Azimuthal Correlation Studies of Charm and Anti-Charm at LHC Energies

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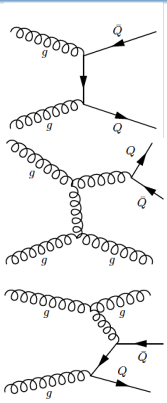
Heavy Flavour Partons

Heavy flavour quarks are produced through hard scattering and experience the whole event evolution. So they are probes for:

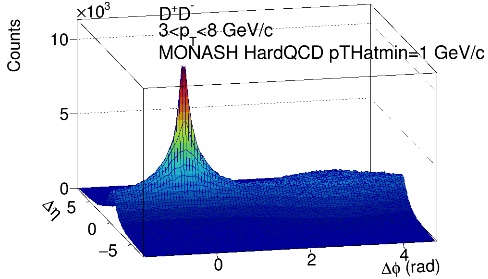
- Testing of pQCD
- Studies of QGP
- Hadronisation studies

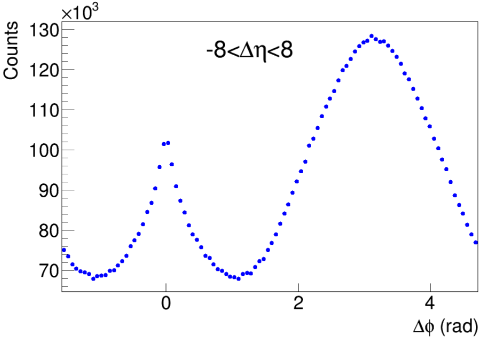
We are studying the hadronisation of the charm quark by looking into the the azimuthal correlations of the $D^{\pm}$ and $\Lambda_c^{\pm}$ hadrons.



Souza et al. 2015

Azimuthal Angular Correlation





The azimuthal angle difference distribution is sensitive to:

- Production mechanism
- In medium interactions
- Hadronisation

The azimuthal angular correlation is the distribution of the difference in azimuthal angle between the trigger and the associate particle, $\Delta\phi = \phi_{tr} - \phi_{as}$.

Hadronisation in Pythia

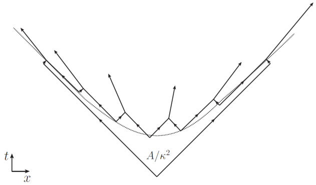
Hadronisation can occur through

- Recombinations, which dominate at low p_T.
- Fragmentations, which dominate at high p_T.

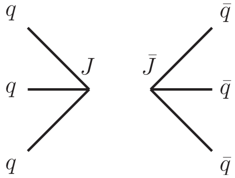
In PYTHIA

- In MONASH partons from different MPIs are allowed to reconnect in order to minimize string length.
  Agreement with the $\langle p_T \rangle (n_{Ch})$.
  Underestimates baryon production.
- Junctions introduction of recombination nodes that allowed the direct combination of partonts to form hadrons.
  Agrees in baryon production.
  Underestimates strangeness yield.

Lund String Model



Bierlich et al. 2022

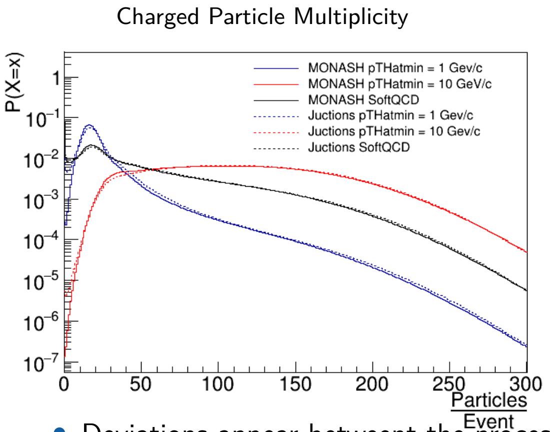


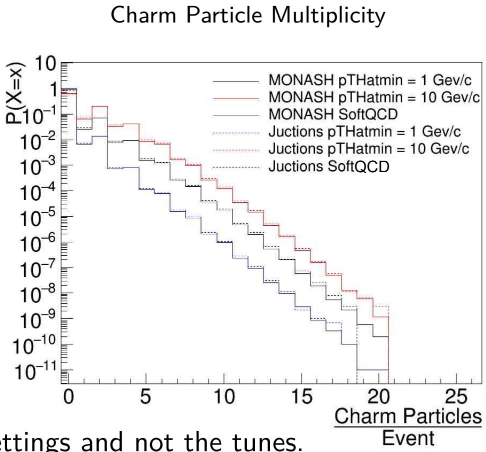
Christiansen et al. 2015

Parameters

- In this simulation we use a simple PYTHIA script to produce p-p collisions at $\sqrt{s} = 14\,TeV$.
- Tunes
  1. MONASH (default)
  2. Junctions
- Process settings
  1. Soft QCD (inelastic processes only)
  2. HardQCD pTHatmin = 1 GeV/c
  3. HardQCD pTHatmin = 10 GeV/c
- Particles decay off: $D^{+}, D^{0}, D^{*}(2007)^{0}, D_s^{*+}, \eta_c, J/\psi, \chi_{c2}(1P), \Lambda_c^{+}, \Sigma_c^{++}, \Sigma_c^{+}, \Sigma_c^{0}, \Xi_c^{+}, \Xi_c'^{+}, \Xi_{cc}^{+}, \Xi_{cc}^{++}, \Omega_{ccc}^{++}, \Omega_c^{0}, \Delta^{++}, \Delta^{0}, \Sigma^{0*}, \Sigma_c^{++*}$.
- Kinematic Acceptance
  1. $p_T \geq 0.15\,GeV/c$
  2. $-4 \leq \eta \leq 4$
- We simulated on average 10^{10} events per simulation.

Tunes Comparison

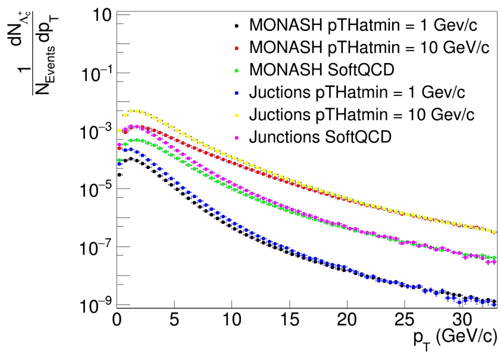




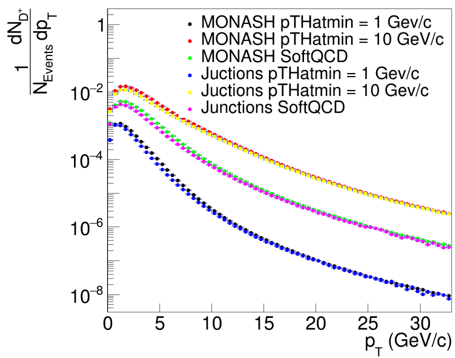
- Deviations appear betweent the process settings and not the tunes.
- Expected since the parameters that affect these observables are common between the tunes

Baryons and Mesons

Λ_c^+ Spectrum



D^+ Spectrum

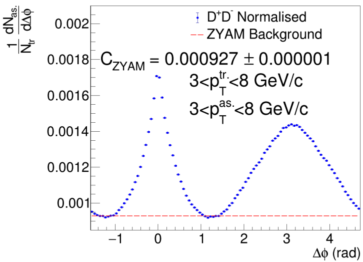


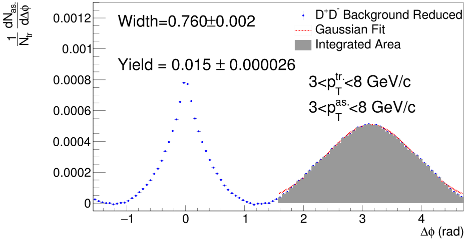
- The Junctions tune increases significantly the baryon production.
- The two tunes converge at higher p_T where hadronisation through fragmentation dominates.

Data Analysis Procedure

For this analysis:

1. We create azimuthal correlation plots by calculating the azimuthal difference between the pair of trigger and associate particles formed within the event.
2. Normalise over the number of triggers.
3. Reduce the background considering the Z.Y.A.M. method.
4. Calculate the integral in the area of interest $[-\pi/2, \pi/2]$ and $[\pi/2, 3\pi/2]$.
5. Fit the peak using the χ^2 minimum method with a Gaussian to calculate the width.





p_T Intervals and Particle Pairs

We follow this procedure for:

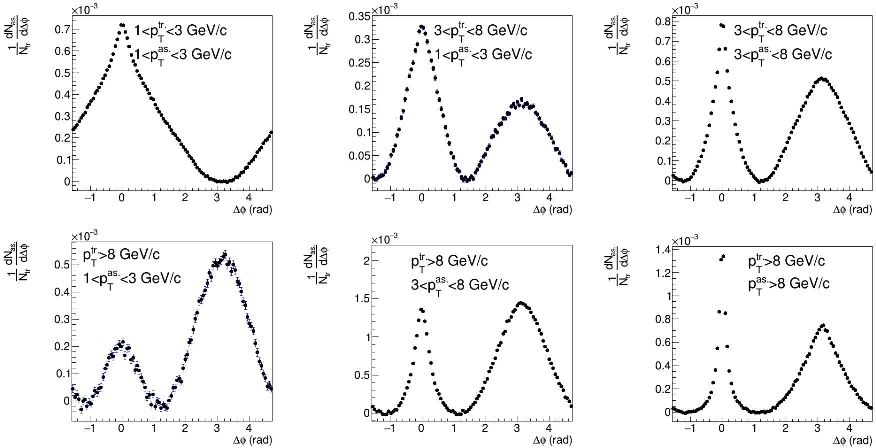
Range	p_T (GeV/c)
Low	$1 \leq p_T < 3$
Intermediate	$3 \leq p_T > 8$
High	$p_T \geq 8$

Baryon Trigger	Meson Trigger
$\Lambda_c^+ \Lambda_c^+$	$D^+ D^+$
$\Lambda_c^+ \Lambda_c^-$	$D^+ D^-$
$\Lambda_c^+ D^+$	
$\Lambda_c^+ D^-$	

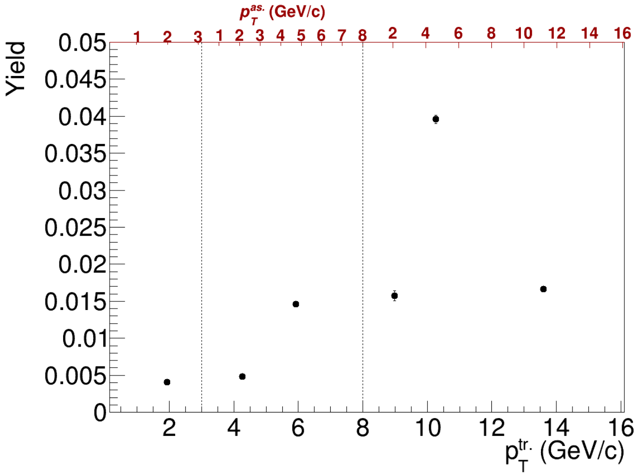
Trigger p_T	Associate p_T
Low	Low
Intermediate	Low
Intermediate	Intermediate
High	Low
High	Intermediate
High	High

Correlation Plots

The ZYAM reduced correlations for the D^+D^- pair from the MONASH SoftQCD.



The Interleaved Axis Plot

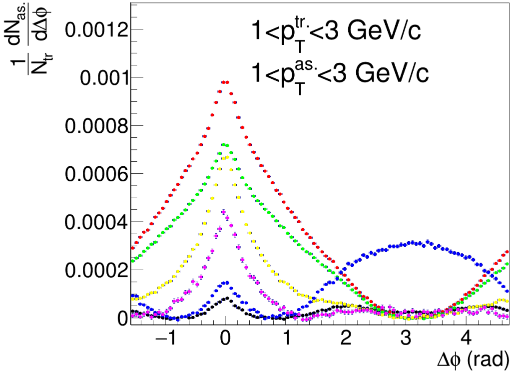


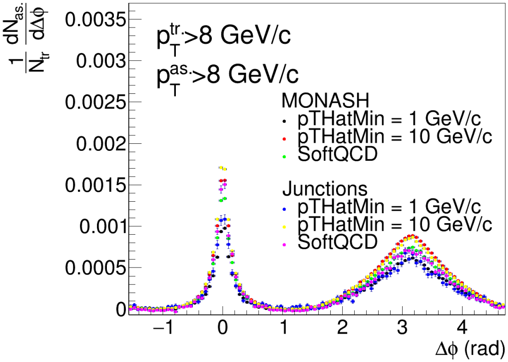
Away side yield of the D^+D^- pair from MONASH SoftQCD.

The calculation was done in 10 data batches:

- Datapoints $\rightarrow$ average from batches.
- Error bars $\rightarrow$ standard deviation from batches.

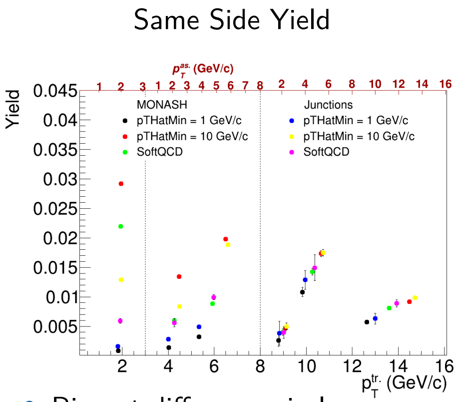
D^+D^- Correlations

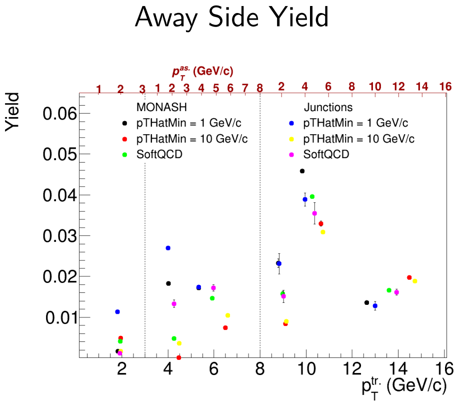




- The expectations align at higher p_T.
- Only the Junctions pTHatmin=1 GeV/c produces an away side peak at low p_T.

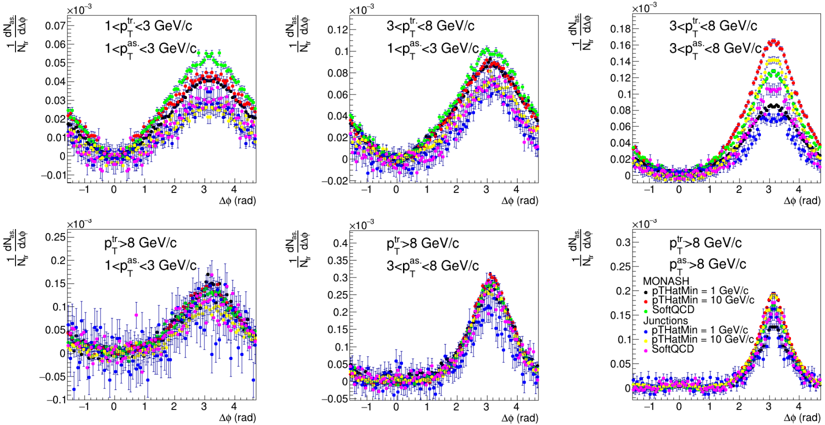
D^+D^- Yields





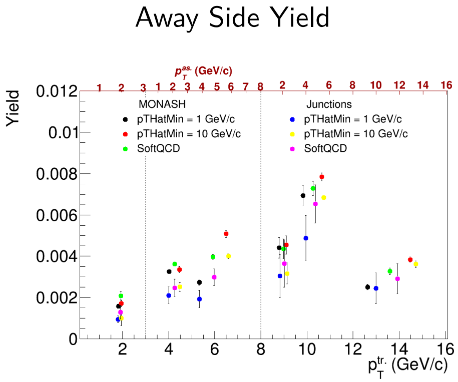
- Biggest differences in low p_T.
- The smaller yield expected in Junctions in combination with the fact that no underproduction of charm was observed suggests that the charm hadronises into a different hadron in Junctions.

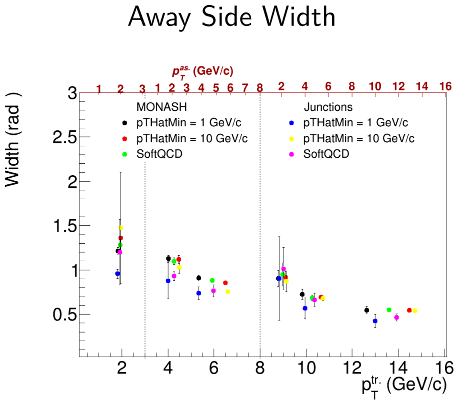
D^+D^+ Correlations



- We notice that only away side peaks are expected.

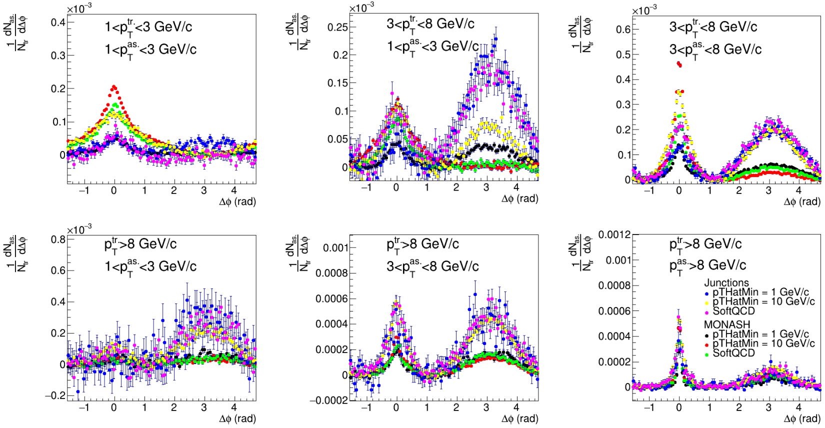
D^+D^+ Yield and Width





- Yields are about an order of magnitude smaller than the same sign cases.
- Widths follow a downward trend p_T.

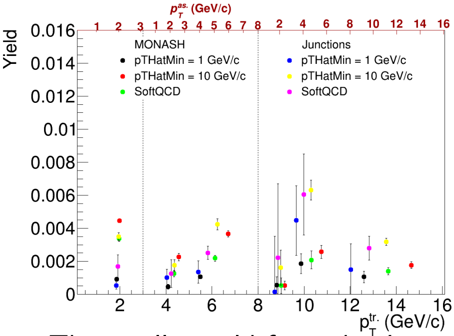
$\Lambda_c^+\Lambda_c^-$ Correlations



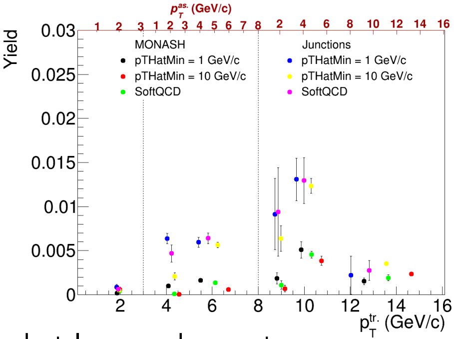
- At low p_T MONASH produces larger peaks
- Significant deviations showing at high p_T trigger intermediate p_T associate.

$\Lambda_c^+\Lambda_c^-$ Yields

Same Side Yield

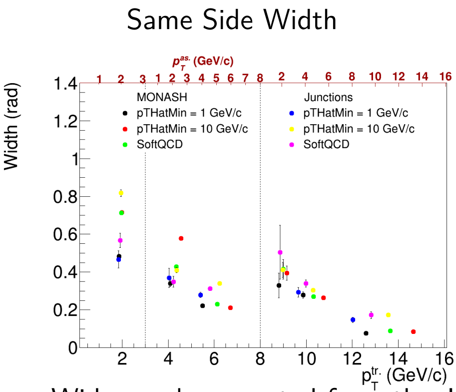


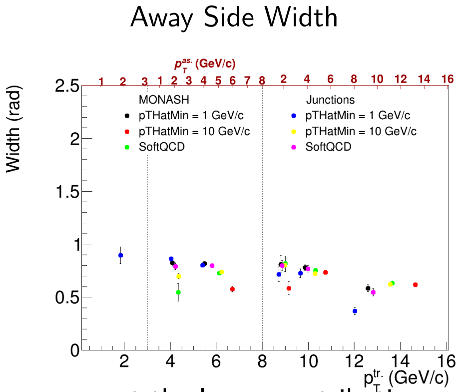
Away Side Yield



- The smaller yield from the Junctions observed at low p_T does not mean underproduction of $\Lambda_c^{\pm}$.
- Recombination contribution in Junctions so large that even suppressed (at high p_T) produces significant deviations.

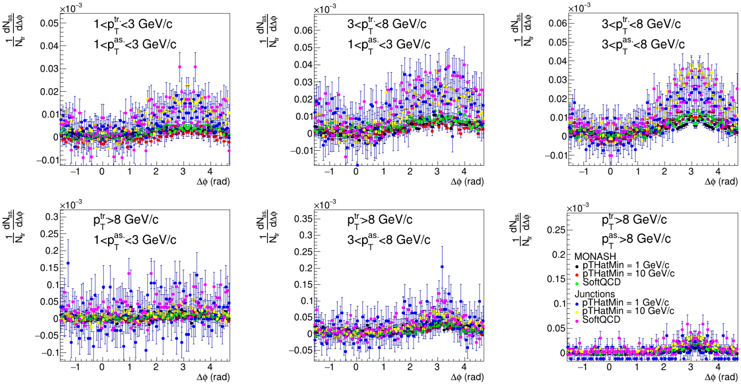
$\Lambda_c^+ \Lambda_c^-$ Widths





- Wider peaks expected from the Junctions tune suggest the larger contribution from recombinations.
- Wider peak imply larger uncorrelated background that explains the smaller yields observed.

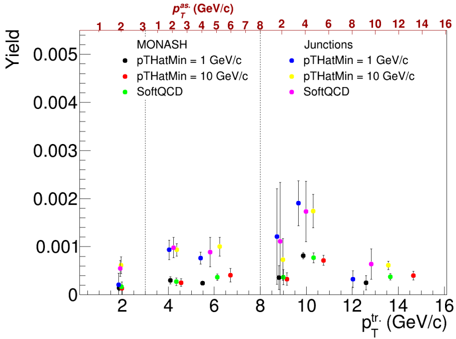
$\Lambda_c^+ \Lambda_c^+$ Correlations



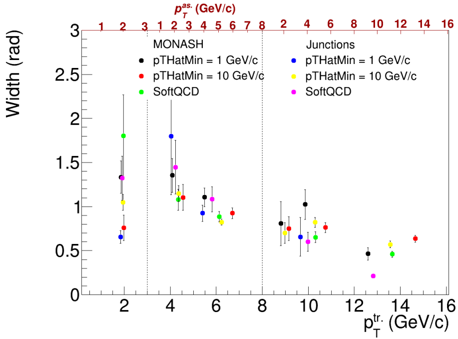
- Here is were the data size issues appear. We have to remember for a $\Lambda_c^+ \Lambda_c^+$ correlations 2 charm pairs need to be produced and both of them need to hadornise into a baryon.

$\Lambda_c^+\Lambda_c^+$ Yield and Width

Away Side Yield

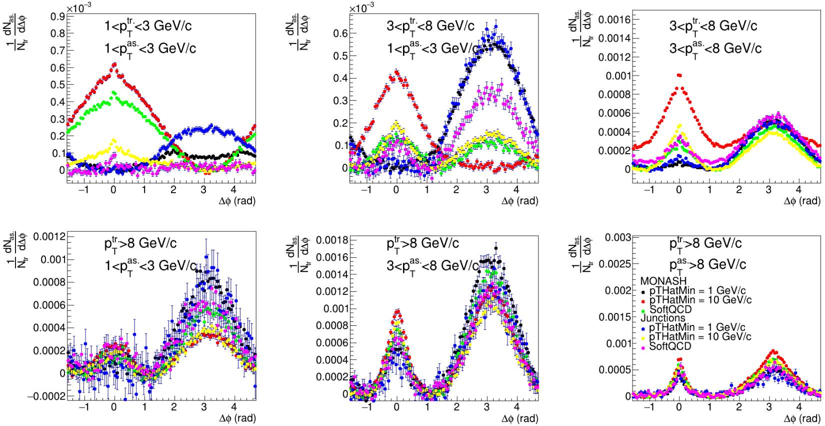


Away Side Width



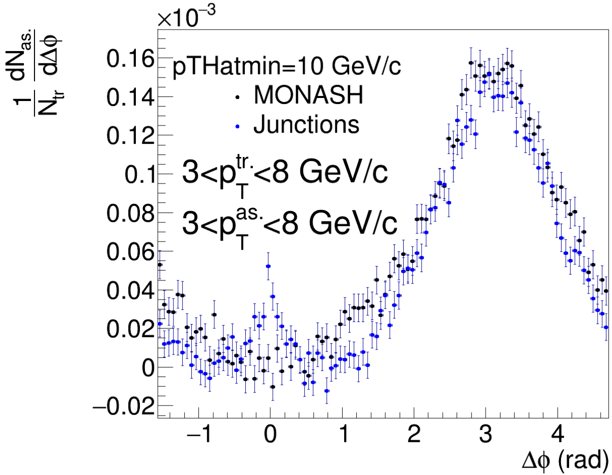
- Larger yields expected from the Junctions tune.
- For the widths more data is needed! For the pTHatmin = 10 GeV/c where it is safe to comment we observe the Junctions expects larger widths.

$\Lambda_c^+ D^-$ Correlations



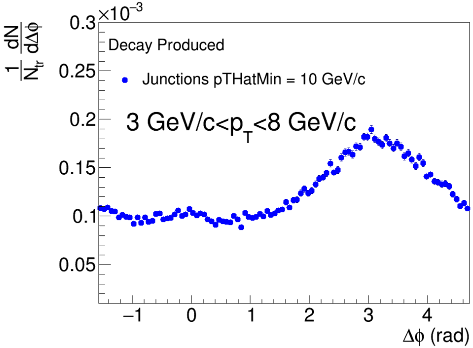
- We observe very similar patterns with the mesons case emerging.

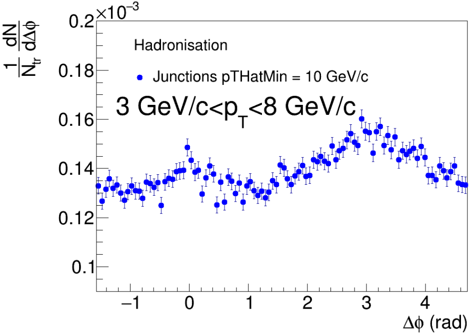
$\Lambda_c^+ D^+$ Correlations



- For the first time so far we observe the formation of an near side peak at same sign correlations.

Further Investigation of the Near Side Peak of $\Lambda_c^+ D^+$.





- This near side peak may originate from a diquark-quark topology which is implemented only in the Junctions tune.

Summary

- Common patterns
  1. In opposite sign correlations, only the Junctions pTHatmin=1 GeV/c expects an away side peak at low p_T
  2. There are no near side peaks at same sign correlations, except in the Junctions tune in the $\Lambda_c^+ D^+$ correlations
  3. The narrowest peaks are expected at high p_T correlation
- For the mesons we observed larger yields from the MONASH at lower p_T
- For the baryon the recombinations resulted in a less "correlated" production at low p_T, and at high p_T (although suppressed) recombinations contribution is still considerable.
- In the baryon meson correlation we observed very similar patterns with the mesons case except the aforementioned same sign correlations.

Future Research

- Same analysis in heavy ions where modifications in the distributions are expected.
  1. Better understanding of the underlying physics implemented in the models.
  2. Information of how the interactions with the QGP are simulated in the model.
- Study as a function of multiplicity.
  1. Different number of partons different effect of recombinations.
  2. Rule out if the away side peak absence is caused from interactions. with parton shower.

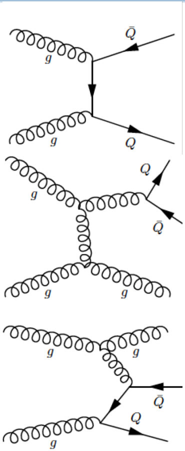
Thank you
for your attention!

Back up Slides

Heavy Flavour Production

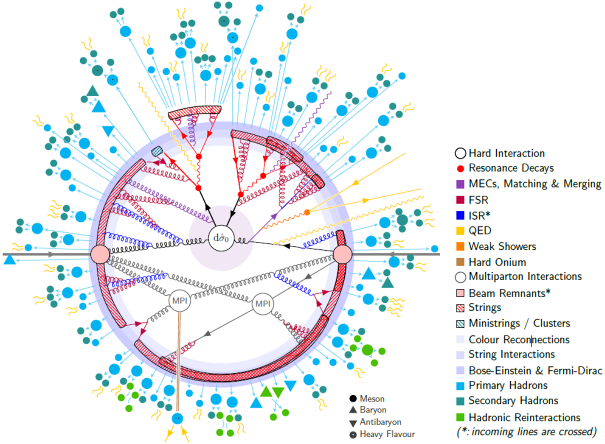
They are produced through:

- Pair creation
- Gluon splitting
- Flavour excitation



Souza et al 2015

Factorisation Approach

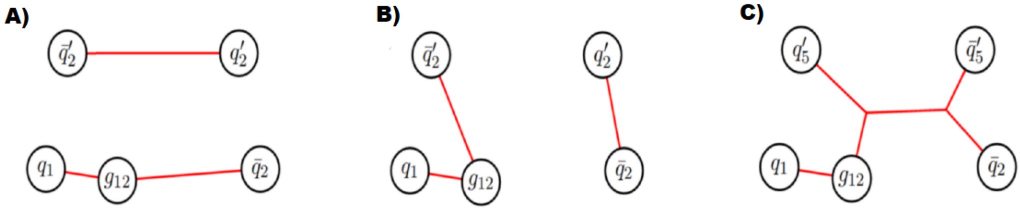


Event step by step:

1. Hard Scattering
2. Resonance
3. Initial/Final State Radiation
4. Multi-Parton Interactions
5. Hadronisation
6. Decays

Bierlich et al. 2022

Original vs MONASH vs Junction Reconnection



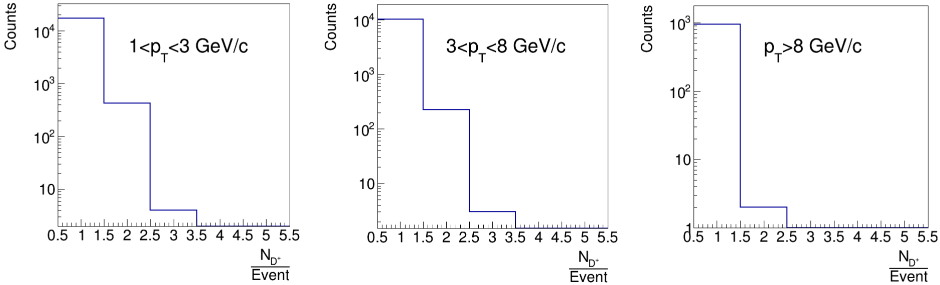
Christiansen et al. 2015

A) Each MPI evolves indepedently. (Original)

B) Reconnection between partons from different MPIs in order to minimise string length. (MONASH)

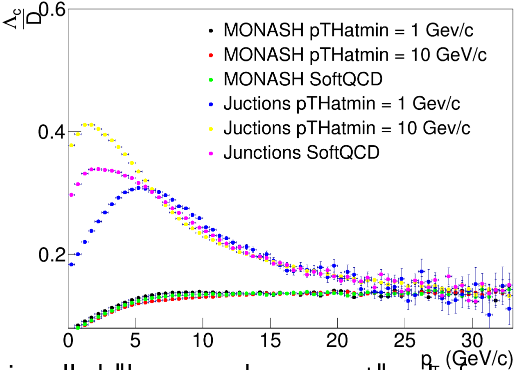
C) Reconnection between partons from different MPIs with beyond leading order string topologies. (Junctions)

Number of D^+ per Event



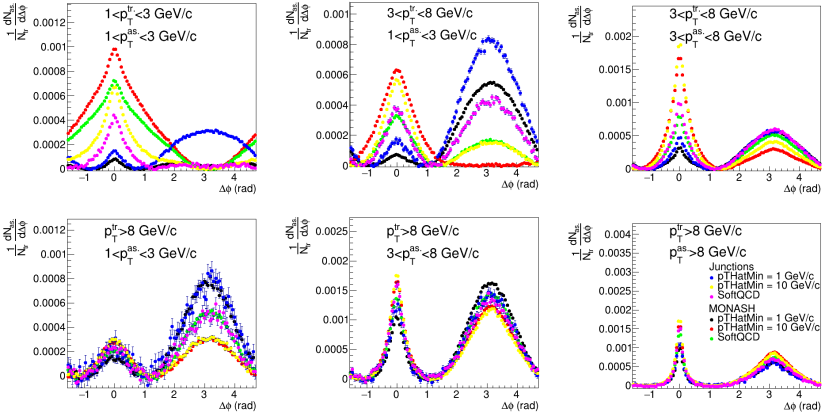
- We observe that the number of event with $N_{D^+}/Event > 1$ is about an order of magnitude less.

Baryon to Meson Ratio



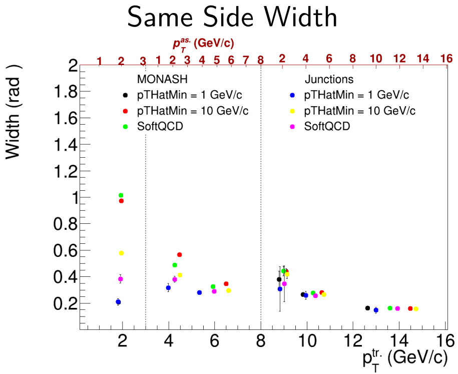
- We observe what is called "baryon enhancement" only from the Junctions tune while for the MONASH where hadronisation occurs only through fragmentation a fla line is observed.
- At high p_T where fragmentations dominate the expectations from the tunes align.

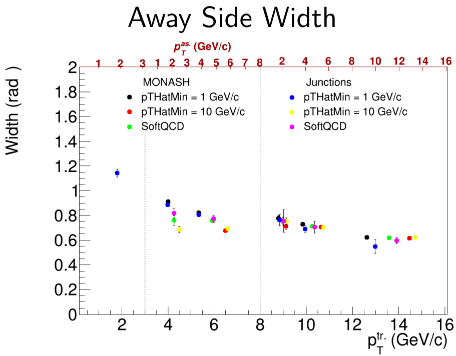
D^+D^- Correlations All p_T Intervals



- The expectations align at higher p_T.
- Only the Junctions pTHatmin=1 GeV/c produces an away side peak at low p_T.

D^+D^- Widths

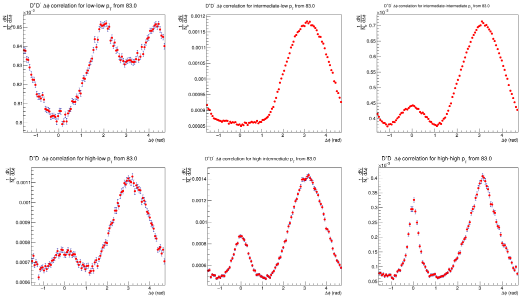




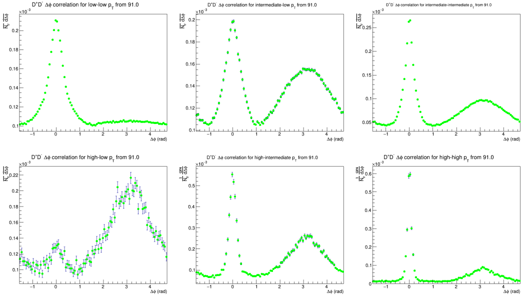
- Missing data points on the away side correspond to missing peaks.
- Expected downward trend is observed.
- Near Side pTHatmin $= 1$ GeV/c fluctuates around 0.3 rad. This suggests that the origin mechanism of this peak has negligible non-perturbative contributions. The most simple is decay.

D^+D^- Mechanism MONASH pTHatmin=1 GeV/c

Hadronisation

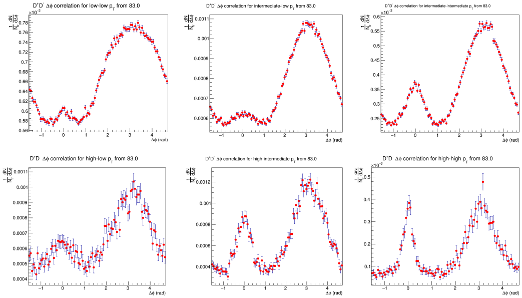


Decay

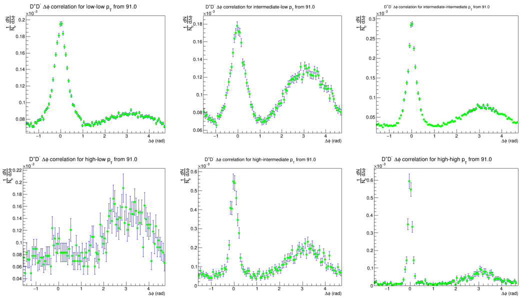


D^+D^- Mechanism Junctions pThatmin=1 GeV/c

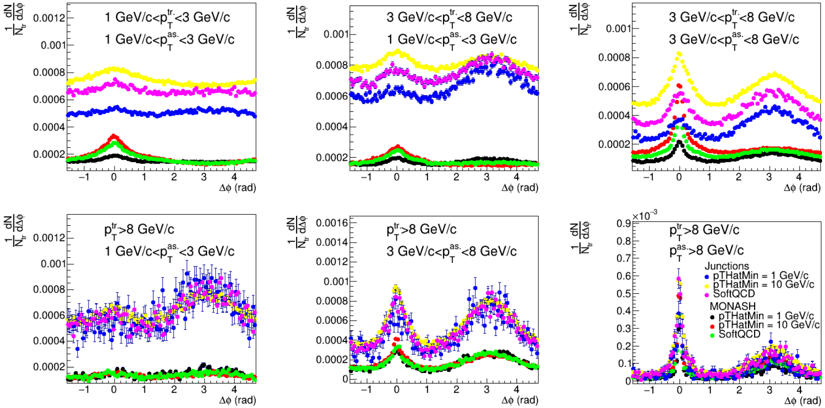
Hadronisation



Decay

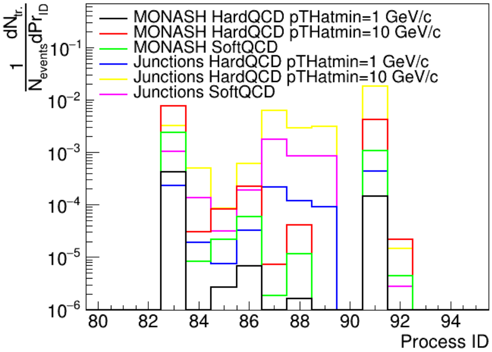


$\Lambda_c^+\Lambda_c^-$ Correlations Prior to ZYAM Reduction.



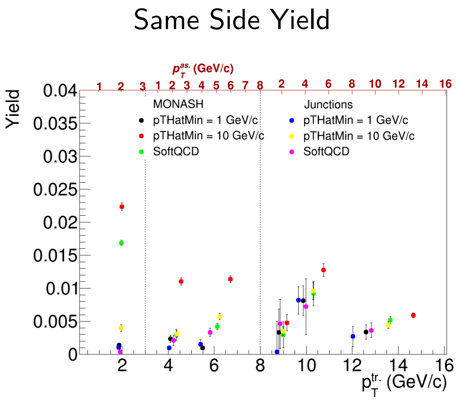
- We observe that prior to the uncorrelated background reduction the Junctions sits a lot higher than the MONASH at low p_T with their scale differences converging at high p_T.

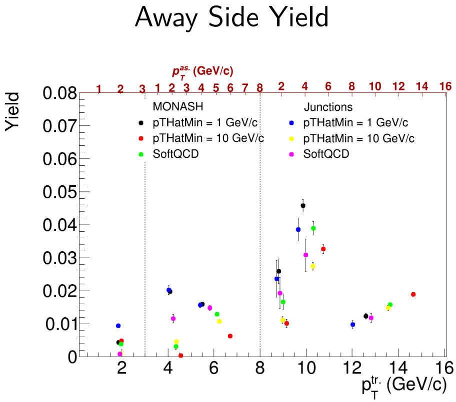
Λ_c^+ Production Mechanism



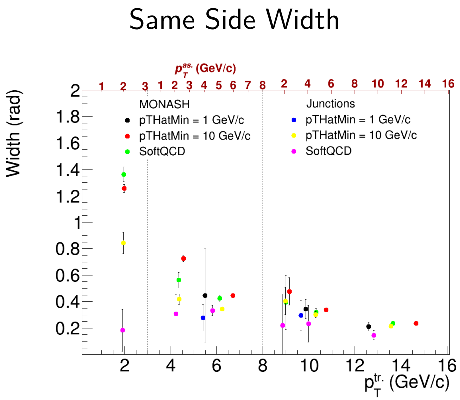
- Large contributions of decays (91) in Junctions, suggest the production of charm is so uncorrelated deu to increased fitdown.
- Nevertheless we still see increased contributions from mechanism 86-89 which are recombinations in Junctions.
- Main production in MONASH is 83 which corresponds to string fragmentation in the case of the baryon through diquarks.

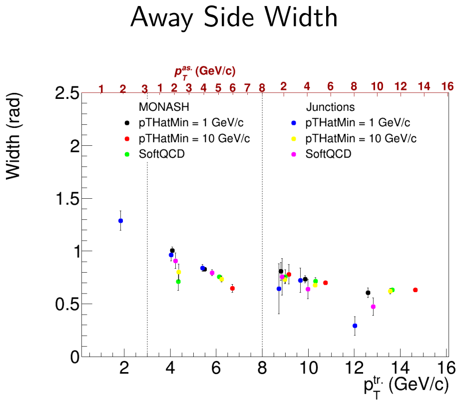
$\Lambda_c^+ D^-$ Yields



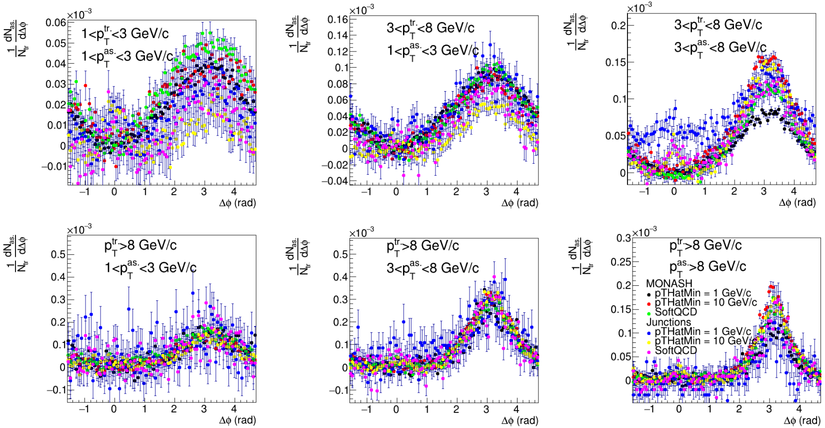


$\Lambda_c^+ D^-$ Widths





$\Lambda_c^+ D^+$ Correlations All p_T *intervals*



- The away side is very similar with the away side of the D^+D^+ case.
- In the near side from the Junctions tune we observe peaks forming from the Junctions tune.

$\Lambda_c^+ D^+$ Yield and Width