Doubly-heavy hadron production:
Does double-parton scattering play a role?

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PHENOmenal: Alice and MC meeting

Outline

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

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

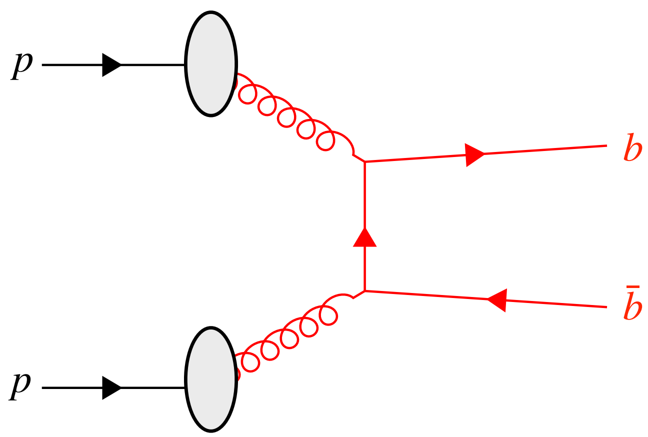
This project has been a collaborative effort between LHCb and Pythia colleagues

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

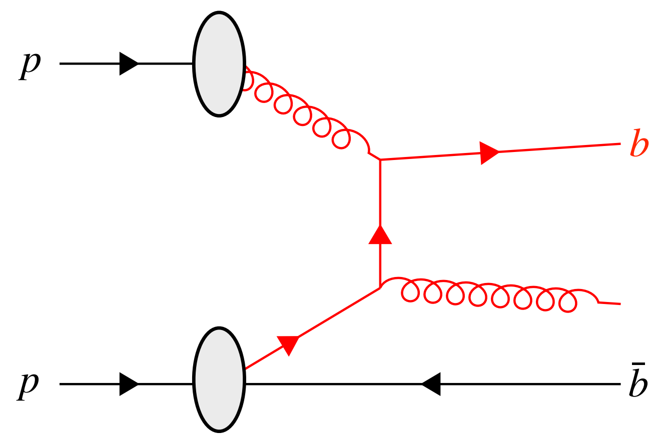
Heavy quarks and Pythia

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

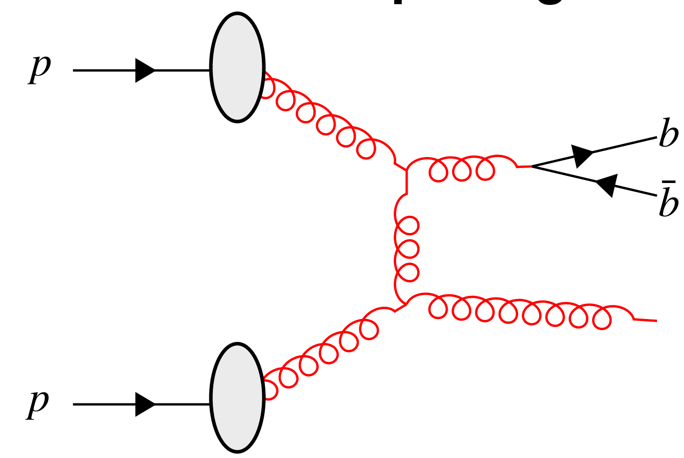
Pair creation



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?

Userhooks

Userhooks

Inbuilt routines that allows users to inspect the event and ***veto*** if required

The event can be inspected at multiple stages

- We've created Userhooks to veto events that we know don't have heavy quarks and can't produce one

    This saves time evolving and hadronising events we later discard

- We don't modify any probabilities so in principle this doesn't bias the generated samples

How can we make Pythia quicker?

Parton-parton collision energy

↓

m_b Heavy quark mass

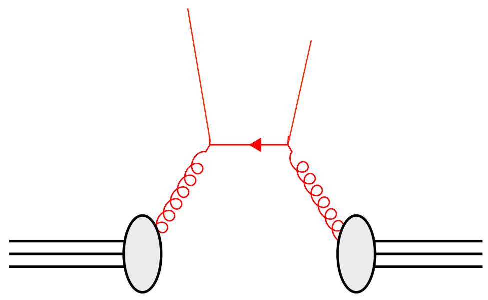
↓

Λ_{QCD}

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

No → **Discard**

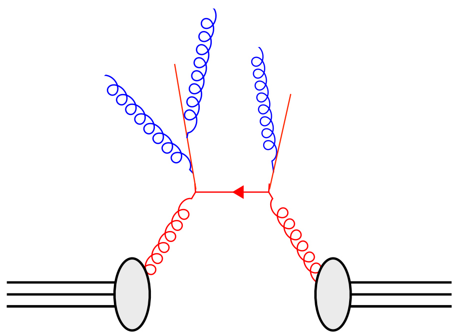
Yes ↓



Is there the required heavy quark?

No → **Discard**

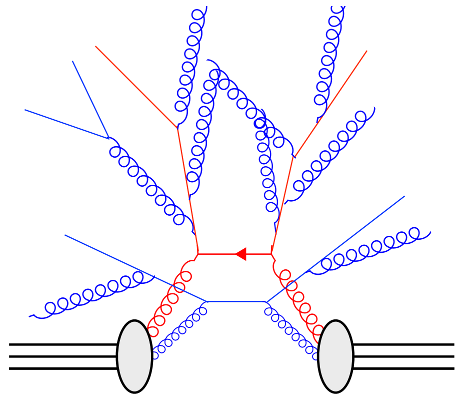
Yes ↓



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

No → **Discard**

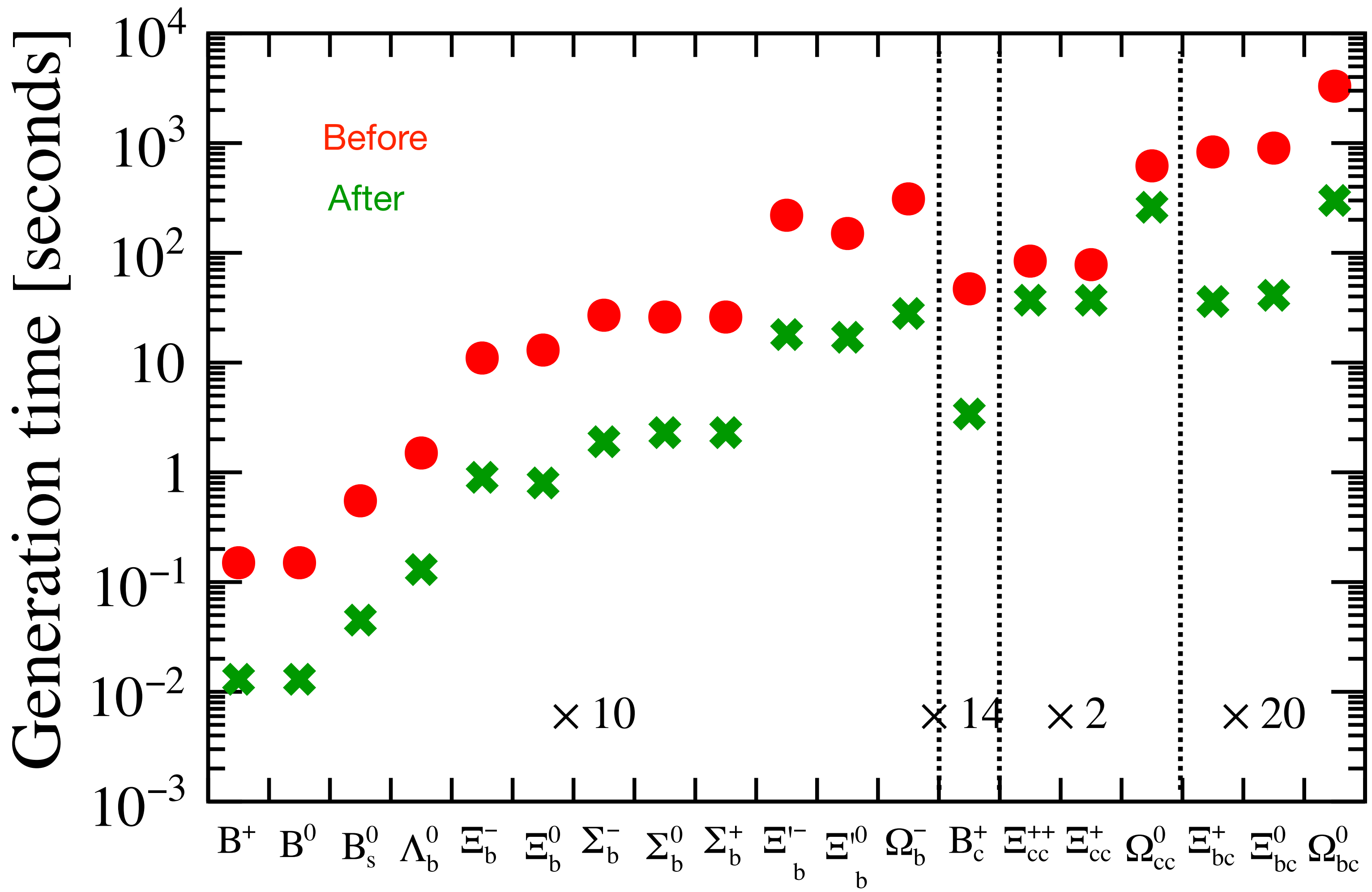
Yes ↓



Hadronise

Speed gains

- These user hooks have significantly reduced generation time for singly- and doubly-heavy hadrons

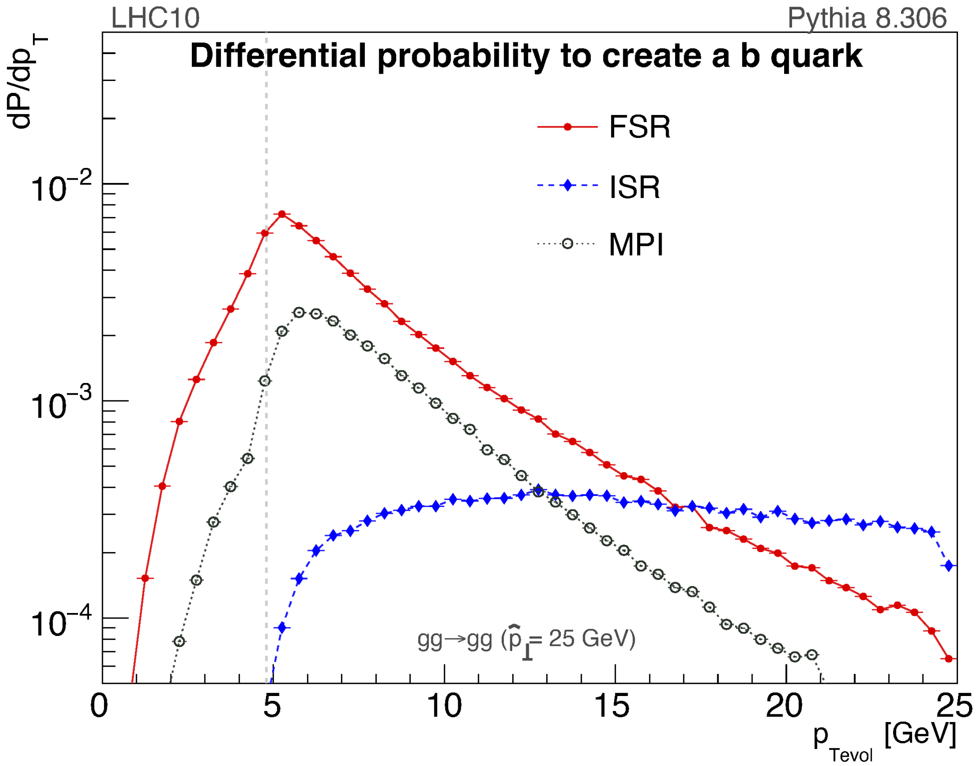


Gain is largest for b hadrons because c mass is closer to hadronisation scale

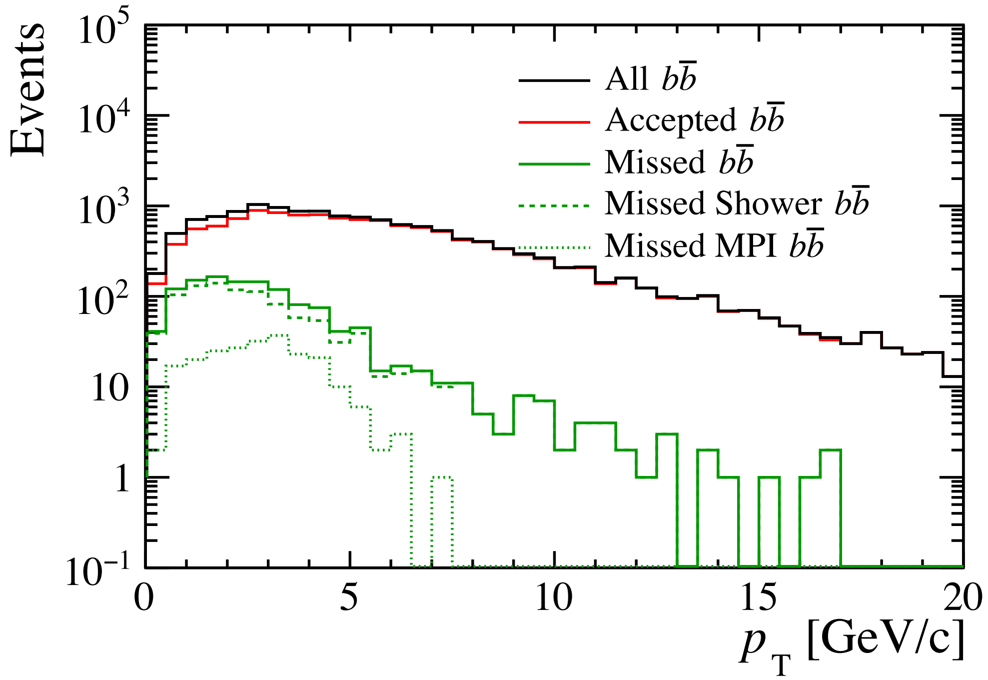
Some heavy flavour is missed

- The scale at which we stop to check the event currently doesn't catch all heavy quarks

- There is a small probability for heavy quarks to be created at scales below their mass threshold



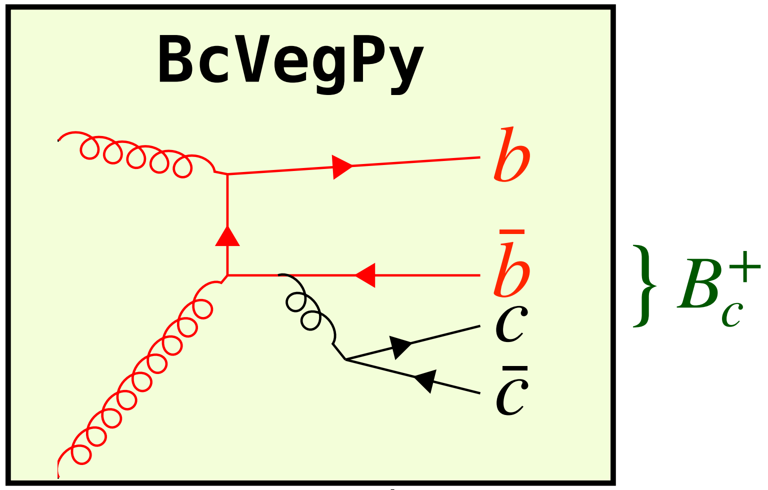
Affects FSR and MPI



- As a result there is a small distortion in the kinematic distribution

Doubly heavy hadrons

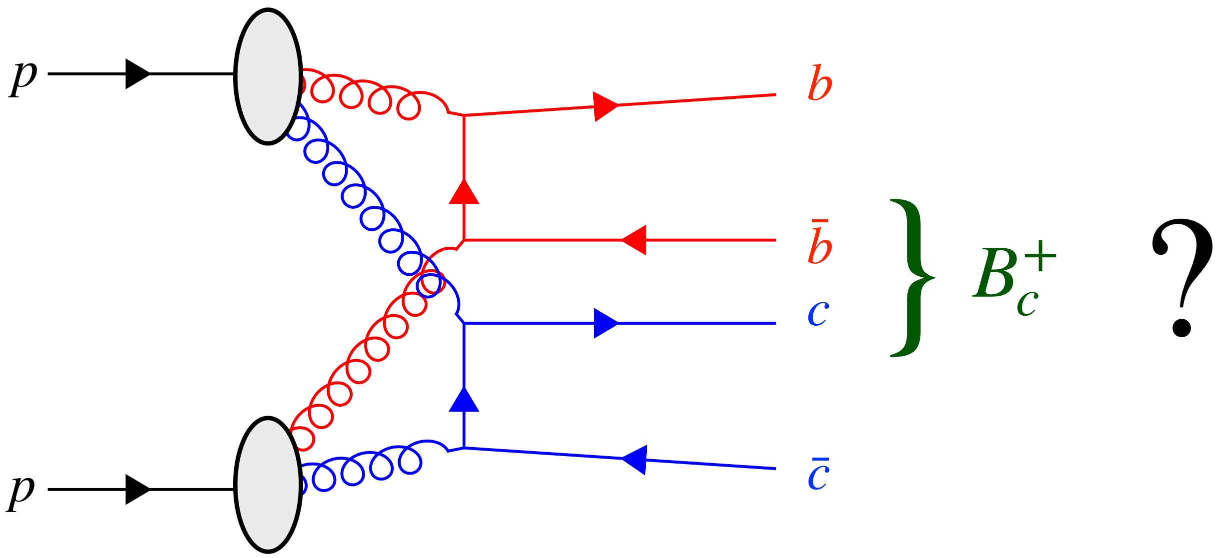
- Dedicated generators (BcVegPy, GenXicc) and predictions for doubly-heavy hadron production assume **single parton interactions**



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

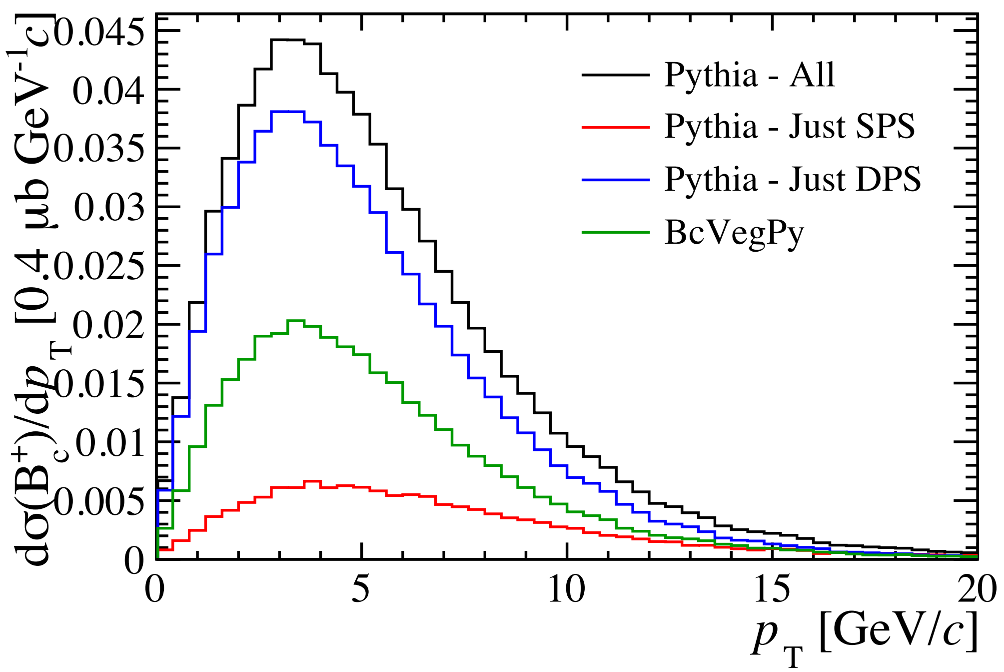
Now we can generate B_c^+ more efficiently we want to test whether **double parton interactions** contribute

i.e. do quarks from *different* parton-parton interactions hadronise?

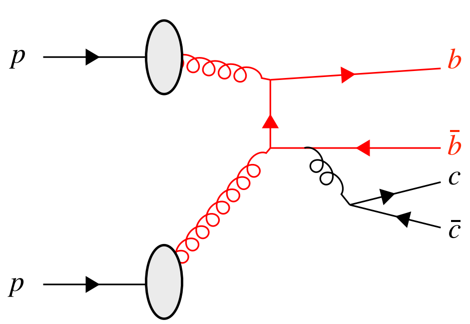


Pythia's predictions

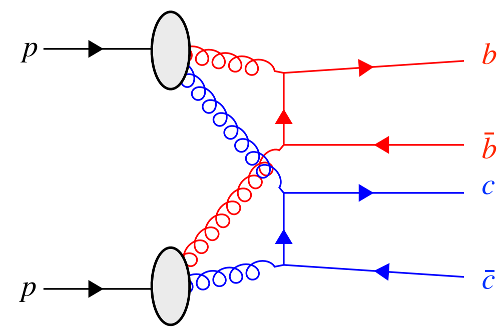
Prediction: Doubly-heavy hadrons *can* come from different parton-parton interactions



SPS: Single parton scattering

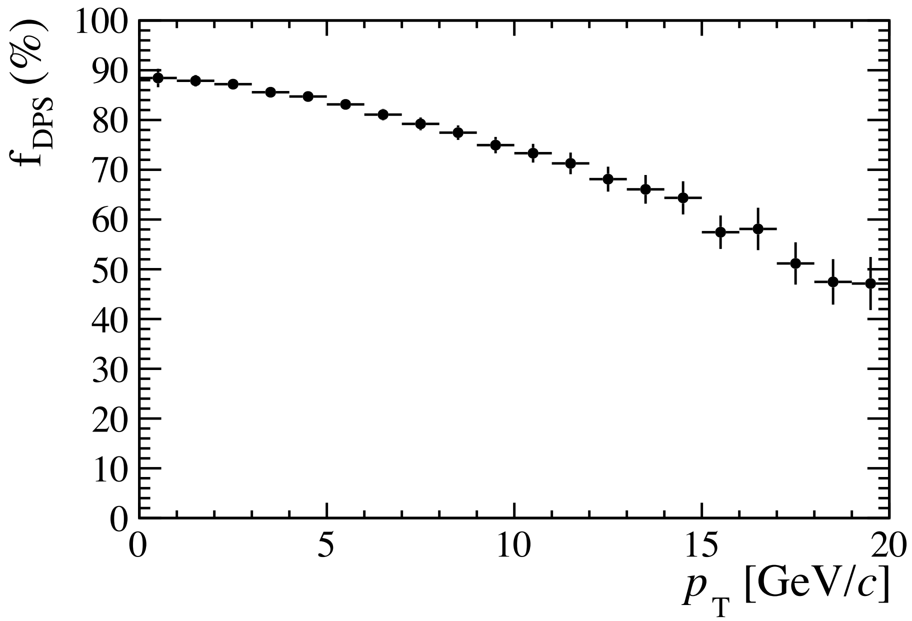


DPS: Double parton scattering



Pythia has higher production rate vs. BcVegPy

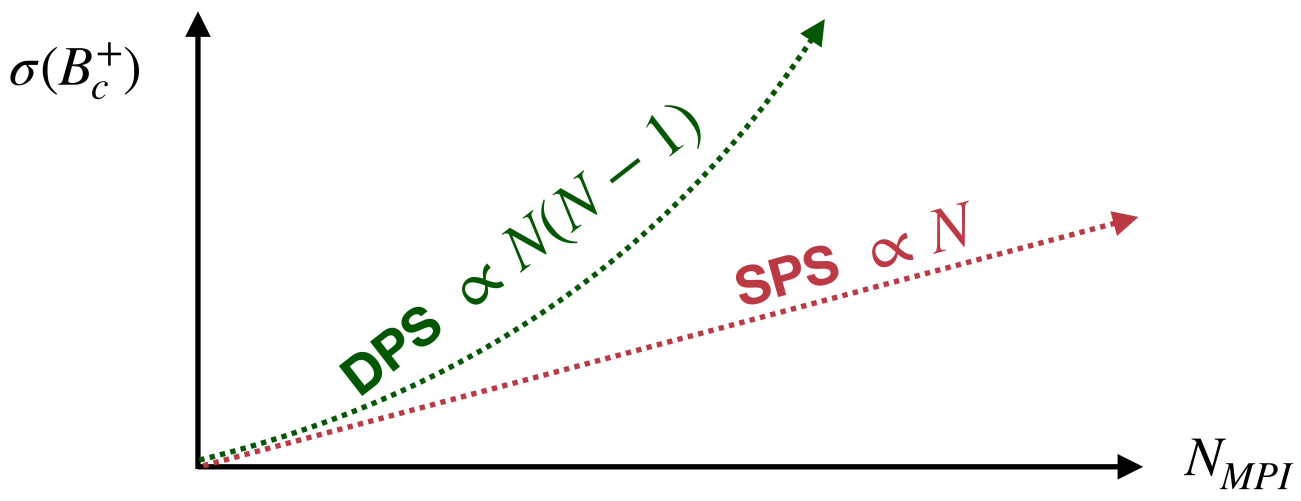
90% of B_c^+ come from DPS

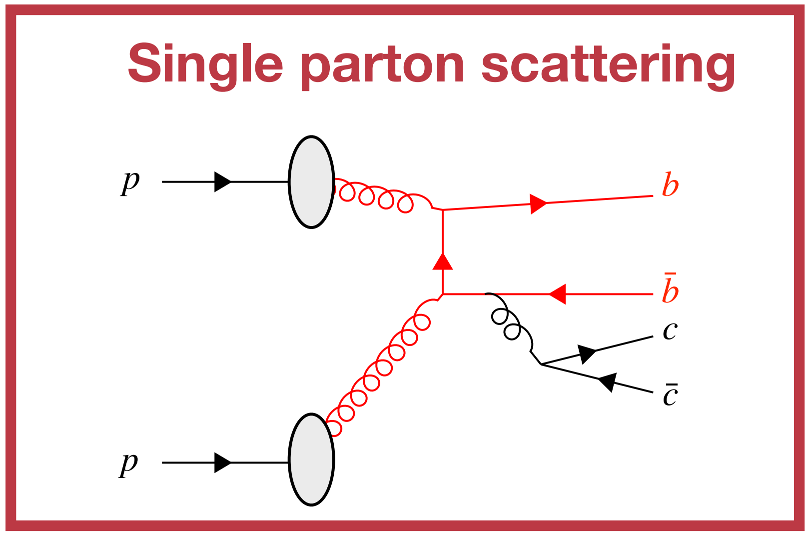


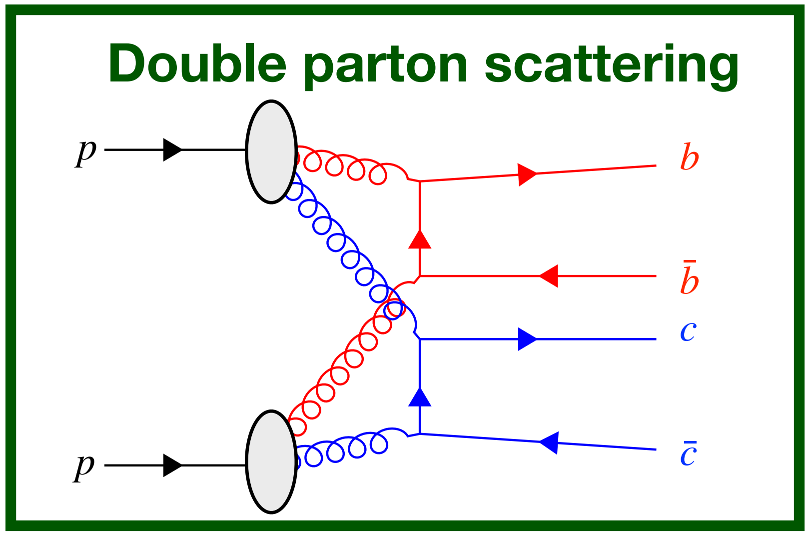
Differentiating DPS vs. SPS

- 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







Multiplicity dependence

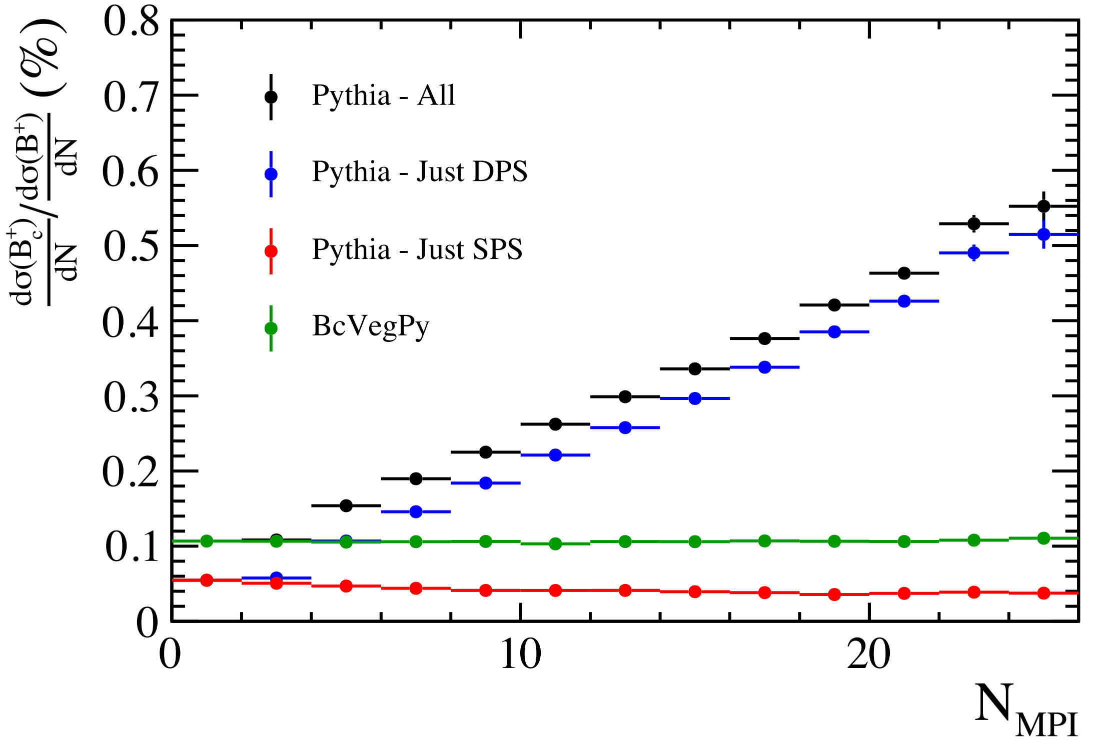
- **Ratio** of doubly-heavy hadrons to singly-heavy hadrons

SPS

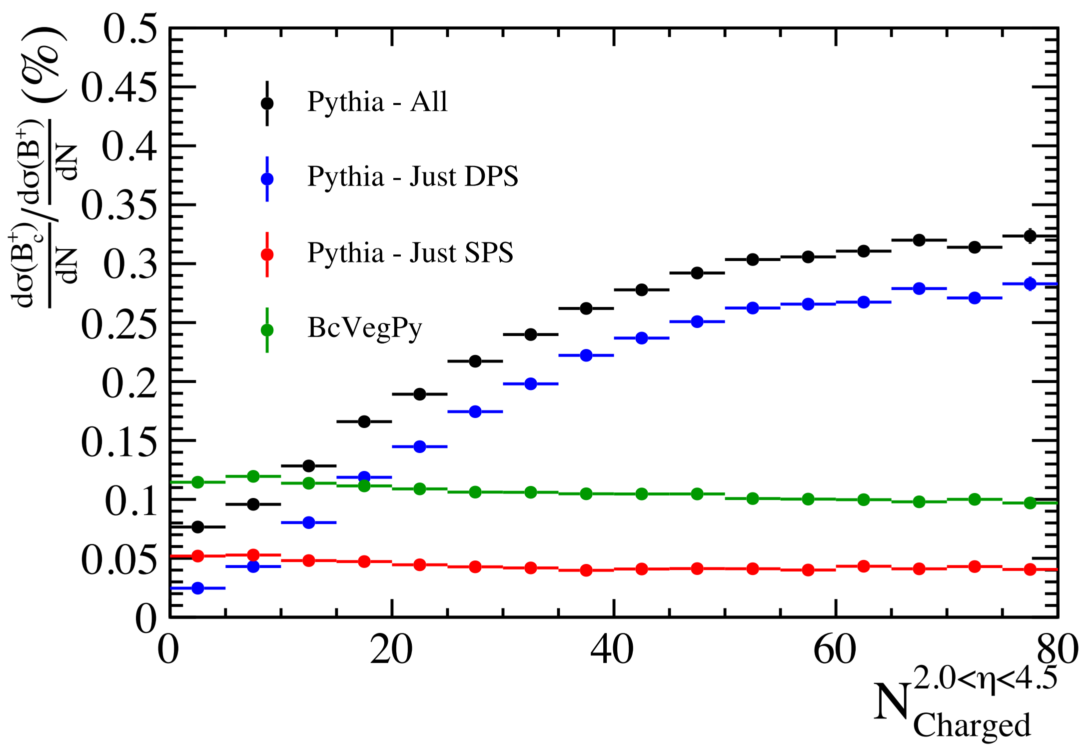
$$\frac{\sigma(B_c^+)}{\sigma(B^+)} \propto 1$$

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

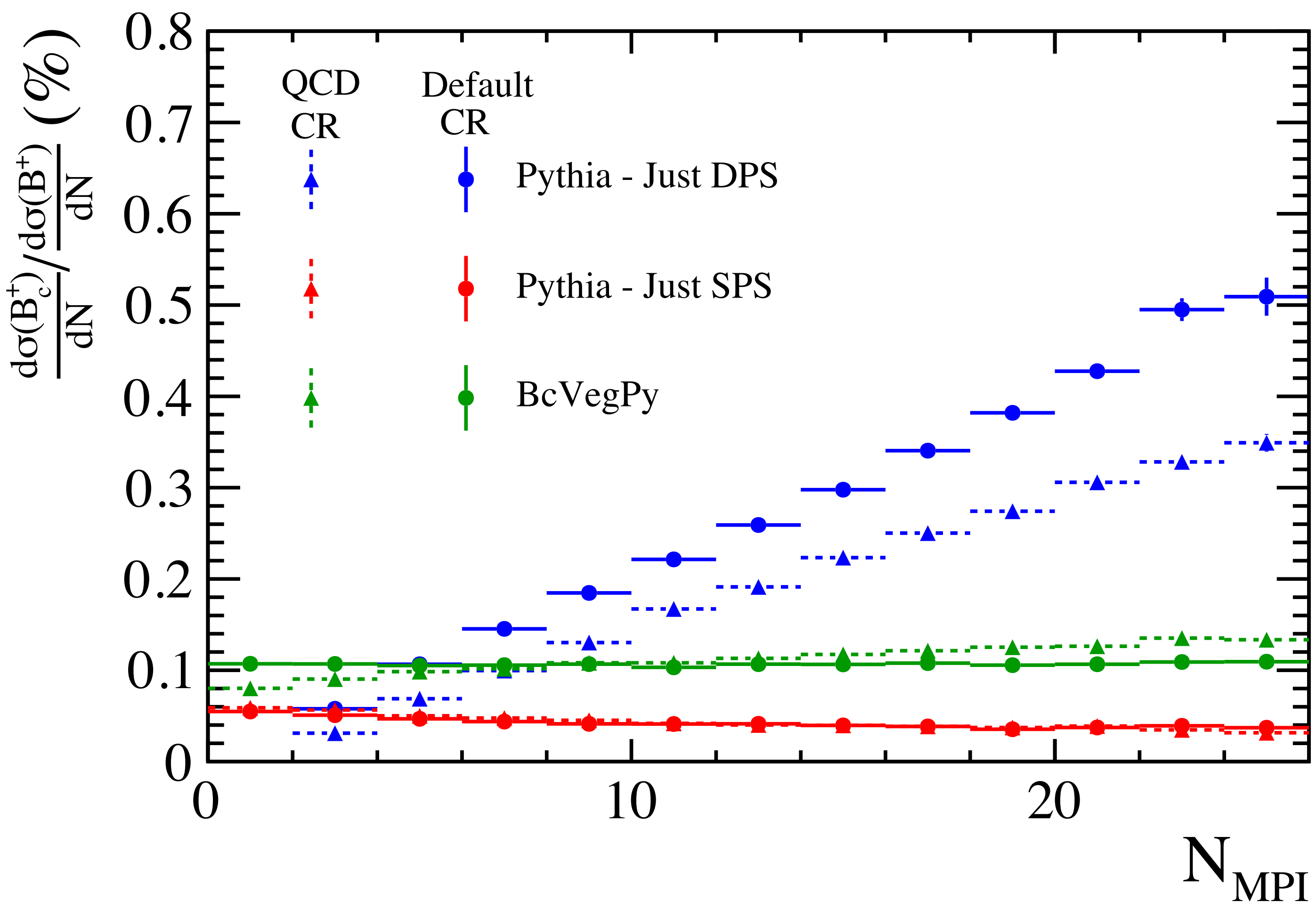


Colour reconnection

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

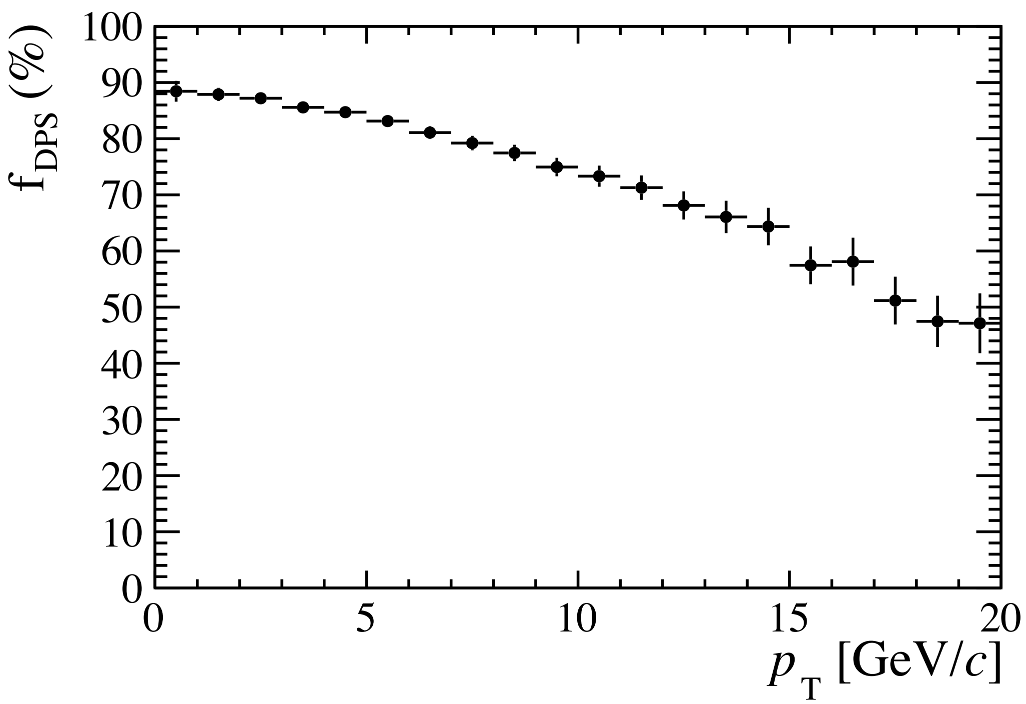
Default CR options are compared to QCD-CR:

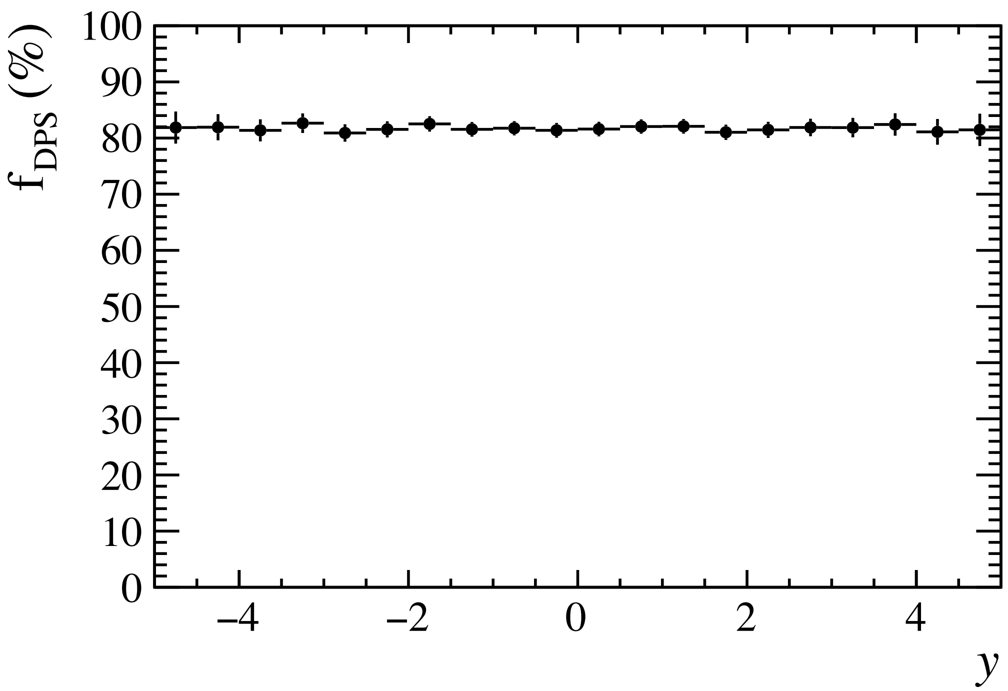
- If DPS contribution is observed in data, the slope could provide important information



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

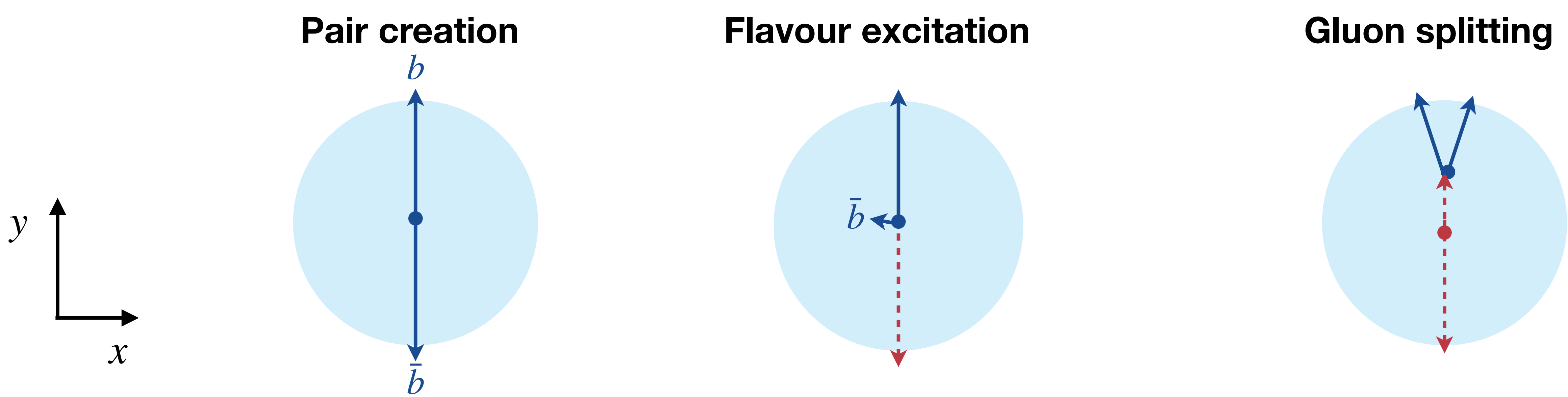
Any recommendations welcome!

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

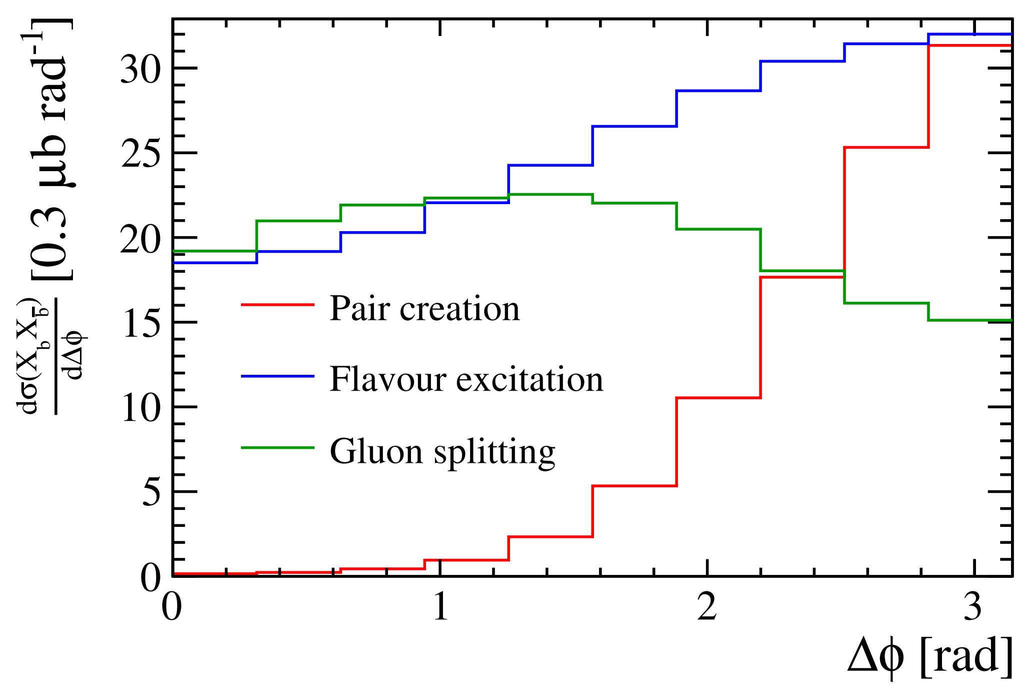
We can study the correlations between the other heavy quarks to further probe the production

Where do heavy quarks come from?

- The heavy quarks produced by the three mechanisms have different kinematic distributions

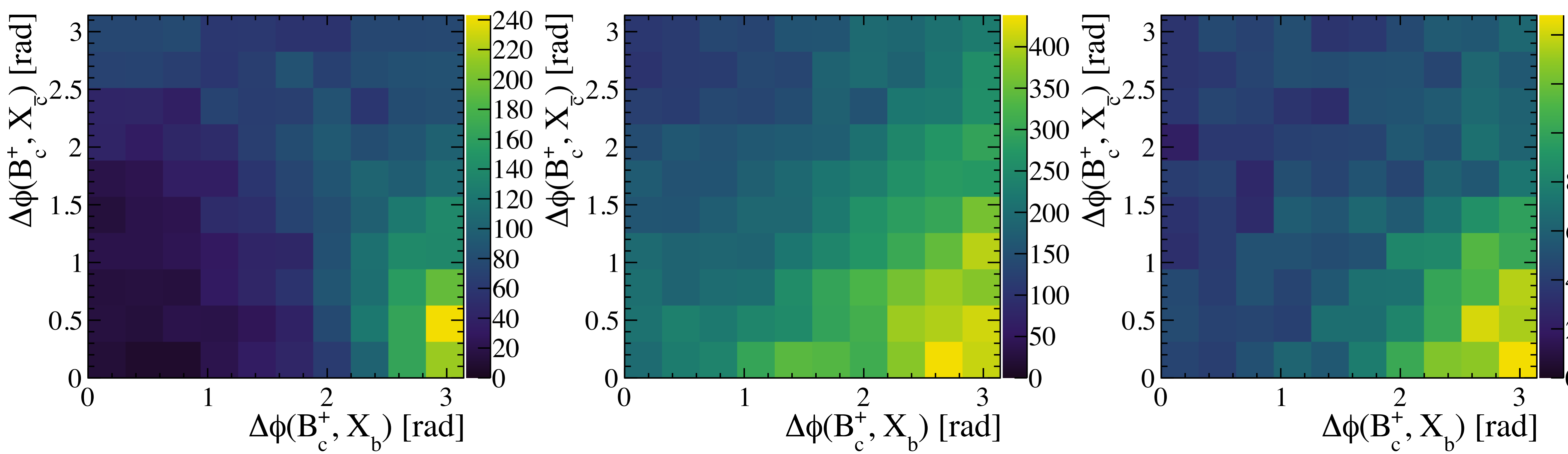


- Protons collide head on, with no momentum transverse the beam axis



What about the other heavy quarks?

- When we produce e.g. B_c^+ we can study angles with respect to X_b and $X_{\bar{c}}$
  - Distributions differ between DPS/SPS and generators

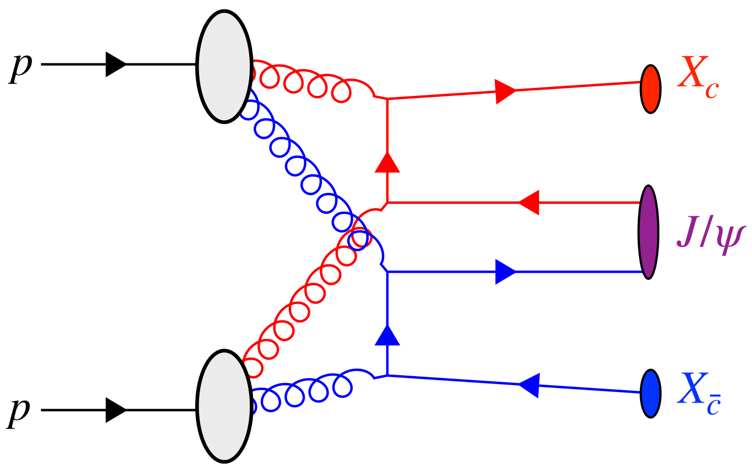


(a) Bcvegpy (b) Pythia- Just DPS (c) Pythia- Just SPS

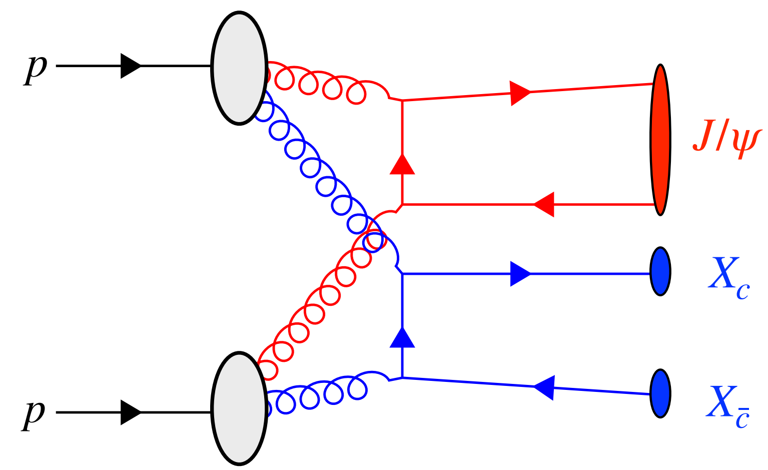
Quarkonia production

- Quarkonia production is more complicated, but in principle we could see a similar effect if we look for events with four heavy quarks

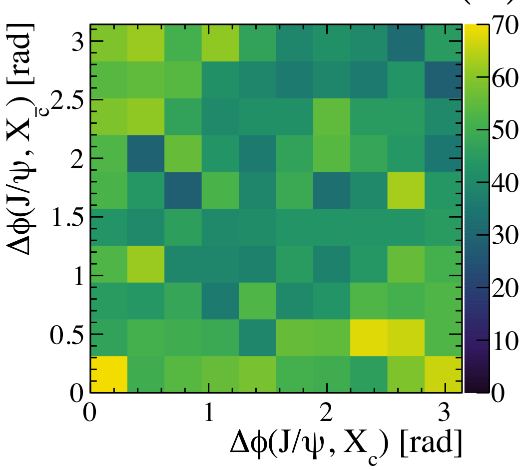
e.g. $J/\psi X_c X_{\bar{c}}$



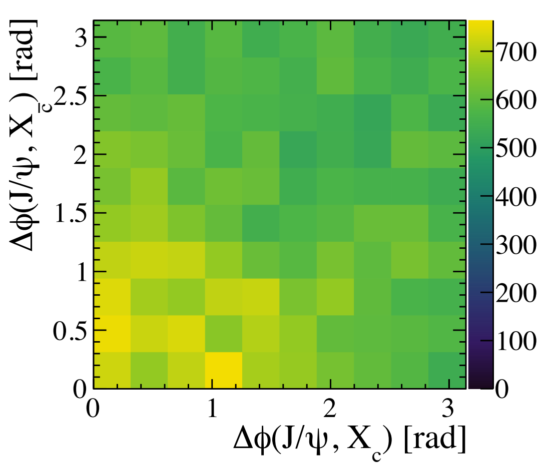
(a) *Mixed*



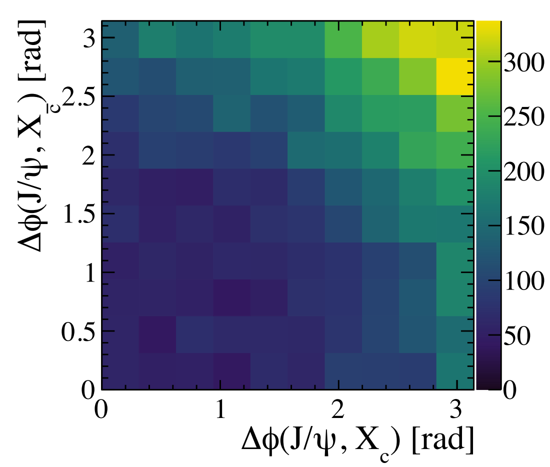
(b) *Unmixed*



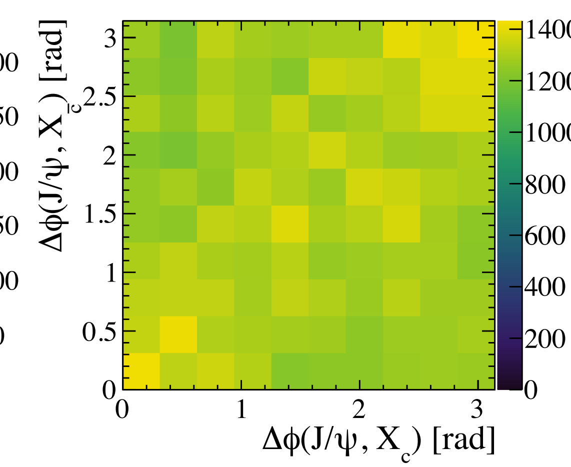
(c) PYTHIA- SPS *mixed*



(d) PYTHIA- DPS *mixed*



(a) PYTHIA- SPS *unmixed*



(b) PYTHIA- DPS *unmixed*

Experimental measurements

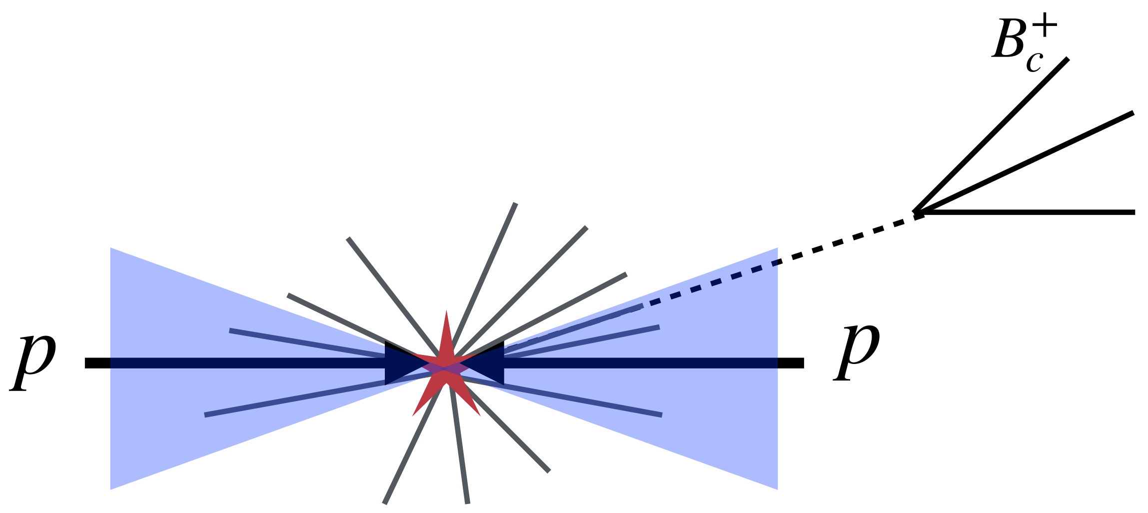
- Multiplicity measurements
  - We believe these are possible with B_c^+ and/or Ξ_{cc}^{++} at LHC experiments
  - LHCb measurements now ongoing

Challenges

Unlike strangeness enhancements, these effects would be global properties of the collision, rather than localised

Important to differentiate these effects from localised enhancements

e.g. forwards vs. backwards tracks



Experimental measurements

- Relative angular distributions
  - Potential to study the effects further in systems containing quarkonia plus singly-heavy hadrons

Challenges

It is difficult to reconstruct both additional heavy hadrons

X_c hadrons: exclusive reconstruction more feasible

X_b hadrons: inclusive reconstruction probably the way forward

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