

Heavy-flavour production at the LHC

Jaime Norman ^{a,1,*}

^a*University of Liverpool,
Oliver Lodge Laboratory, Oxford St, Liverpool, L69 7ZE, UK*
E-mail: jaime.norman@cern.ch

Heavy flavour production measurements in pp collisions are a crucial test of QCD. The LHC experiments ALICE, ATLAS, CMS and LHCb, provide complementary abilities to measure many aspects of heavy-flavour production. This contribution summarises recent LHC measurements within this topic.

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*Speaker

Heavy-flavour (charm or beauty) hadron production in proton-proton collisions can be described with the factorisation approach as a convolution of the heavy quark partonic cross section, the parton distribution functions (PDFs) of the proton, and the fragmentation function (FF) of the heavy-flavour quark into a given hadron. The hard parton cross sections are calculated with perturbative QCD techniques, where the large mass of the heavy quark sets the hard scale meaning production can be calculated over all p_T . The PDFs and FFs on the other hand must be determined through measurements. At the LHC, the quark and gluon densities in the proton means multiple hard-parton scattering becomes more relevant, and the underlying event activity becomes much larger, which may affect the fragmentation and hadronisation of quarks into hadrons. Measurements of heavy-flavour hadrons in general constitute some of the most important tests of QCD over many length scales at hadron colliders.

Heavy-flavour meson and quarkonia production has been studied extensively at the LHC. Measurements of the prompt [1, 2] and non-prompt (from beauty decays) [3] production of D mesons agree well with QCD calculations [4, 5], indicating that heavy-flavour meson production is well understood. The measurement of strange to non-strange beauty meson production has also been measured from non-prompt D mesons with ALICE [3], and a combined analysis of B meson decays from LHCb [6]. The LHCb measurement hints at a slight increase in the production ratio of strange to non-strange beauty meson with collision energy. This is also a crucial measurement for reducing the uncertainty in many B_s^0 branching fractions, which are a dominant source of uncertainty in many searches for new physics. Prompt J/ψ production has been measured by ALICE [7], ATLAS [8], CMS [9] and LHCb [10], and non-prompt J/ψ production is also measured by ALICE [7], ATLAS [8] and CMS [9].

Comprehensive studies of heavy-flavour baryon production have recently been performed at the LHC, and currently heavy-flavour baryon production is less well understood than heavy-flavour meson production. Λ_c^+ production has been measured in pp collisions by ALICE [11–13] and CMS [14], and is significantly underestimated by QCD calculations. The baryon-to-meson production ratio Λ_c^+/D^0 is significantly larger than the same measurements in e^+e^- and ep collisions, by up to a factor of 5 at low p_T , and exhibits a strong p_T dependence. Recently the baryon-to-meson ratios $\Xi_c^{0,+}/D^0$ [15, 16], $\Sigma_c^{++,+}/D^0$ [11] and Ω_c^0/D^0 [17] have also been measured by ALICE to be significantly underestimated by predictions utilising fragmentation parameterisations based on measurements in e^+e^- and ep collisions. The fragmentation fractions of charm quarks into charmed hadrons have been measured for the first time in pp collisions [18], which are shown in figure 1. The charmed hadron fragmentation fractions differ significantly from measurements in e^+e^- and ep collisions, indicating the assumption of universal, independent parton-to-hadron fragmentation across collision systems is not sufficient to describe charmed hadron production in pp collisions at the LHC. Possible explanations of this difference include colour reconnection between independent partons [19], quark coalescence [20, 21], or enhanced baryon production originating from the decay of as-yet-undiscovered charm baryon states [22], which describe baryon-to-meson ratios better, though still underpredict the Ω_c^0/D^0 and $\Xi_c^{0,+}/D^0$ ratios. The relative production of beauty baryons and mesons has also been measured by LHCb [23], where a similar enhancement of the ratio $\Lambda_b^0/(B^0 + B^+)$ is measured at low p_T . A measurement of the ratio of non-prompt Λ_c^+ baryons and D^0 mesons was made as a function of p_T by ALICE which aims to indirectly probe beauty quark fragmentation. This measurement was compared to predictions utilising quark production with

FONLL, and hadronisation/hadron decays with PYTHIA - the predictions require the fragmentation fractions measured by LHCb to describe the data, and the measurement is underestimated if utilising fragmentation fractions measured in e^+e^- collisions. These measurements also suggest that fragmentation fractions of beauty baryons are not universal in different collision systems. The production cross section measurements of different charmed hadrons has allowed for precise measurement of the total $c\bar{c}$ [18] and $b\bar{b}$ [7] production cross sections.

Heavy-flavour hadron production has been studied as a function of the event multiplicity. The strange to non-strange production ratio of beauty mesons B_s^0/B^0 measured by LHCb in pp collisions [24] is shown in figure 1 (right). When measuring the multiplicity in the same rapidity region as the beauty hadron (with the VELO tracker) there is evidence at a level of 3.4σ that the ratio B_s^0/B^0 increases with multiplicity. When measuring the multiplicity in the opposite rapidity direction as the beauty hadron, the ratio is instead independent of this multiplicity, indicating the enhancement is due to the local event multiplicity. The charmed baryon-to-meson ratio measured by ALICE [25] also displays a significant enhancement in the region $2 < p_T < 12$ GeV/c at high multiplicity compared to low multiplicity. This multiplicity dependence is described well by PYTHIA when including colour reconnection mechanisms beyond the leading colour approximation. The charmed strange to non-strange ratio D_s^+/D^0 is instead independent of multiplicity within the current experimental uncertainties [25].

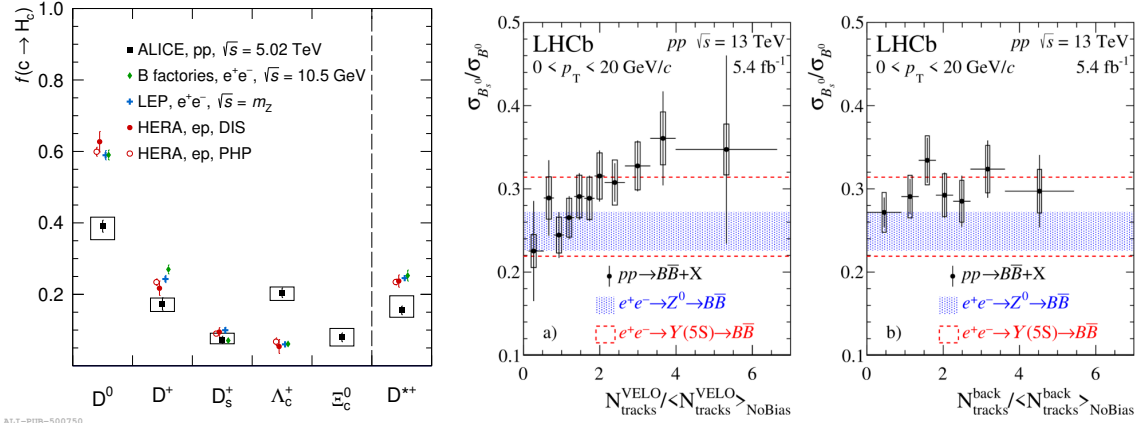


Figure 1: Left: Charm quark fragmentation fractions into charm hadrons in pp collisions at $\sqrt{s} = 5.02$ TeV, compared with measurements at LEP and B factories, and ep collisions [18]. Right: The production ratios of strange to non-strange B mesons B_s^0/B^0 as a function of the event multiplicity measured either in the direction of the beauty meson (left) or in the opposite direction (right) [24].

Fragmentation dynamics of heavy quarks are probed with measurements of heavy flavour hadrons within jets. Figure 2 (left) shows a measurement of $B^\pm$ mesons within jets by ATLAS [26] - in particular, the relative momentum of the jet that is carried by the hadron in the direction of the jet, $z = \frac{\vec{p}_{B,D} \cdot \vec{p}_j}{|\vec{p}_j|}$. The transverse momentum profile is also reported in [26]. ALICE measured the z distribution of D mesons [27] at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 13$ TeV. Comparisons to Monte Carlo event generators were made in all cases, which helps constrain different approaches to fragmentation in these generators.

The first observation of b -hadron production asymmetry (i.e., asymmetrical production of a

beauty hadron compared to its anti-particle, measured using $A_{prod} = \frac{\sigma(pp \rightarrow \Lambda_b^0 Y) - \sigma(pp \rightarrow \bar{\Lambda}_b^0 Y)}{\sigma(pp \rightarrow \Lambda_b^0 Y) + \sigma(pp \rightarrow \bar{\Lambda}_b^0 Y)}$ was reported by LHCb [28]. Figure 2 shows A_{prod} as a function of Λ_b^0 rapidity at $\sqrt{s} = 7$ TeV. Combining the measurement at $\sqrt{s} = 7$ TeV and 8 TeV, the results are incompatible with symmetric production with a significance of 5.8 standard deviations, assuming no CP violation in the decay. There is also evidence at the level of 4σ of an increase in production asymmetry with rapidity. Comparisons from MC generators show that the results agree with PYTHIA when an improved colour reconnection model is included.

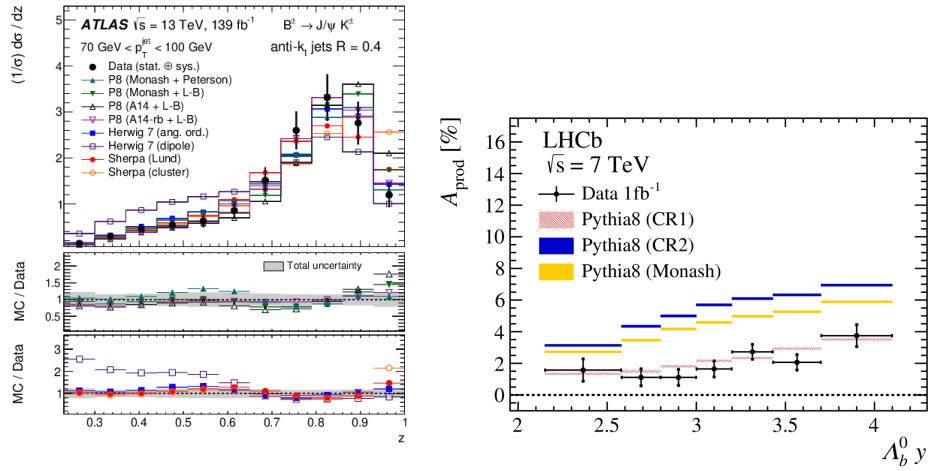


Figure 2: Left: The distribution of the longitudinal profile z of $B^\pm$ mesons in jets [26]. Right: the production asymmetry of Λ_b^0 baryons [28].

CMS reported the observation of simultaneous production of three J/ψ meson particles [29]. In this analysis, five events are found to be consistent with triple- J/ψ production, with a statistical significance relative to the background-only expectation of 5 standard deviations. The measured cross section is $\sigma(pp \rightarrow J/\psi J/\psi J/\psi X) = 272_{-104}^{+141}(\text{stat.}) \pm 17(\text{syst.})$ fb. This cross section is consistent with theoretical expectation of production via primarily double-parton scattering and triple-parton scattering (under the simplest assumption of factorization of multiple hard-scattering probabilities in terms of SPS cross sections). This measurement is the first observation of the simultaneous production of three heavy particles, and represents an important step in the quest to constrain the proton PDF.

In summary, heavy-flavour production at the LHC constitutes a stringent test of QCD, and Run 2 of the LHC has allowed for a diverse range of heavy-flavour production measurements. Run 3 has just begun after significant detector upgrade programmes for all 4 LHC experiments during Long Shutdown 2, which will provide unprecedented accuracy for future heavy-flavour production measurements.

References

- [1] LHCb collaboration, *Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **03** (2016) 159 [[1510.01707](#)].
- [2] CMS collaboration, *Measurement of prompt open-charm production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **11** (2021) 225 [[2107.01476](#)].
- [3] ALICE collaboration, *Measurement of beauty and charm production in pp collisions at $\sqrt{s} = 5.02$ TeV via non-prompt and prompt D mesons*, *JHEP* **05** (2021) 220 [[2102.13601](#)].
- [4] B.A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, *Inclusive Charmed-Meson Production at the CERN LHC*, *Eur. Phys. J. C* **72** (2012) 2082 [[1202.0439](#)].
- [5] M. Cacciari, M. Greco and P. Nason, *The P(T) spectrum in heavy flavor hadroproduction*, *JHEP* **05** (1998) 007 [[hep-ph/9803400](#)].
- [6] LHCb collaboration, *Precise measurement of the f_s/f_d ratio of fragmentation fractions and of B_s^0 decay branching fractions*, *Phys. Rev. D* **104** (2021) 032005 [[2103.06810](#)].
- [7] ALICE collaboration, *Prompt and non-prompt J/ψ production cross sections at midrapidity in proton-proton collisions at $\sqrt{s} = 5.02$ and 13 TeV*, *JHEP* **03** (2022) 190 [[2108.02523](#)].
- [8] ATLAS collaboration, *Measurement of the production cross-section of J/ψ and $\psi(2S)$ mesons at high transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Tech. Rep. [ATLAS-CONF-2019-047](#), CERN, Geneva (2019).
- [9] CMS collaboration, *Measurement of prompt and nonprompt J/ψ production in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Eur. Phys. J. C* **77** (2017) 269 [[1702.01462](#)].
- [10] LHCb collaboration, *Measurement of J/ψ production cross-sections in pp collisions at $\sqrt{s} = 5$ TeV*, *JHEP* **11** (2021) 181 [[2109.00220](#)].
- [11] ALICE collaboration, *Measurement of Prompt D^0 , Λ_c^+ , and $\Sigma_c^{0,++}(2455)$ Production in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. Lett.* **128** (2022) 012001 [[2106.08278](#)].
- [12] ALICE collaboration, *Λ_c^+ Production and Baryon-to-Meson Ratios in pp and p-Pb Collisions at $\sqrt{s_{NN}}=5.02$ TeV at the LHC*, *Phys. Rev. Lett.* **127** (2021) 202301 [[2011.06078](#)].
- [13] ALICE collaboration, *Λ_c^+ production in pp and in p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV*, *Phys. Rev. C* **104** (2021) 054905 [[2011.06079](#)].
- [14] CMS collaboration, *Production of Λ_c^+ baryons in proton-proton and lead-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Lett. B* **803** (2020) 135328 [[1906.03322](#)].
- [15] ALICE collaboration, *Measurement of the production cross section of prompt Ξ_c^0 baryons at midrapidity in pp collisions at $\sqrt{s} = 5.02$ TeV*, *JHEP* **10** (2021) 159 [[2105.05616](#)].

- [16] ALICE collaboration, *Measurement of the Cross Sections of Ξ_c^0 and Ξ_c^+ Baryons and of the Branching-Fraction Ratio $BR(\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e)/BR(\Xi_c^0 \rightarrow \Xi^- \pi^+)$ in pp collisions at 13 TeV*, *Phys. Rev. Lett.* **127** (2021) 272001 [2105.05187].
- [17] ALICE collaboration, *First measurement of Ω_c^0 production in pp collisions at $\sqrt{s} = 13$ TeV*, *Submitted to Phys. Lett. B* [2205.13993].
- [18] ALICE collaboration, *Charm-quark fragmentation fractions and production cross section at midrapidity in pp collisions at the LHC*, *Phys. Rev. D* **105** (2022) L011103 [2105.06335].
- [19] J.R. Christiansen and P.Z. Skands, *String Formation Beyond Leading Colour*, *JHEP* **08** (2015) 003 [1505.01681].
- [20] V. Minissale, S. Plumari and V. Greco, *Charm hadrons in pp collisions at LHC energy within a coalescence plus fragmentation approach*, *Phys. Lett. B* **821** (2021) 136622 [2012.12001].
- [21] J. Song, H.-h. Li and F.-l. Shao, *New feature of low p_T charm quark hadronization in pp collisions at $\sqrt{s} = 7$ TeV*, *Eur. Phys. J. C* **78** (2018) 344 [1801.09402].
- [22] M. He and R. Rapp, *Charm-Baryon Production in Proton-Proton Collisions*, *Phys. Lett. B* **795** (2019) 117 [1902.08889].
- [23] LHCb collaboration, *Measurement of b hadron fractions in 13 TeV pp collisions*, *Phys. Rev. D* **100** (2019) 031102 [1902.06794].
- [24] LHCb collaboration, *Evidence for modification of b quark hadronization in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV*, *Submitted to Phys. Rev. Lett.* [2204.13042].
- [25] ALICE collaboration, *Observation of a multiplicity dependence in the p_T -differential charm baryon-to-meson ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Lett. B* **829** (2022) 137065 [2111.11948].
- [26] ATLAS collaboration, *Measurement of b -quark fragmentation properties in jets using the decay $B^\pm \rightarrow J/\psi K^\pm$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **12** (2021) 131 [2108.11650].
- [27] ALICE collaboration, *Measurement of the production of charm jets tagged with D^0 mesons in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV*, *Submitted to JHEP* [2204.10167].
- [28] LHCb collaboration, *Observation of a $\Lambda_b^0 - \bar{\Lambda}_b^0$ production asymmetry in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV*, *JHEP* **10** (2021) 060 [2107.09593].
- [29] CMS collaboration, *Observation of triple J/ψ meson production in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Submitted to Nature Physics* [2111.05370].