B_c^+ Production at LHCb

And what it can tell us about multi-parton interactions

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Introduction

- Today I will discuss some recent work studying B_c^+ production at hadron colliders
- Predictions of B_c^+ production using **`Pythia`** are guiding studies into different production mechanisms

Outline:

- Exisiting production measurements
- Predictions and simulations of B_c^+ at hadron colliders
- B_c^+ formation in hadronisation
- Future directions

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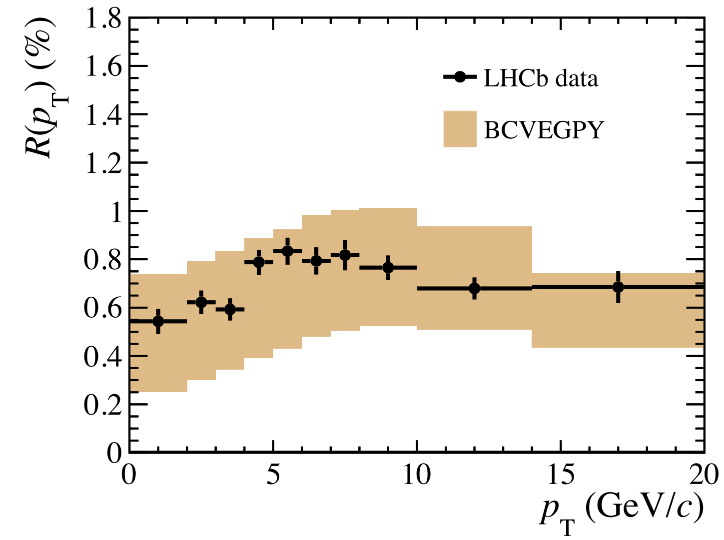
Measurements of the B_c^+ production cross section have been performed at LHCb using different final states

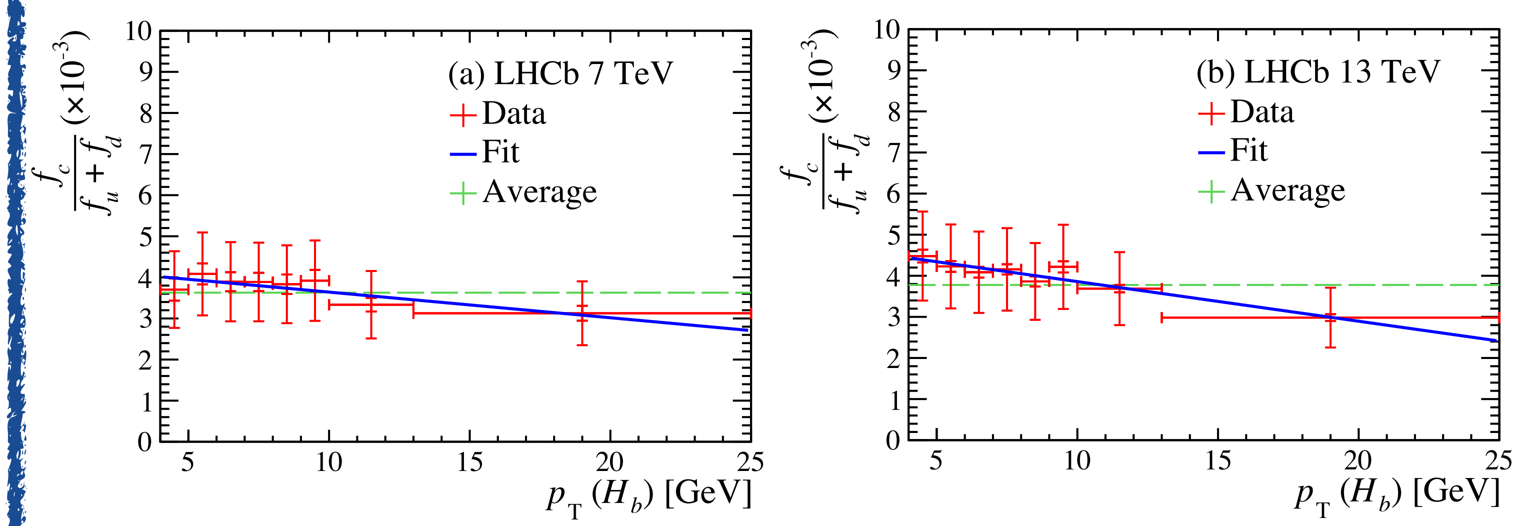
$$B_c^+ \to J/\psi\pi^+$$

[LHCb-PAPER-2012-028]

$$R = \frac{\sigma(B_c^+)}{\sigma(B^+)}\frac{BF(B_c^+ \to J/\psi\pi^+)}{BF(B^+ \to J/\psi K^+)}$$



[LHCb-PAPER-2019-033]



$$B_c^+ \to J/\psi\mu^+\nu_\mu$$

B_c^+ production predictions

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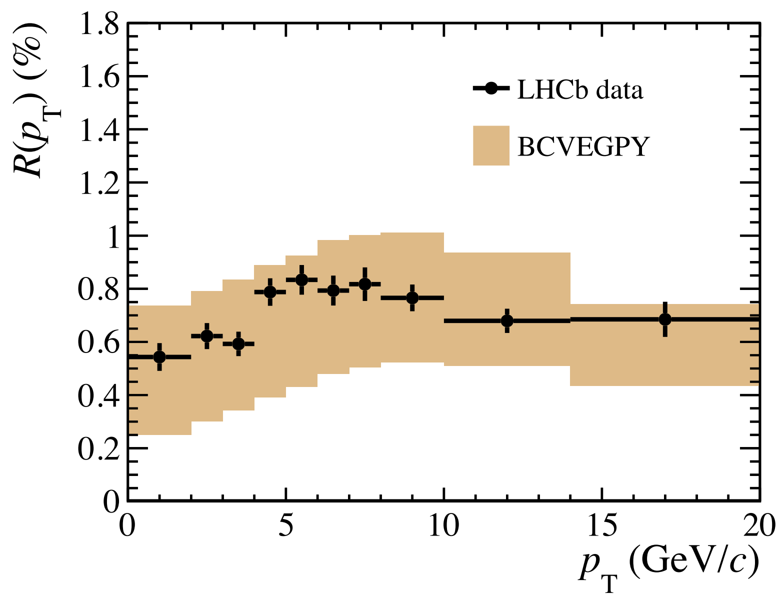
- To compare these measurements with predictions, we must assume branching fractions for the B_c^+ decays
  - **Absolute** branching fractions haven't ever been measured

[LHCb-PAPER-2012-028]



[LHCb-PAPER-2019-033]

Ref.\Mode	$J/\psi\,\mu^-\overline{\nu}$
[15]	6.4
[16]	
[17]	1.4
[18]	7.5
[19]	1.9
[20]	2.3
[21]	2.7
[22]	1.6
[23]	1.7
[24]	1.7
[25]	1.9
[26]	2.3
[27]	2.2
[28]	2.6
[29]	2.5
[30]	1.3
[31]	1.4
[32]	1.5
[33]	1.9
[34]	2.2

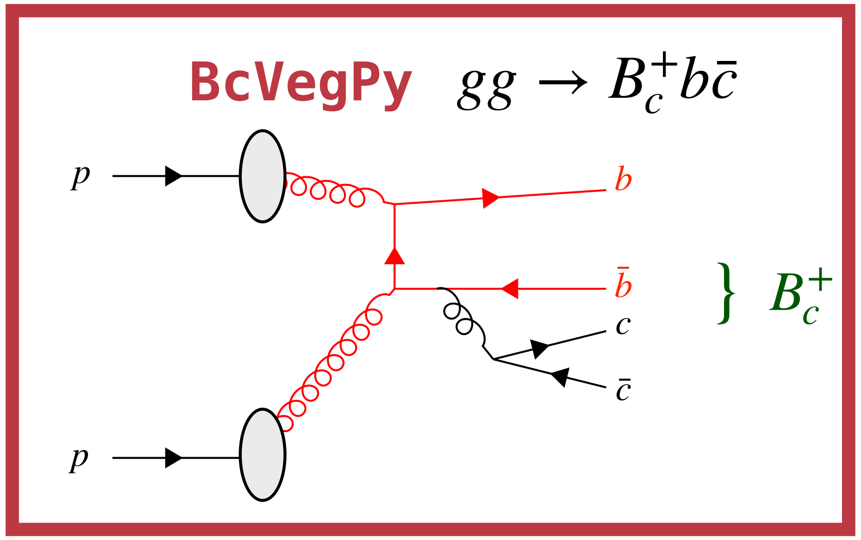
- There is a significant range in the available theoretical predictions, making it harder to draw firm conclusions

- So whilst current measurements are broadly in agreement with some theoretical predictions, there are large uncertainties

Current simulation assumptions

- At LHCb we simulate B_c^+ production using the hard matrix element calculator **BcVegPy**

- This simulates the dominate contributions to B_c^+ production, e.g. gluon-gluon fusion $gg \rightarrow B_c^+ b\bar{c}$



- This process is then interfaced with **Pythia**, an event generator
  - This adds the underlying event and performs hadronisation

This makes **two** assumptions:

1. That both the $\bar{b}$ and c were produced in the same parton-parton interaction
2. That this process was the hardest interaction in the event

Recent developments

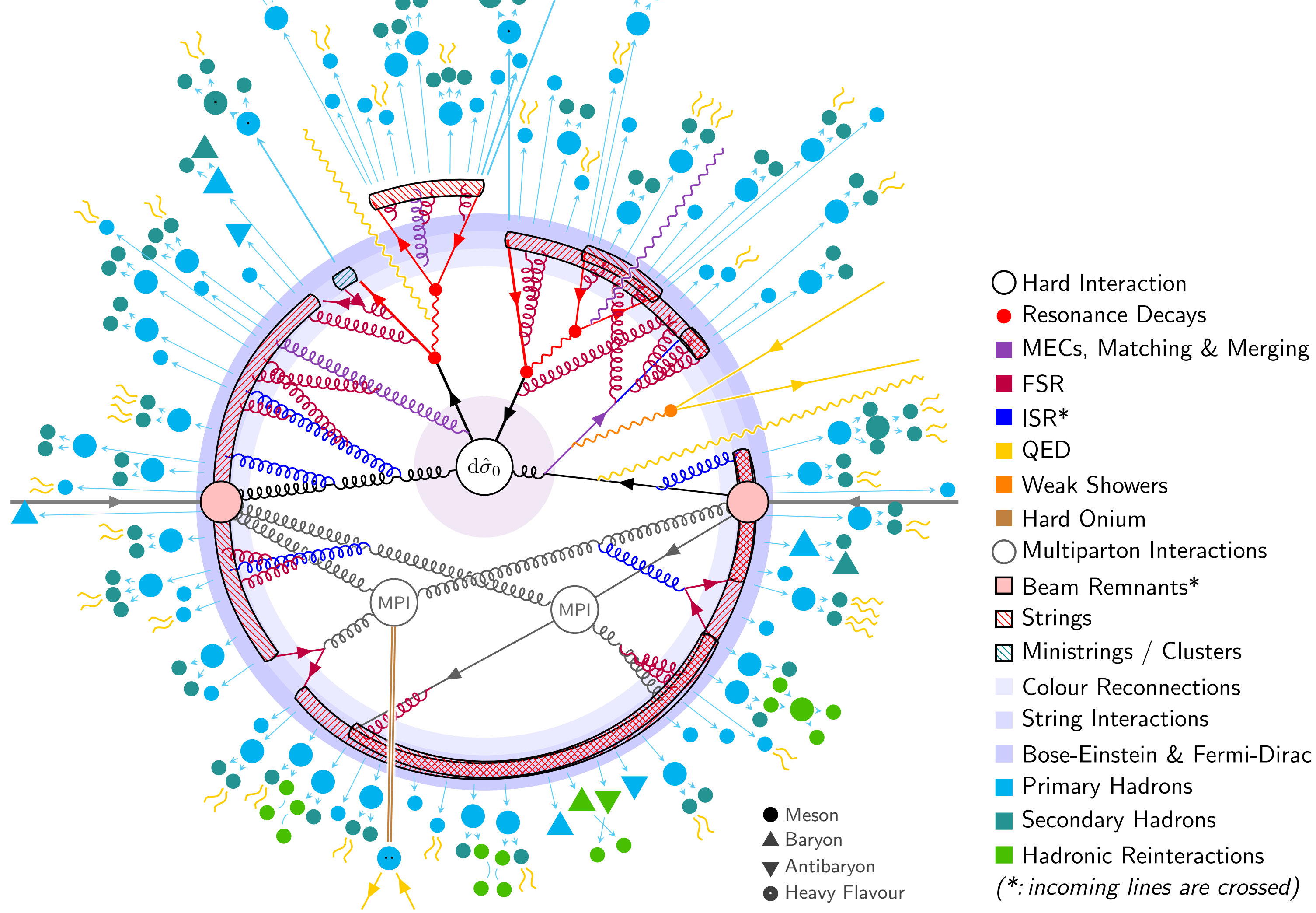
- In general it would be preferable to have a **fully inclusive simulation** sample of B_c^+ mesons from **minimum bias** events
    - Rather than assuming it's produced in a specific hard interaction
- This is possible with **`Pythia`**, but **extremely slow**
    - As in nature, it is rare to produce both $\bar{b}$ and c quarks that form a single hadron
- Recent developments in **`Pythia`** are helping to speed up the production of heavy quarks in inclusive events
    - Further details in the back-up slides

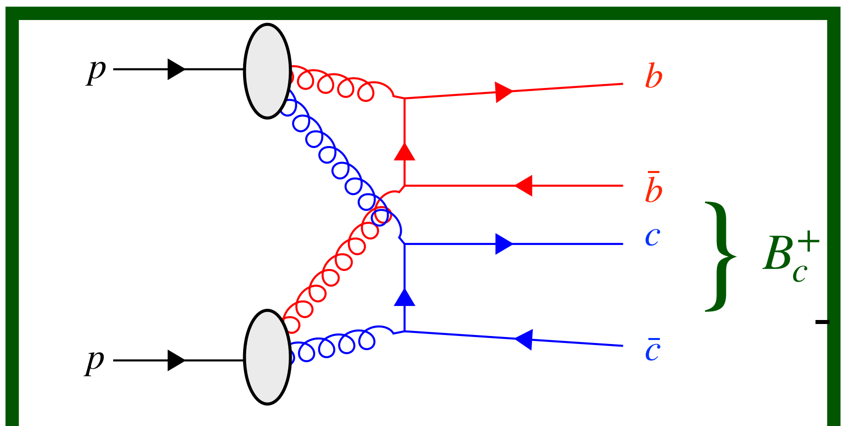
Recent developments

Aim: Produce inclusive samples of B_c^+ including all contributions, not just production in the hard scatter

[arxiv:2203.11601]

- Production during hard interaction
- Production during parton showers
- Production during hadronisation





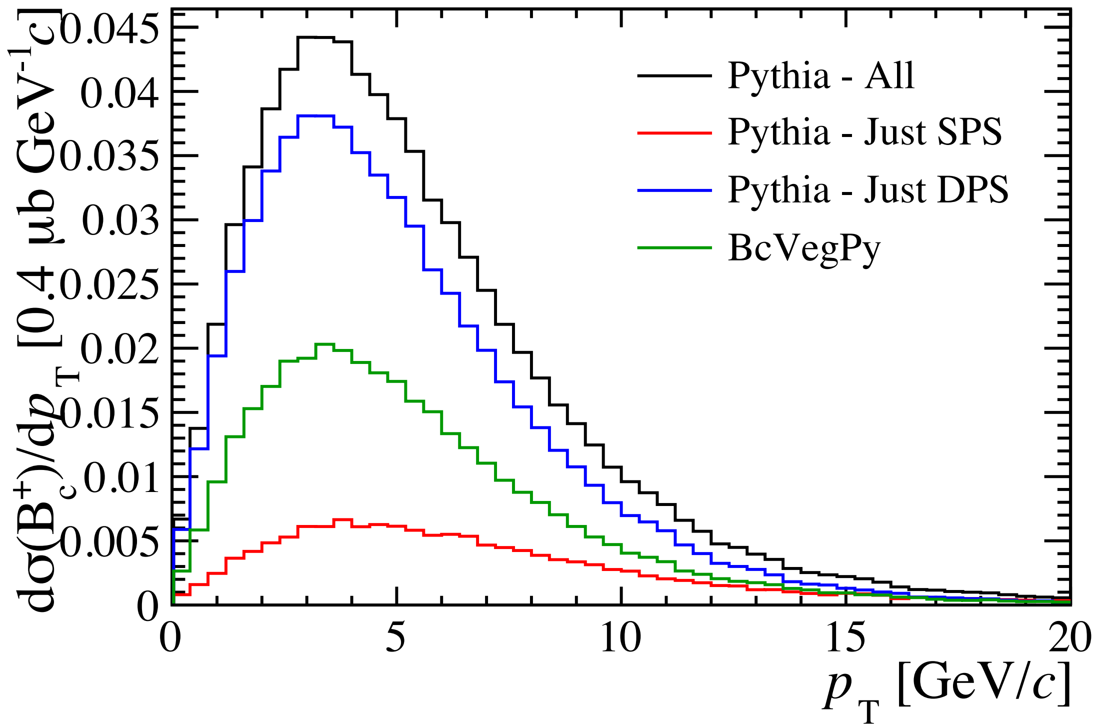
Double parton scattering

This creates opportunity for production from **double parton scattering**, i.e. $\bar{b}$ and c quarks formed in different parton interactions

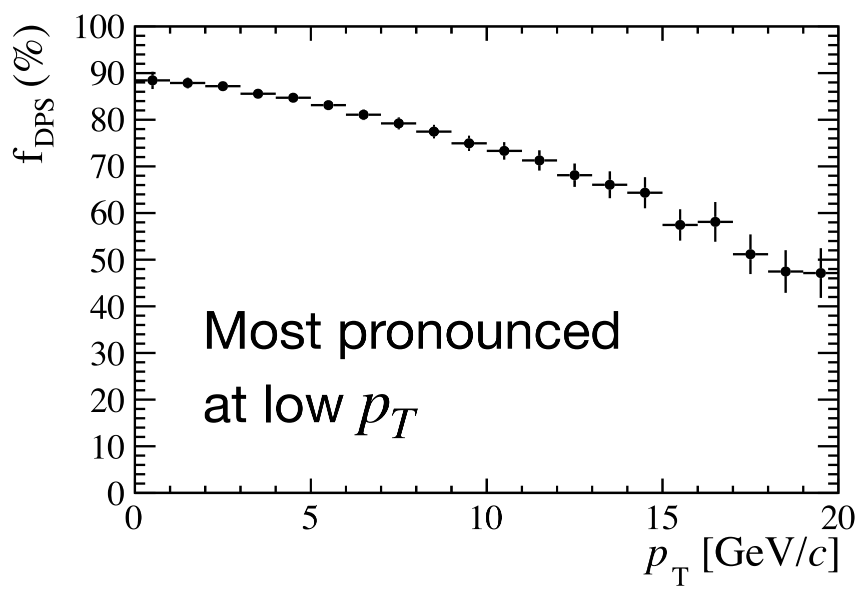
Pythia predictions

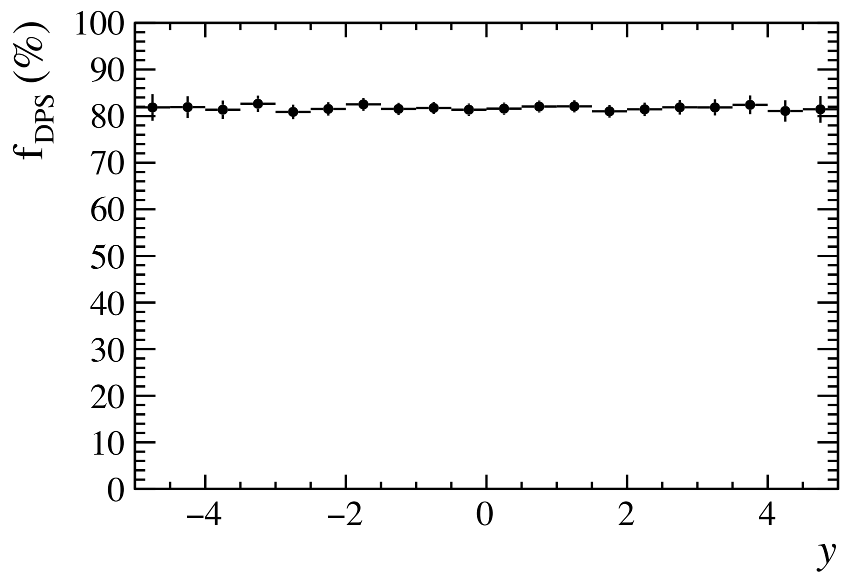
[arxiv:2205.15681]

- Inclusive samples produced with Pythia show a significant contribution from **DPS**
- There is some disagreement with the absolute cross-sections predicted by **`Pythia`** vs. **`BcVegPy`**



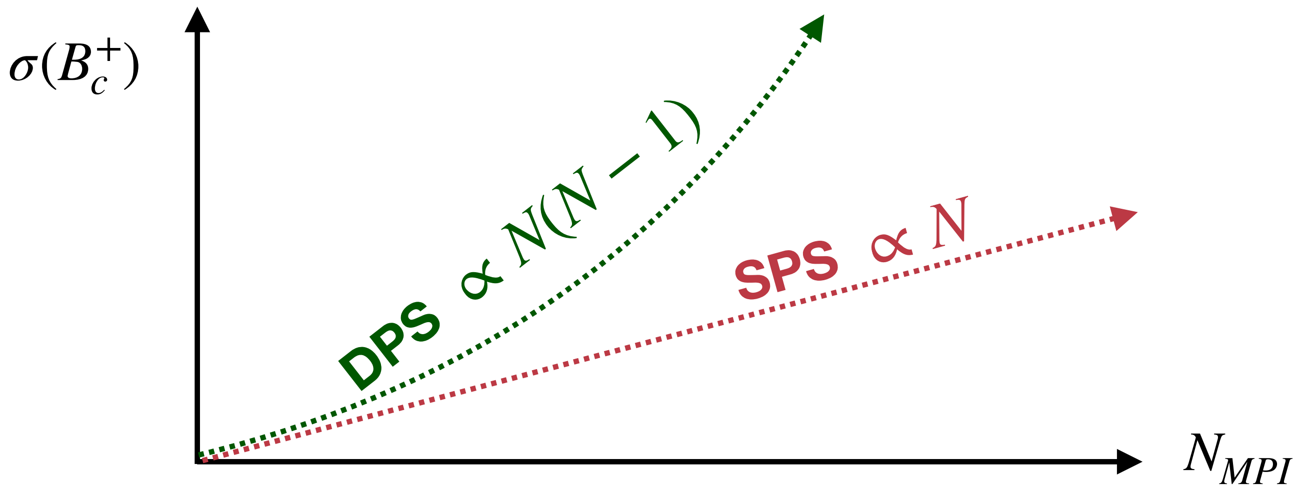
Pythia currently predicts **as much as 90%** of B_c^+ mesons produced in DPS





Disentangling production

- Measuring the **absolute cross section** comes with **large uncertainties**
  - Instead we can deduce if DPS is present by studying the **event characteristics**



The different behaviour in events with more parton-parton interactions can distinguish the two

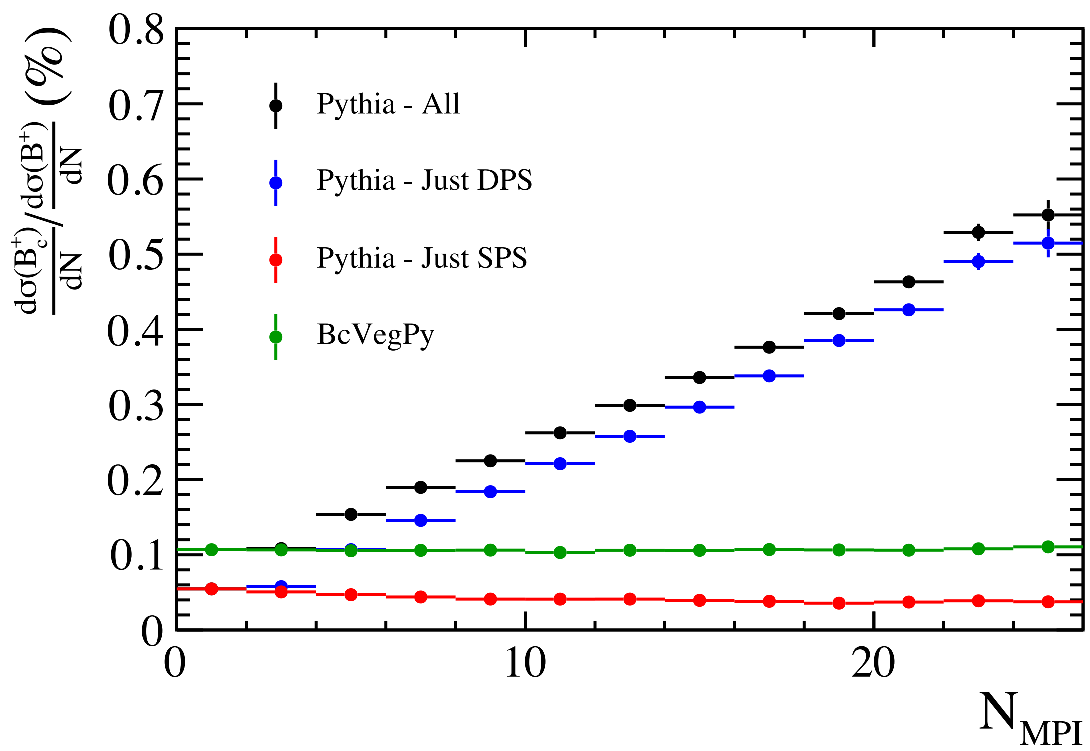
SPS

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

DPS

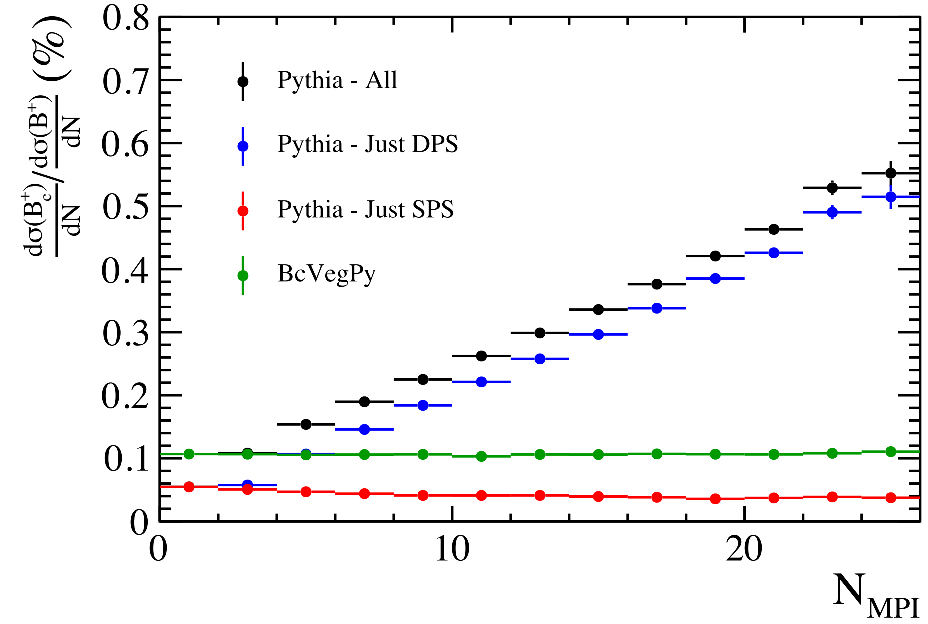
$$\frac{\sigma(B_c^+)}{\sigma(B^+)} \propto (N-1)$$

We can measure the differential cross section ratio to identify the production mechanism



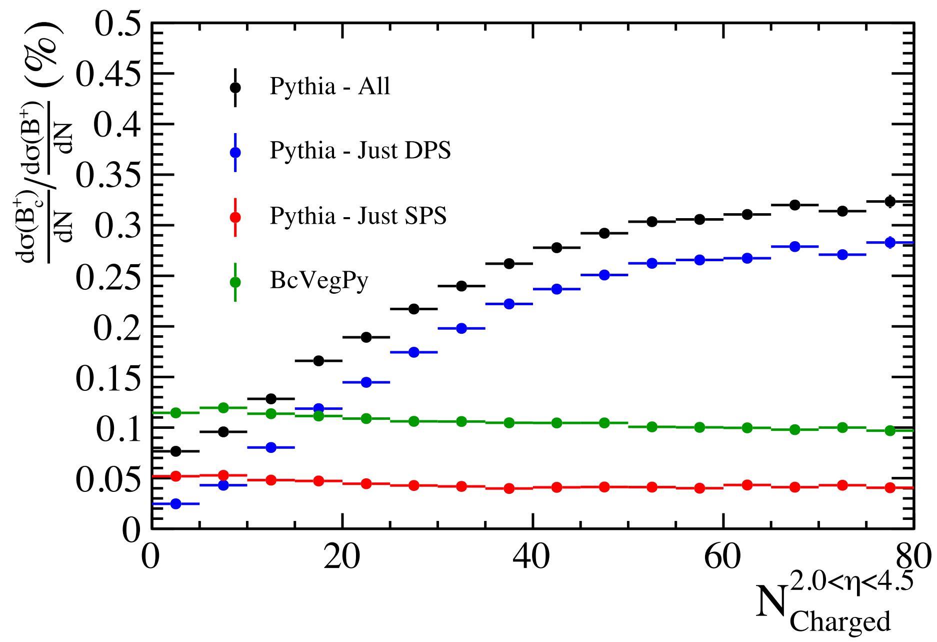
Tom Hadavizadeh

- Measurements of the differential B_c^+ cross section can provide more information on the formation mechanisms



The number of tracks in an event is a simple proxy for the number of parton interactions

$$N_{\text{Tracks}} \propto N_{MPI}$$

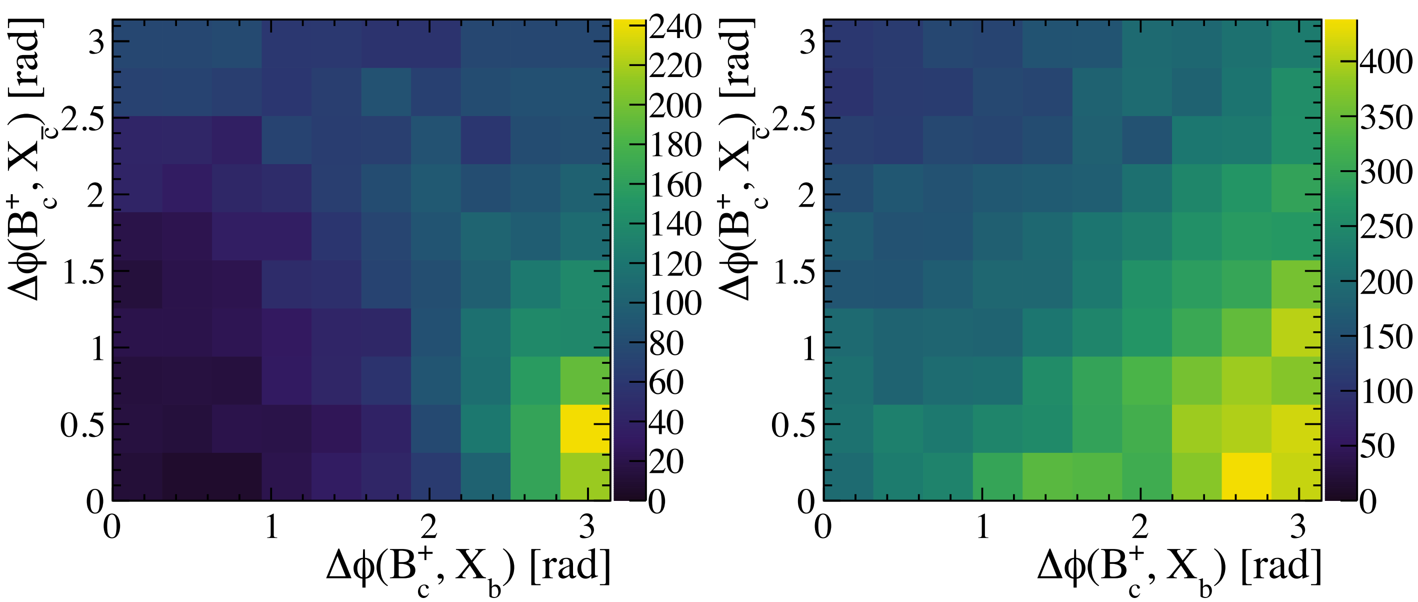


This measurement can be performed at LHCb and other experiments

Future studies

- Studies of the rest of the underlying event containing B_c^+ mesons can provide more information
    - ***Quantitative*** measurements of DPS vs. SPS contributions can provide insight into different models of **Colour Reconnection** in hadronisation
    - Production of B_c^+ mesons in jets can help us understand production in parton showers vs. production in the hardest interaction

Associated production of B_c^+ and other heavy hadrons can provide complementary information



(a) BCVEGPY (b) PYTHIA- Just DPS

E.g. relative transverse kinematics

Conclusions

- Measurements of B_c^+ meson production are can provide important information about the different production mechanisms

- Absolute production cross sections are subject to theoretical uncertainties
    - Multiplicity dependence of B_c^+ vs. B^+ cross section ratio can disentangle production mechanisms

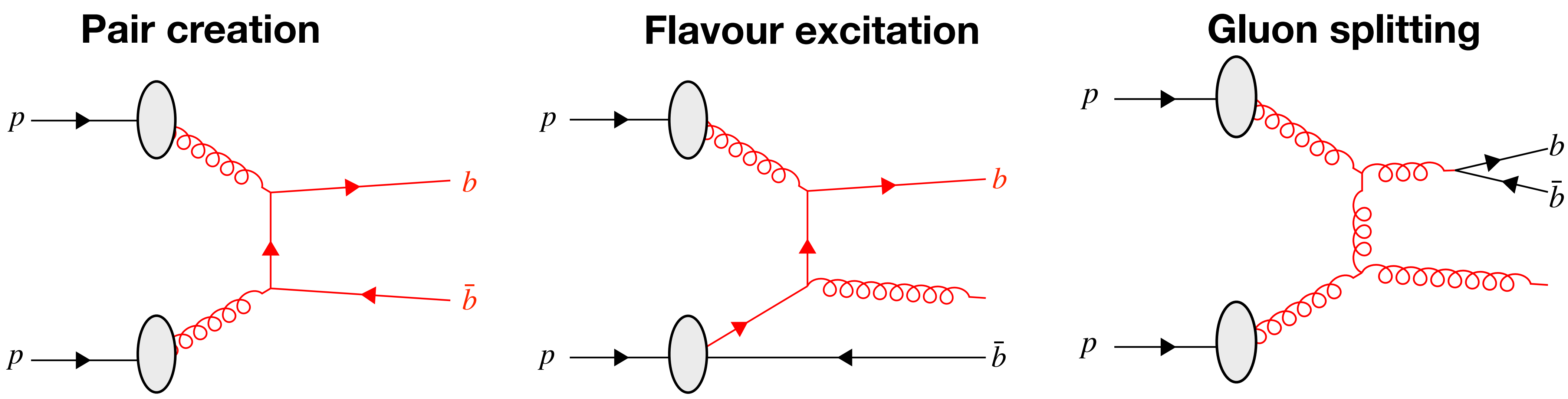
- These methods apply more broadly to other types of doubly heavy hadrons

- The results will help inform models of QCD in hadronisation and parton showers

Back up

Heavy quarks and Pythia

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



- 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

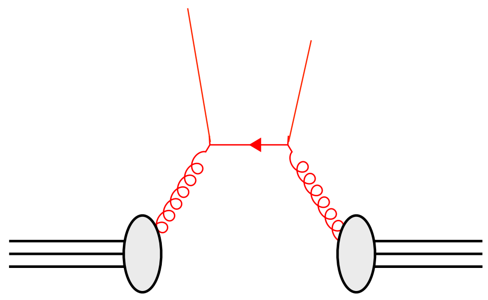
m_b
Heavy quark mass

Λ_{QCD}

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

No → **Discard**

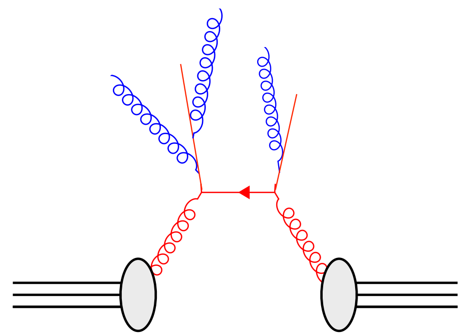
Yes ↓



Is there the required heavy quark?

No → **Discard**

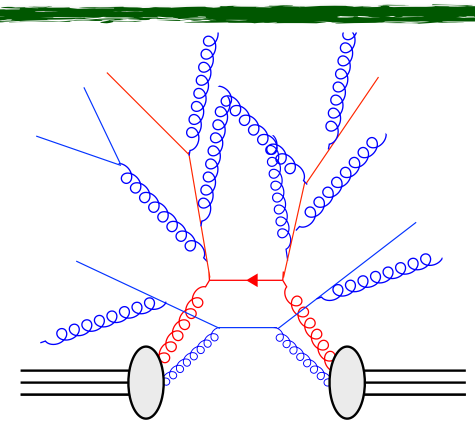
Yes ↓



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

No → **Discard**

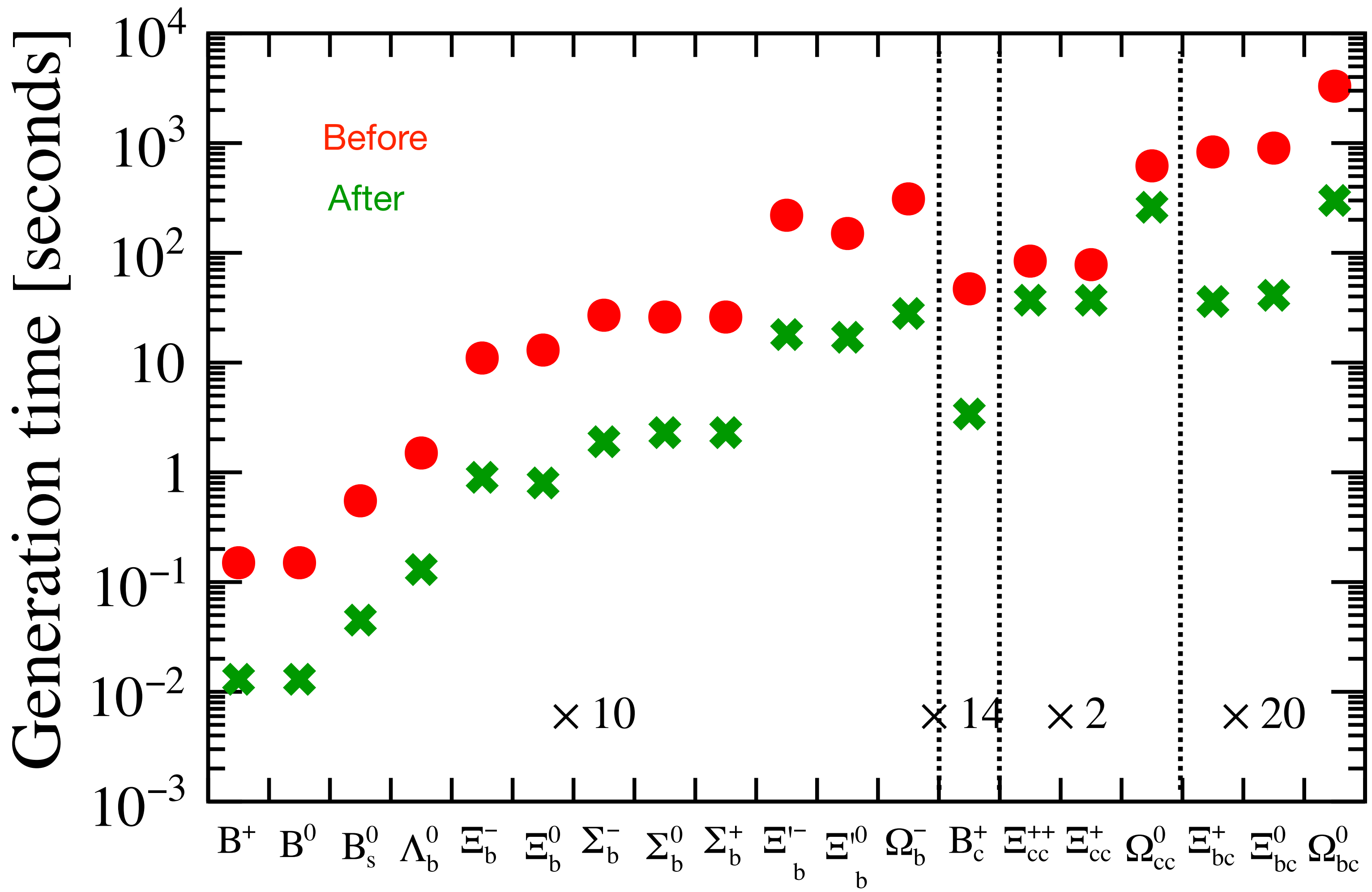
Yes ↓



Hadronise

Speed gains

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

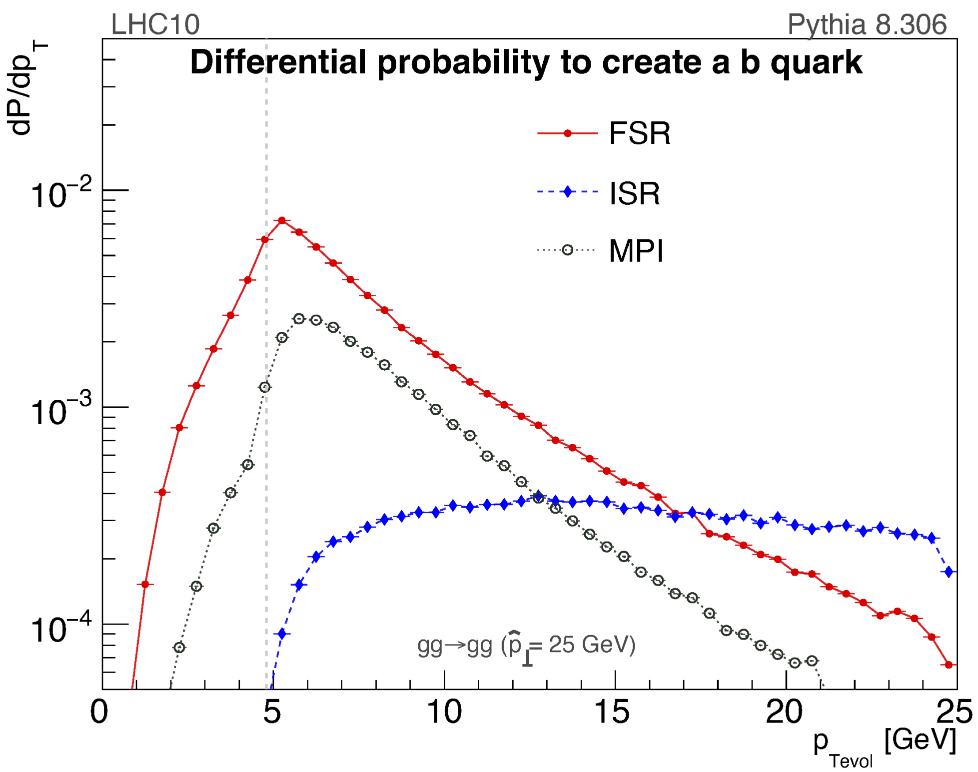


Gain is largest for b hadrons because c mass is closer to hadronisation scale

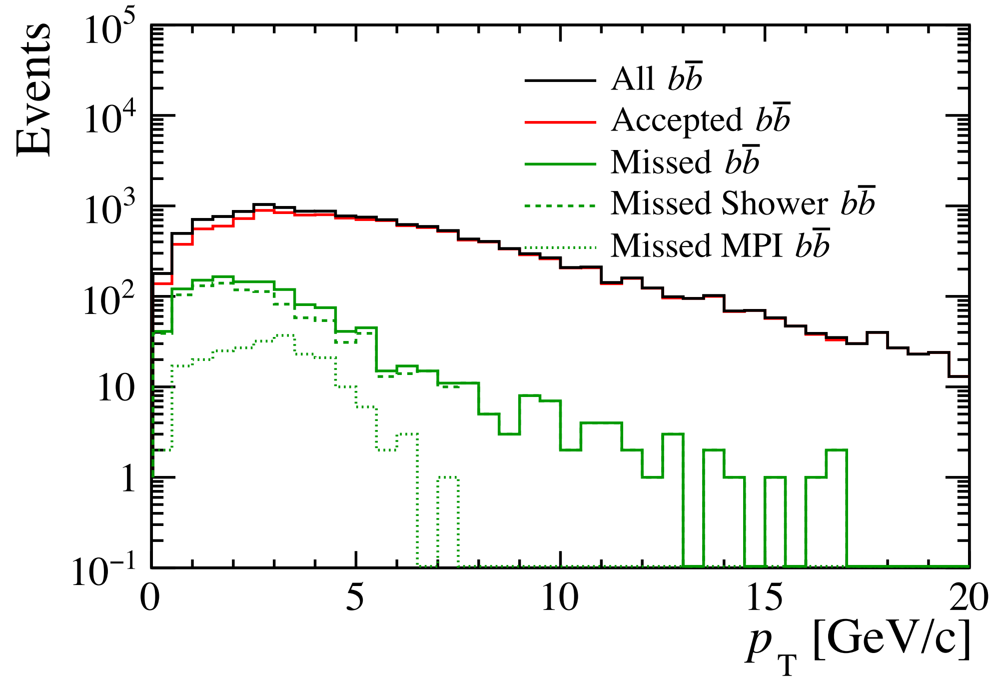
Some heavy flavour is missed

- 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



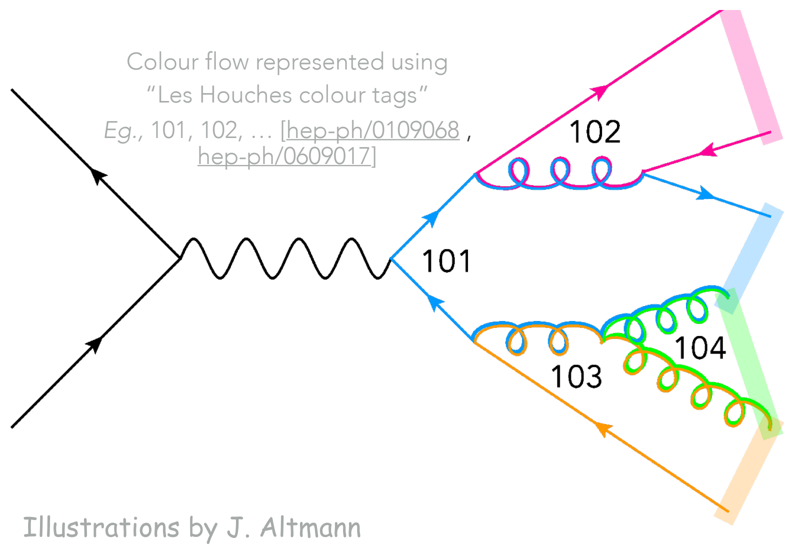
Affects FSR and MPI



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

Colour reconnection

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

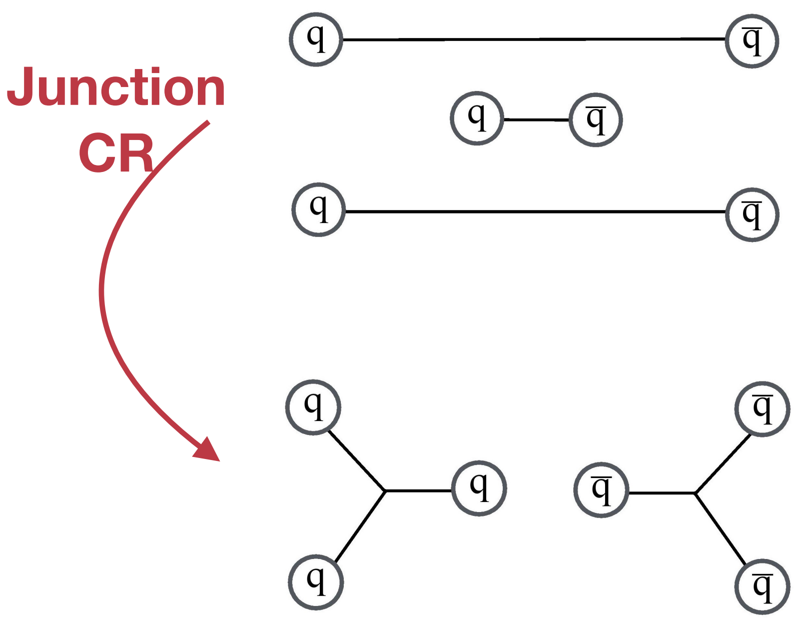


Pythia uses the *Leading Colour* limit

$$N_c \to \infty$$

Partons need to be reconnected to recover correct N_c

Illustrations by J. Altmann



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]