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13th International Workshop on Multiple Parton Interactions at the LHC

The role of **Multi Parton Interactions** in **doubly-heavy hadron** formation

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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?

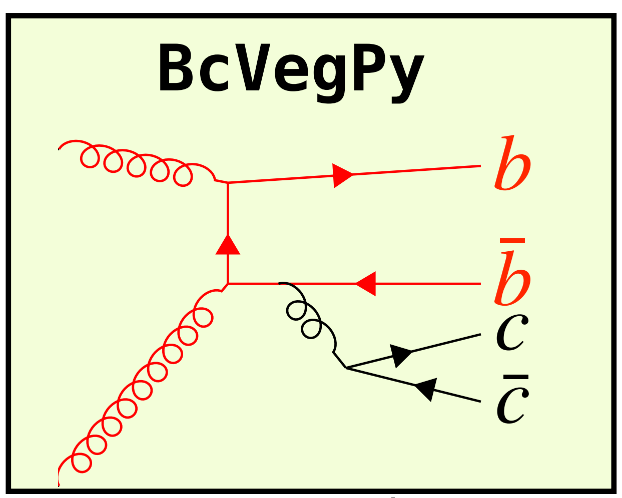
Project motivation

Production of **doubly-heavy hadrons:** $Q\bar{Q}'$ $QQ'q$

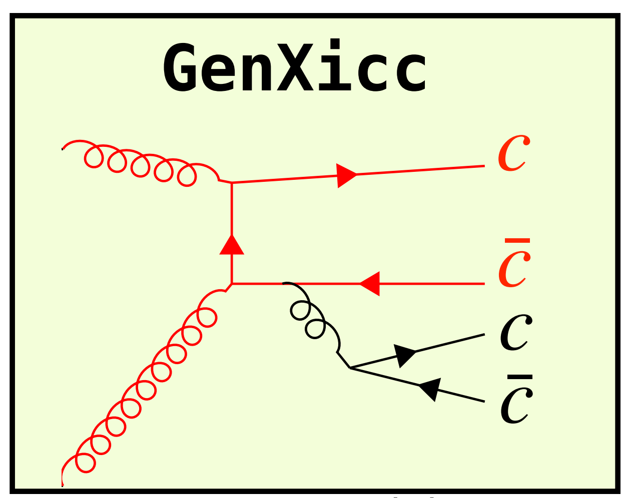
Single Parton Scattering or Double Parton Scattering?

Current status: Generally assumed SPS is the main mechanism

Inclusively simulating doubly-heavy hadrons is ***slow*** with standard event generators



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



$gg \to \Xi_{cc}^{++}\bar{c}\bar{c}\ldots$

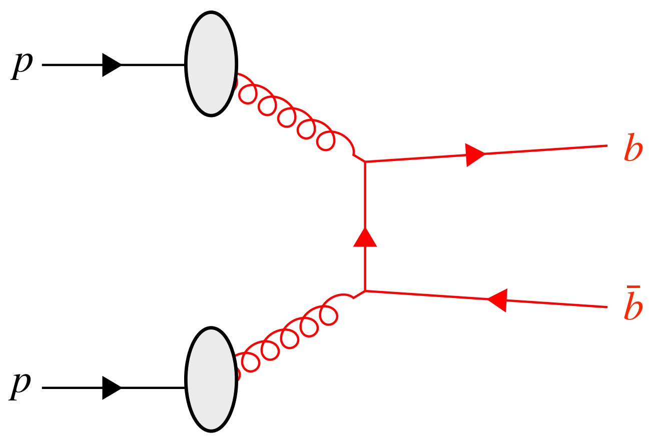
Standalone generators are used to simulate the hard process

Event generators add the rest of the event

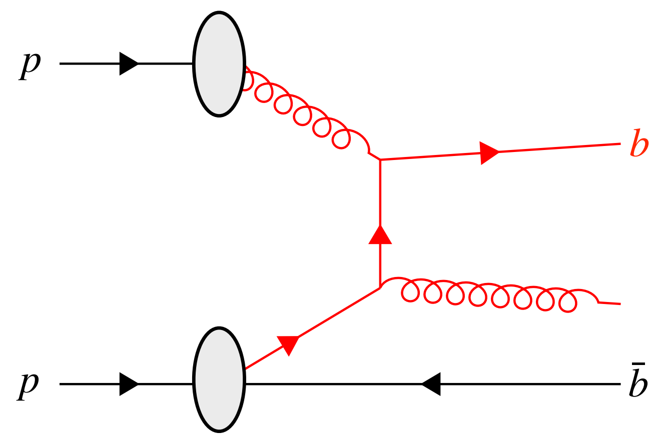
Heavy quarks and Pythia

- In proton-proton collisions there are three ways heavy quarks are produced via perturbative QCD

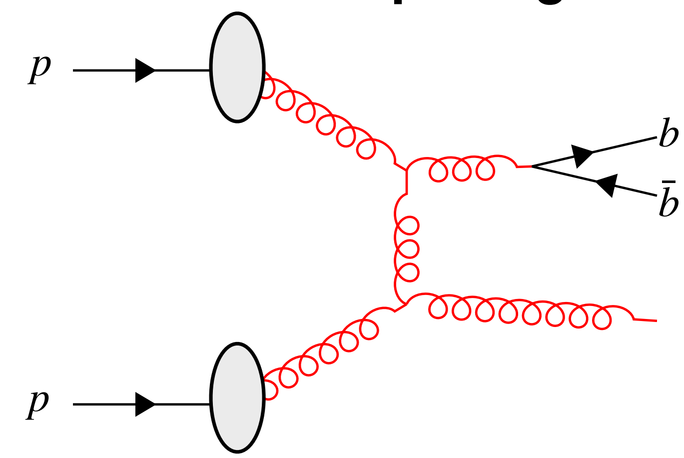
Pair creation



Flavour excitation



Gluon splitting



- The first two involve heavy quarks in the hard process, so can be simulated efficiently
    - Heavy quarks in produced in ***parton showers*** or in additional parton-parton interactions require inclusive samples

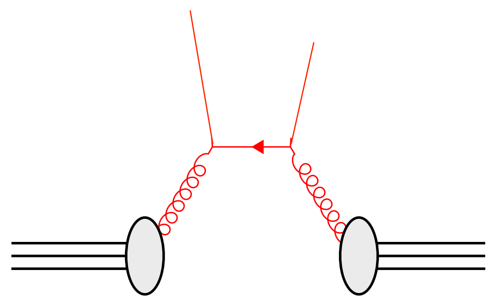
How can we generate these more efficiently?

Speeding up Pythia

Userhooks

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

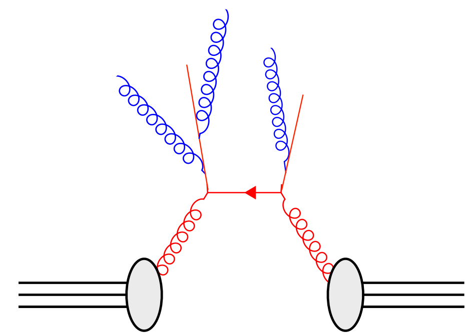
We can check at difference energy scales μ



$\mu = \sqrt{s}$

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

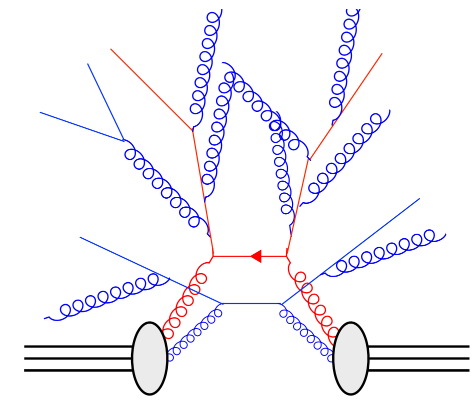
Yes → / No ↓ **Try again**



$\mu = m_b$

Is there the required heavy quark?

Yes → / No ↓ **Try again**



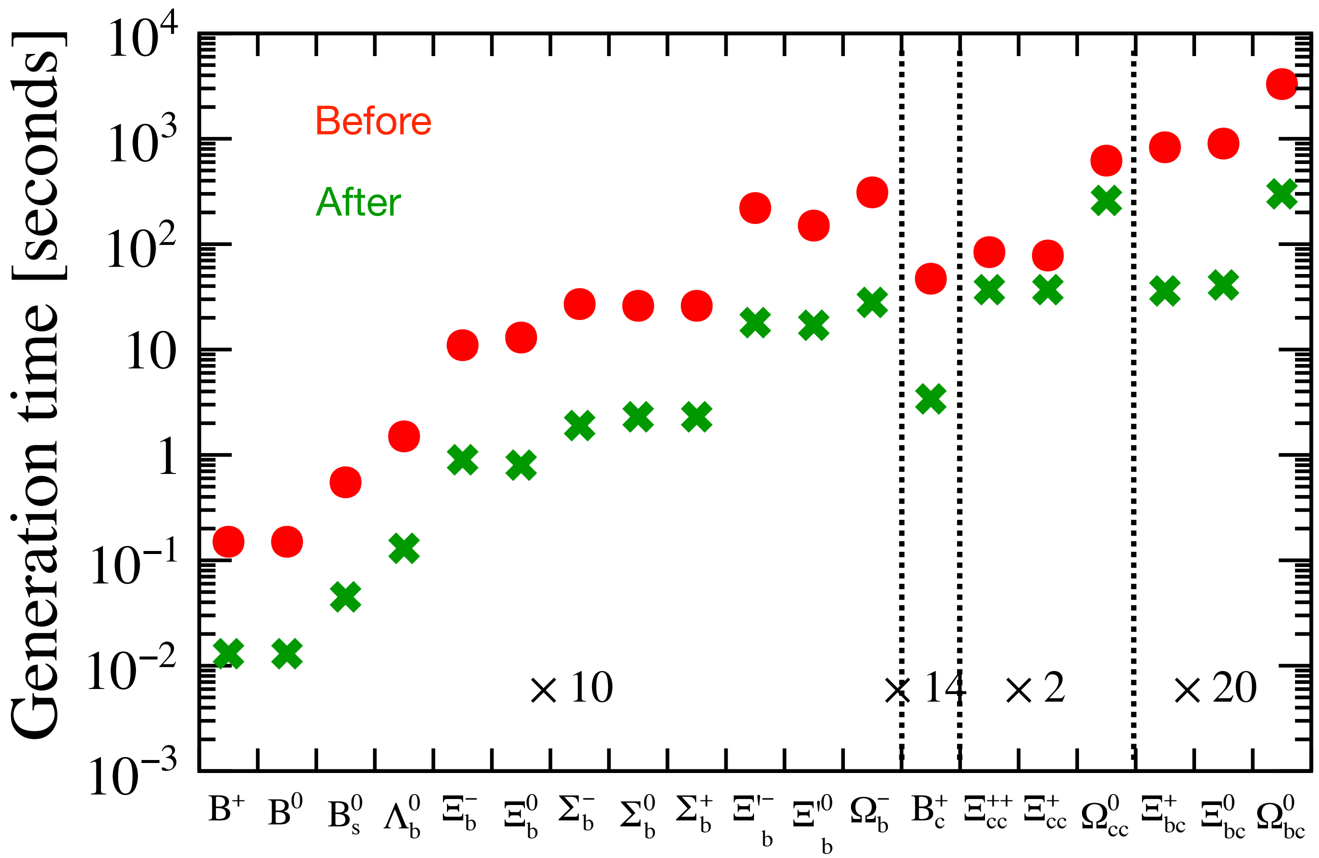
$\mu = \Lambda_{QCD}$

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

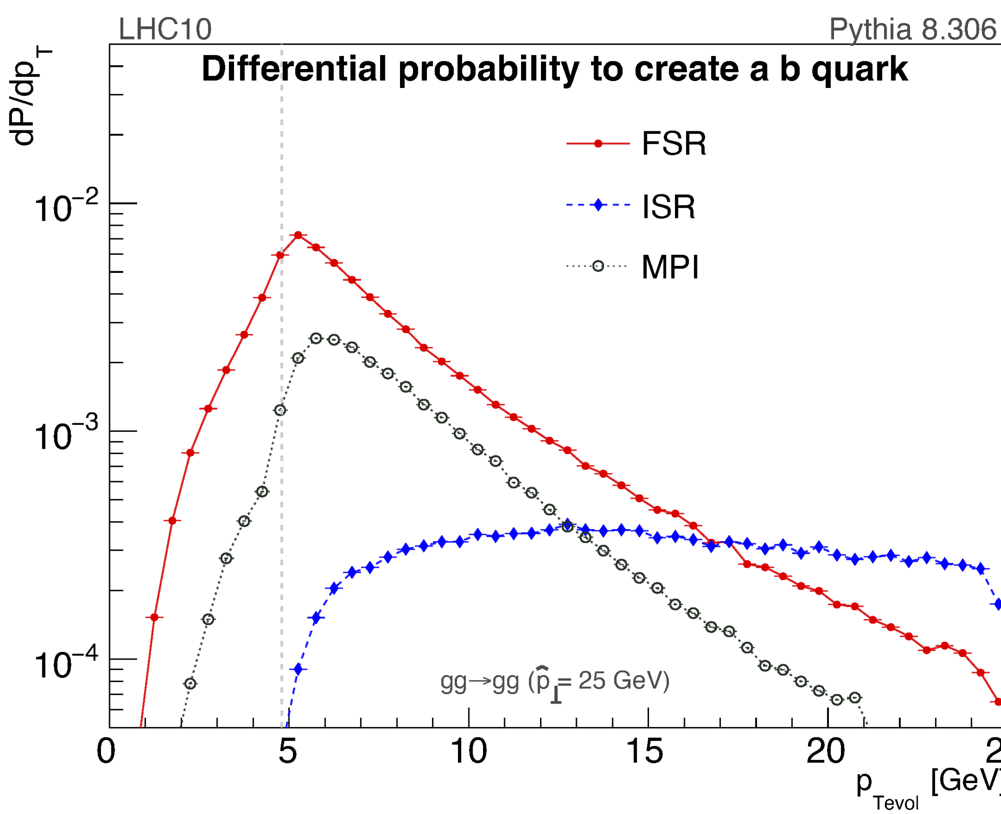
Yes → **Keep!** / No ↓ **Try again**

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

Benefits



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

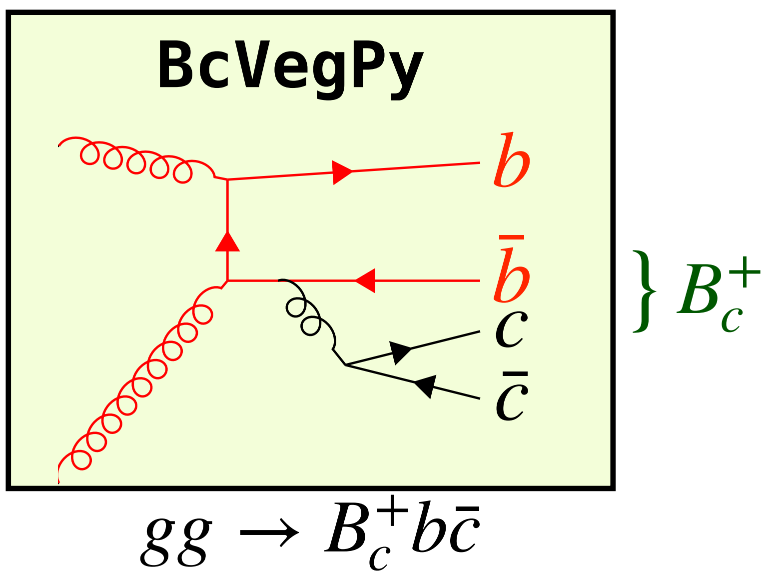


Current implementation isn't perfect

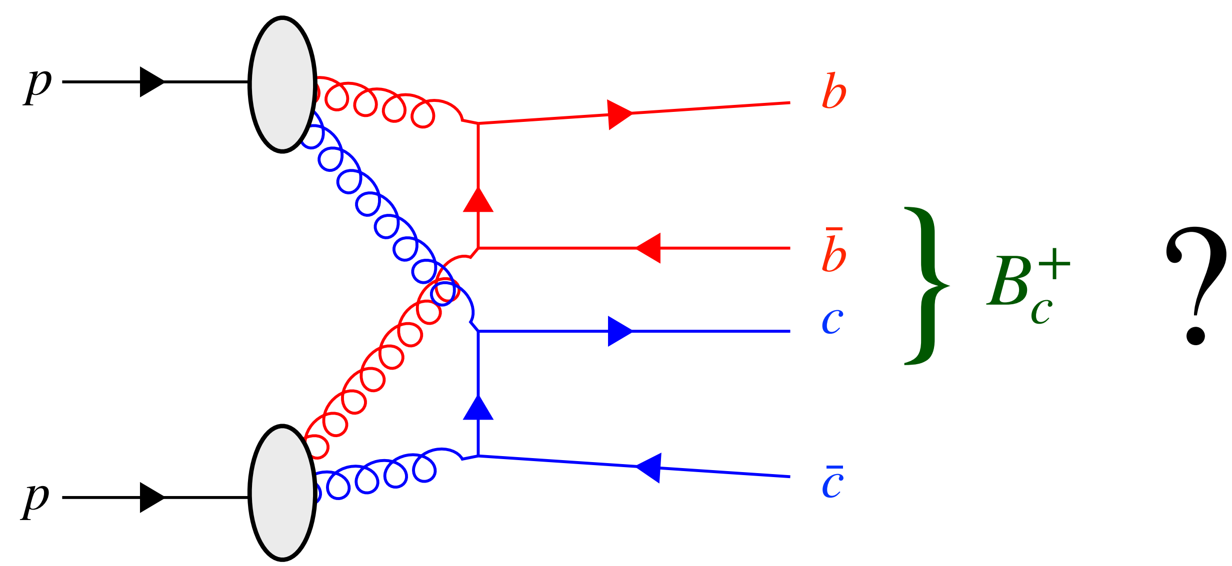
- Small probability for heavy quarks to be produced at scales *below* their mass

Doubly heavy hadrons

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



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

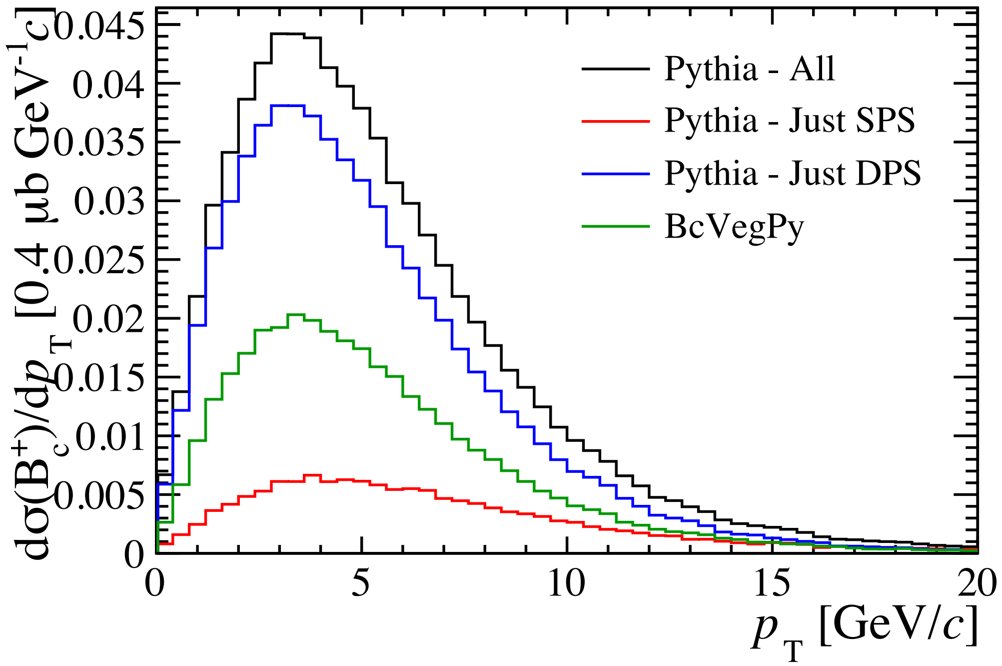


There is experimental evidence that multiple pairs of heavy quarks can be produced in MPI

*But can quarks from **different** parton-parton interactions hadronise together?*

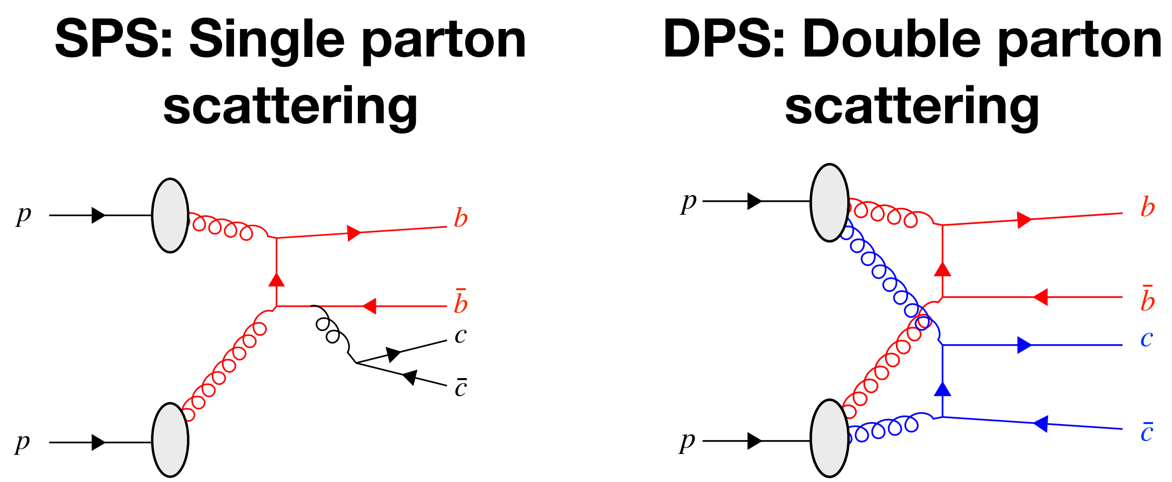
Pythia's predictions

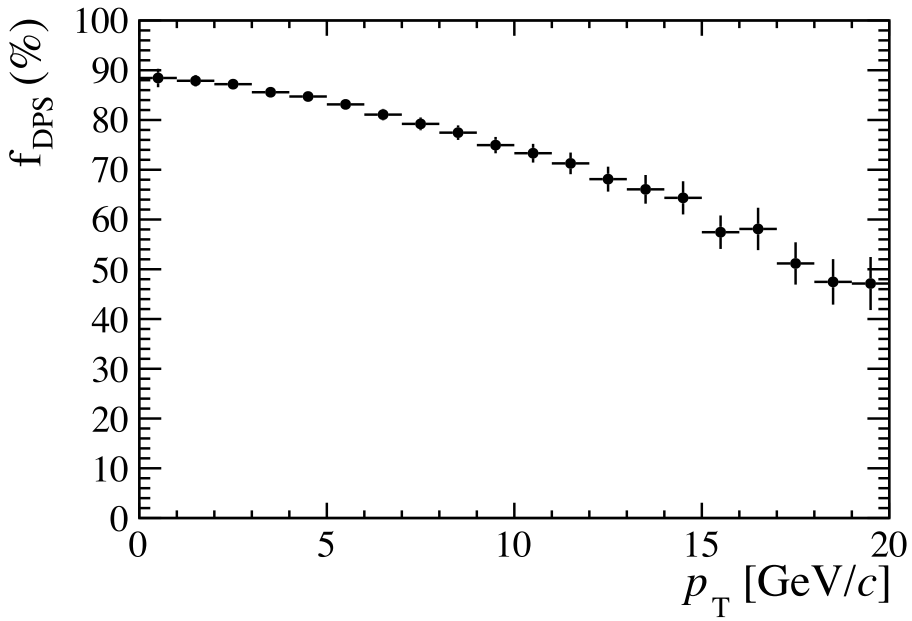
Prediction: Doubly-heavy hadrons *can* come from different parton-parton interactions



Pythia has higher production rate vs. BcVegPy

90% of these B_c^+ come from DPS



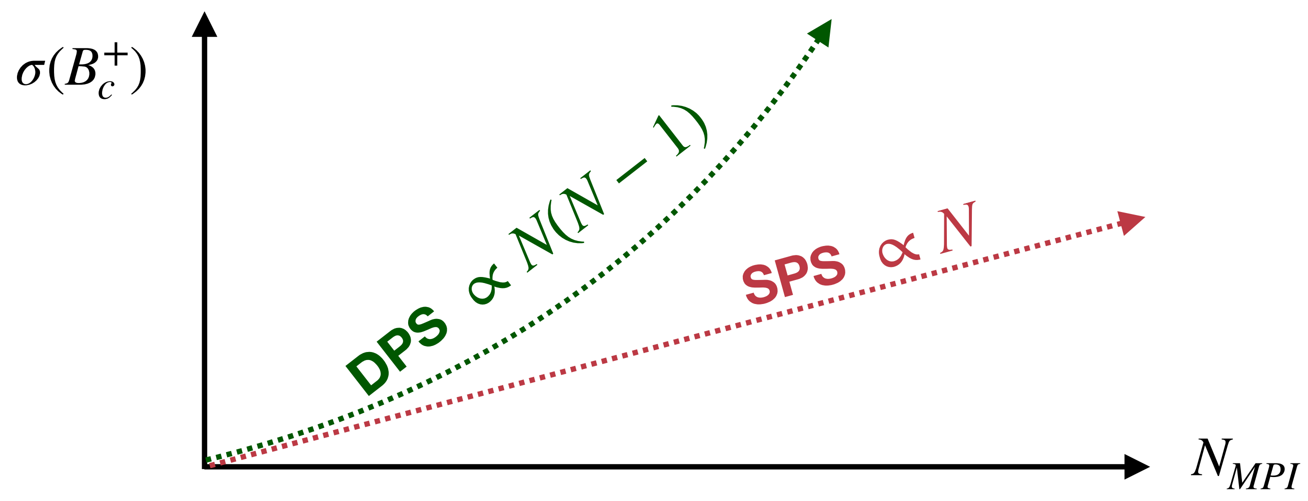


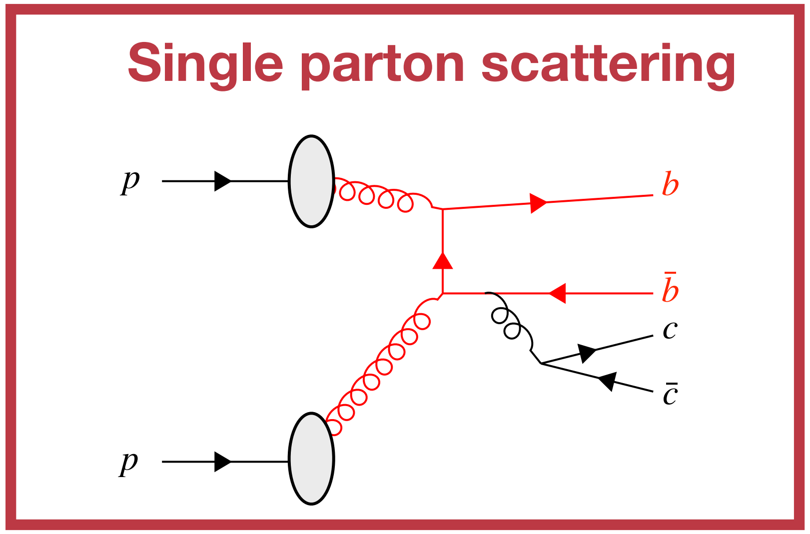
Differentiating DPS vs. SPS

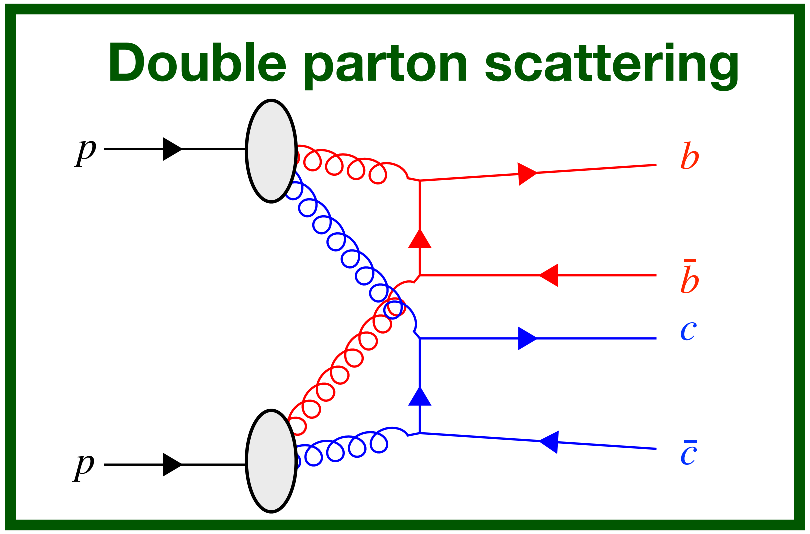
- Measuring the absolute B_c^+ cross-section precisely is difficult
  - Requires theoretical input on branching fractions

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

Similar to faster-than-linear effects seen elsewhere







Multiplicity dependence

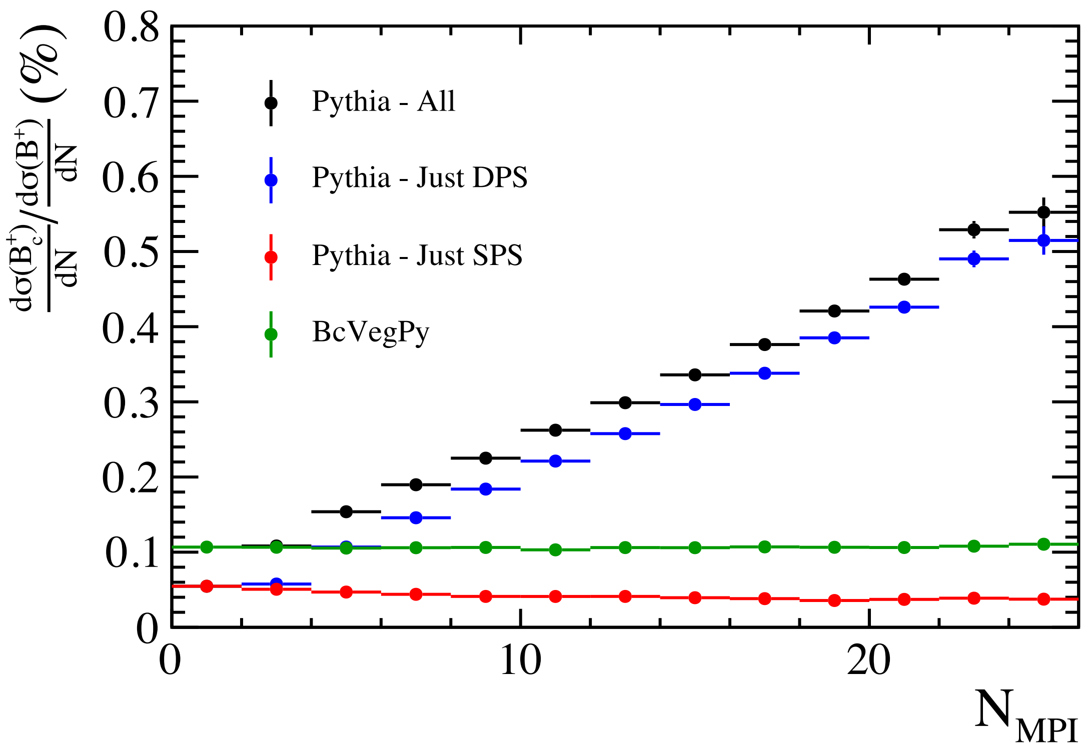
- **Ratio** of doubly-heavy hadrons to singly-heavy hadrons

SPS

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

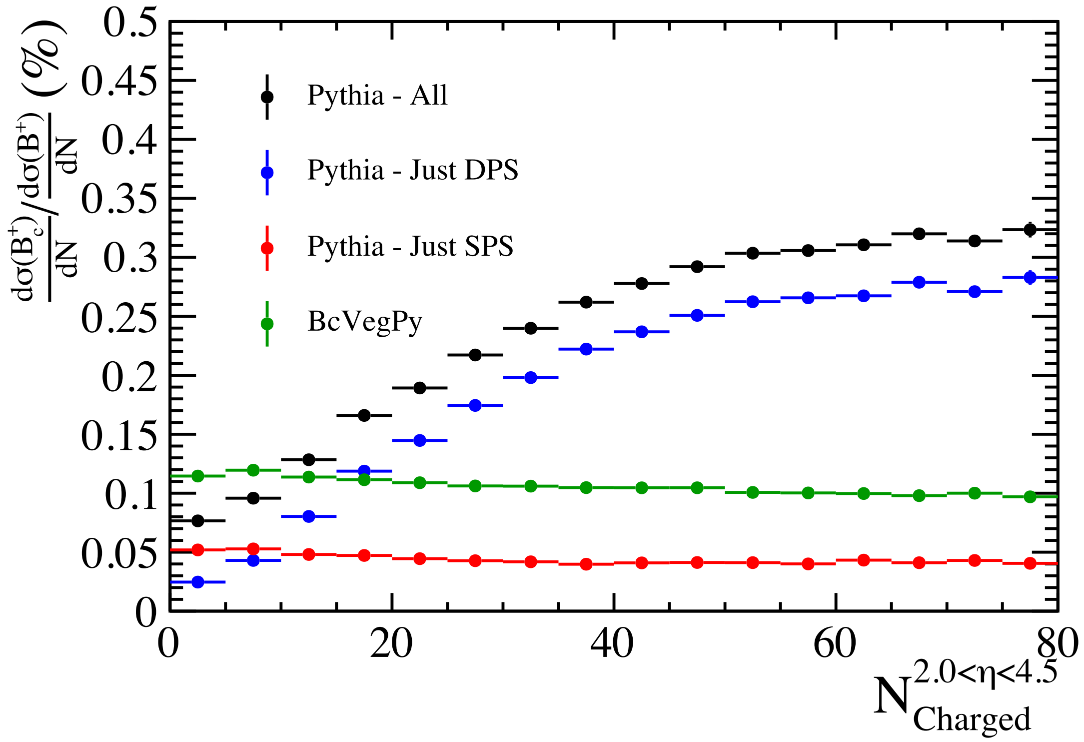
DPS

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



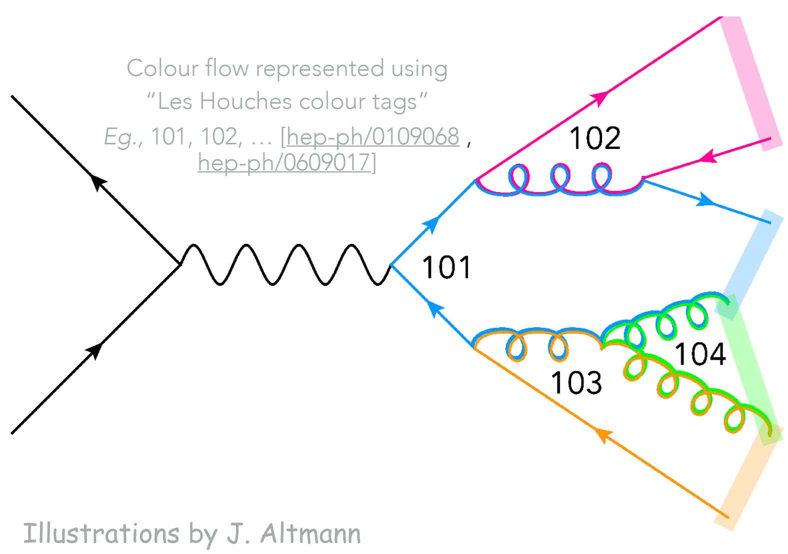
- In reality we can't measure the number of parton-parton interactions

- However, it's highly correlated to the number of particles produced

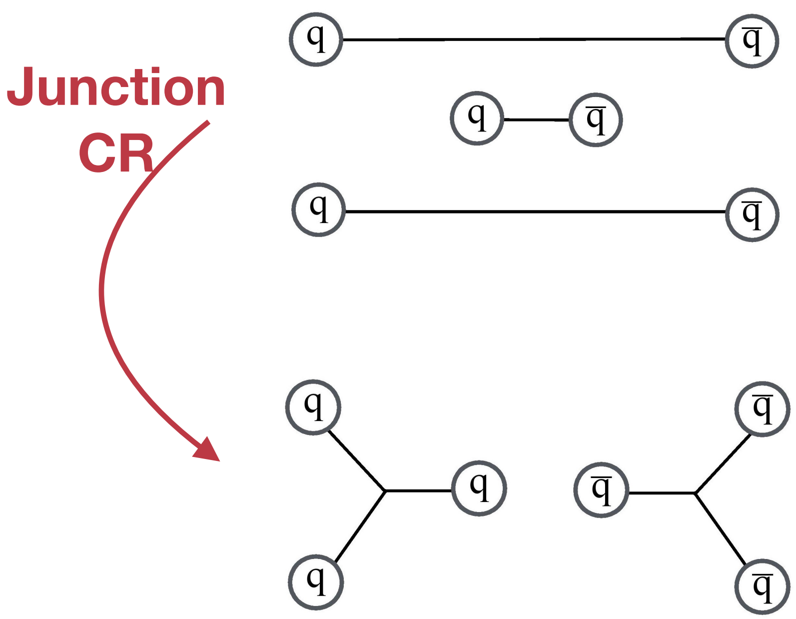


Colour reconnection

- The specific model of colour reconnection affects the size of the DPS contribution



Illustrations by J. Altmann



Pythia uses the *Leading Colour* limit

$$N_c \to \infty$$

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)

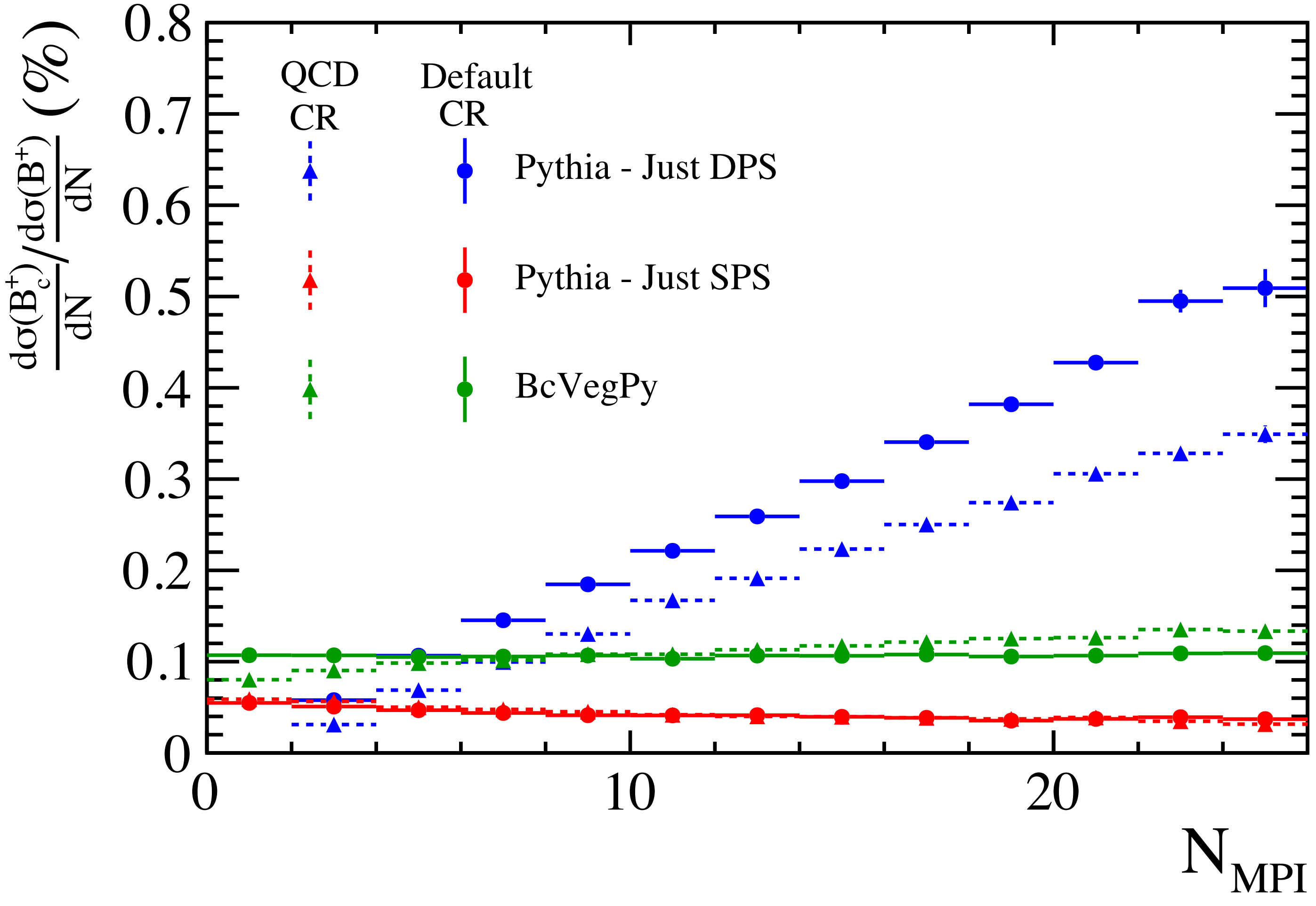
[Christiansen, Skands arxiv:1505.01681]

Colour reconnection

- The specific model of colour reconnection affects the size of the DPS contribution

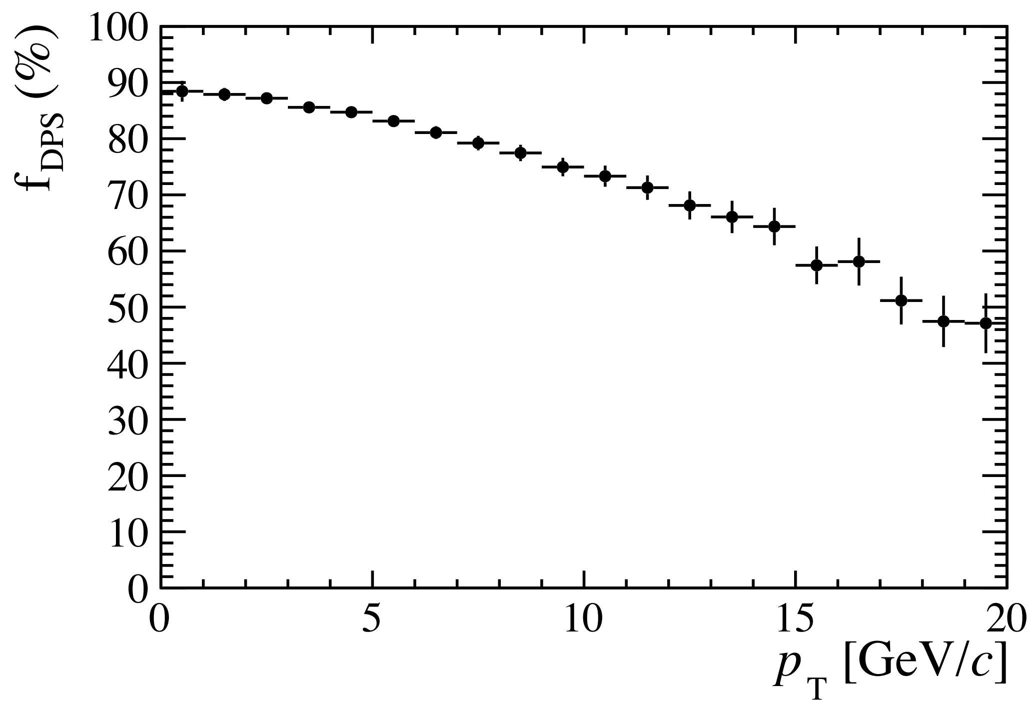
Default CR options are compared to QCD-CR:

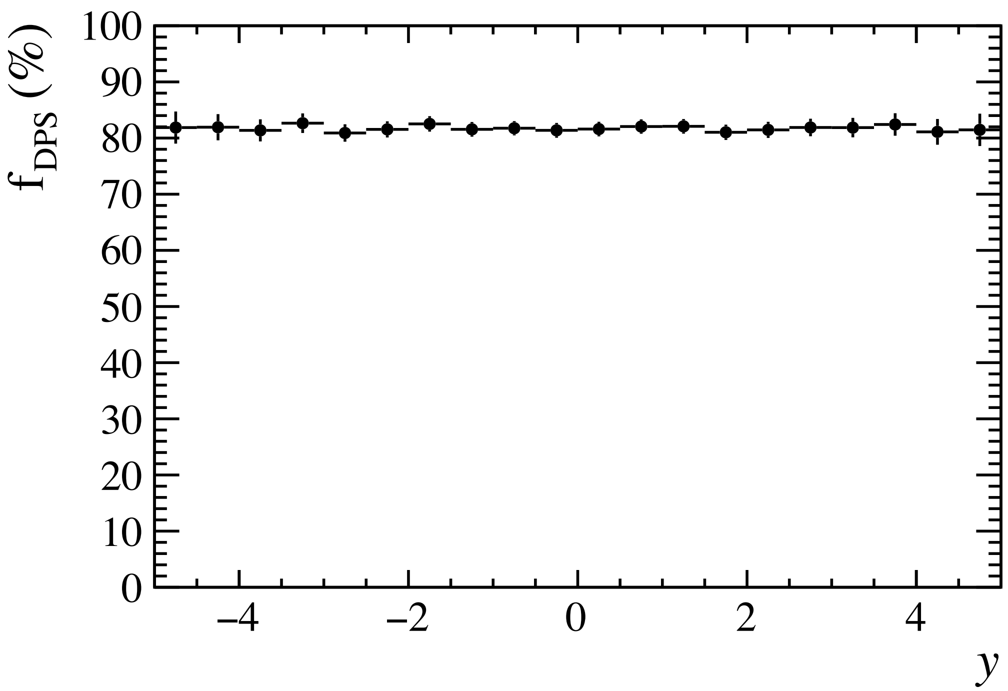
- If DPS contribution is observed in data, the slope could provide important information



Kinematic dependence

- Our studies suggest the DPS contribution is largest at low transverse momentum





- The contribution is uniform in rapidity
    - This motivates measurements in both the forward and central regions

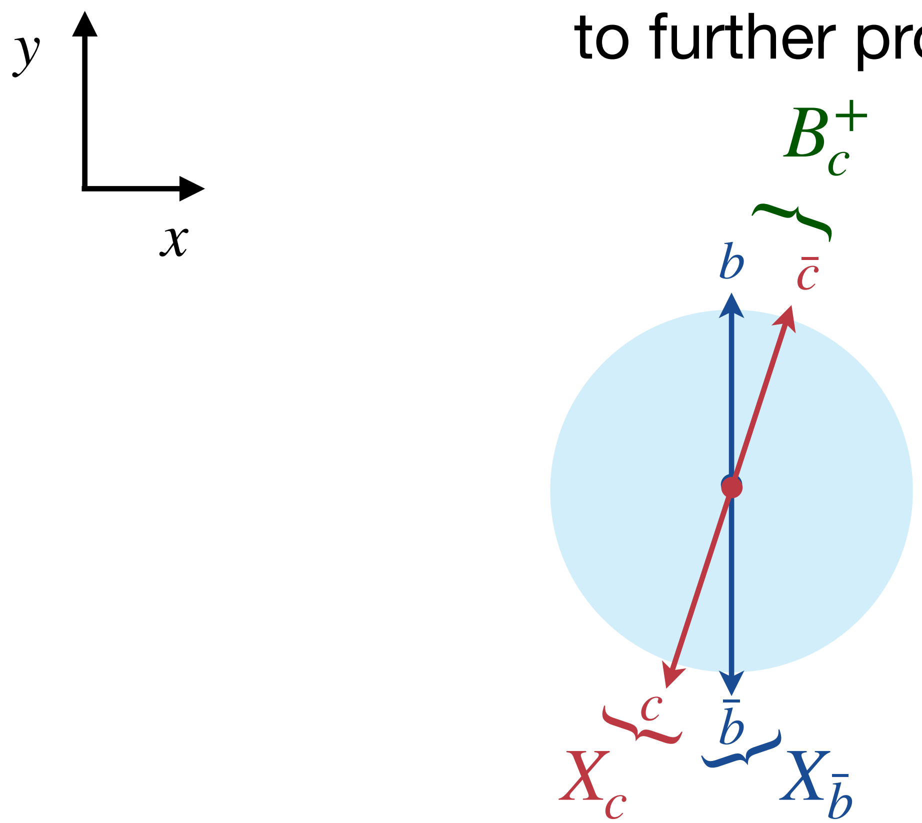
What else can we measure?

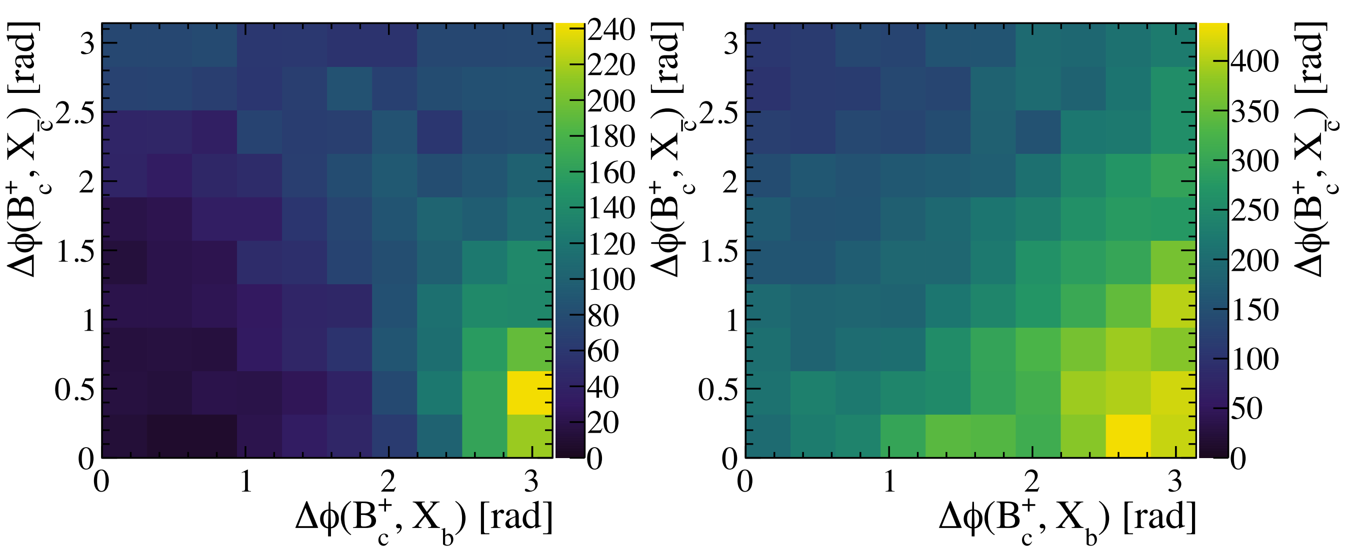
- Other than multiplicity there may be other quantities that tell us about the general character of the event

  Any recommendations welcome!

- Another unique handle is: *where do the other heavy quarks go?*

  We can study the correlations between the other heavy quarks to further probe the production





(a) BcVEGPY (b) Pythia- Just DPS

Experimental measurements

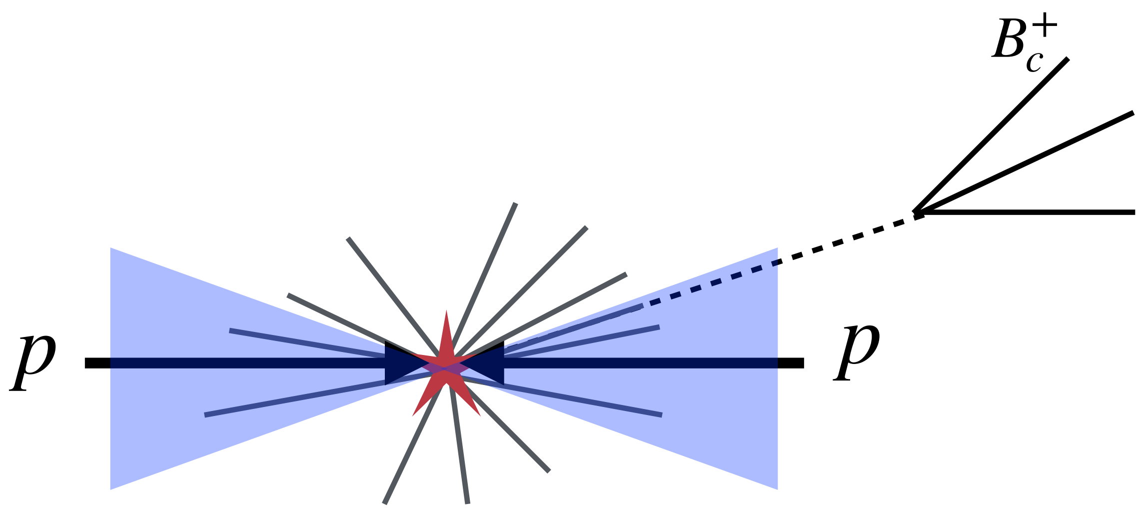
- Multiplicity measurements
  - We believe these are possible with B_c^+ and/or Ξ_{cc}^{++} at LHC experiments
  - LHCb measurements now ongoing

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