Charm and beauty production cross sections and fractions

11th Large Hadron Collider Physics Conference

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CERN

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Heavy flavours in proton-proton collisions

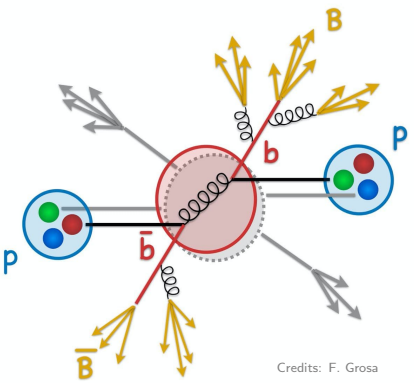
- Heavy flavours (charm and beauty quarks) are produced in hadronic collisions from hard-scattering processes due to their large masses
- Production described by perturbative QCD calculations based on the factorisation theorem down to zero p_{T}

$$\sigma_{\mathrm{hh}\to\mathrm{Hh}} = PDF(x_{\mathrm{a}}, Q^2)\ PDF(x_{\mathrm{b}}, Q^2) \otimes \sigma_{\mathrm{ab}\to\mathrm{q\bar{q}}} \otimes D_{\mathrm{q}\to\mathrm{H}}(z_{\mathrm{q}}, Q^2)$$

Parton distribution functions (non perturbative)

Partonic cross section (perturbative)

Fragmentation functions (non perturbative)

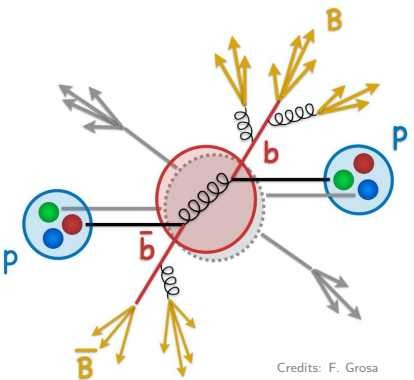


Credits: F. Grosa

Heavy flavours in proton-proton collisions

- Heavy flavours (charm and beauty quarks) are produced in hadronic collisions from hard-scattering processes due to their large masses

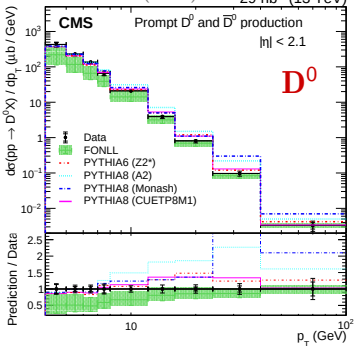
- LHC experiments provide precise measurements of heavy-flavour hadron production down to low p_{T} and in a broad rapidity interval
  - test of pQCD model calculations
  - insights on heavy-flavour hadronisation, via yield ratios of different particle species
  - measurements of fragmentation fractions (FF) in hadronic collisions



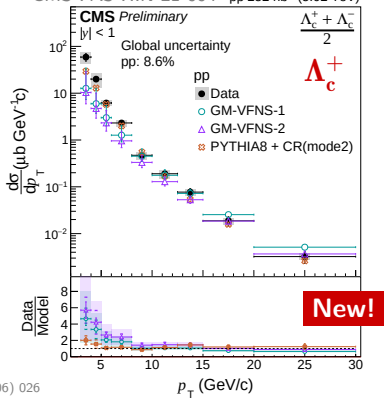
Credits: F. Grosa

Charm hadron cross sections

CMS: JHEP 11 (2021) 225



CMS-PAS-HIN-21-004 pp 252 nb^{-1} (5.02 TeV)

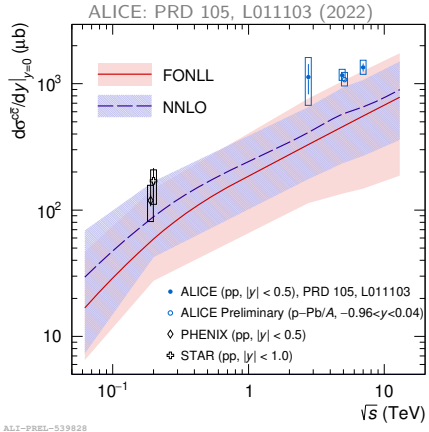


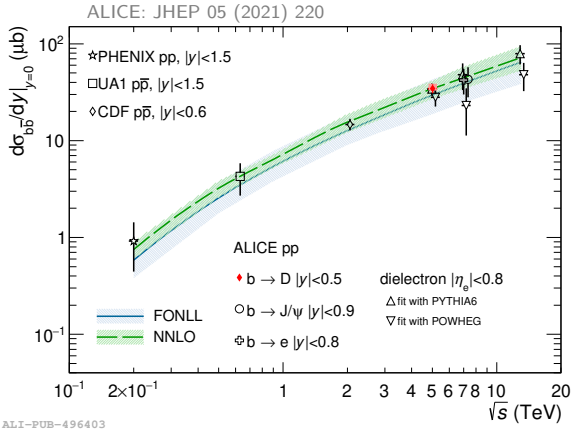
- Prompt D-meson cross sections well described using FF from e^+e^- measurements
  - PYTHIA overestimates prompt D^0 at high p_T
- GM-VFNS calculations underestimate prompt Λ_c^+ measurement for p_T below 8 GeV/c

FONLL: JHEP 1210 (2012) 137
GM-VFNS: PRD 101 (2020) 114021
PYTHIA: JHEP 05 (2006) 026
PYTHIA8+CR2: JHEP 08 (2015) 003

- Λ_c^+ cross section better described by PYTHIA8 calculations including mechanism to enhance baryon production
  - caveat: same PYTHIA8 configuration leads to higher proton yield than observed

Total charm and beauty production cross sections



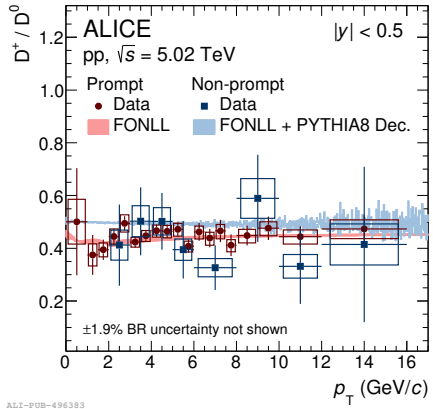


- Heavy-flavour production at midrapidity described by FONLL and NNLO calculations over a wide interval of center-of-mass energies
  - NNLO calculations characterised by smaller uncertainties than FONLL ones

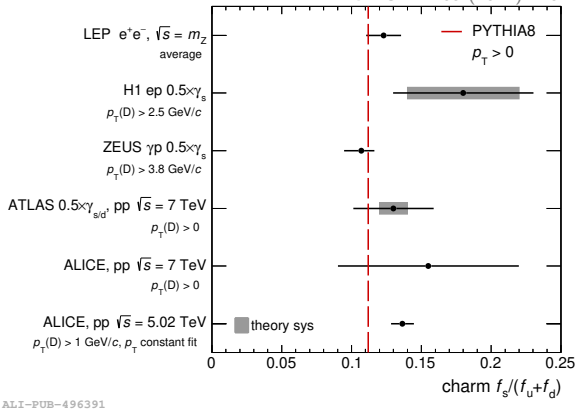
FONLL: JHEP 1210 (2012) 137 NNLO charm: PRL 118 (2017) 122001 NNLO beauty: JHEP 03 (2021) 029

D-meson yield ratios and fragmentation fractions

FONLL: JHEP 1210 (2012) 137 PYTHIA8: EPJC 74 (2014) 3024



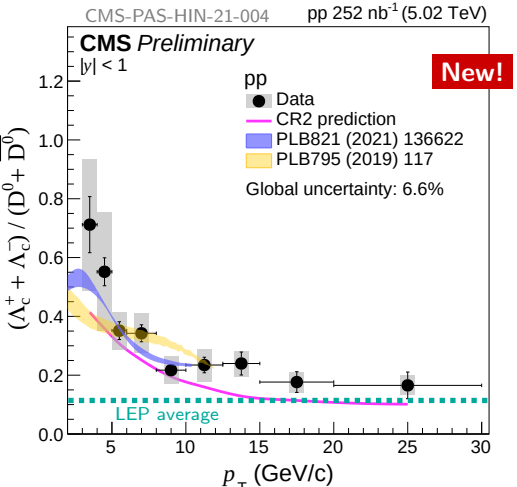
ALICE: JHEP 05 (2021) 220



- Non-strange D-meson ratios flat in p_T and in good agreement with FONLL predictions
- Charm-quark $f_s/(f_u + f_d)$ compatible between different collision systems and with PYTHIA8 Monash-tune simulations

Charm baryon-to-meson yield ratios

PYTHIA8+CR2: JHEP 08 (2015) 003 Catania: PLB 821 (2021) 136622 SHM+RQM: PLB 795 (2019) 117

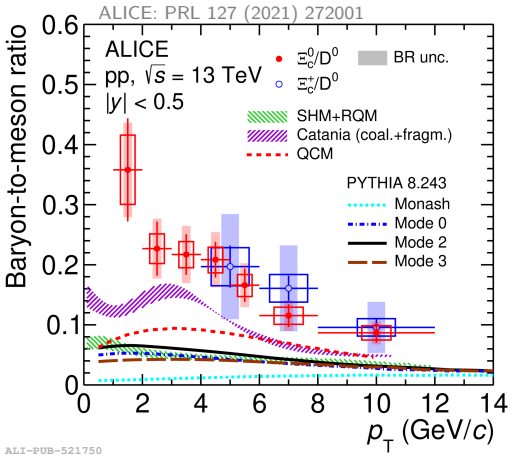


L. Gladilin: EPJ C75 (2015) 19

- Charm baryon-to-meson ratios in pp collisions significantly enhanced w.r.t. e^+e^- collisions
- Models successfully describe Λ_c^+/D^0 ratio with completely different theoretical frameworks
  - **PYTHIA8 CR Mode 2** → string formation beyond leading colour approximation
  - **Catania** → coalescence and fragmentation processes in a thermalised QGP-like system
  - **SHM+RQM** → statistical hadronisation model with feed-down from an augmented set of charm-baryon states

Charm baryon-to-meson yield ratios

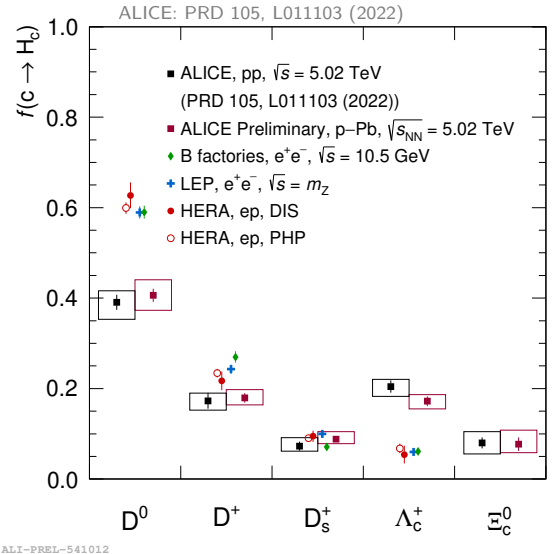
SHM+RQM: PLB 795 (2019) 117 Catania: PLB 821 (2021) 136622 QCM: EPJC 78 (2018) 344 PYTHIA8: EPJC 74 (2014) 3024, JHEP 08 (2015) 003



- Charm baryon-to-meson ratios in pp collisions significantly enhanced w.r.t. e^+e^- collisions
  - enhancement even larger in the charm-strange sector than for Λ_c^+
- Models underestimate the magnitude of the $\Xi_c^{0,+}/D^0$ yield ratios
  - Catania describes the shape of the measurements down to $p_T \simeq 2$ GeV/c
- Charm-strange baryon measurements have large constraining power on model predictions!

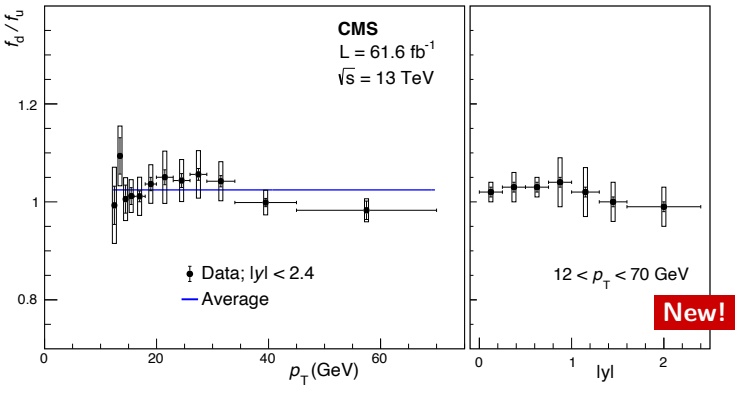
Charm-quark fragmentation fractions

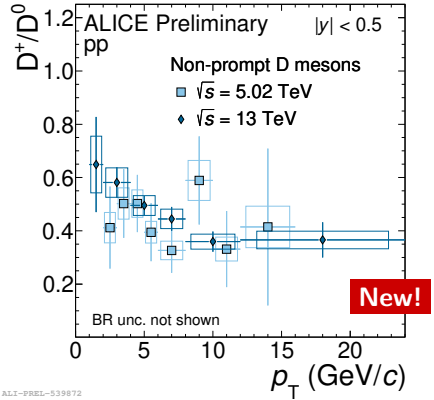
- Charm-quark FF obtained from measurements of ground-state hadron cross sections
- Significant modifications w.r.t. e^+e^- and e^-p collisions
  - D mesons lower by factor $1.2 - 1.4$
  - Λ_c^+ baryon higher by factor ~ 3.3
- Results in pp and p–Pb collisions are in good agreement



B-meson fragmentation fractions

CMS: arXiv:2212.02309

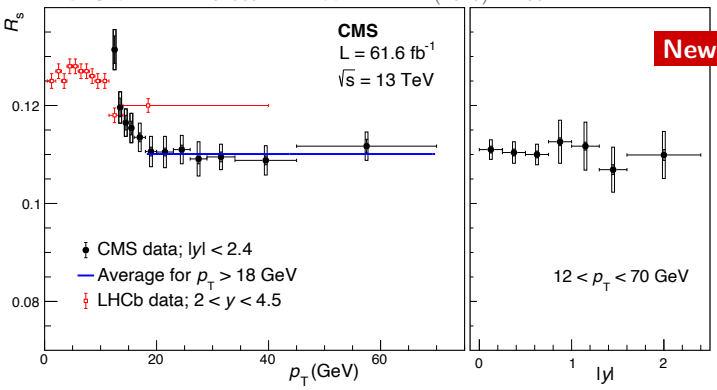




- Ratio of B^0 to B^+ fragmentation fractions $f_\mathrm{d}/f_\mathrm{u}$ does not depend on p_T and rapidity
  - in agreement with measurements of non-strange D mesons from b-hadron decays
- $f_\mathrm{d}/f_\mathrm{u}$ average consistent with unity as expected from strong isospin symmetry

B-meson fragmentation fractions

CMS: arXiv:2212.02309 LHCb: PRL 124 (2020) 122002

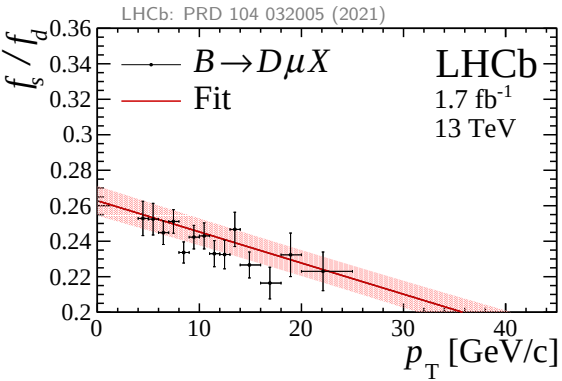


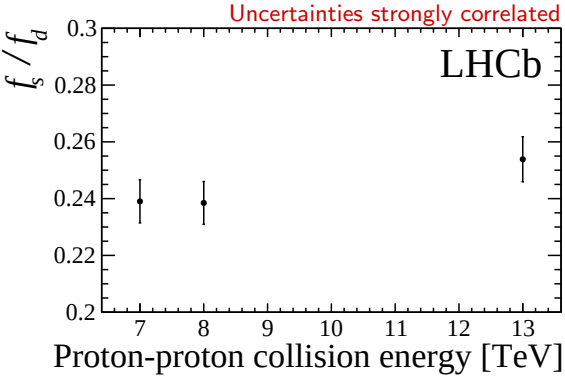
- Efficiency-corrected $\mathrm{B_s^0}$ to $\mathrm{B^+}$ yield ratio R_s used since available f_s and $\mathcal{B}(\mathrm{B_s^0} \to \mathrm{J}/\psi\,\phi)$ measurements are correlated

$$\mathcal{R}_\mathrm{s} = f_\mathrm{s}/f_\mathrm{u}\,\frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{J}/\psi\,\phi)\mathcal{B}(\phi \to \mathrm{K^+K^-})}{\mathcal{B}(\mathrm{B^+} \to \mathrm{J}/\psi\,\mathrm{K^+})}$$

- R_s shows a p_T dependence at low momentum, while it is flat above $p_\mathrm{T} \simeq 18\ \mathrm{GeV}/c$ ($R_\mathrm{s} \sim 0.11$)
  - LHCb result at forward rapidity supports the observed transverse-momentum dependence
- No indication of R_s ratio dependence from rapidity

B-meson fragmentation fractions

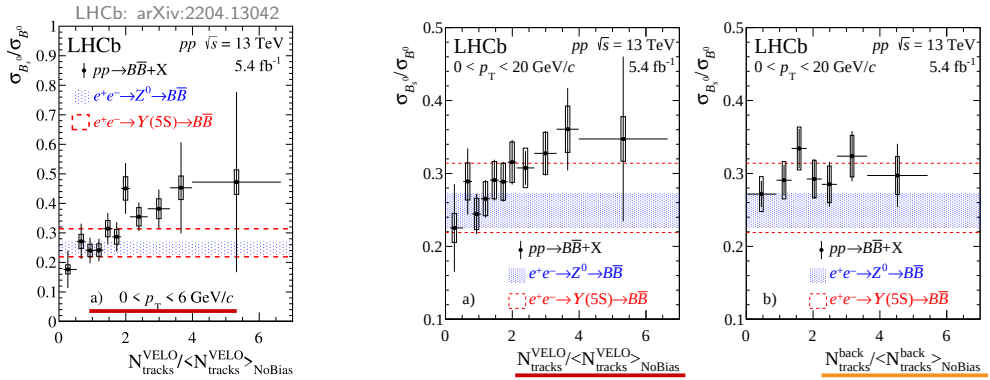




- Ratio of $\mathrm{B_s^0}$ to $\mathrm{B^0}$ fragmentation fractions f_s/f_d significantly depends on transverse momentum and centre-of-mass energy of pp collisions

$$\frac{f_s/f_d\,(13\ \mathrm{TeV})}{f_s/f_d\,(8\ \mathrm{TeV})} = 1.065 \pm 0.007$$

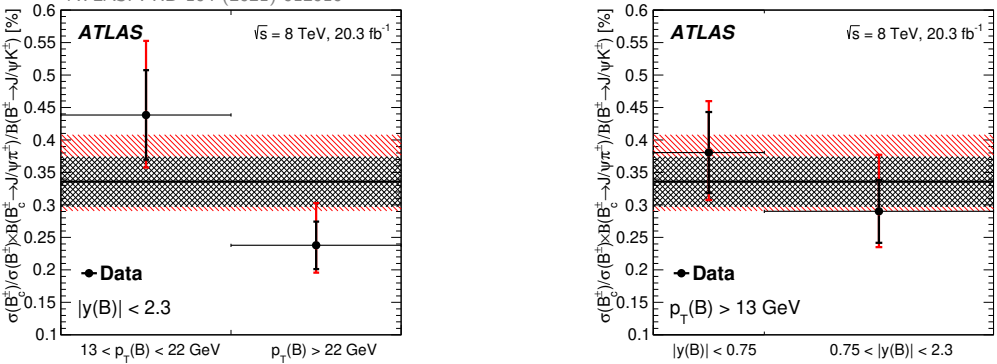
B_s^0/B^0 cross-section ratio as a function of multiplicity



- Evidence (3.4σ) that B_s^0/B^0 cross-section ratio increases with multiplicity for $p_T < 6$ GeV/c
  - qualitatively consistent with hadronisation via quark coalescence in high-multiplicity pp collisions
- No significant dependence on backward multiplicity of B_s^0/B^0 ratio at forward rapidity
  - mechanism responsible for the ratio increase could be related to local particle density

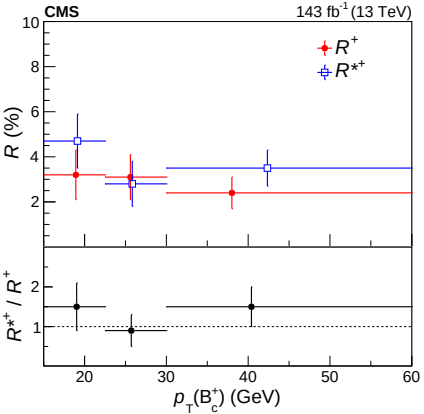
B_c^+/B^+ cross-section ratio

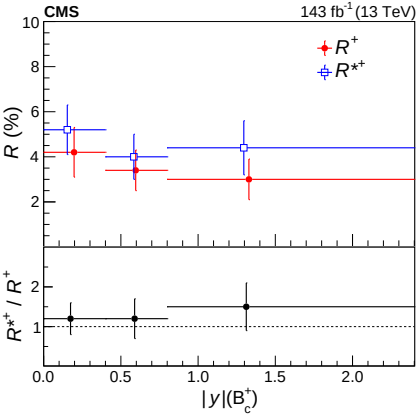
ATLAS: PRD 104 (2021) 012010



- B_c^+-meson production requires collinear production of two distinct heavy quarks ➔ unique insights into heavy-flavour hadronisation
- Hint of faster decrease with transverse momentum of B_c^+-meson cross section w.r.t. B^+ mesons
  - consistent with LHCb measurement of $f_c/(f_u + f_d)$ at forward rapidity PRD 100 (2019) 112006

Production of $\mathrm{B_c}(2S)^+$ and $\mathrm{B_c^*}(2S)^+$ mesons





CMS: PRD 102 (2020) 092007

$R^+ \to \mathrm{B_c}(2S)^+/\mathrm{B_c^+}$

$R^{*+} \to \mathrm{B_c^*}(2S)^+/\mathrm{B_c^+}$

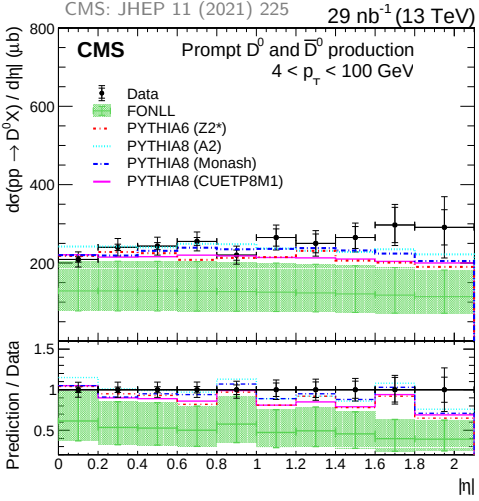
- Excited to ground-state $\mathrm{B_c^+}$-meson cross-section ratios show no variations with p_T and rapidity
- Ratio of $\mathrm{B_c^*}(2S)^+$ to $\mathrm{B_c}(2S)^+$ production R^{*+}/R^+ is compatible with unity
  - caveat: unknown branching fractions to ground state $\mathcal{B}(\mathrm{B_c^{(*)}}(2S)^+ \to \mathrm{B_c^{(*)+}}\pi^+\pi^-)$ included

Summary

- Total charm- and beauty-quark cross sections in pp well described by pQCD calculations
- Heavy-flavour hadron production
  - D mesons described using FF from $\mathrm{e^+e^-}$ measurements
  - full description of charm baryons still a puzzle
- Beauty fragmentation-fraction ratio $f_\mathrm{s}/f_\mathrm{d}$ depends on
  - B-meson transverse momentum
  - charged-particle multiplicity
  - collision centre-of-mass energy
- Stay tuned for results on Run 3 data providing new measurements and smaller uncertainties

Backup

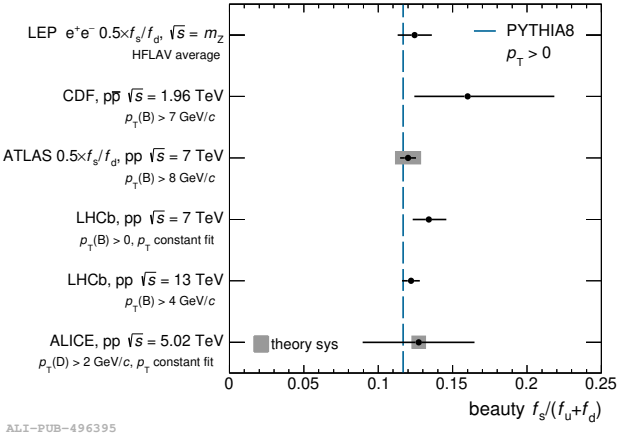
D mesons — Rapidity



ALICE — Fragmentation fractions of beauty quarks

PYTHIA8: P. Skands et al. EPJC 74 3024 (2014)
LEP: Y. Amhis et al. (HFLAV) arXiv:1909.12524
CDF: Phys. Rev. D 77 072003 (2008)

ATLAS: PRL 115 262001 (2015)
LHCb, 7 TeV: Phys. Rev. D 85 032008 (2012)
LHCb, 13 TeV: Phys. Rev. D 100 031102 (2019)



ALI-PUB-496395

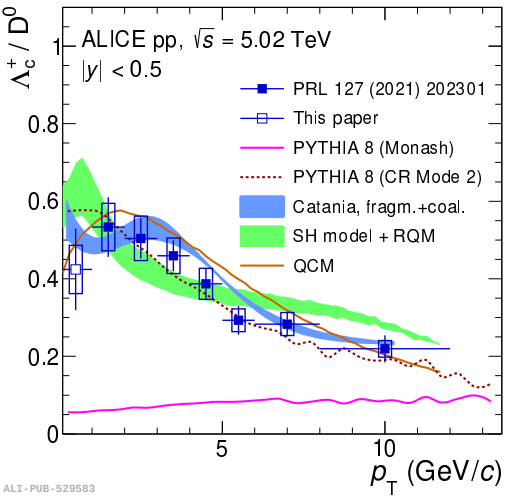
ALICE: JHEP 05 (2021) 220

- Beauty-quark $f_s/(f_u + f_d)$ from constant fit to non-prompt $D_s^+/(D^0 + D^+)$ ratio
- Correction to account for non-prompt D_s^+ mesons from B^0 and B^+ decays
- Value compatible with previous measurements and PYTHIA8

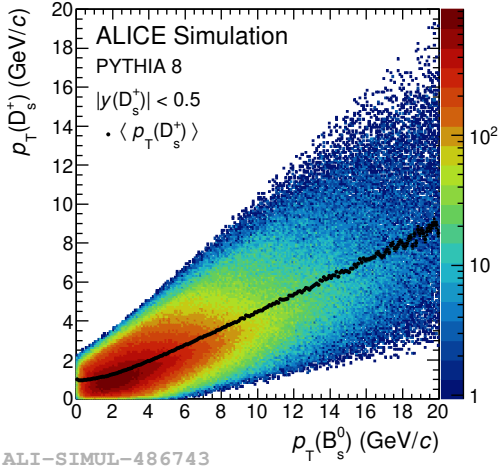
$$\left(\frac{f_s}{f_u + f_d}\right)_{\text{beauty}} = 0.127 \pm 0.036(\text{stat}) \pm 0.014(\text{tot.syst})$$

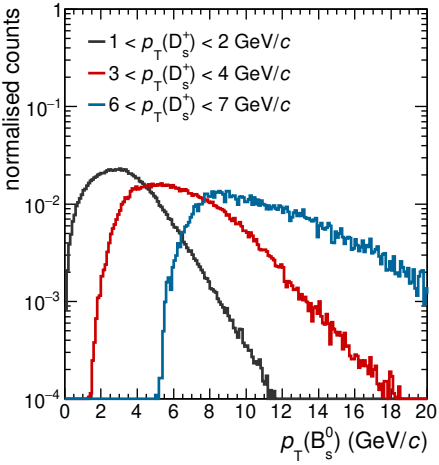
ALICE — Λ_c^+/D^0 ratio

ALICE: arXiv:2211.140324

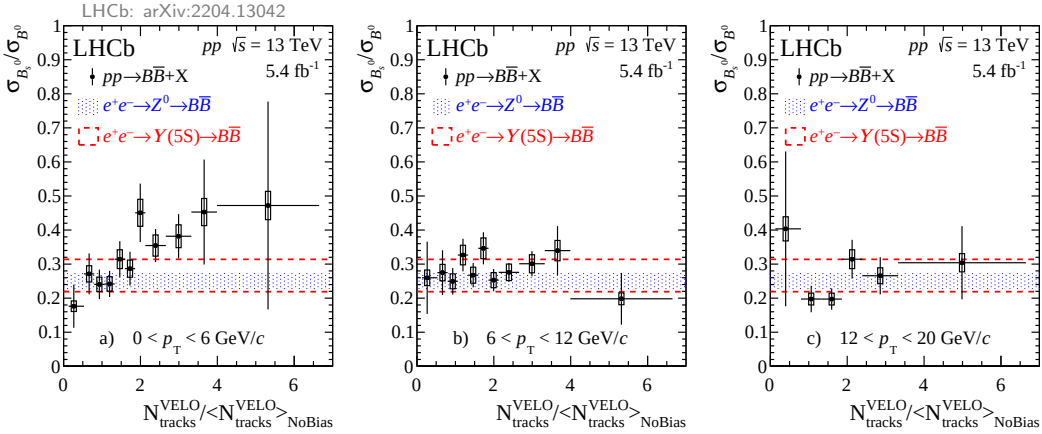


D_s^+ vs B_s^0 transverse momentum





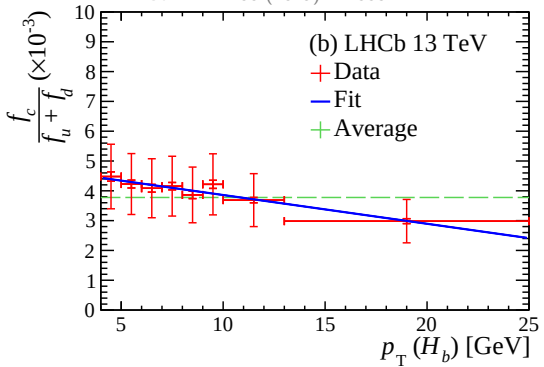
LHCb — B_s^0/B^0 cross-section ratio as a function of multiplicity

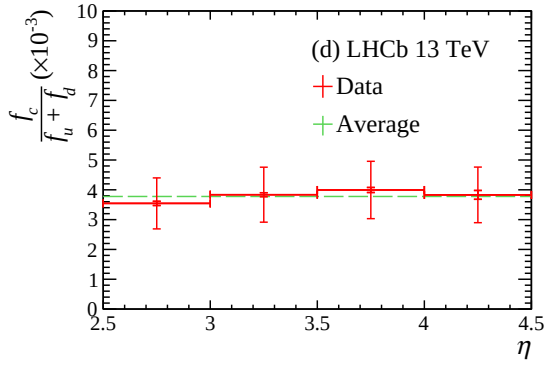


- Measurements at low charged-particle multiplicity or high p_{T} are consistent with $\mathrm{e^+e^-}$ collisions
- Indication that strangeness enhancement is present in B-hadron production

LHCb — B_c^+ production relative to non-stange B mesons

LHCb: PRD 100 (2019) 112006





- Ratio depends on transverse momentum while it is flat in pseudorapidity
- Average fraction in pp at 13 TeV: $(3.78 \pm 0.04 \pm 0.15 \pm 0.89) \times 10^{-3}$