HELIX STRING FRAGMENTATION AND CHARGED PARTICLE CORRELATIONS WITH ATLAS* **

Šárka Todorova-Nová

on behalf of the ATLAS Collaboration

IPNP, Charles University, Prague, Chech Republic

Received 29 November 2022, accepted 26 January 2023,
published online 25 May 2023

Correlations between charged particles provide important insight into the hadronization process. The analysis of the momentum difference between charged hadrons in proton–proton, proton–lead, and lead–lead collisions at the LHC is performed by the ATLAS Collaboration in order to study the dynamics of hadron formation. The spectra of correlated hadron chains are explored and compared to the predictions based on the quantized fragmentation of a three-dimensional QCD helix string. This provides an alternative view of the two-particle correlation phenomenon typically attributed to the Bose–Einstein interference.

DOI:10.5506/APhysPolBSupp.16.5-A39

1. Introduction

The notion that correlations between hadrons are an important source of information about hadron formation is widely accepted but not sufficiently explored. Recently, an alternative approach to the modelling of the confinement, replacing the 1-dimensional string of the Lund fragmentation model with a 3-dimensional helical string, brought some insight into rules governing the hadronization. There are several essential properties that the 3-dimen-sional string brings into consideration: the intrinsic transverse momentum of hadron is defined by the transverse shape of the string, and the correlation between intrinsic transverse and longitudinal momentum components are also defined. Of special interest is the possibility to study, for the first time, the causal relations between string breakups which define direct hadrons. The parametrization of the shape of a helical string is shown in

* Presented at the Diffraction and Low-x 2022 Workshop, Corigliano Calabro, Italy, 24–30 September, 2022.

Fig. 1. The requirement of a cross-talk between endpoint vertices reveals a quantization scheme in which different hadron species correspond to a helical string breaking in regular intervals of helix phase $\Delta\Phi \sim 2.8$ rad [1, 2]. The mass spectrum of light hadrons is described, with precision of 1–3%, with the help of only two parameters: $\Delta\Phi$ and the energy scale κR, where κ stands for string tension and R for the radius of helix. Since the quantization proceeds in the transverse mass $m_{\mathrm{T}} = \sqrt{m^2 + p_{\mathrm{T}}^2}$ rather than mass m alone, the model predicts non-trivial correlations between colour-adjacent hadrons. Two studies of these correlations were performed by the ATLAS Collaboration [3] using pp data at $\sqrt{s} = 7$ TeV [4, 5].

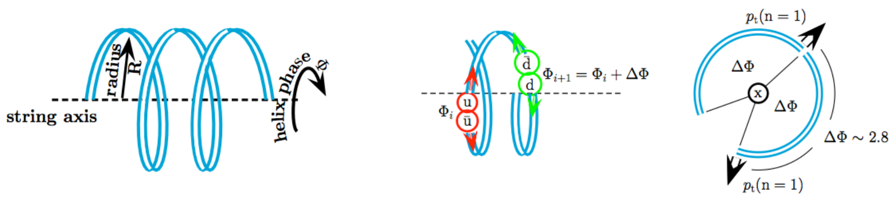


Fig. 1. Left: Parametrization of helical shape of the QCD string. Middle: In quantized string fragmentation, hadrons are created by string breakups separated by a multiple of helix phase quantum difference $\Delta\Phi$. Right: The shape of QCD string is reflected in the momentum distribution of emitted hadrons, and the size of their momentum difference is quantized.

2. Anomalous production of like-sign pions

For the specific case of a helical string with a constant string pitch, fragmenting into a chain of direct pions, the momentum difference $Q = \sqrt{-(p_i - p_j)^2}$ between pions can be calculated as a function of their rank difference, where rank describes the hadron ordering along the string according to colour flow. An anomaly appears for colour adjacent pairs (of rank difference 1) which have the largest momentum difference (~ 270 MeV), while pairs with rank difference 2 are separated by ~ 90 MeV only. This is of course a consequence of $\Delta\Phi$ being ~ 2.8 rad, and colour adjacent pion pairs nearly back-to-back in the transverse plane. This anomaly is coupled with a charge-combination asymmetry since local charge conservation in string breaking forbids creation of colour-adjacent pairs with the identical sign of charge. Another prediction of the model suggests that the mass of a chain of n direct pions has the smallest mass possible, among any combination of n hadrons produced from a given piece of string.

Model predictions are tested using various ATLAS data collected during LHC Run 2: pp at $\sqrt{s}$ =13, 5.02, and 0.9 TeV, and the heavy-ion collisions p+Pb and Pb+Pb at $\sqrt{s} = 5.02$ TeV, Ref. [6]. The observable

$\mathit{\Delta}(Q) = \frac{1}{N_{\rm ch}}[N^{\rm OS}(Q) - N^{\rm LS}(Q)]$ is used, which is based on the difference between inclusive spectra of the like-sign (LS) and opposite-sign (OS) hadron pairs, normalised to the number of charged particles in the sample ($N_{\rm ch}$). $\mathit{\Delta}(Q)$ is uniquely sensitive to the momentum difference between colour-adjacent hadrons. Anomalous production of LS pairs appears as a negative part of the $\mathit{\Delta}(Q)$ distribution (Fig. 2 (a)). The discrepancies observed between data and conventional hadronization models are substantial which means the modelling does not guarantee a reliable estimation of hadronization systematics. In a model-independent way, the excess of LS pairs is associated with the presence of charge-ordered triplets (chains) with properties predicted by the quantized fragmentation (Fig. 2 (b)), $\mathit{\Delta}_{3h}$ in Fig. 2 (c), and with the modification of the inclusive $p_{\rm T}$ spectra (Fig. 2 (d)). The latter does not appear by surprise either, since the intrinsic $p_{\rm T}$ of direct pions is ∼130 MeV in the model and the strings tend to be aligned with the beam direction in minimum bias samples.

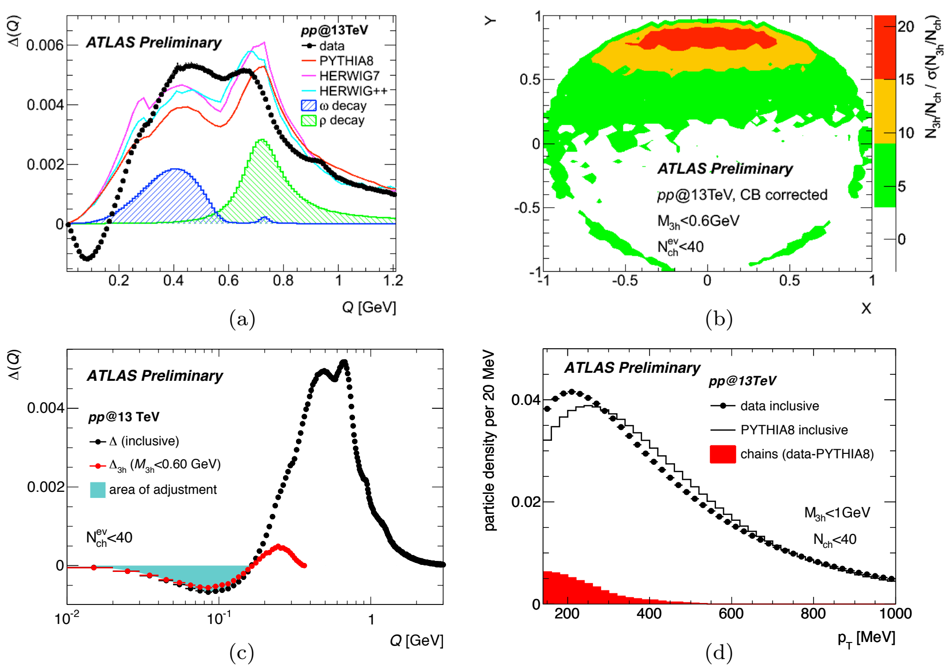


Fig. 2. Anomalous production of the like-sign hadrons (pions) seen as a negative part of measured $\mathit{\Delta}(Q)$ (a) is explained by the presence of mass-minimized, charge-ordered triplets (“chains”) in the configuration predicted by quantized fragmentation as shown in the Dalitz plot (b). The bottom plots indicate the contribution ($\mathit{\Delta}_{3h}$) of the chain selection to $\mathit{\Delta}(Q)$ (c) and to the inclusive $p_{\rm T}$ spectrum (d). Source: Ref. [6].

The shape of Δ_{3h} (Fig. 2 (c)) is used to perform an independent measurement of string parameters. The measurement is done in a way which eliminates contribution from the (unknown) variation of longitudinal shape of the string, with the help of an additional observable sensitive to the local variation of fragmentation function, $\zeta = \min(\frac{|p_i|}{|p_j|}, \frac{|p_j|}{|p_i|})$. Very good agreement is obtained between all samples as shown in Fig. 3 (a). The combined result is shown in Fig. 3 (b) and compared with constraints imposed on the model by hadron masses.

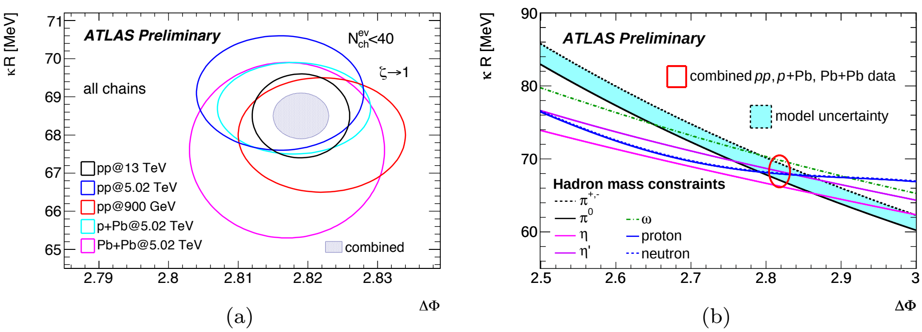
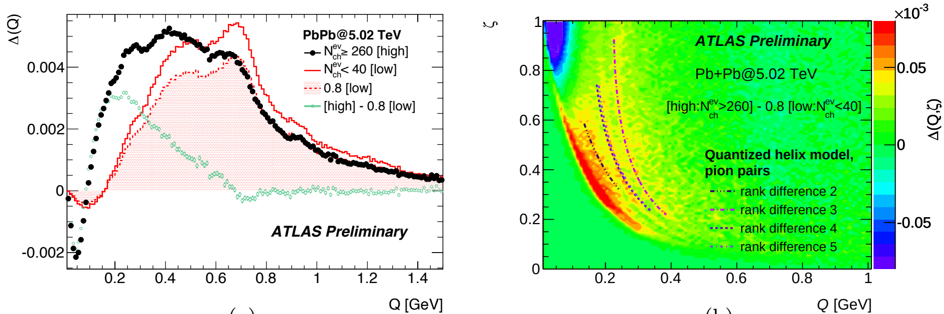


Fig. 3. Measurement of string parameters using particle correlations. (a) Comparison and combination of intermediate results obtained in various Run 2 samples. (b) The combined final result compared with constraints derived from hadron masses. The blue area indicates the intrinsic uncertainty of the model of quantized fragmentation. Source: Ref. [6].

3. Signature of long pion chains

The shape of $\Delta(Q)$ evolves with particle multiplicity and this evolution indicates a growing contribution from hadronic sources with mass below 0.7 GeV, kinematically compatible with a signature of wounded nucleons (Fig. 4 (a)). A two-dimensional study (Q, ζ) of this low-mass contribution in peripheral Pb+Pb collisions reveals a distinct stripe structure which fits the expected quantized signature of direct pion pairs from long pions chains, as shown in Fig. 4 (b). The observation of long pions chains may be instrumental in the understanding of long-range correlations.



(a) (b)

Fig. 4. (a) Shape evolution of $\Delta(Q)$ with particle multiplicity reveals growing contribution from low-mass sources (green points) in peripheral Pb+Pb collisions. (b) The low-mass sources in high multiplicity peripheral Pb+Pb events exhibit the signature of quantized long pion chains. Source: Ref. [6].

4. Conclusions

The anomalous production of like-sign charged pions is studied using LHC Run 2 data and found conform to predictions of the model of quantized fragmentation which is — at the time of writing — the only model capable to calculate the mass spectrum of light hadrons from properties of the parametrized strong field. The signature of quantized fragmentation is found by the ATLAS Collaboration at the LHC in 1-, 2-, and 3-particle spectra, and the link between these phenomena is experimentally established in a model-independent way. Quantitative estimates suggest the quantized fragmentation accounts for the entire anomalous production of the close like-sign pairs traditionally attributed to the Bose–Einstein interference.

This work was partially supported by the Inter-Excellence/Inter- Transfer grant LTT17018 and the Research Infrastructure project LM2018104 funded by the Ministry of Education, Youth and Sports of the Czech Republic, and the Charles University project UNCE/SCI/013.

REFERENCES

[1] Š. Todorova-Nová, *Phys. Rev. D* **89**, 015002 (2014).
[2] Š. Todorova-Nová, *Phys. Rev. D* **104**, 034012 (2021).
[3] ATLAS Collaboration (G. Aad *et al.*), *J. Instrum.* **8**, S08003 (2008).
[4] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev D* **86**, 052005 (2012).
[5] ATLAS Collaboration (M. Aaboud *et al.*), *Phys. Rev. D* **96**, 092008 (2017).
[6] ATLAS Collaboration, «Study of ordered hadron chains in proton–proton, proton–lead and lead–lead collisions with the ATLAS detector», ATLAS-CONF-2022-055, `https://cds.cern.ch/record/2819852`