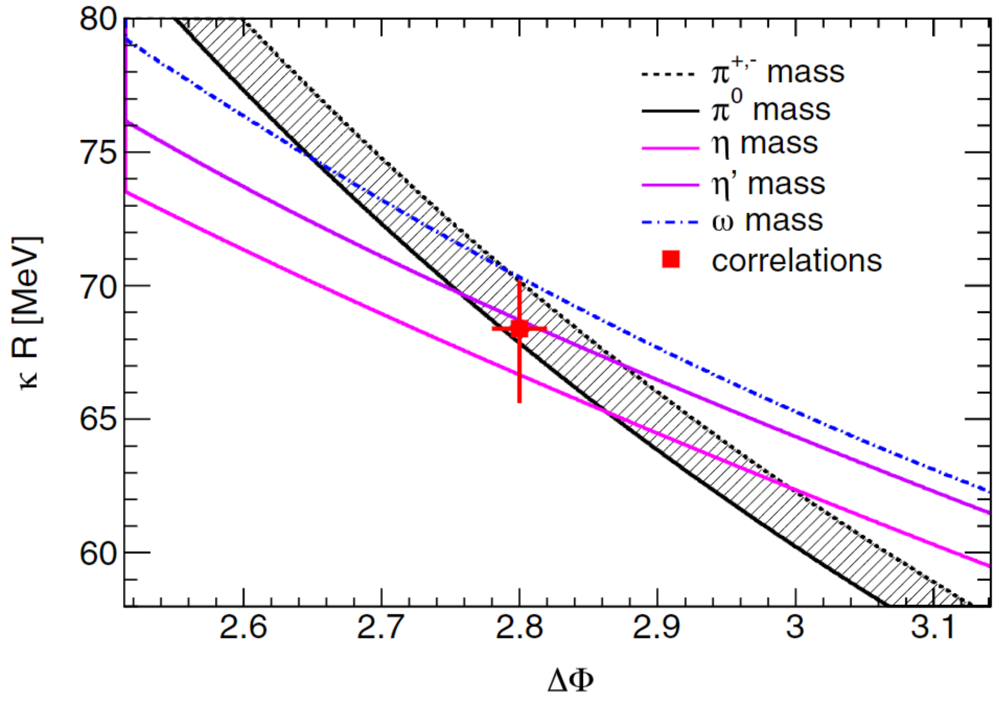
negative part of Δ(*Q*) marks the anomalous production of LS pairs, traditionally attributed to Bose-Einstein interference (also called HBT effect)

better understood as a signature of quantized fragmentation

production of mesons



Phys.Rev. D104 (2021) 034012,
arXiv: 2103.05269 [hep-ph]



the model is particularly interesting:
it is empirically **over-constrained**, the number of sensitive observables vastly outnumbers the number of adjustable parameters.

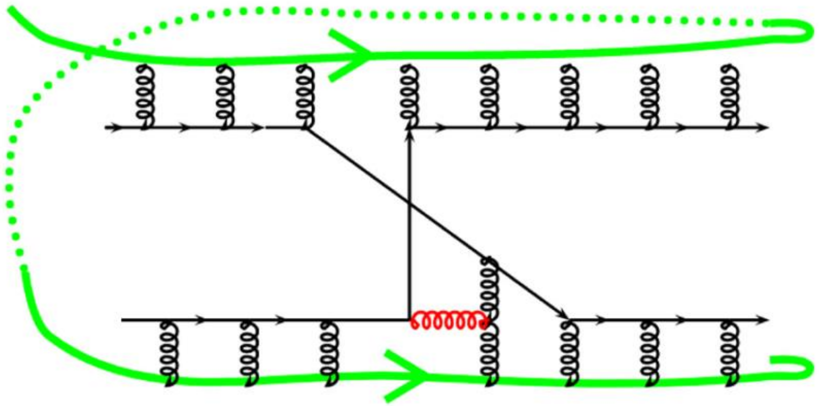
hadron mass spectra:
pseudoscalars mesons (π; η; $η_0$) can be associated with quantum states n=(1, 3, 5), and vector meson ω fills the slot n=4

on the other hand, the underlying helical field defines intrinsic transverse momenta of hadrons and, for specific configurations—homogeneous

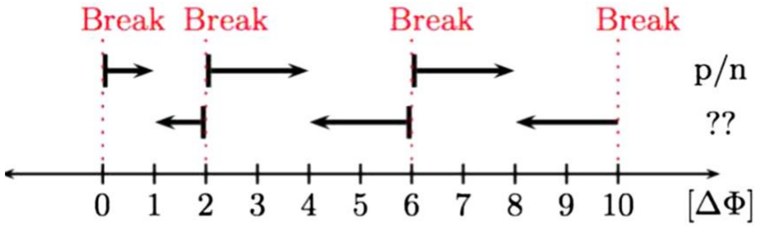
a detailed description of the interaction $qg \to qq\bar{q}$ is not included

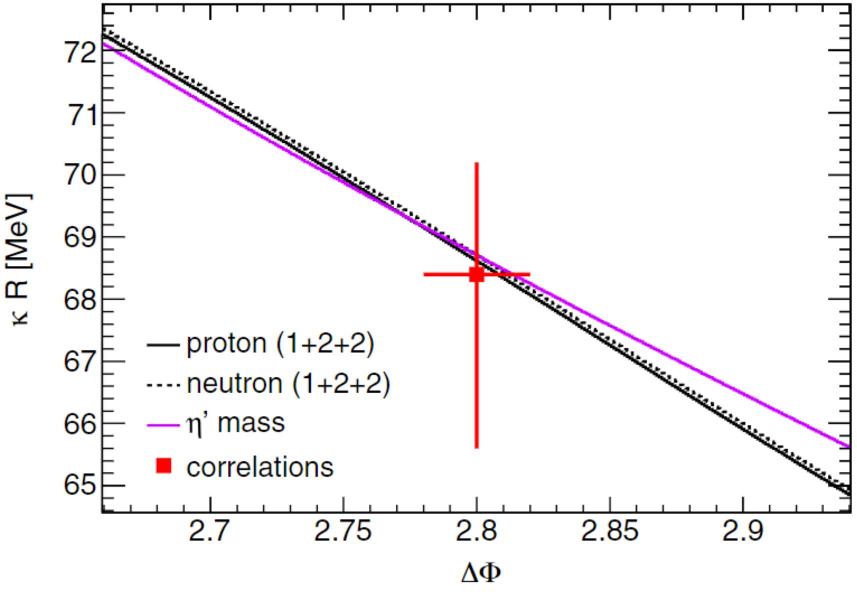
what about baryons?

production of baryons

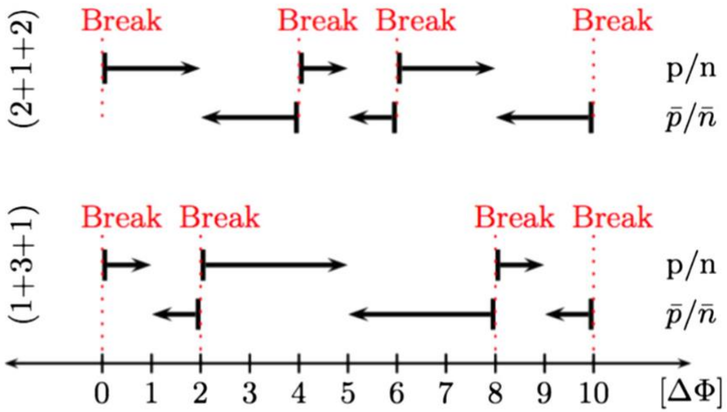


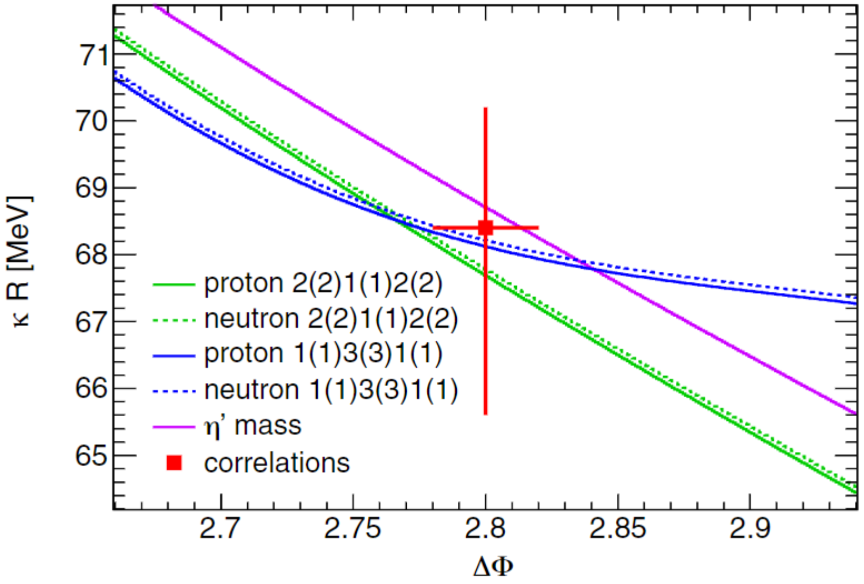
2+2+1





1+3+1





we can go even further…

further color-flow sensitive measurements by ATLAS

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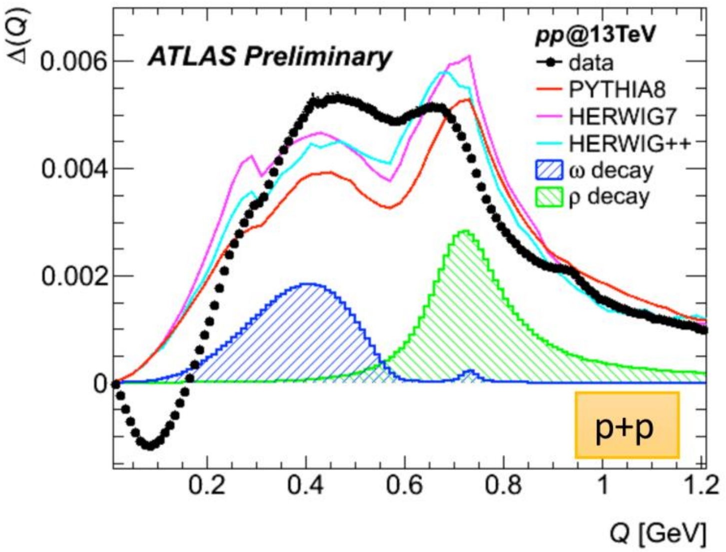
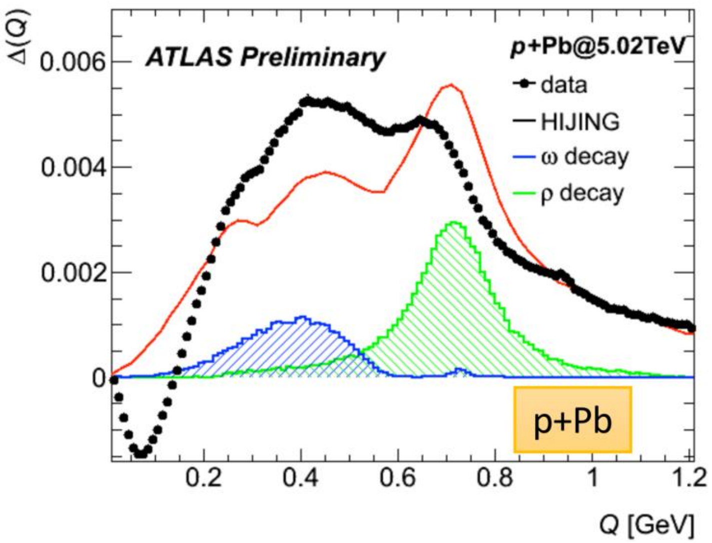
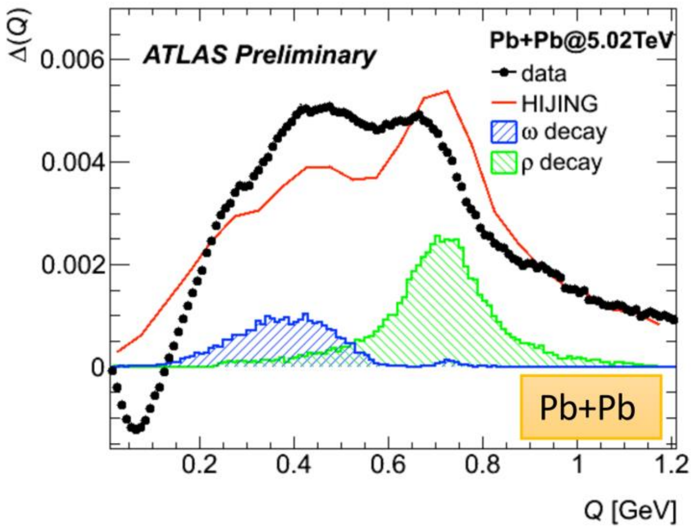
- correlations along color flow (= dynamics of hadronization) described poorly by conventional models
- the modeling does not allow to evaluate the hadronization systematics …. models fail in similar way







pp and HI data very similar – do we see some universality of hadronization?

quantized string parameters from pp, p+Pb and Pb+Pb data

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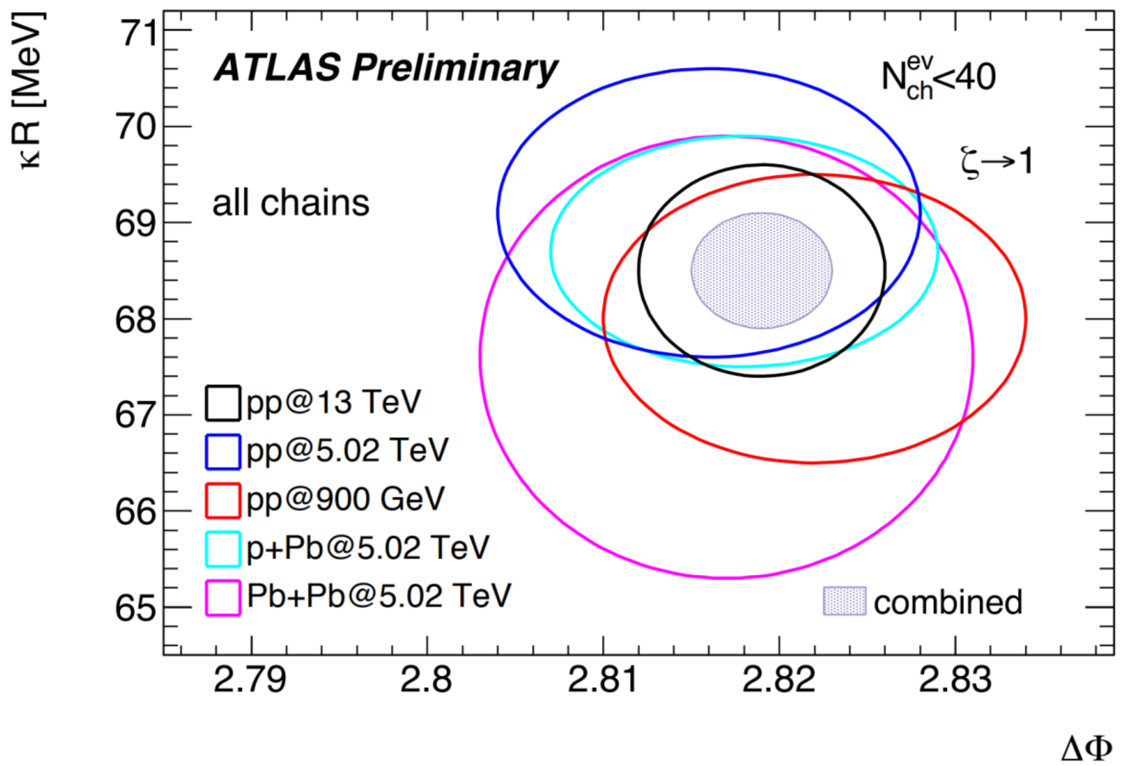

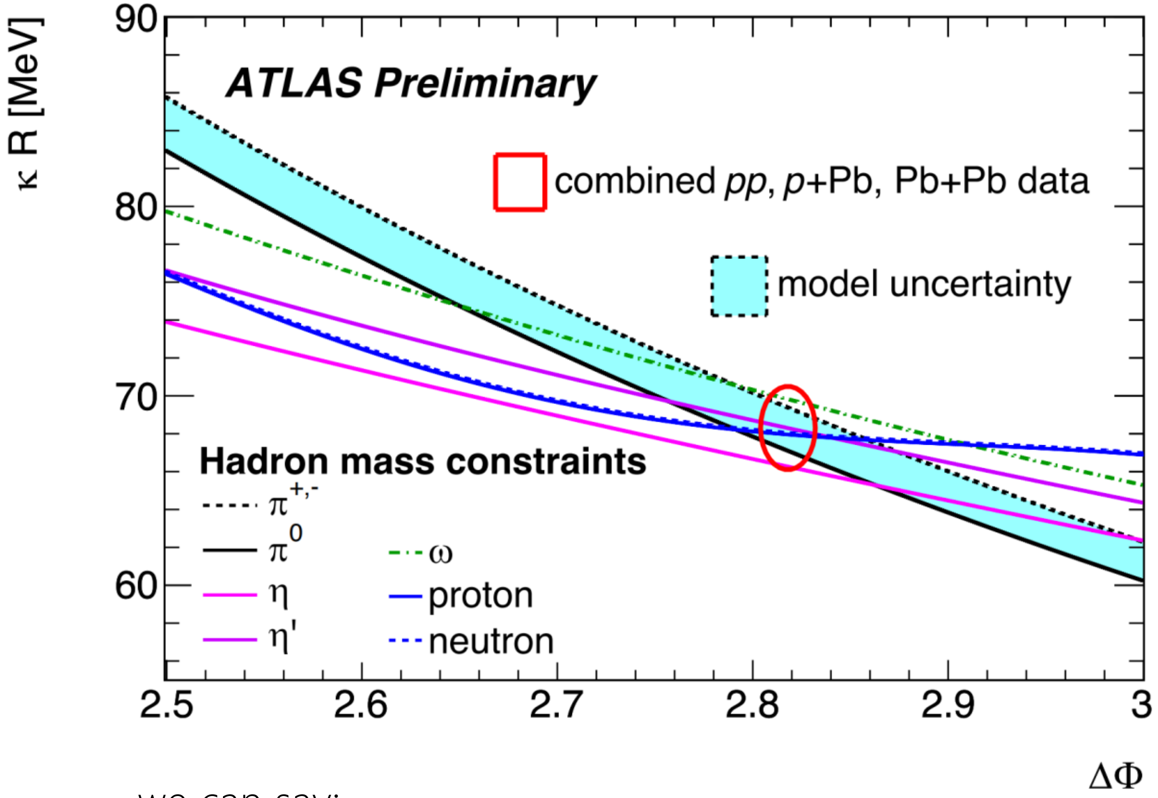

a good agreement between pp data at various collision energies

an excellent agreement between p-p and HI data

we can say:

- quantized fragmentation capable to explain ALL data previously associated with Bose-Einstein interference
- anomalous production of close LS pions strongly suggests it is a hadronization effect

further color-flow sensitive measurements by ATLAS II

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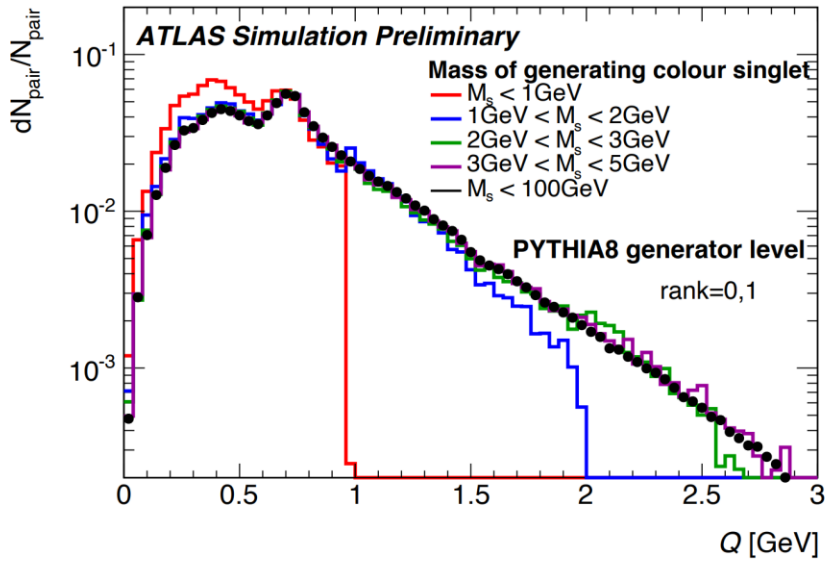
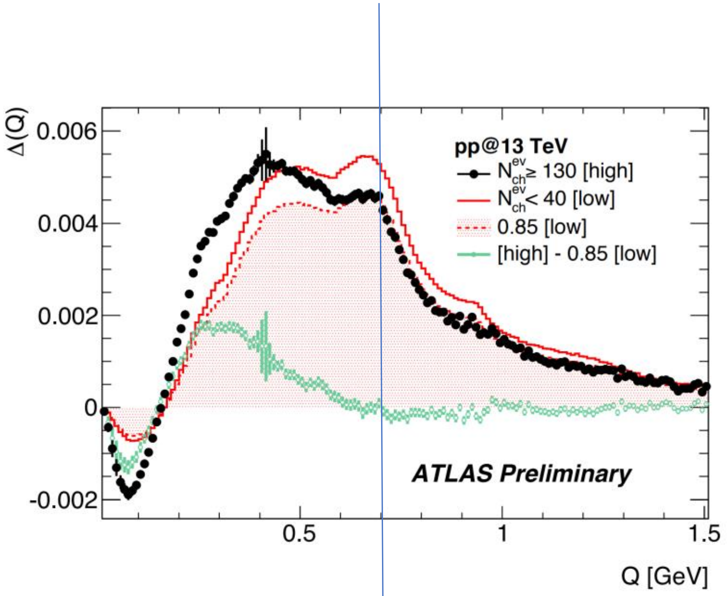
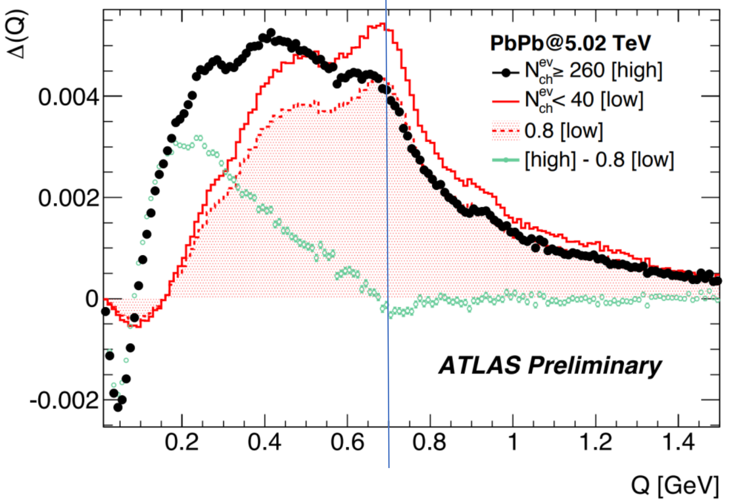
- the subject is of particular interest for diffractive studies of mass spectrum of hadron source



- data show growing presence of very light hadron sources with increasing particle multiplicity; possible signature of hadronization of "wounded" nucleons

- little difference for Q > 0.7 GeV for sources with mass > 2 GeV





distribution is limited by the mass of the source but otherwise rather stable (there is no or very little difference in Δ shape below Q~1.5GeV for sources with masses above 2 GeV) => evolution of shape signals variation of low mass sources

observable sensitive to local evolution of fragmentation function
(for color-adjacent hadrons)

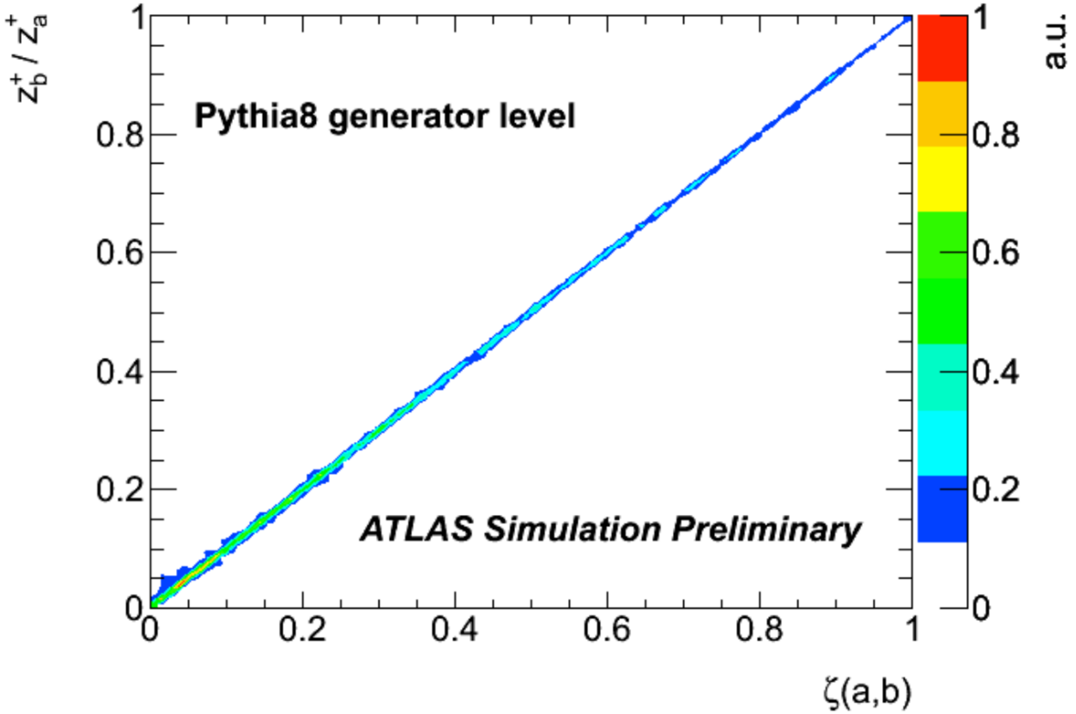
z^+, z^- fractions of longitudinal partons of a hadron (*a* or *b*)

$$Q^2(p_a, p_b) = (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t,a}^2\left(\frac{z_b^+}{z_a^+} - 1\right) + m_{t,b}^2\left(\frac{z_a^+}{z_b^+} - 1\right)$$

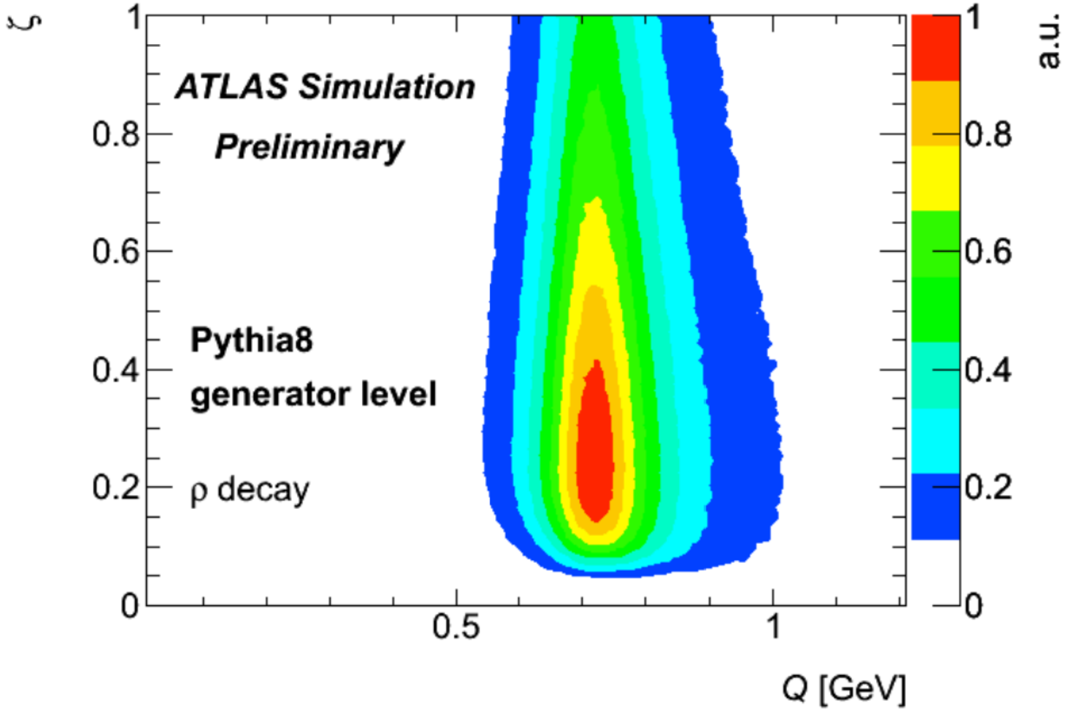
$$\sim (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t_a}^2(\zeta(p_a, p_b) - 1) + m_{t_b}^2(1/\zeta(p_a, p_b) - 1), \quad \text{for } |\vec{p}_a| > |\vec{p}_b|$$

$$p = (E, \vec{p}) = (0, \vec{p}_T) + z^+(|\vec{P}|, \vec{P}) + z^-(|\vec{P}|, -\vec{P})$$

$$\zeta(\vec{p}_i, \vec{p}_j) = min\left(\frac{|\vec{p}_j|}{|\vec{p}_i|}, \frac{|\vec{p}_i|}{|\vec{p}_j|}\right)$$



the "check" of how the approximations works



a way to distinguish between rank 0 and rank 1 contributions

isotropic decays (r = 0) independent from ζ and produce a vertical band

quantized fragmentation, signature of long chains found in Pb+Pb – the first observation

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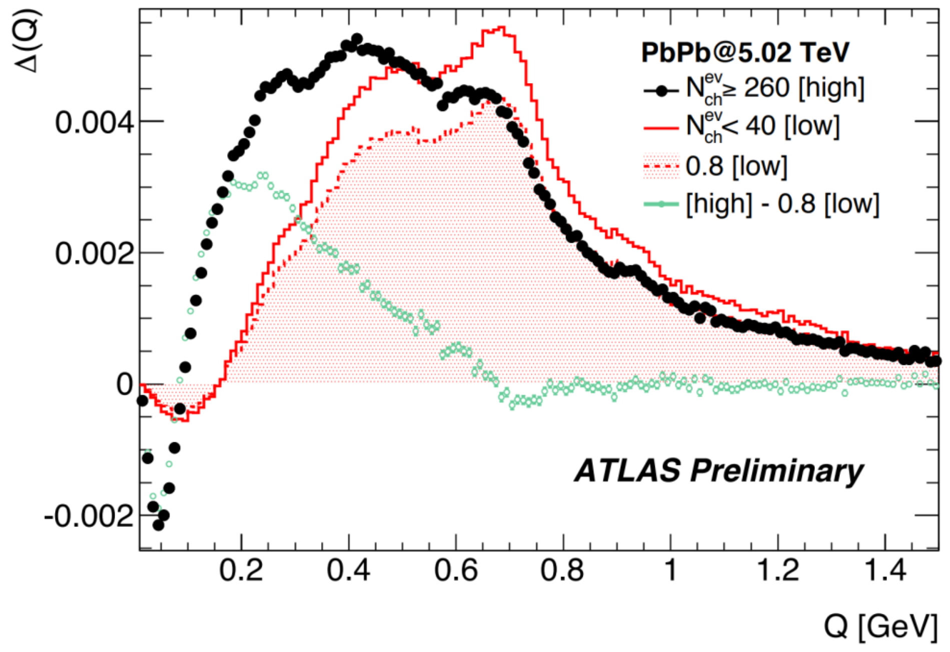
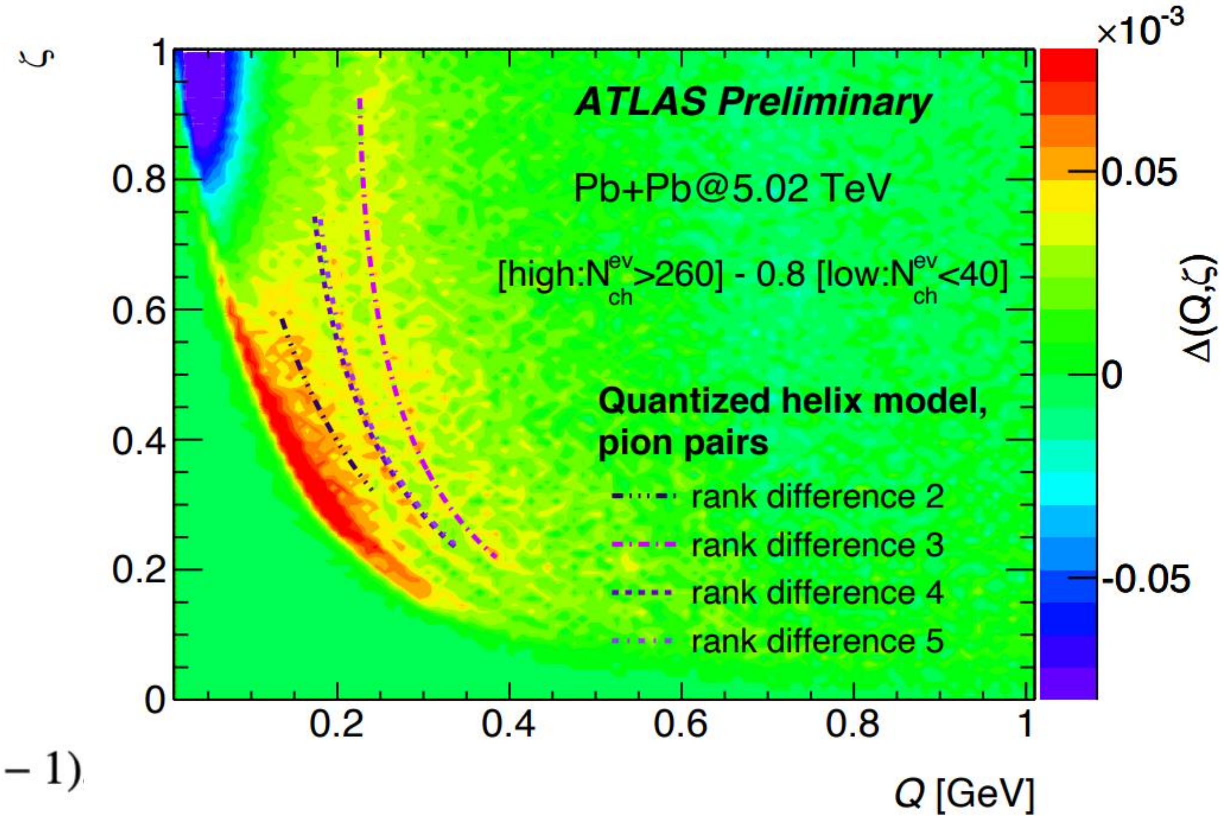




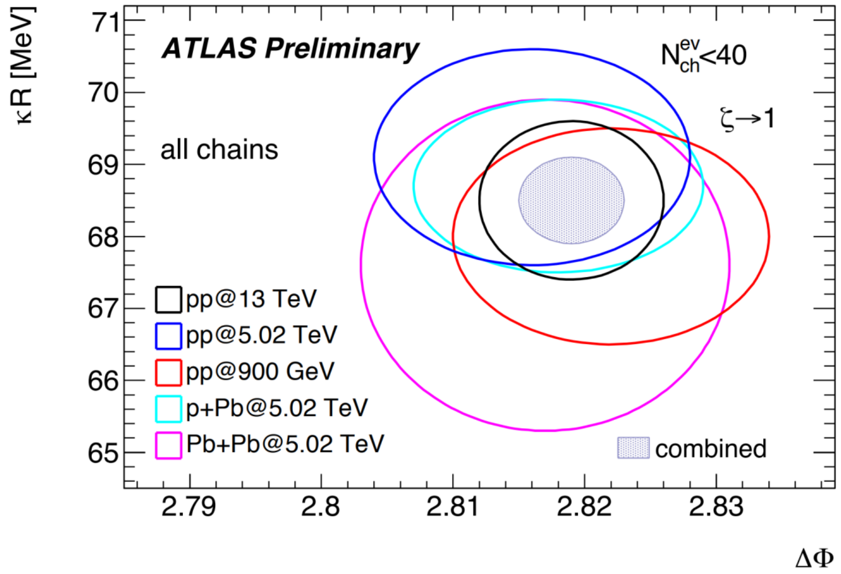
$$Q^2 \sim (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t_a}^2(\zeta(p_a,p_b) - 1) + m_{t_b}^2(1/\zeta(p_a,p_b) - 1)$$

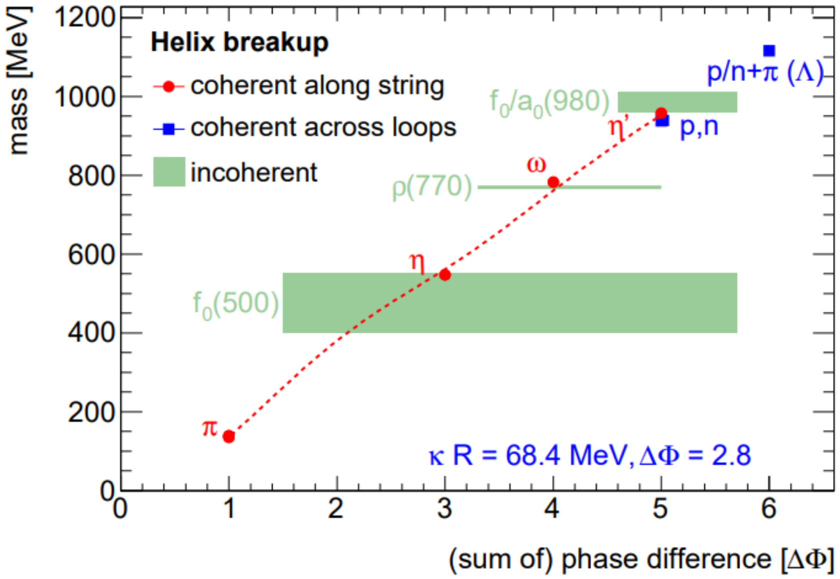
Pair rank difference r	1	2	3	4	5
Q expected (MeV)	266 ± 8	91 ± 3	236 ± 7	171 ± 5	178 ± 5

the observation of long pion chains demonstrates the predictive power of the model and validates the whole framework

summary

- recent ATLAS results indicate that causal approach to the description of confining field quite efficiently resolves a number of long-standing issues in the hadronization. (hadron mass spectrum / p_T spectra / particle correlations / … the list is growing)
- new observables sensitive to color flow and local variations of fragmentation function are deployed by ATLAS which allow to combine hadronization measurements from pp and HI samples; these can be useful for diffractive studies, as well
- properties of QCD field in transverse plane (helical string shape) were measured using particle correlations and lead to very good agreement with values derived from hadron mass spectrum
- so called Bose-Einstein effect (an anomalous production of close like-sign pions) is also fully covered as a side-effect of helical ordering of color-adjacent hadrons

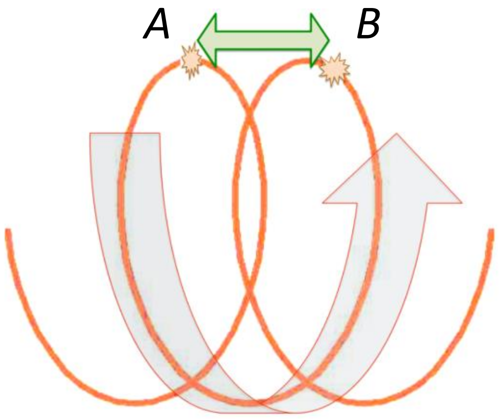




backup

string fragmentation – kinematics

Phys. Rev. D 89 (2014), p. 015002



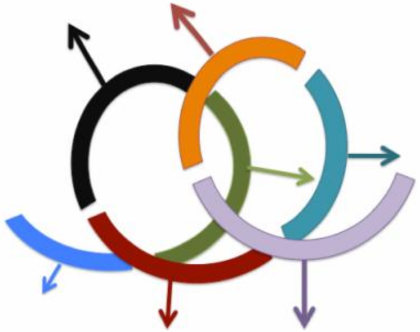
$$p_{||}^{AB} = \pm\kappa\beta c(t_B - t_A) \qquad \beta = \sqrt{1-(R\omega)^2}$$

κ is string tension, R is helix radius, ω is angular velocity

$$\vec{p}_{\mathrm{T}}^{\pm AB} = \kappa R \left(\mathrm{Re}\int_A^B \exp^{i\left(\Phi\pm\frac{\pi}{2}\right)} d\Phi\,,\ \mathrm{Im}\int_A^B \exp^{i\left(\Phi\pm\frac{\pi}{2}\right)} d\Phi \right)$$

$$m^{AB} = \kappa R \sqrt{(\Phi^B - \Phi^A)^2 - \left(2\sin\frac{\Phi^B - \Phi^A}{2}\right)^2}$$

quantization of fragmentation $\qquad \Phi^B - \Phi^A = n\Delta\Phi, n = 1,2,3,\ldots$



selection algorithm

The triplet chain selection is performed, event by event, in the following way:

1. Each particle is paired with the same charge particle which minimizes the LS pair momentum difference Q calculated from the three-momenta and the pion mass hypothesis.
2. Each pair is completed with an opposite charged particle chosen with the aim to minimize the triplet mass. This simple chain selection is further refined in order to avoid double-counting of particle pairs. In cases of ambiguity, priority is given to the lightest configuration which satisfies the picture of QCD string fragmentation, i.e. the following criteria (3-4) are applied in an iterative way, preserving the lightest configurations found so far.
3. The number of single particle associations is calculated, in the order of increasing pair momentum difference. If a particle is associated with more than two different LS partners, the two pairs with minimal momentum difference are retained and the remaining associations are discarded. A new search for closest LS partner is performed using the, currently unmatched, available particles. Each proto-chain is assigned a weight of w_i = 0.5 in the case of exclusive association of LS particles or w_i = 1 in the case of non-exclusive association of LS particles in order to prevent double-counting,
4. Following the completion of chains with OS particles, the weighted number of chains in which a given OS pair participates is calculated, for all OS pairs, in the order of increasing chain mass. According to the string fragmentation picture, a pair of adjacent hadrons can be shared by at most two adjacent chains. In case an OS pair belongs to three or more chains, the two chains with minimal mass are retained and a new search of an opposite charged partner is performed for the other chains. If that search fails, the weight of the corresponding chain is set to zero. Zero weight is also assigned to incomplete chains in cases where there are not enough particles in the event to construct triplets.

At the end of the procedure, the chain selection - in an event with N_{ch}^{ev} charged particles - contains N_{ch}^{ev} chains, composed of three(complete chain) or fewer(incomplete chain) particles, with some of these chains effectively eliminated, having a zero weight.

good track definition

A reconstructed track passes the selection if it has

- transverse momentum above 130 MeV, and lies in the pseudorapidity range $|\eta| < 2.5$,
- absolute values of transverse and projected longitudinal impact parameters below 1.5 mm, with respect to the event primary vertex,
- a hit in the first Pixel layer when expected, and at least one Pixel hit in total,
- at least two (for p_T <300 MeV), four (for 300 MeV< p_T <400 MeV), or six (for p_T >400 MeV) SCT hits,
- a χ^2 fit probability above 0.01 for p_T >10 GeV .