Phenomenological descriptions of heavy flavour production in *p-p* collisions with multiparton interactions

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Abstract
A study of charm hadron production in proton-proton (*p-p*) events generated in PYTHIA8.2 at $\sqrt{s} = 13\,\mathrm{TeV}$ is presented. The mechanics of various QCD-based phenomenological models of colour reconnection and fragmentation in events with multiple parton-parton interactions are discussed and their description of phenomena formerly attributed to radial flow in *p-p* collisions is investigated. Generation of hard process $c\bar{c}$ events is performed to study D^0, D_s^+ and Λ_c^+ production in association to their respective antiparticles. Coherent behaviour of interacting Lund strings is shown to enhance the strange flavour content of *p-p* events, via the $\mathrm{D_s}/\mathrm{D}^0$ production ratio. Additionally, the description of complex topologies between 3 or more partons in colour reconnection models is found to enhance the p_T and multiplicity dependent cross-section ratio, $\Lambda_\mathrm{c}/\mathrm{D}^0$, reproducing a similar form of baryon/meson enhancement to that expected from the formation of a thermalised medium, with only standard QCD processes.

Keywords
PYTHIA; heavy flavour; multiparton interactions; colour reconnection; rope hadronisation; Quark-gluon-plasma

1 Introduction

The *A Large Ion Collider Experiment* (ALICE) collaboration is dedicated to the study of the behaviour and properties of strongly-interacting particles at extreme energies and densities. An experiment of the Large Hadron Collider (LHC), it is optimised to make precision measurements of particles produced in heavy ion collisions, in which the abundance of colliding nucleons (and consequently, interacting partons) can lead to the formation of a thermalised equilibrium state of free quarks and gluons - the Quark-Gluon-Plasma (QGP). Colour carrying particles in the QGP become confined in colourless mesons and baryons, whose cross sections, kinematic properties and lifetimes can be measured precisely - due to the optimisation of the ALICE detector - with the aim of improving our understanding of Quantum Chromodynamics (QCD) and the nature of the production, interaction and fragmentation of strongly-interacting elementary particles.

The ratio of baryon to meson production is a key tool in analysing the dynamics of strongly interacting systems. The multiplicity and transverse momentum (p_T) dependence of light flavour meson and baryon production in proton-proton (*p-p*) collisions has been measured at $\sqrt{s} = 7\,\mathrm{TeV}$ and compared to the predictions of different QCD configurations of Monte Carlo generated *p-p* events [1]. In lead-lead (*Pb-Pb*) events, collective dynamics are a result of the interaction of many particles in the thermal equilibrium of the QGP, leading to an enhancement of the light flavour baryon to meson ratio at high p_T, in high multiplicity events. At the energy and luminosity of the LHC, probing *p-p* collisions for light-flavour hadrons has revealed indications of collective behaviour similar to those observed in the equilibrated systems formed in *p-Pb* and *Pb-Pb* collisions. However, the significantly lower partonic densities and interactions in *p-p* events are expected to hinder the formation a thermalised medium. Furthermore, the production ratios of charmed baryons to mesons as a function of transverse momentum in *p-p* collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ and *p-Pb* events at $\sqrt{s} = 5.02\,\mathrm{TeV}$ have been found to be enhanced for high multiplicity events, in comparison with those of low multiplicity [2]. The higher masses and shorter lifetimes of heavy flavour particles further reduce the likelihood of thermalisation in *p-p* systems, highlighting the importance of heavy flavour physics in probing such events for more QCD-based descriptions of radial flow.

The project presented in this report seeks to illustrate the effect of various models of QCD processes on production and kinematics of charm hadrons in *p-p* collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, as generated in PYTHIA8. Focus will be placed on models of *colour reconnection* and *rope hadronisation* in events with multiple parton-parton interactions, to determine whether models for gluon interaction and colour flow are capable of reproducing the heavy flavour baryon/meson enhancement, even in the absence of a thermalised system.

2 The PYTHIA8 Event Generator

PYTHIA8 [3] is a Monte Carlo event generator of high energy particle collisions that, based on a set of configurable parameters, simulates the production, interaction, fragmentation and decay of particles in beam collider events such as those at the LHC. PYTHIA8 performs such tasks by recreating the main physical processes of a standard particle collision. These are:

- **hard processes**, defined as high momentum transfer, short-ranged interactions between particles. Such processes include $2 \longrightarrow 2$ hard-QCD scatterings between constituent partons of incoming beam particles, the nature of which can be determined by a set of parton distribution functions (PDFs), leading order (LO) perturbative and non-perturbative QCD calculations;
- **initial-state and final-state radiative processes** (ISR and FSR, which precede and succeed hard scatterings, respectively) such as Bremsstrahlung or gluonic radiation, and constitute a first correction to leading order hard interactions;
- **multiple parton-parton interactions** (MPIs), due to multiple hard scatterings of partons in composite particle collisions. The process by which colour can flow between separate MPIs in an event - known as colour reconnection - is not well defined and current models will be explored further on in this report;
- **hadronisation and fragmentation** of colour-charged quarks and gluons, forcing unbound partons from hard-QCD and radiative processes to be confined in colourless hadronic states;
- **resonance and particle decays** of unstable states in their allowed decay channels. Sequential decays produce showers of stable particles, transforming the products of the intial hard process into a final state akin to what is observed in detectors such as ALICE.

The implementation of various theoretical and phenomenological models of particle interactions and decays is possible due to a library of parameters that can be configured to develop *tunes* of PYTHIA. The production and kinematics of heavy flavour hadrons in MPI events provides insight into the behaviour of strongly interacting particles in the LHC environment. Of particular interest is the discrepancy in hadronic p_T-differential cross sections between data and theoretically motivated configurations of standard event generators [2]. For this purpose, alternative QCD-based tunes can be implemented to analyse the effects of MPIs, colour reconnection models, gluonic self-coupling and hadronisation on the production rate and kinematic properties of charmed hadrons.

The default configuration of PYTHIA8 models the constituent partons of the incoming hadrons as essentially free, uncorrelated particles. Consequently, hard process scatterings are almost exclusively $2 \longrightarrow 2$ particle interactions.

Fragmentation in PYTHIA8 follows the Lund string model of hadronisation, which recognises that a strongly bound quark-antiquark pair forms a colour-singlet with a QCD potential that increases linearly for spatial separations greater than 0.5 fm. Fragmentation occurs when the energy stored in the gluonic string is sufficient to produce a new quark-antiquark pair, giving rise to two new colour-singlet dipoles in the form of hadrons.

The default mode of colour reconnection looks to minimise the total length of colour-carrying strings of self-coupling partons (predominantly low momentum gluons) by considering the systems produced by two separate MPIs and fusing the gluons of the low p_T system onto the colour dipoles of the higher p_T one [5].

The distinction between resonances and particles in PYTHIA is a technical one: in the standard configuration, states with a lifetime shorter than the hadronisation timescale, such as the electroweak bosons, the top quark and the Higgs boson, are defined as resonances; whilst those with a lifetime larger than the hadronisation timescale (hadrons, leptons) are classified as particles [3].

2.1 Tunes of PYTHIA8

The majority of the mechanisms that define the evolution of a PYTHIA event are configurable, either through variable parameters that redefine the scales at which certain processes occur, or via entire alternative methods to the default model. The majority of these parameters cannot, however, be changed independently without diverging from a physically coherent description of phenomena.

PYTHIA8.2 includes the Monash 13 tune [4] in its default configuration for ISR, FSR, string fragmentation and hadronisation parameters, based on the most up-to-date data obtained from the LHC, Tetravon and LEP. Experimentally developed configurations of Parton Density Functions (PDFs) for protons are included in the PYTHIA libraries. The LHAPDF packages can be accessed through the `Tune:PreferLHAPDF` parameter, which by default is set for PYTHIA8 to use the LHAPDF5 library. The more modern LHAPDF6 [6] version of this library, recommended since LHC Run 2, is used for all other tunes implemented in this analysis.

Due to the analysis of daughter particle kinematics, the `ParticleDecays:limitTau0` parameter, which limits the decays of particles based on their lifetime, has been turned off for all tunes in study, as in the default configuration of PYTHIA8.2. Similarly, but of less relevance, the random number generation for events has been kept to its standard parameterisation, namely `Random:setSeed = Off`, for consistency.

The tunes employed in this study focus primarily on phenomenological models of colour reconnection and rope hadronisation. A complete list of relevant parameters and their settings is included in table A.1 of appendix A.

2.1.1 The Colour Reconnection Schemes

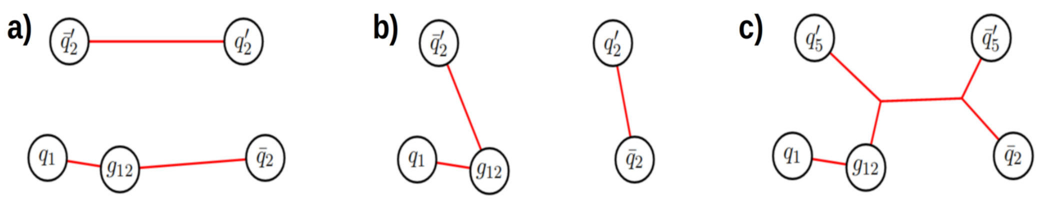

Figure 1: Schematic diagrams for methods of colour reconnection in PYTHIA8: a) a leading colour description (MPIs evolve independently); b) the *MPI-based* model (minimising string length) c) the *More-QCD-based* model(introduces QCD-like junctions and complex topologies). Adapted from [7].

Models of colour reconnection have been developed to describe the dynamics of a system with MPIs. The simplest MPI models treat each partonic scattering individually, as colour singlet systems that evolve independently of other MPIs in an event [7], as represented in figure 1a. However, since partons carry colour charge and, in general, partonic scatterings will not form a colour neutral system, interactions with partons from the beam remnant must be included to conserve colour charge. Whilst such *leading colour* (LC) models are physically consistent, a more realistic phenomenological treatment would allow colour flow across different MPI systems. Although the exact nature of the connections between MPIs is unknown, a few models included in the PYTHIA documentation have come closer to describing observed phenomena than LC models.

The *MPI-Based* model is the default method of colour reconnection in PYTHIA8. Partons are classified by the MPI interaction that produced them and MPI systems are ordered by increasing p_T. For each MPI system, gluons are determined to be merged onto the colour dipole of the next highest momentum system with a probability P, dependent on a reference value, `MultiPartonInteractions:pT0Ref`, and a range parameter, `ColourReconnection:range`, via the equation

$$P = \frac{(\mathrm{pT0Ref} \times \mathrm{range})^2}{(\mathrm{pT0Ref} \times \mathrm{range})^2 + p_T^2} , \tag{1}$$

such that the overall length of colour strings - and, consequently, the potential energy - is minimised [5], as depicted in figure 1b. This process is iterated over all higher p_T MPIs in increasing order and once the dipoles to be fused have been determined, the actual implementation of the fusion is performed in order of decreasing p_T. Whilst there is no explicit p_T cut-off point for colour reconnection, from equation (1) and the fact that fusion of low-momentum MPIs is determined in order of increasing p_T, the likelihood of fusing the highest momentum strings is significantly reduced when compared to those of lower p_T systems.

This method of colour reconnection is the focus of the `MPIBased` tune of PYTHIA and is employed in all tunes that inherit the standard colour reconnection configuration, as such, the only non-default setting of the `MPIBased` tune is the usage of the LHAPDF6 library.

An alternative method of colour reconnection is explored in the `MoreQCDBased` tune [7]. Once again looking to reconnect partons through the minimisation of string length, this new method of colour reconnection employs a simplistic model of the colour rules of QCD to determine the formation of strings and introduce the concept of junctions in PYTHIA, illustrated in figure 1c. The minimisation is performed by iterating over all permitted connections between pairs, triplets or, in certain circumstances, quadruplets of dipoles and adopting those that lower the total string length.

The advantage of QCD-based model lies in its capacity to describe the formation of complex colour structures, beyond those available in LC models, and to extend upon the MPI-based method of string length minimisation by including QCD oriented rules for dipole colour connections. The implementation of colour singlet-state formation rules is performed by assigning each quark a colour index ranging from 1 to 9, with a distinct set of 9 anticolour indices for antiquarks. Gluons are assigned two different colour and anticolour indices, such that a total of 72 gluon states are possible. Quark-antiquark pairs are allowed to form between partons with matching colour-anticolour indices, representing the $1/9$ likelihood that an uncorrelated colour triplet-antitriplet pair will form a colour singlet. LC connections are incorporated in this model due to the correlation between the colour indices of a LC parton-antiparton pair. This concept is extended to allow for colour reconnection between separate MPI systems, through the pairing of uncorrelated partons that are randomly attributed matching colour indices. Furthermore, junctions are introduced in this model, which are permitted when two colour(anticolour) triplets can sum to form an anticolour(colour) triplet. For this purpose, the colour index groups {1,4,7}, {2,5,8} and {3,6,9} can create a junction, for example, by the colour states 1 and 4 appearing as an anti-7 state and forming a singlet with a parton of index 7.

Some corrections are applied to the QCD-based model to constrain the colour reconnections MPI system to more realistic topologies. Causal contact between dipoles is loosely required in the model via the `ColourReconnection:timeDilationPar`, whilst low mass structures - those falling beneath the invariant mass cut-off point `ColourReconnection:m0` - are replaced by pseudo-particles, to avoid reconnection issues that arise within the model at the lower end of the energy scale. The actual implementation of the new model is configurable via a series of other parameters, with the relevant documentation available in [5].

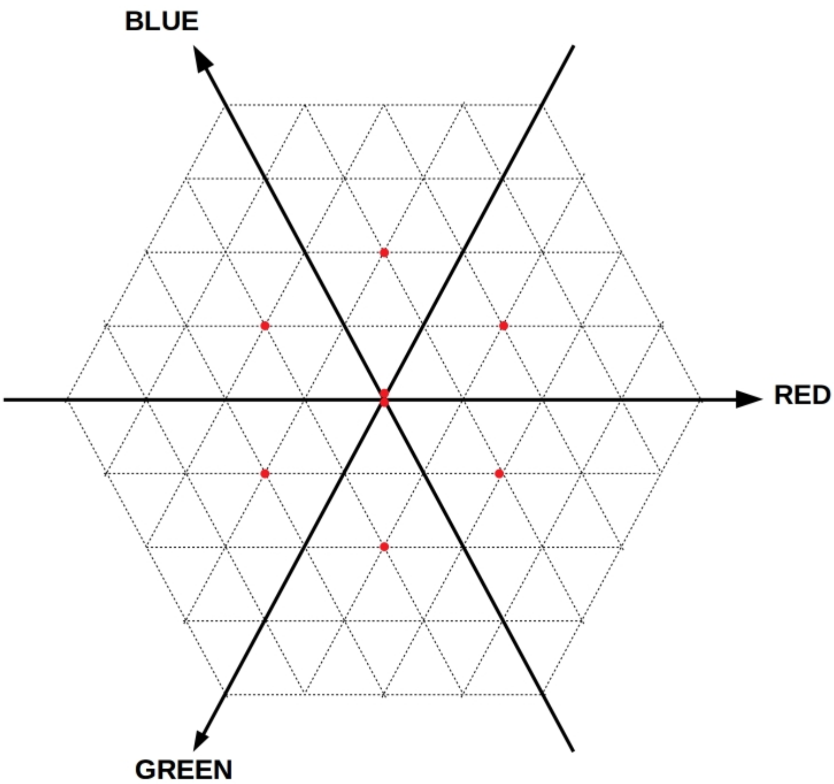

Figure 2: Representation of a two-dimensional colour space. The quantum numbers (p,q) form a colour multiplet that is sufficient to describe any set of points on the triangular grid. Exemplified are the points of the (1,1) octet. Adapted from [9].

2.1.2 Methods of Rope Hadronisation

Due to the size of the proton, MPIs in high energy *p-p* collisions will lead to many strings occupying a relatively small region of space. The interactions between these strings is the object of study of *rope hadronisation* models. None of these models are embedded in the default configuration of PYTHIA8.2, but they can be activated through a series of available parameters.

The `PartonVertex` class [8] provides a rudimentary set of configurations that define the shape and radius of the proton and transverse smearing of the partonic production vertices. This information, which is accessed through the `PartonVertex:setVertex` parameter, provides the basis for rope hadronisation, as it defines the proton profile at the point of collision, the spacial distribution of MPI vertices and the transverse smearing of partonic vertices from ISR and FSR. The two models of rope hadronisation explored in this analysis can be activated by turning on the `Ropewalk:doShoving` or the `Ropewalk:doFlavour` flags in combination with the `Ropewalk:RopeHadronisation` master switch. Generic rope hadronisation properties are also accessible once rope hadronisation has been turned on, namely the `Ropewalk:m0` and the `Ropewalk:r0`, which define an invariant mass lower limit for rope hadronisation and a string transverse radius parameter, respectively.

The concept of a rope describes the coherent behaviour of closely spaced, interacting strings. Ropes are formed when overlapping triplet-antitriplet strings in transverse space are fused. Thus, a rope constitutes the colour field formed by m quarks and n antiquarks. Despite the overall colour neutrality of the system, colours and anticolours are assumed to be randomly distributed and, as such, the overall colour charge of a rope can be determined by considering a random walk in colour space [9]. Any such random walk can thus be represented by the colour multiplet (p,q), where p and q represent the number of coherent colour and anticolour triplets, respectively, required to reach a certain point in colour space. Hence, (1,0) and (0,1) represent the colour and anticolour triplets and (1,1) represents the SU(3) octet (which is expected as the combination of a colour triplet with an anticolour triplet form all possible gluon states), as illustrated in figure 2.

Through QCD lattice calculations [10], the effective tension in the rope, $\tilde{\kappa}$ relative to the string tension, κ, is given by [11]

$$\frac{\tilde{\kappa}}{\kappa} = \frac{1}{4}(p^2 + q^2 + pq + 3(p+q)) \ . \tag{2}$$

As such, the energy density in the system increases for any combination of p and q. This description of Lund string interactions, known as the *Flavour Ropes* model, has shown greater success in describing the ratio of production of strange to non-strange hadrons in observations at ALICE [12].

The *Ropes Shoving* model [11] looks to describe how repulsive forces between ropes can lead to collective behaviour in *p-p* collisions. In this model, an event is divided in ranges of rapidity, δy, to define a series of transverse planes within which the distribution of Lund strings can be analysed. The proton profile is defined, using the `PartonVertex:modeVertex = 2` setting, as a two-dimensional Gaussian, with the collision occurring along the longitudal z axis at $z = 0$. As the longitudinal separation of connected partons grows, the tension within the string that binds them increases. The higher energy densities caused by regions of overlapping strings will create a dynamically evolving outward pressure, forcing strings away from the centre of the collision region as their transverse momenta rises. As the region continues to expand, the energy density and, consequently, the pressure gradient will decrease. This procedure is time iterative and evaluated between pairs of strings. Changes in transverse momenta, δp_T, are evaluated in time intervals δt, via the equation $\delta p_T = f\delta z\delta t$, where $\delta z = t\delta y$ is longitudinal length rapidity range of with δy at time t and f is the force per unit length between two strings, separated by a transverse distance d_T, defined as [13]

$$f(d_T) = \frac{g\,\kappa\,d_T}{R^2}\exp\left(-\frac{d_T^2}{4R^2}\right) \ . \tag{3}$$

Here, R is the time-dependent transverse width of the colour dipole energy distribution, κ is the effective string tension of overlapping strings and g is a scalable amplitude parameter. An ample set of variable parameters for this model, including δy, δt and g, are available in the PYTHIA documentation [14].

3 Event Generation and Selection

A method for event generation, selection and analysis, which is flexible to study any flavour of hadron production in PYTHIA , can be found in [15].

Hard process production of $c\bar{c}$ pairs in proton beam collisions, of centre of mass energy $\sqrt{s} = 13\,\mathrm{TeV}$ were generated using PYTHIA8.2, to study $\mathrm{D}^0 + \bar{\mathrm{D}}^0$, $\mathrm{D}_\mathrm{s}^+ + \mathrm{D}_\mathrm{s}^-$ and $\Lambda_\mathrm{c}^+ + \Lambda_\mathrm{c}^-$ production and dynamic properties. Event generation was performed using tunes of PYTHIA for each of the MPI models described in the previous section, namely: the default CR scheme, `MPIBased`; a leading colour model, `NoCR`; a QCD-based CR model, `MoreQCDBased`; and the two rope hadronisation methods, `Ropes` and `RopesShoving` (for flavour and shoving ropes, respectively). The charm-anticharm hadron pairs were forced to decay to pions and kaons, via the channels

$$\begin{gathered}
\mathrm{D}^0 \longrightarrow \mathrm{K}^- + \pi^+ \\
\mathrm{D}_\mathrm{s}^+ \longrightarrow \pi^+ + \phi^0, \quad \phi^0 \longrightarrow \mathrm{K}^+ + \mathrm{K}^- \\
\Lambda_\mathrm{c}^+ \longrightarrow \mathrm{p} + \mathrm{K}^0, \quad \mathrm{K}^0 \longrightarrow \pi^+ + \pi^- \ ,
\end{gathered}$$

with conjugate decays for their respective antiparticles.

Kinematics of all mother and daughter particles and measures of event multiplicity were stored in a data frame, for posterior analysis of variable distributions and correlations, along with kinematic properties of the hard process charm pair, at leading order (immediately after production) and in their final stages before hadronisation. Events were selected by having a single hadron pair and charm quark-antiquark pair at hadronisation correctly matched to the outgoing pair from the hard process. Table 1 lists the number of selected events in each hadronic channel, for each tune, along with a percentual fraction of generated events that passed selection.

Channel	`MPIBased`	`MoreQCDBased`	`NoCR`	`Ropes`	`RopesShoving`
D^0 (200k)	61364 (30.7%)	57292 (28.6%)	61222 (30.6%)	60661 (30.3%)	61969 (30.8%)
D_s (400k)	3897 (0.97%)	3709 (0.93%)	3824 (0.96%)	4213 (1.05%)	3978 (0.96%)
Λ_c (500k)	1041 (0.21%)	5167 (1.03%)	966 (0.19%)	1045 (0.21%)	1059 (0.20%)

Table 1: Table of number of events selected in each channel, during the generation process for each tune. Percentages represent the efficiency of the generation and selection method: the number of selected events over the number of generated (in brackets in left column).

It is of note that charmed hadrons are not guaranteed to be produced in each of the three channels in study, so this percentage does not represent the efficiency of the selection method, nor does it represent all the events in which two conjugate charmed hadrons are produced from the initial $c\bar{c}$ pair. It is, however, a rudimentary indication of the relative production of hadron pairs between tunes and between hadronic channels, hinting at an increase in baryon production for the `MoreQCDBased` tune and increased strangeness in the `Ropes` model.

4 Analysis and Results

All final particles (charged and neutral) were considered as a measure of global event multiplicity, as presented in the distributions of figure 3. In the current study, no cut in rapidity is applied at the particle level and the total number of final particles is not restricted those with charge. Therefore, the global event multiplicity is not representative of the number of charged tracks withing a given pseudorapidity range, as measured by experiments, although it remains largely correlated.

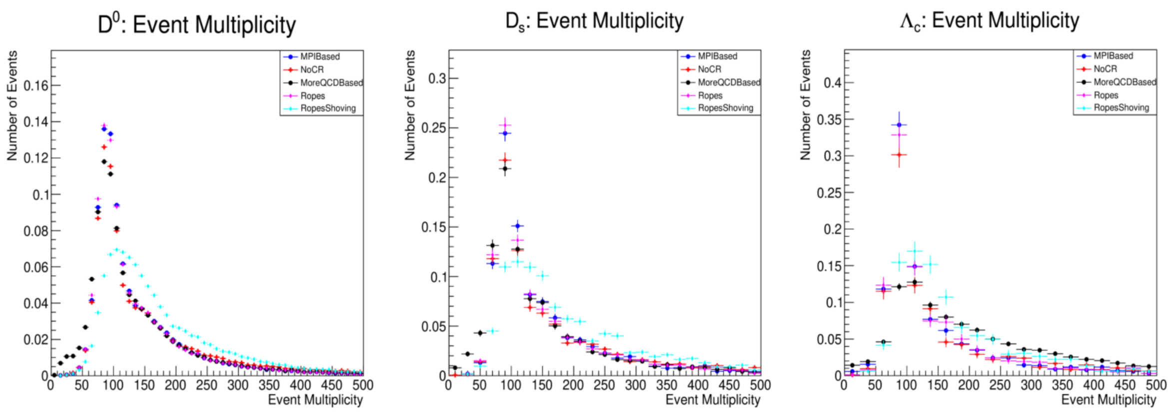

Figure 3: Normalised distributions for each tune of the number of final particles per event in the D^0, D_s and Λ_c channels (left, center and right, respectively).

Although the `NoCR` and `Ropes` tunes have very similar distributions in global multiplicity to that of the default `MPIBased` method, the `RopesShoving` and `MoreQCDBased` tunes present some deviations:

the former configuration generates events with more final particles, producing wider distributions; whilst the latter only follows this trend for Λ_c pair production, slightly favouring low multiplicity events in the mesonic channels.

Methods for single variable distributions are included in the analysis software, however only minor differences in particle kinematic properties are observed. In parallel, the physical processes described by MPI, CR and fragmentation models are embodied in the properties of the charm hadronic states and do not affect simulations of particle resonances and decays. However, hadron dynamics and correlations between mother and daughter particles become useful when defining kinematic ranges for experimental data comparisons and preselection of daughter tracks. On the other hand, hadron-antihadron correlations are of greater interest in probing heavy flavour production mechanisms and will continue to be measured by ALICE in *p-p* and *Pb-Pb* collisions over the coming years. None of the models discussed include mechanisms that affect the rotational symmetry of events, however the rapidity dependence of the `RopesShoving` model is reflected in the flatness of the distribution for the pseudorapidity separation between heavy flavour hadrons, as presented in figure 4. The process of generation of the $c\bar{c}$ pair is inherited from default configurations, however the interaction between gluon strings manifests in the aformentioned deviation, as visible in the pseudorapidity separation for the charm pair in the immediacy of the hadronisation stage.

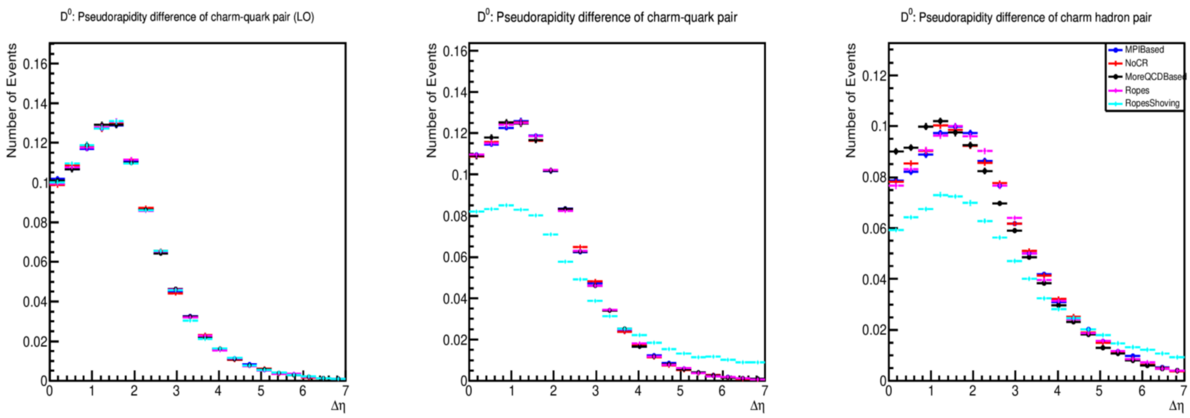

Figure 4: Normalised distributions for each tune of the pseudorapidity separation, $\Delta\eta$, between the charm-anticharm quarks at leading order (upon generation), immediately before hadronisation and confined in the mesonic $\mathrm{D}^0\bar{\mathrm{D}}^0$ state (left, center and right, respectively).

The multiplicity dependent cross section ratios for $\mathrm{D_s}/\mathrm{D}^0$ and Λ_c/D^0 are presented in the distributions of figure 5, along with the p_T-differential cross section ratios, in ranges of multiplicity, presented in figures 6 and 7.

The $\mathrm{D_s}/\mathrm{D}^0$ ratio is not heavily dependent on global event multiplicity or transverse momentum. Across the multiplicity ranges, the ratio varies only slightly between the tunes, with the `Ropes` model - already shown to enhance strange flavour content - producing the highest values. Even at low momenta, there is a clear distinction in the relative production of $\mathrm{D_s}$ mesons when flavour rope formation is enforced, potentially due to the increase in effective string tension, opening up low energy systems to greater $s\bar{s}$ production. At higher values of p_T, this distinction appears to reduce, as strange quark production in regular Lund string fragmentation becomes more likely.

Resemblances of collective behaviour are more evident in the multiplicity and p_T-dependent charmed baryon to meson ratios. The `MoreQCDBased` distribution for Λ_c/D^0 in figure 5 shows a dramatic increase in relative baryonic production with higher multiplicities, as expected due to its description of junctions and other complex topologies, establishing connections between 3 or more partons and modifying the p_T dependence, to favour low momentum baryon formation, as demonstrated in the higher multiplicity distributions of figure 7.

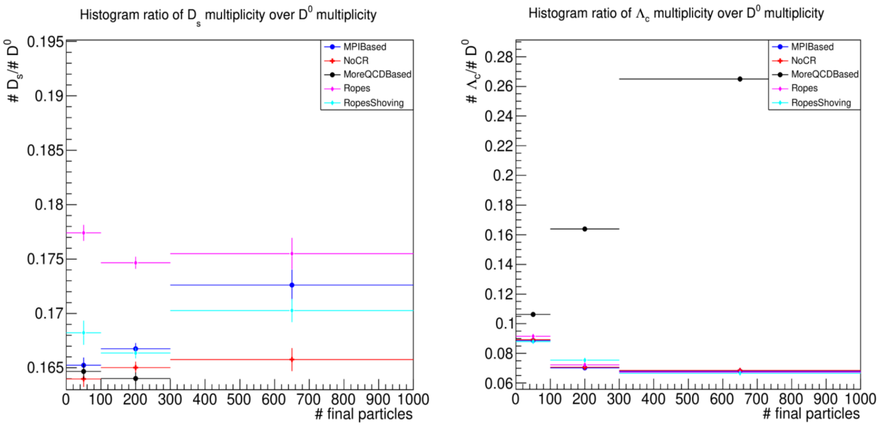

Figure 5: The cross section ratios as a function of multiplicity for $\mathrm{D_s}/\mathrm{D}^0$ (left) and $\Lambda_\mathrm{c}/\mathrm{D}^0$ (right).

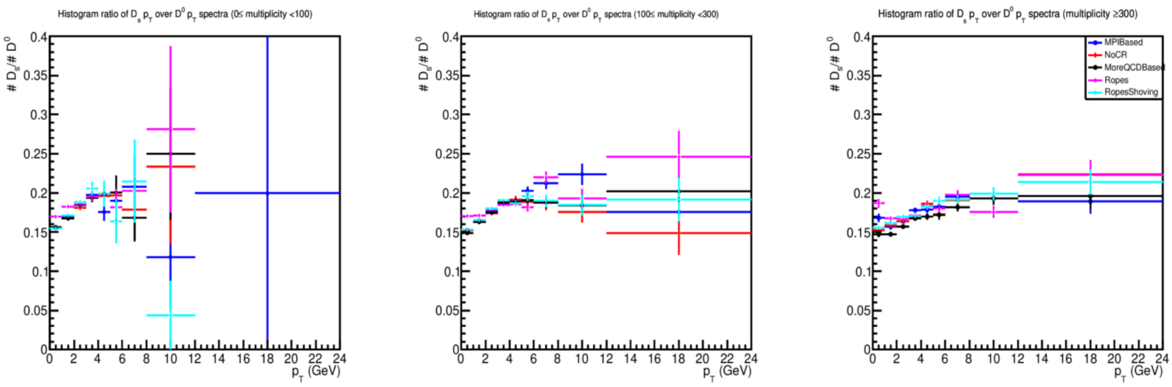

Figure 6: The p_T-differential cross section ratio for $\mathrm{D_s}/\mathrm{D}^0$, in low, medium and high multiplicity events (left, center and right, respectively).

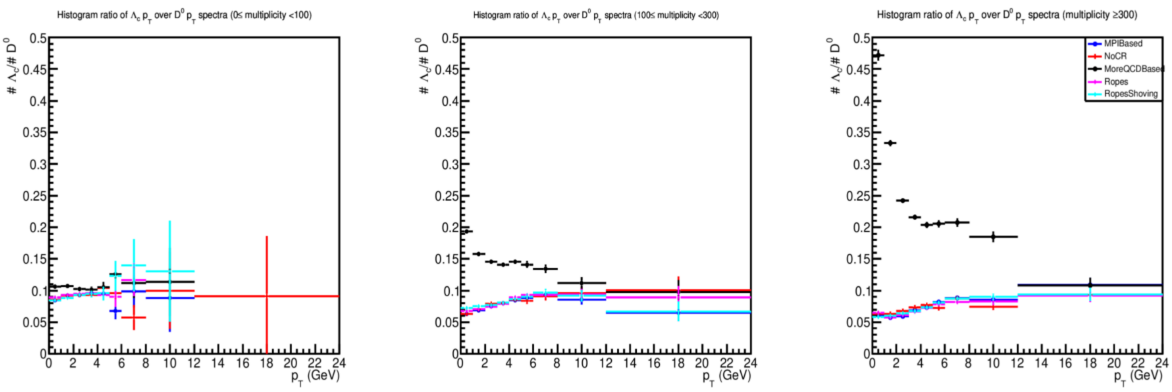

Figure 7: The p_T-differential cross section ratio for $\Lambda_\mathrm{c}/\mathrm{D}^0$, in low, medium and high multiplicity events (left, center and right, respectively).

5 Conclusion

The production of heavy flavour hadrons was used as a probe to investigate varied models of multiple parton-parton interactions in PYTHIA8.2 generated *p-p* events at $\sqrt{s} = 13\,\mathrm{TeV}$. A preliminary analysis of hadronic kinematic correlations and production ratios was performed to test the models for descriptions of collective behaviour in *p-p* collisions with MPIs.

The models studied focus primarily on the description of colour flow and Lund string interactions across a set of MPI systems. Rope hadronisation methods for the coherent behaviour of overlapping gluonic strings predict higher energy densities that allow for increased strange content, reflected in the strange to non-strange hadronic production ratio, $\mathrm{D_s}/\mathrm{D}^0$. Evidence of strong modification of heavy flavour baryon production has been presented, as a consequence of QCD-based colour reconnection processes and junction formation.

This study is primarily focused on the PYTHIA event generator and its tunes. Experimentally-oriented fine-tuning of the developed tool, for event selection, variable definitions and kinematic ranges, must be performed to produce realistic predictions for ALICE measurements. Furthermore, studies of jet fragmentation and the identification other observables that may discriminate between each models' effectiveness in describing collective behaviour could be significant in investigating the physical properties of systems produced in MPI *p-p* collisions. Finally, PYTHIA tunes including models of colour reconnection and rope hadronisation must be appropriately configured to be investigated for elements of collective behaviour and to be compared to ALICE measurements.

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Appendix

A Tune Settings

Parameters	MPIBased	MoreQCDBased	NoCR	Ropes	RopesShoving
Tune:PreferLHAPDF	2	2	2	2	2
Tune:pp (Monash13)	14	14	14	14	14
ColourReconnection:reconnect	On (def)	On (def)	Off		
ColourReconnection:mode	0 (def)	1			
ColourReconnection:timeDilationPar		0.18 (def)			
ColourReconnection:junctionCorrection		1.2 (def)			
PartonLevel:earlyResDec			Off (def)		
MultiPartonInteractions:pT0Ref	2.28 (def)	2.15	2.30		
PartonVertex:setVertex				On	On
PartonVertex:protonRadius				0.7 (def)	0.7 (def)
PartonVertex:emissionWidth				0.1 (def)	0.1 (def)
Ropewalk:RopeHadronisation				On	On
Ropewalk:doShoving				Off (def)	On
Ropewalk:doFlavour				On	Off (def)
Ropewalk:r0				0.5 (def)	0.41
Ropewalk:m0				0.2 (def)	0.2 (def)
Ropewalk:beta				0.1	0.2 (def)
Ropewalk:rCutOff					10
Ropewalk:limitMom					On (def)
Ropewalk:pTcut					2 (def)
Ropewalk:gAmplitude					10
Ropewalk:gExponent					1 (def)
Ropewalk:deltat					0.1 (def)
Ropewalk:deltay					0.1
Ropewalk:tShove					1 (def)
Ropewalk:tInit					1.5 (def)

Table A.1: Parameterisation of tunes employed in PYTHIA configuration. Unfilled cells imply that the parameter is not of relevance to the model, such that either the tune inherits default configurations or the setting has no effect on the overall configuration (e.g. if Ropewalk:doShoving is not turned on, all the parameters regarding the rope shoving mechanism have no relevance). Values with (def) in front of them are of relevance to the model and inherit the default value for PYTHIA8.2.