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Studying the role of ***multi-parton interactions*** in ***doubly-heavy hadron*** formation

Ulrik Egede, **Tom Hadavizadeh**, Minni Singla,
Peter Skands, Mika Vesterinen, Eliot Walton

MONASH University

Outline

Today I will give an overview of our recent studies into ***doubly-heavy hadron*** production

This project has been a collaborative effort between **LHCb** and **Pythia** colleagues

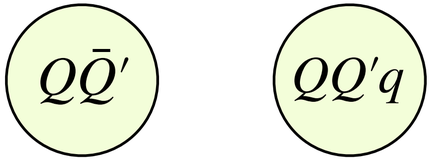
U. Egede, T. Hadavizadeh, M. Singla, P. Skands, M. Vesterinen
Eur. Phys. J. C 82, 773 (2022)
arxiv:2205.15681

Today's outline

1. Efficiently simulating heavy quarks with **Pythia**
2. Predicting doubly-heavy hadron production
3. What should we measure experimentally?

What are doubly-heavy hadrons?

Doubly-heavy hadrons contain two heavy b and/or c quarks

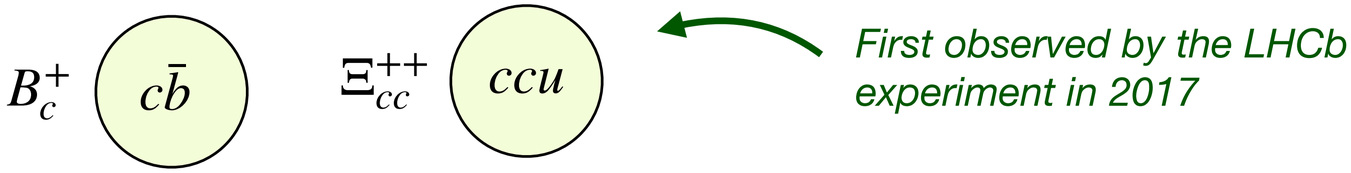


Meson **Baryon**

These hadrons are relatively rare

- They require ***two*** pairs of heavy quarks to be produced

$b\bar{b}c\bar{c}$ $c\bar{c}c\bar{c}$

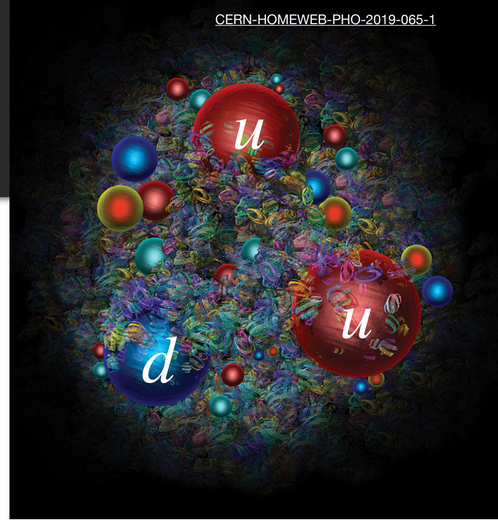


First observed by the LHCb experiment in 2017

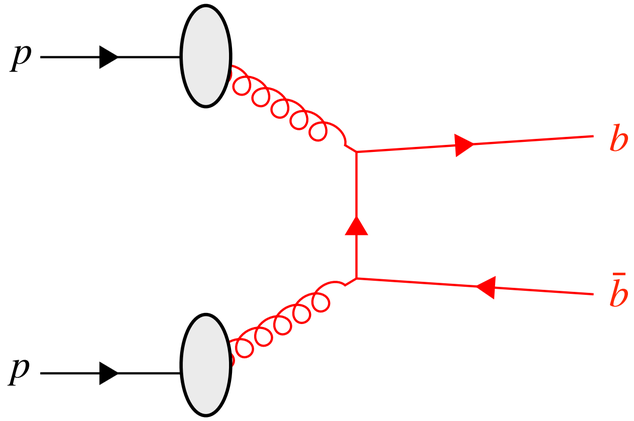
Due to their larges masses the b and c quarks are only produced at high energy scales

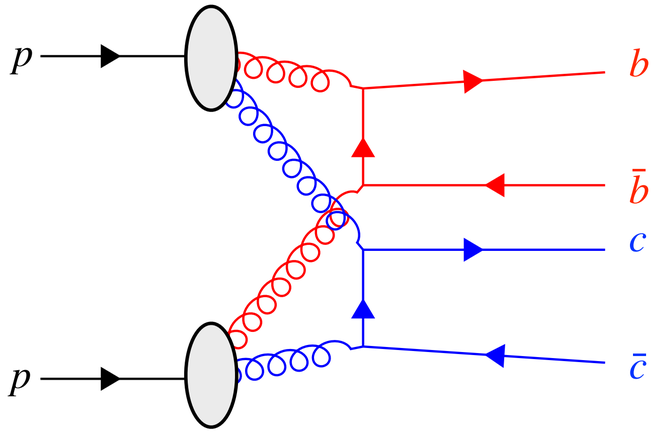
- They uniquely contain ***two*** probes of perturbative Quantum Chromodynamics

What are multi-parton interactions?



- When protons collide at the LHC, pairs of their constituents (***partons***) can interact





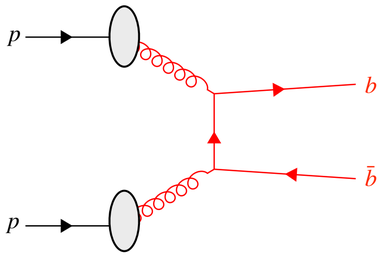
- It's also possible for multiple pairs of partons to interact within the *same* proton-proton collision

- Measurements have shown that multiple pairs of heavy quarks can be produced in different parton-partons interactions

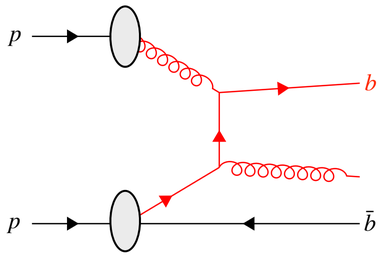
Simulating heavy quarks

- Proton-proton collisions at the LHC can be simulated with ***Event Generators*** e.g. Pythia
- Heavy quarks are produced early on in the evolution due to perturbative QCD

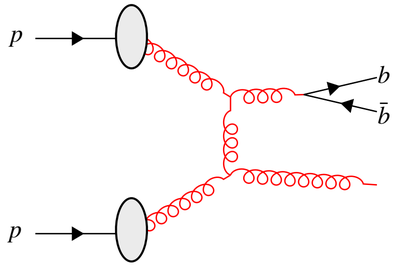
Pair creation



Flavour excitation



Gluon splitting



- Generating inclusive samples can be ***slow***
  - Heavy quarks can be produced throughout ***parton showers***
- Generating doubly-heavy hadrons is ***even slower***
  - Requires two pairs of heavy quarks to be produced and correctly hadronise

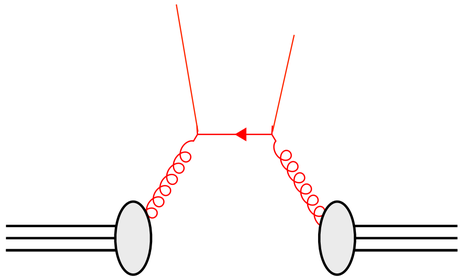
How can we generate these more efficiently?

Speeding up Pythia

Userhooks

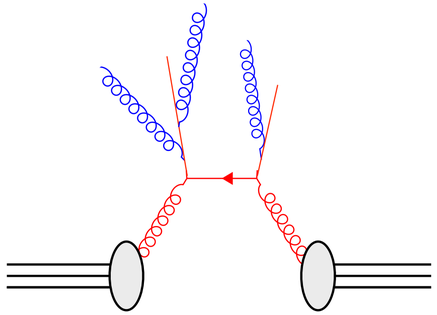
Inspect the event and ***veto*** if there isn't what we want

We can check at difference energy scales μ



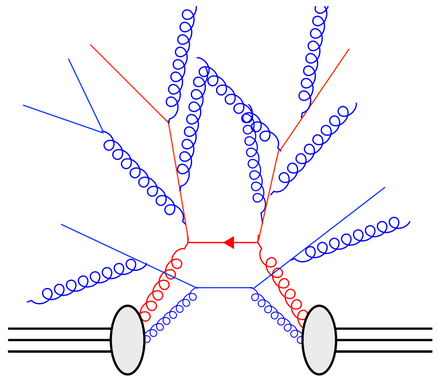
$\mu = \sqrt{s}$

Is there the required heavy quark, or enough energy to create one?



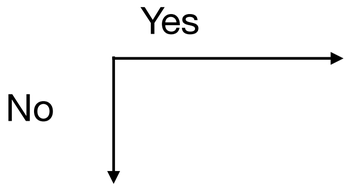
$\mu = m_b$

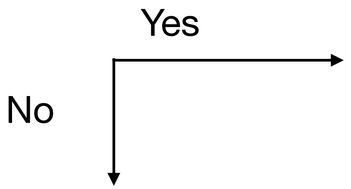
Is there the required heavy quark?

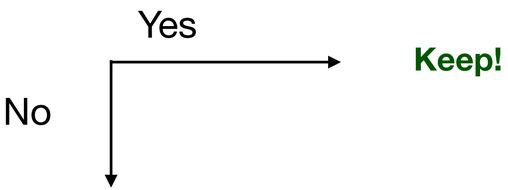


$\mu = \Lambda_{QCD}$

Are there the required heavy quarks? (If you want more than one)

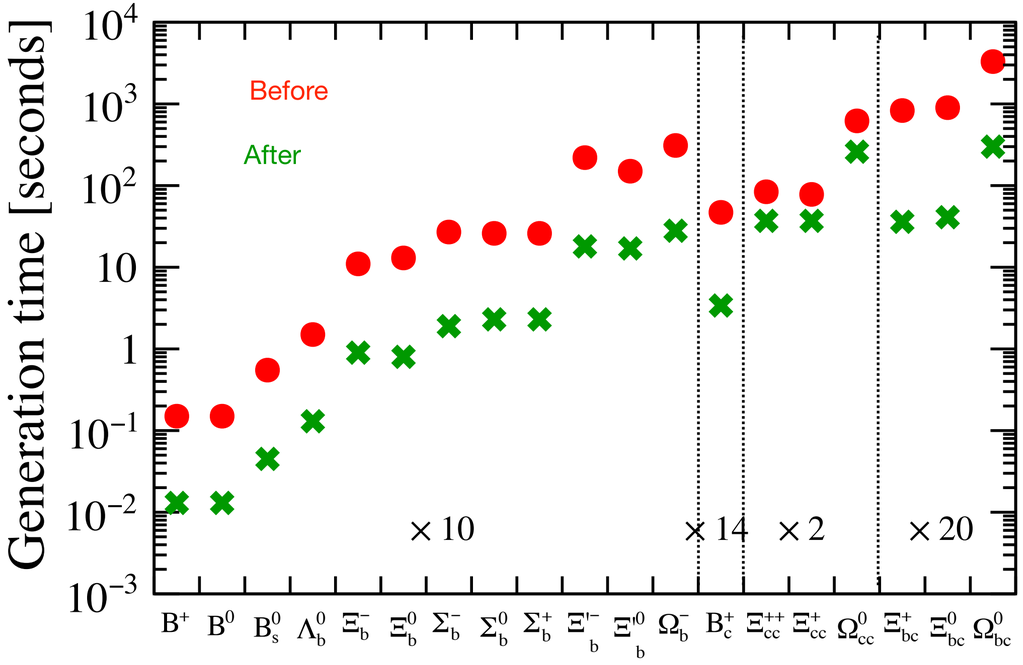




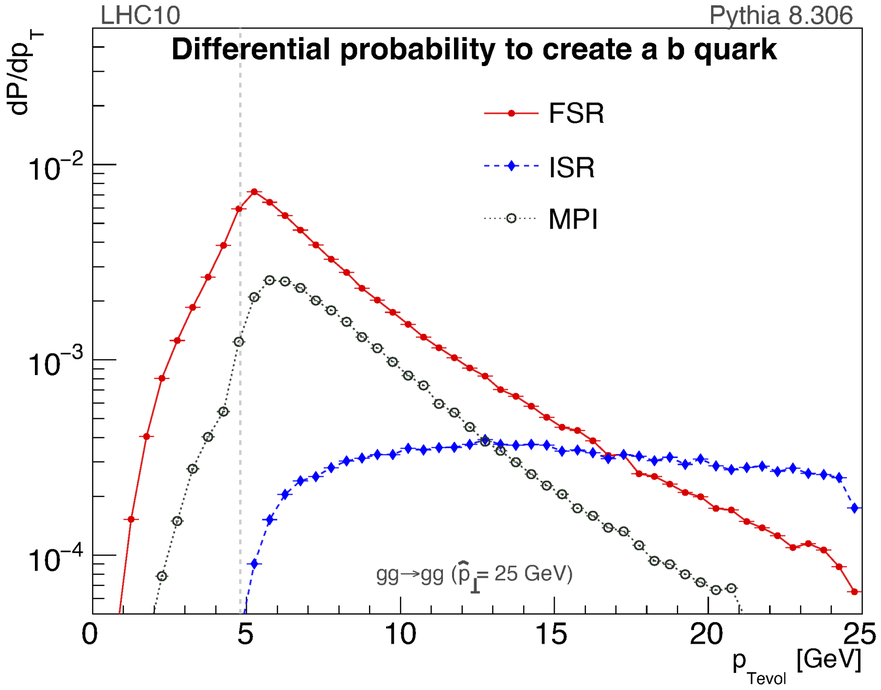


This saves the time spent evolving and hadronising events we later discard

Benefits



These user hooks have **significantly** reduced generation times



Current implementation isn't perfect

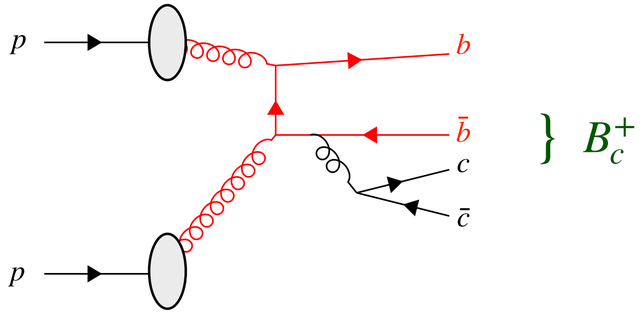
- Small probability for heavy quarks to be produced at scales *below* their mass

Doubly heavy hadrons

Dedicated generators (BcVegPy, GenXicc) and predictions for doubly-heavy hadron production assume **single parton interactions**

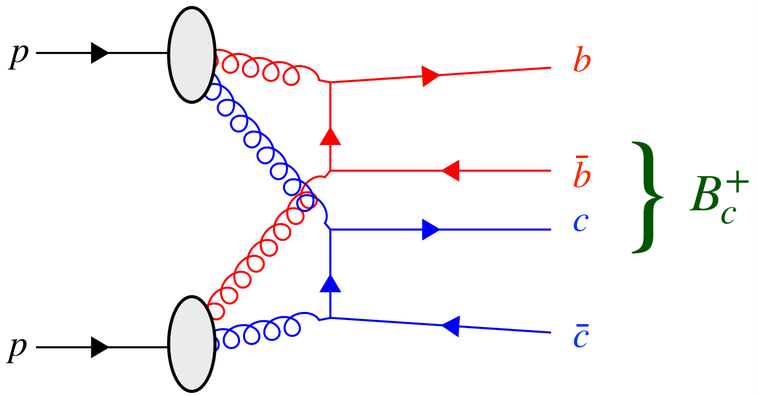
This is when a single pair of partons produce both pairs of heavy quarks

BcVegPy: $gg \to B_c^+ b\bar{c}$



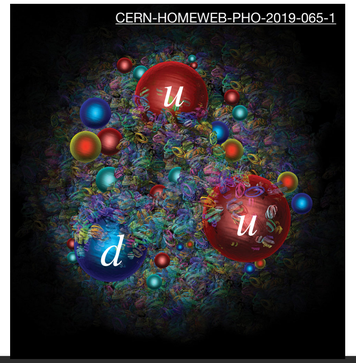
Single parton scattering

Now we can generate B_c^+ more efficiently we want to test whether **double parton interactions** contribute



Double parton scattering

?

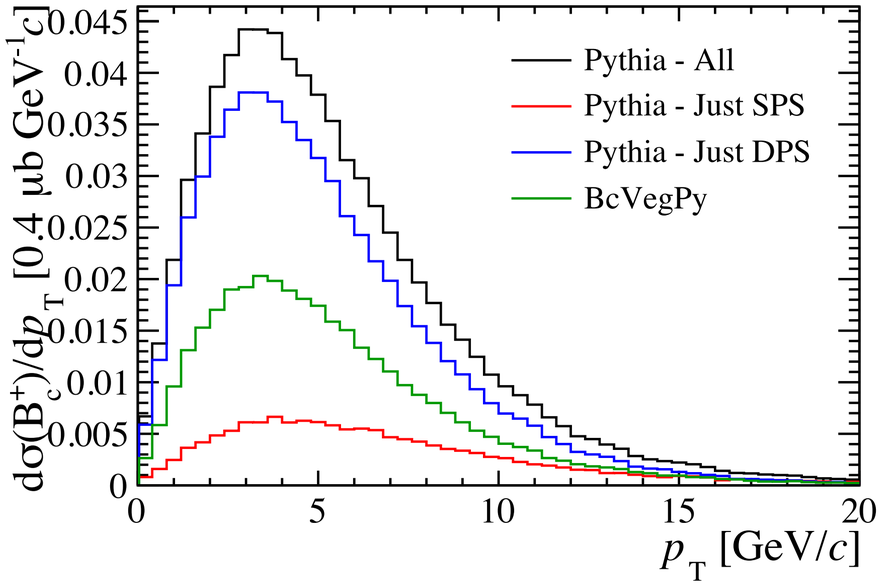


*Can quarks from **different** parton-parton interactions hadronise together?*

Or are spatially separated interactions suppressed?

Pythia's predictions

Prediction: Doubly-heavy hadrons ***can*** come from different parton-parton interactions



Pythia predicts a higher production rate with 90% of B_c^+ come from DPS

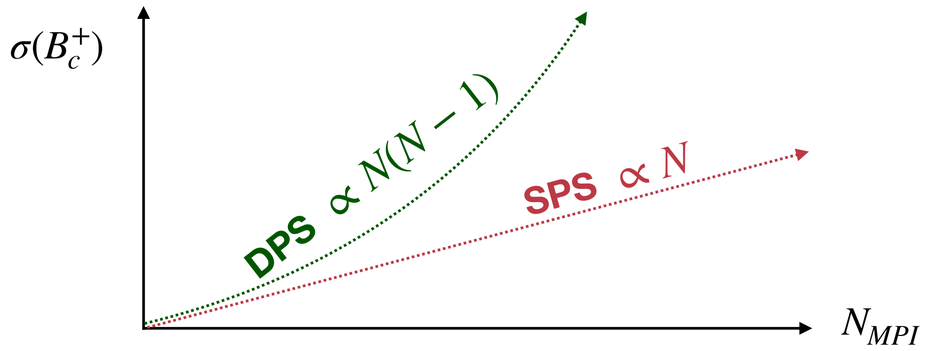
However, measuring the absolute B_c^+ cross-section precisely is difficult

Requires theoretical input on branching fractions

Alternative approach

Exploit the different behaviour in events with more parton-parton interactions

Similar to faster-than-linear effects seen elsewhere



Multiplicity dependence

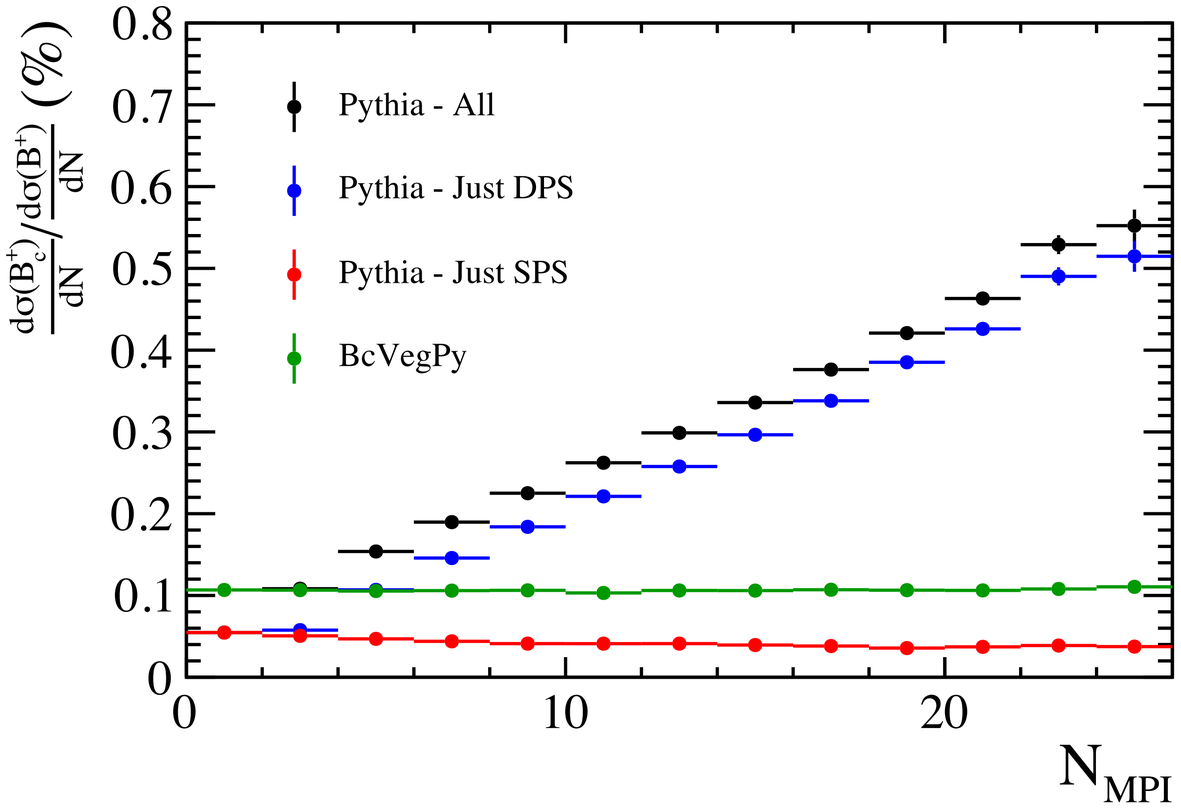
- **Ratio** of doubly-heavy hadrons to singly-heavy hadrons

SPS

$$\frac{\sigma(B_c^+)}{\sigma(B^+)} \propto 1$$

DPS

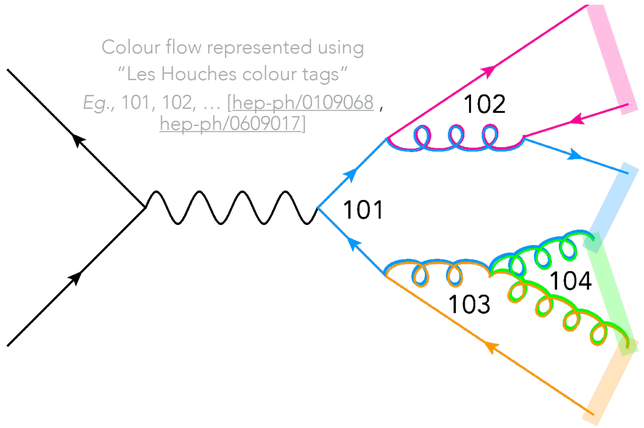
$$\frac{\sigma(B_c^+)}{\sigma(B^+)} \propto (N-1)$$



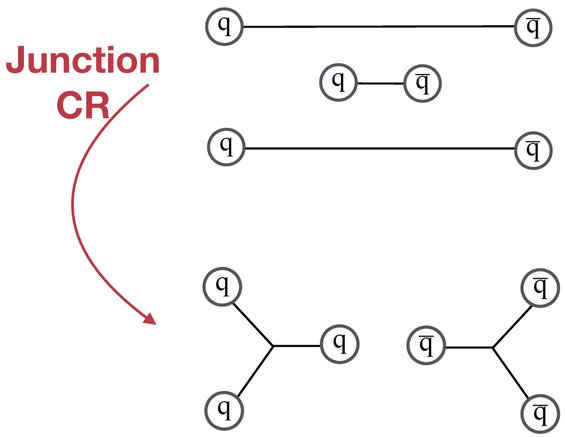
- In reality we can't measure the number of parton-parton interactions
- However, it's highly correlated to the number of particles produced

Colour reconnection

- The specific modelling of the strong force strongly affects the DPS contribution



Illustrations by J. Altmann



Pythia uses the *Leading Colour* limit

$N_c \to \infty$ *Colours are unique*

Partons need to be reconnected to recover correct N_c

There are different models of colour reconnection

QCD-CR: allows for 'junction baryons' to form (important for doubly-heavy baryons)

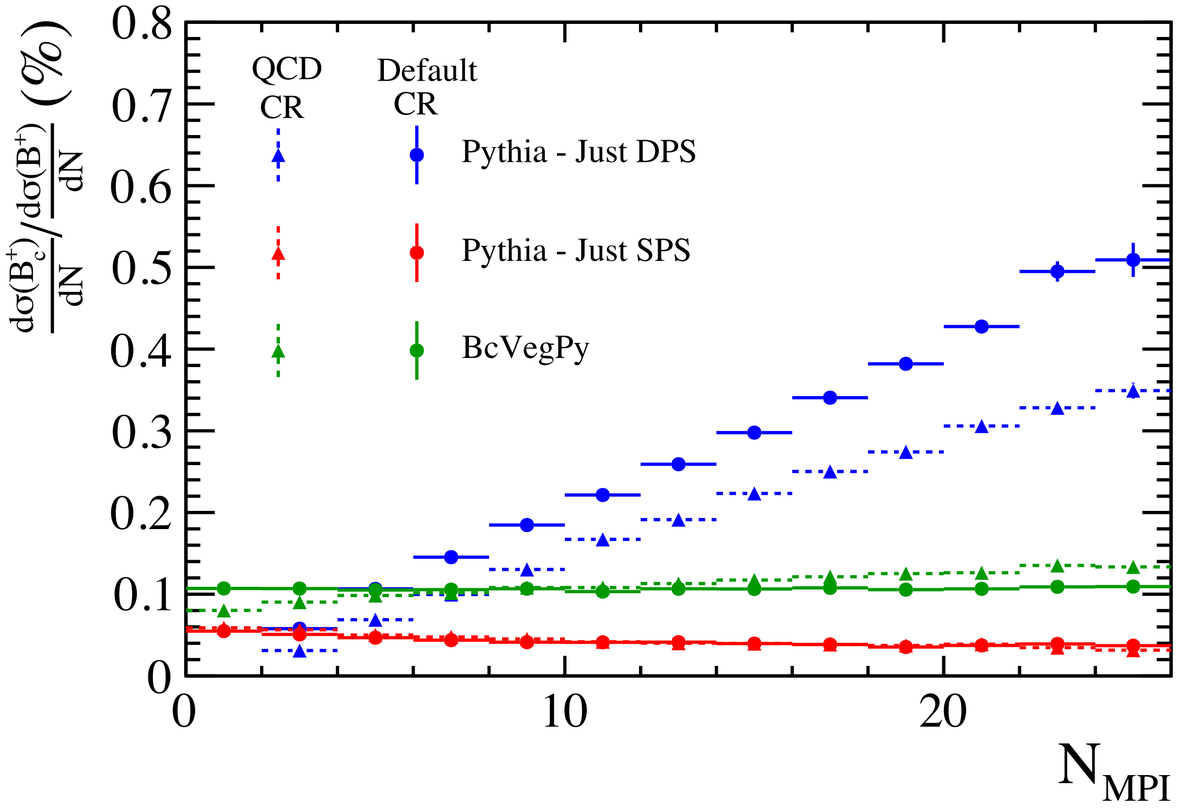
[Christiansen, Skands arxiv:1505.01681]

Colour reconnection

- Varying the choice of colour reconnection model impacts the size of the DPS contribution

- If DPS contribution is observed in data, the slope can provide quantitative information about QCD

Default CR options are compared to QCD-CR:



Experimental measurements

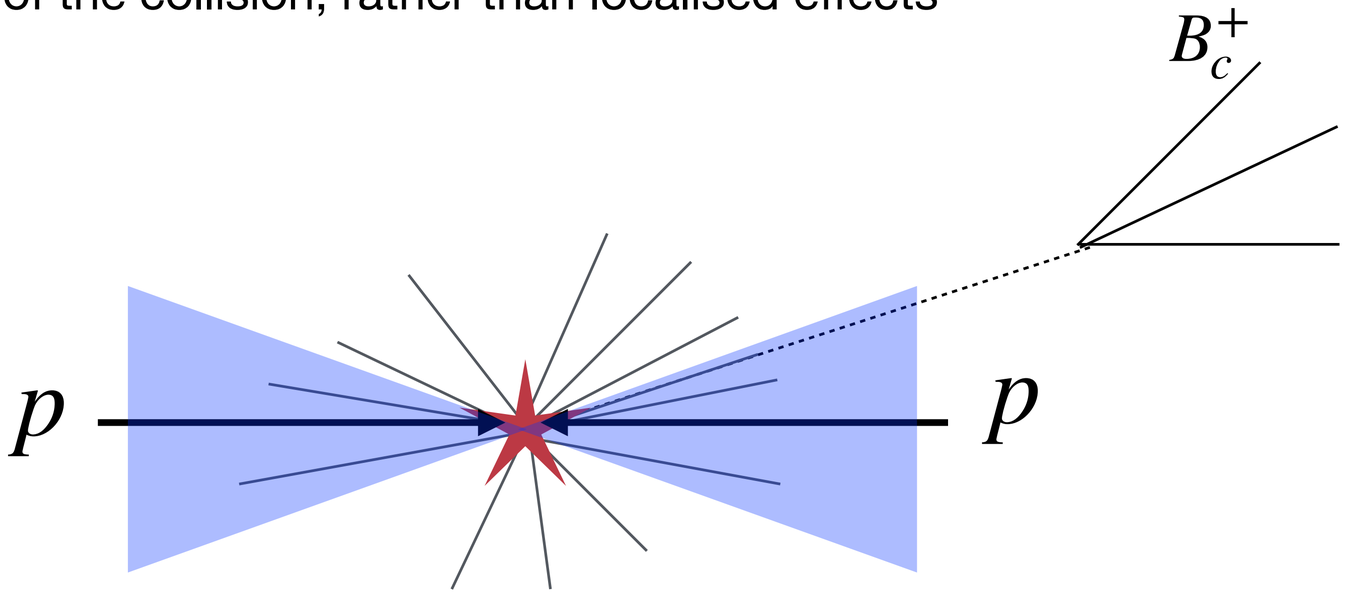
- We believe these are possible with B_c^+ and/or Ξ_{cc}^{++} at LHC experiments
  - LHCb measurements now ongoing

Challenges

These effects would be global properties of the collision, rather than localised effects

Important to test this prediction by using track multiplicities in different regions

e.g. forwards vs. backwards tracks



Outlook

- Recent studies with Pythia suggest DPS may significantly contribute to doubly-heavy hadron production

- Measurements of doubly-heavy hadron production as a function of event multiplicity can differentiate SPS vs. DPS production

- If DPS contribution is observed it can provide further insight into colour reconnection modelling