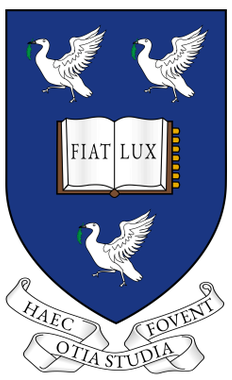
Heavy-flavour baryon production and implications for fragmentation functions

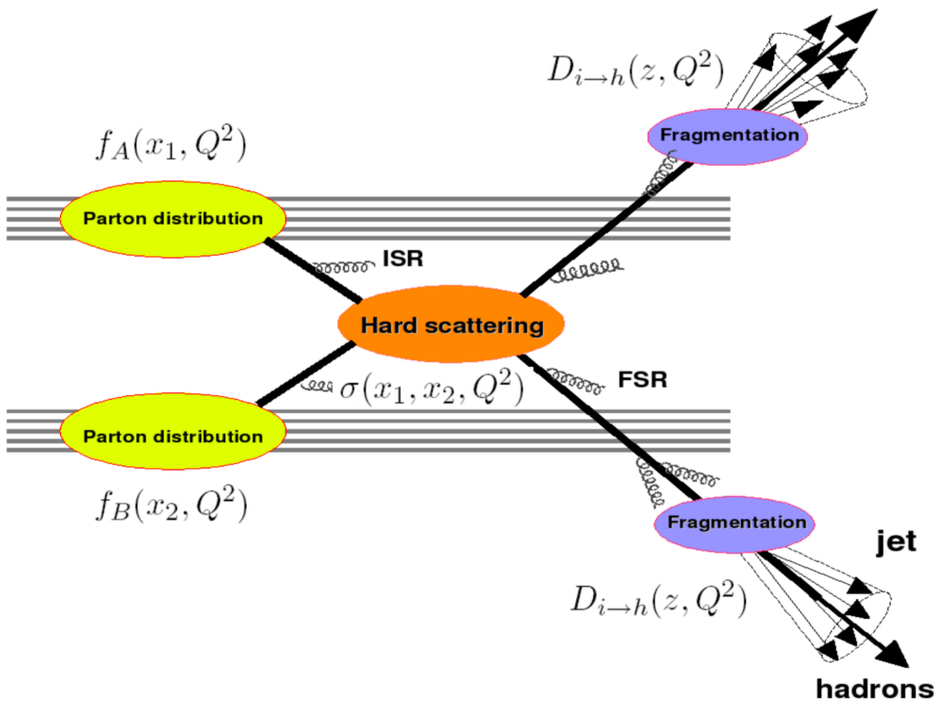
WG1 GDR-QCD meeting

Jaime Norman
University of Liverpool (UK)



Open heavy-flavour production in pp collisions

- Heavy quarks (charm and beauty) are produced in hard partonic scattering processes
  - $m_{c,b} >> \Lambda_{QCD} \rightarrow \alpha_s(m_q^2) \propto \ln^{-1}(m_q^2/\Lambda_{QCD}^2) << 1$
  - m_Q sets hard scale - perturbative QCD applicable



"Factorisation":

$$d\sigma^{hard}_{AB\to h} = \boxed{f_{b/B}(x_1,Q^2)} \otimes \boxed{f_{a/A}(x_2,Q^2)} \otimes \boxed{d\sigma^{hard}_{ab\to c}(x_1,x_2,Q^2)} \otimes \boxed{D_{c\to h}(z,Q^2)}$$

Parton distribution within proton (PDFs) | **Hard scattering cross section** | **Fragmentation function**

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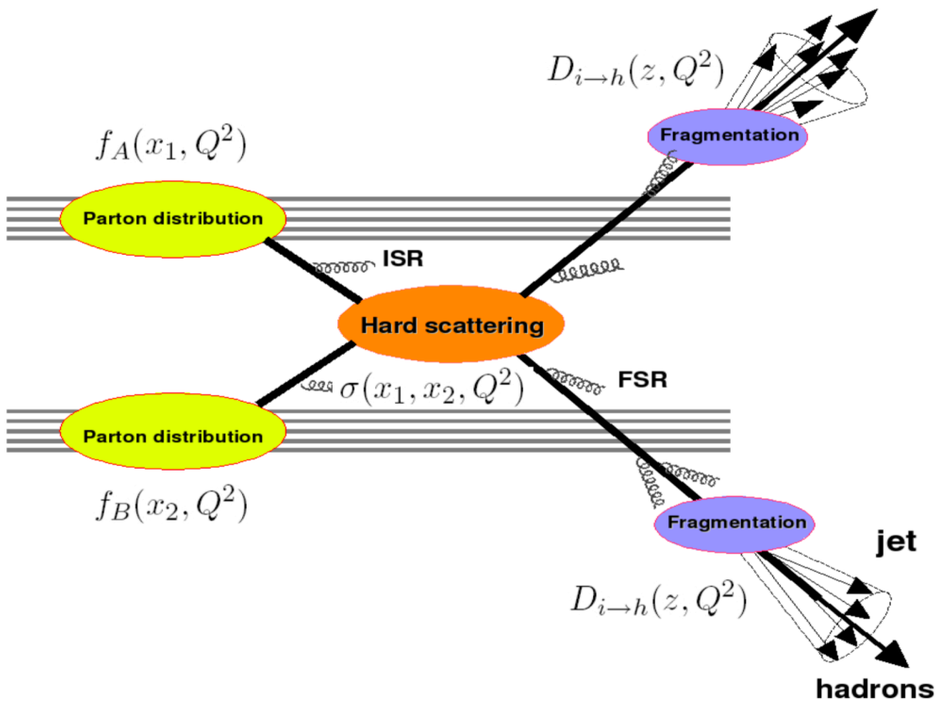

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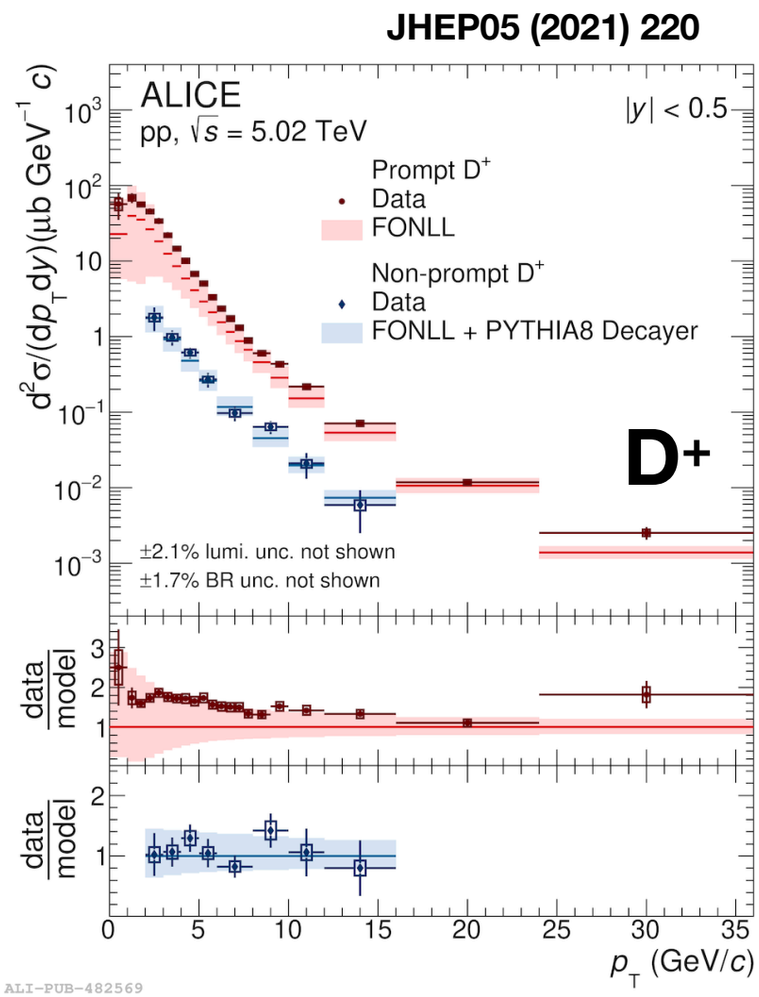
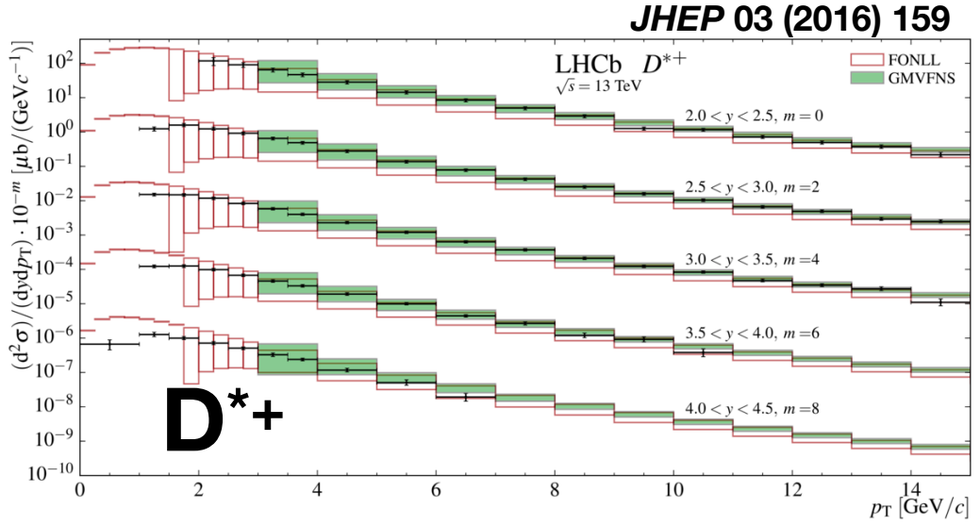
Parton distribution within proton (PDFs) | **Hard scattering cross section** | **Fragmentation function**

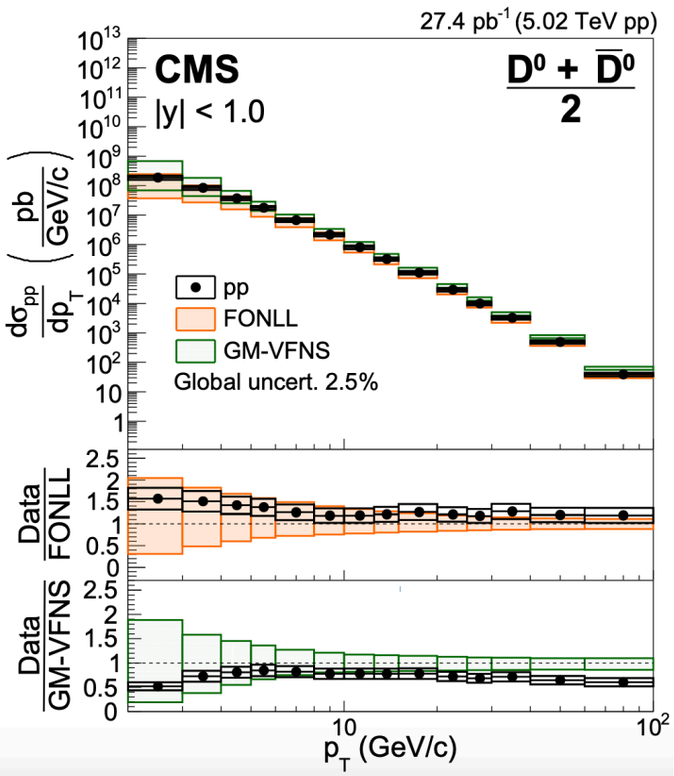
- **fragmentation functions** → assumed to be universal and determined from e^+e^-/ep collisions
  - Incorporates fragmentation kinematics *plus* fraction of charm going to given hadron $f(c \to H_c)$ **(fragmentation fraction)**
  - Hadron ratios (meson-over-meson, baryon-over-meson) sensitive to fragmentation

Heavy-flavour meson production

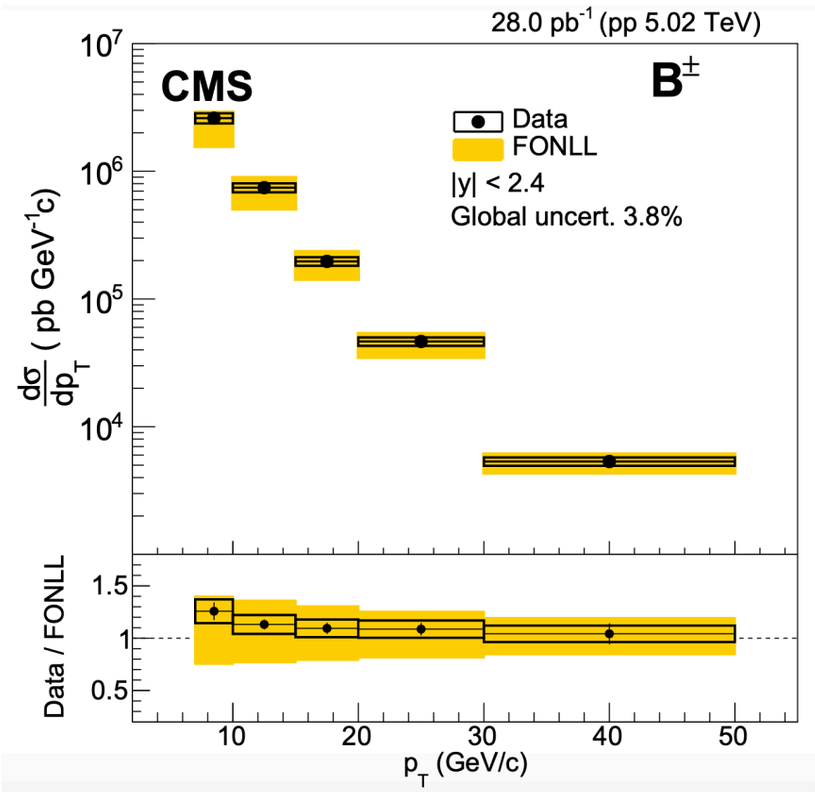




- **Charm and beauty meson** production extensively studied at the LHC in pp collisions from 0.9 → 13 TeV
- Cross sections of D and B mesons at the LHC **in agreement with pQCD predictions** at central rapidity (ALICE, CMS) and forward rapidity (LHCb)
  - Predictions based on factorisation approach with universal fragmentation functions



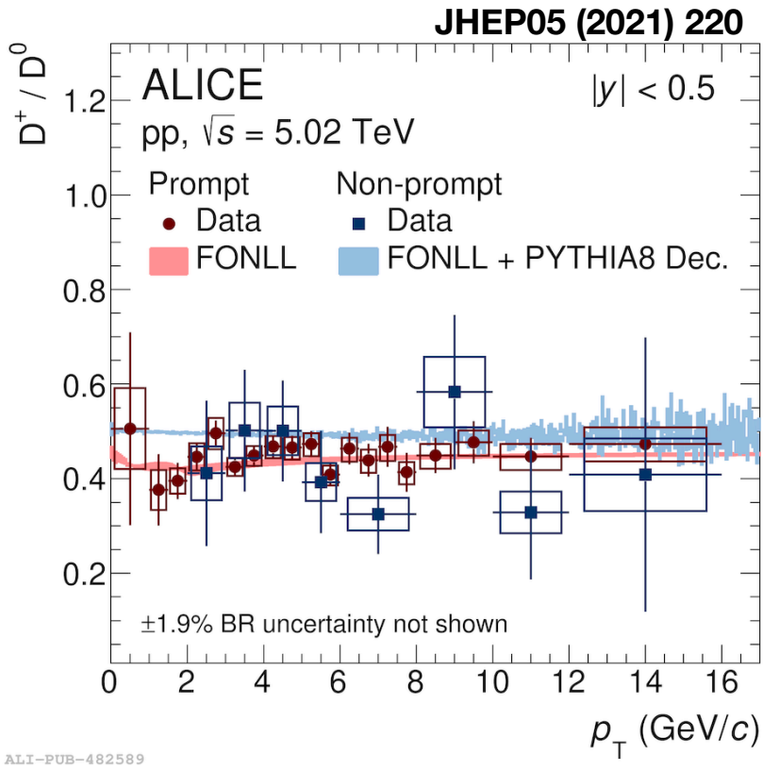
Phys.Lett.B 782 (2018) 474-496

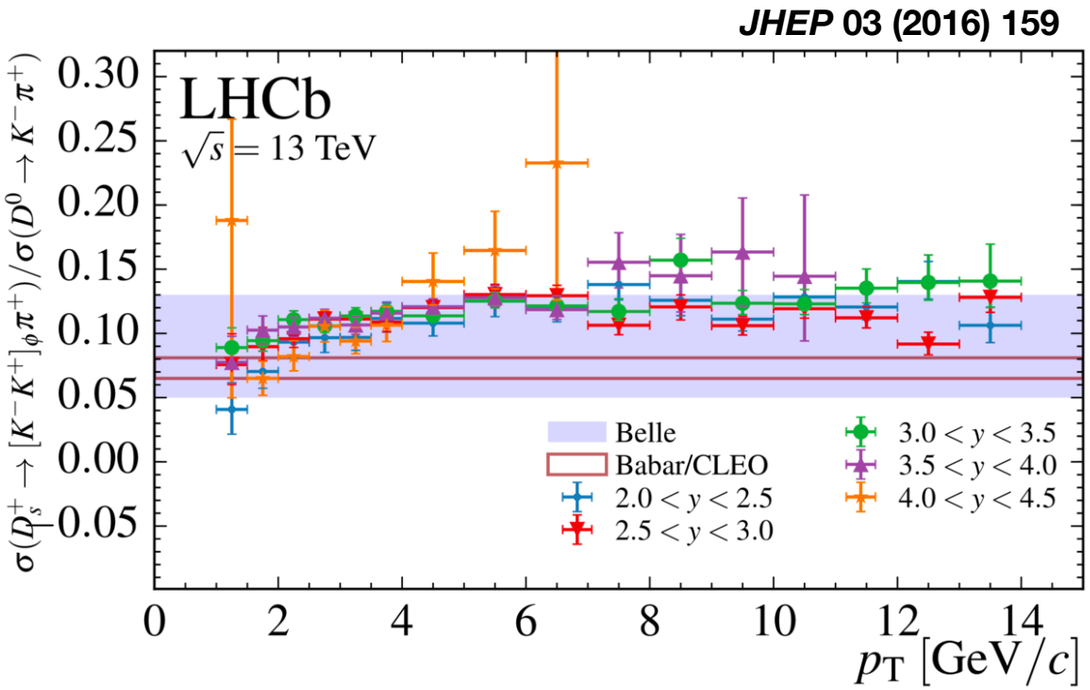


Phys. Rev. Lett. 119, 152301 (2017)

Meson production ratios

- Fragmentation to mesons probed with meson-to-meson ratios
  - **Relatively independent of pT**
  - In agreement with measurements in e+e- collisions (Belle/Babar/Cleo) plus calculations utilising fragmentation functions measured in e+e- collisions

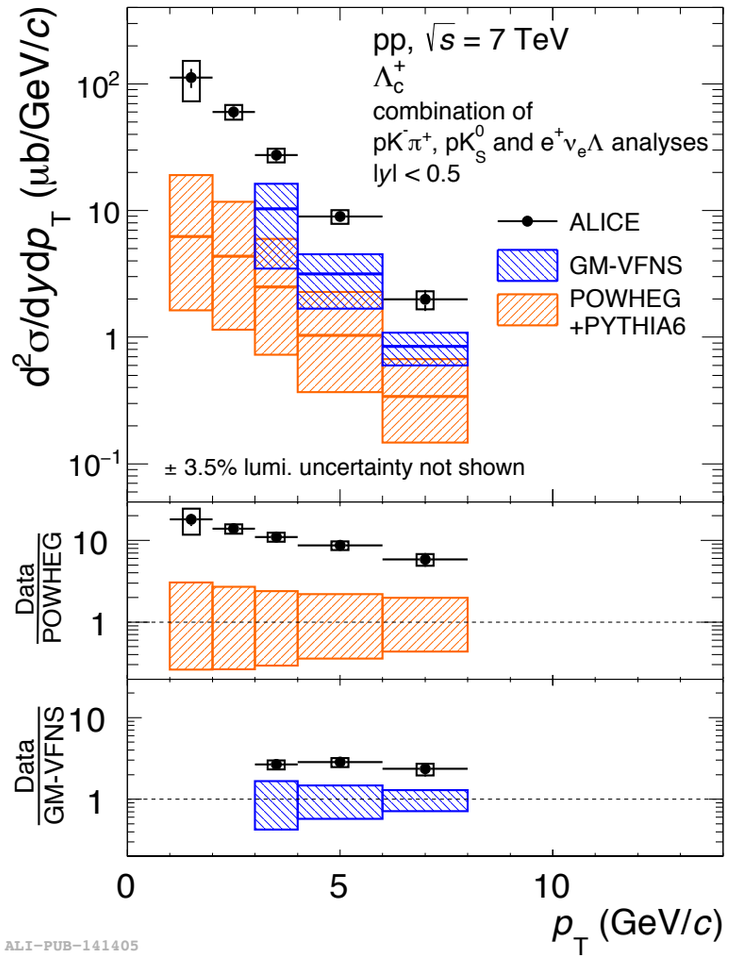




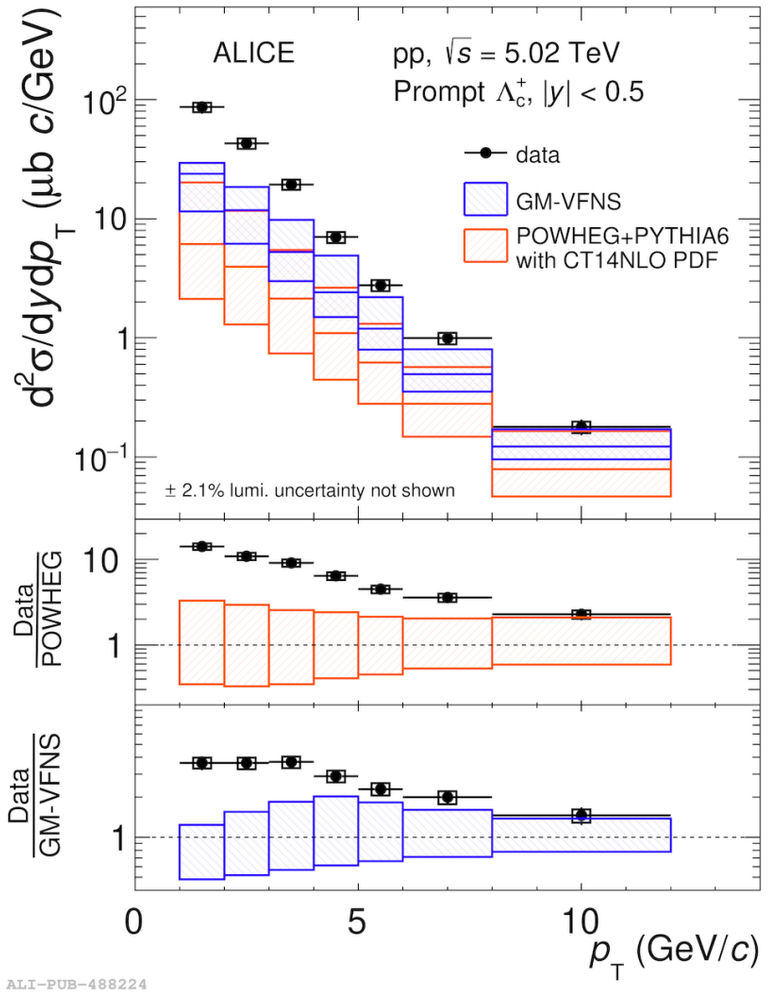
→ Factorisation with 'universal' fragmentation functions relatively successful for heavy-flavour meson production over wide kinematic region!

Charmed baryon Λ_c^+ production

- The Λ_c^+ baryon production cross section is significantly underestimated by the same models at mid-rapidity (ALICE, CMS), incorporating pQCD + universal fragmentation functions
  - **Factorisation failing for Λ_c^+ production…?**

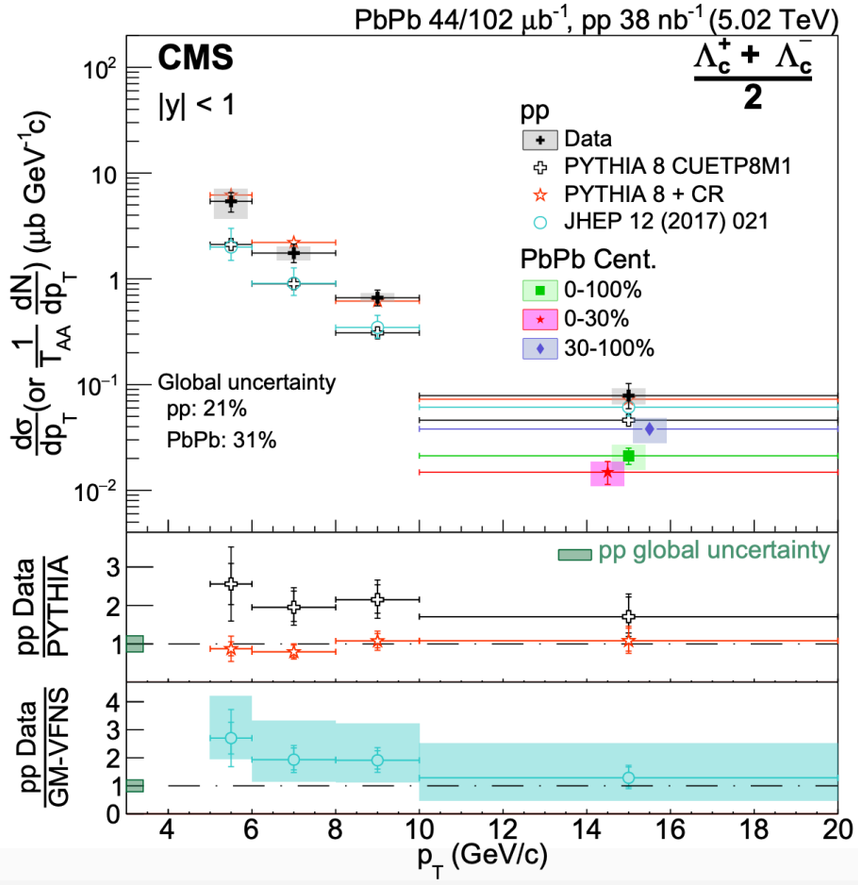


JHEP 04 (2018) 108



arXiv:2011.06078

arXiv:2011.06079



Phys. Lett. B 803 (2020) 135328

Λ_C^+/D^0 Baryon-to-meson ratio

Fragmentation fractions in e^+e^-/ep from combination of previous measurements:

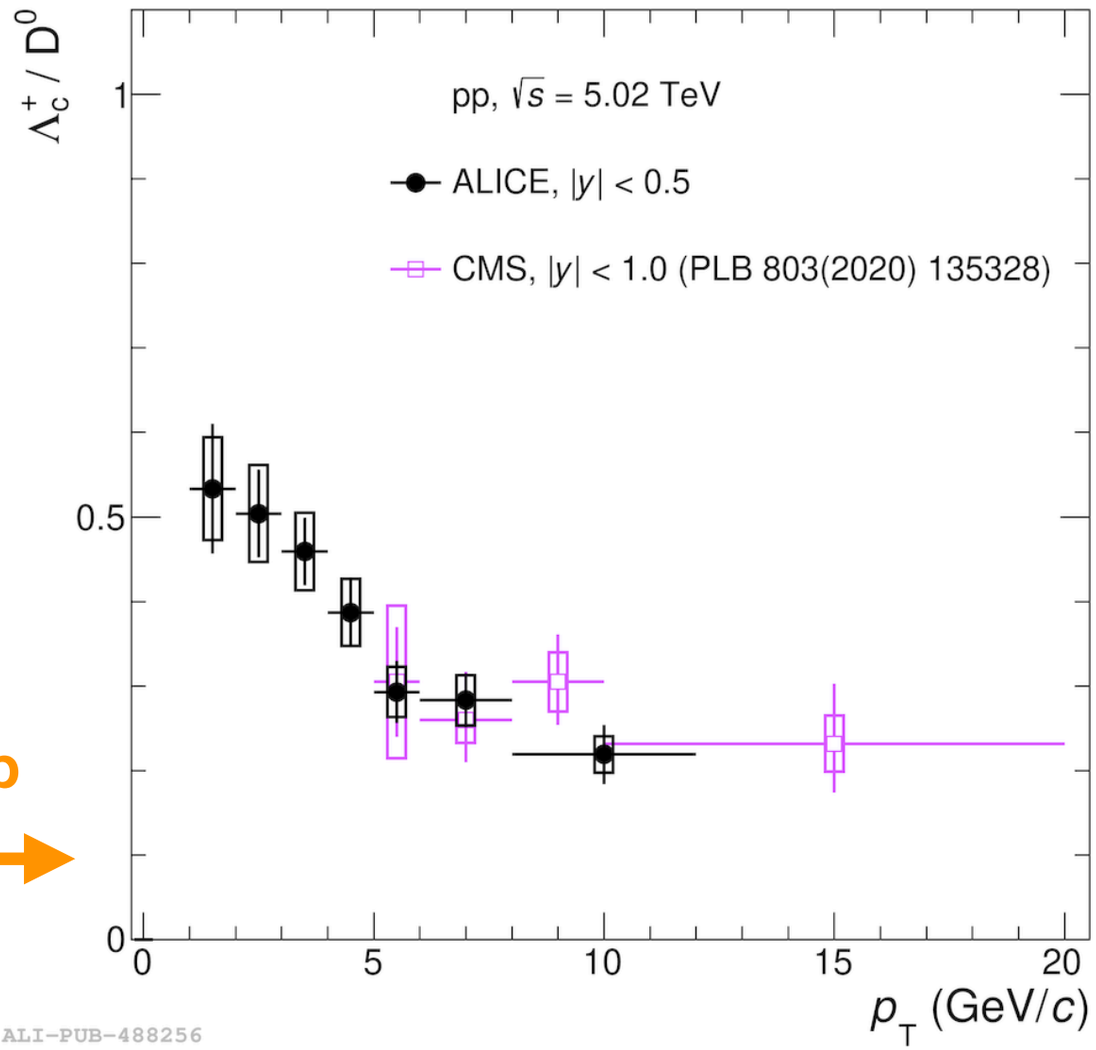
$f(c \to \Lambda_c^+) \sim 0.06$

$f(c \to D^0) \sim 0.6$

$\to \Lambda_c^+/D^0 \sim 0.1$

See e.g. combined analysis of charm fragmentation fractions:
M. Lisovyi, A. Verbytskyi, O. Zenaiev: EPJ C 76 (2016) no.7, 397
L. Gladilin: EPJC 75 (2015) 19

e^+e^-/ep

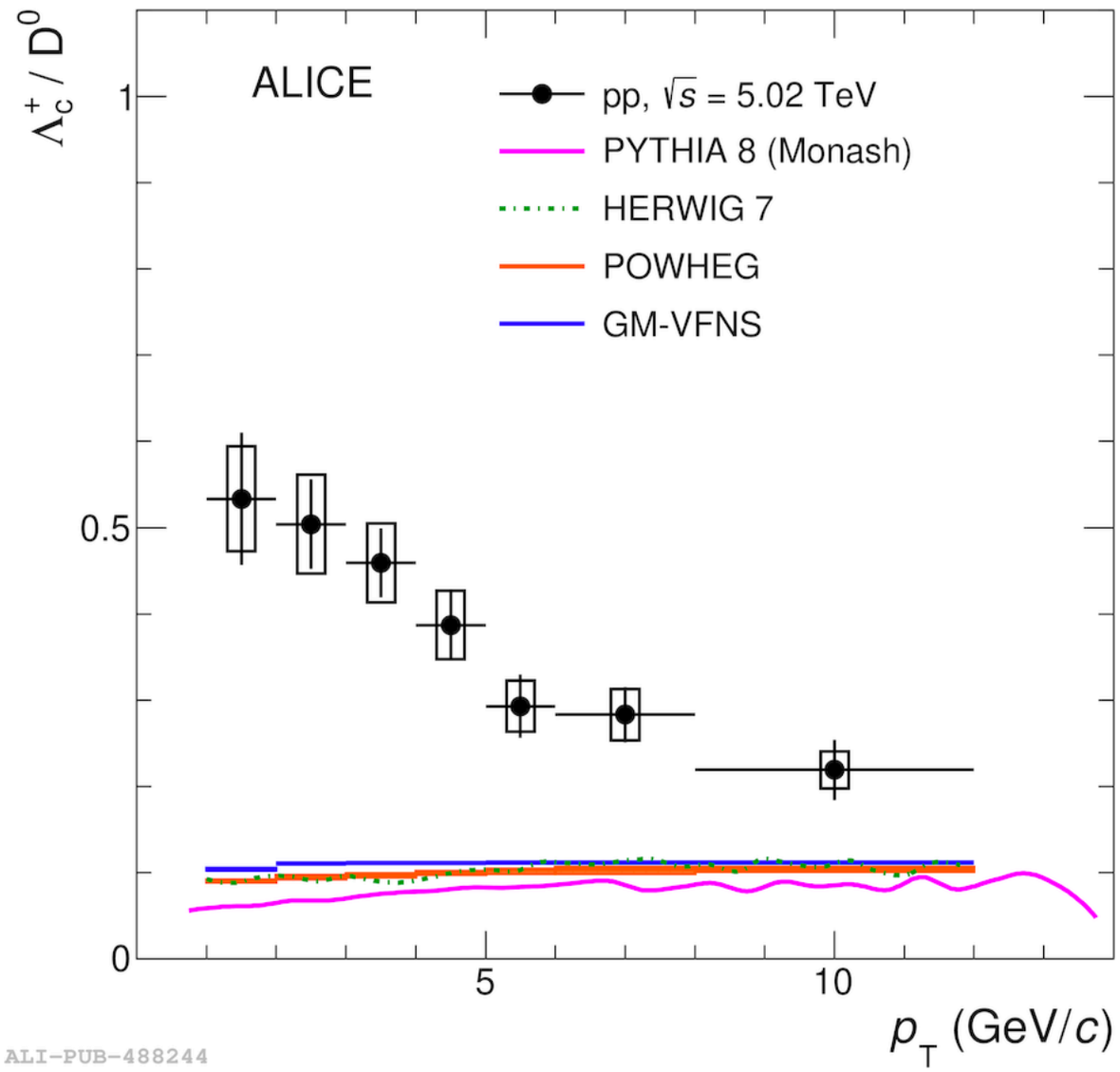


arXiv:2011.06078
arXiv:2011.06079

- Relative production of Λ_c^+ baryons with respect to D^0 mesons **significantly higher than e^+e^- and ep collisions**
  - Consistent results between CMS and ALICE at mid-rapidity
  - **Significant p_T-dependence** - indicates significant difference between **fragmentation functions** of mesons and baryons

Λ_C^+/D^0 Baryon-to-meson ratio vs models

arXiv:2011.06078
arXiv:2011.06079



- Λ_c^+/D^0 ratio significantly underestimated by models which incorporate fragmentation functions from e^+e^-/ep collisions

Λ_C^+/D^0 Baryon-to-meson ratio vs models

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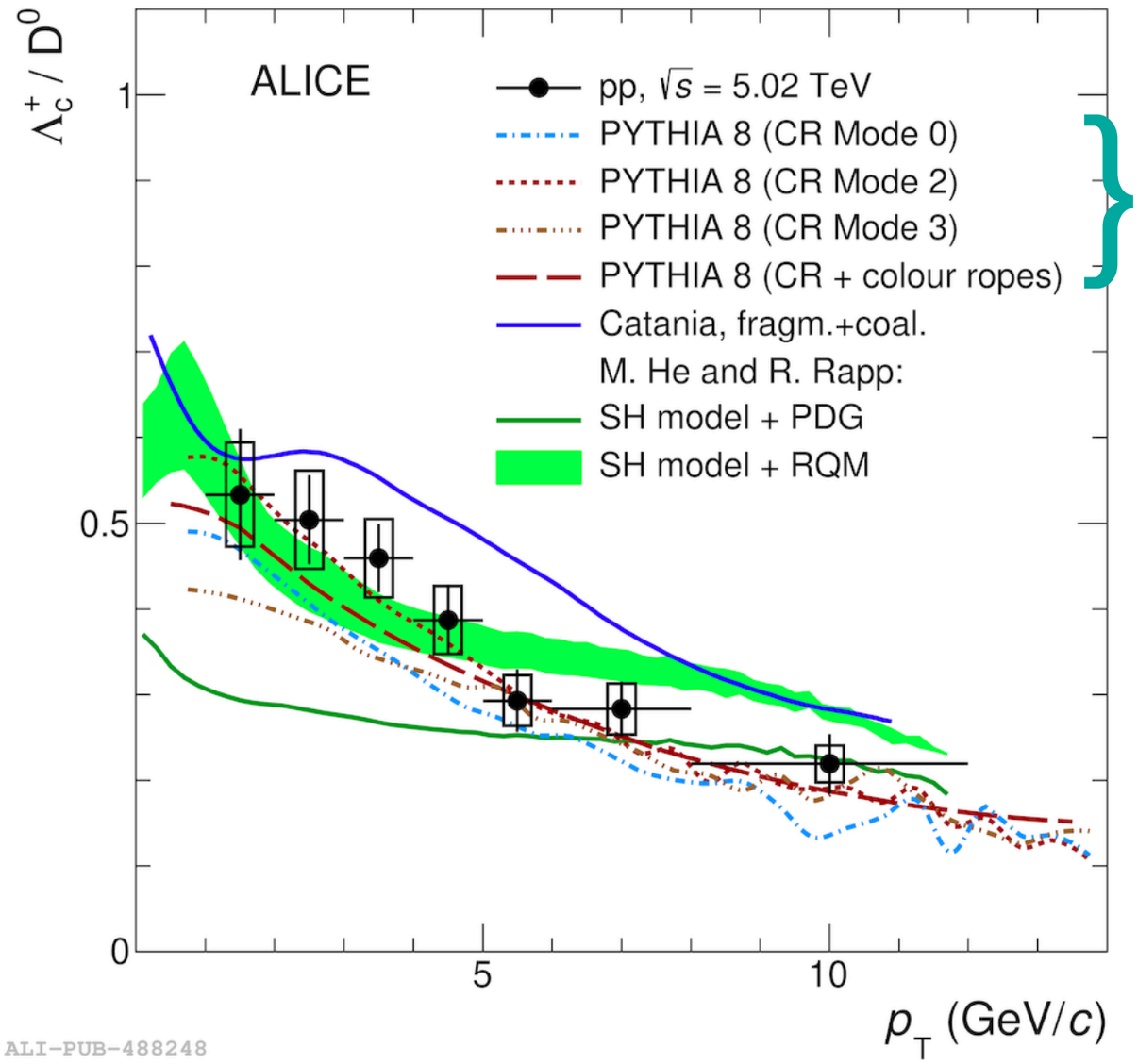
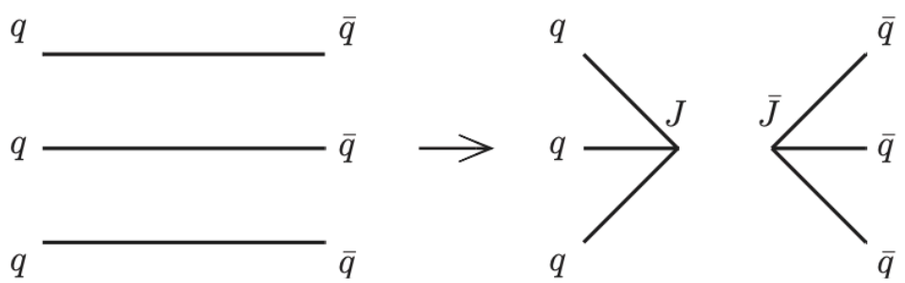


- Better description of Λ_c^+/D^0 with models which lead to modified baryon production
  - **PYTHIA8 + colour reconnection modes**
    - Colour reconnection beyond the leading colour approximation was implemented in PYTHIA as attempt to better describe light flavour observables (e.g. Λ/K_S^0)
    - Reconnection between uncorrelated strings in multi-parton system
    - Leads to *'junction'* configurations → **baryon enhancement**

J. Christiansen, P. Skands: JHEP08(2015)003



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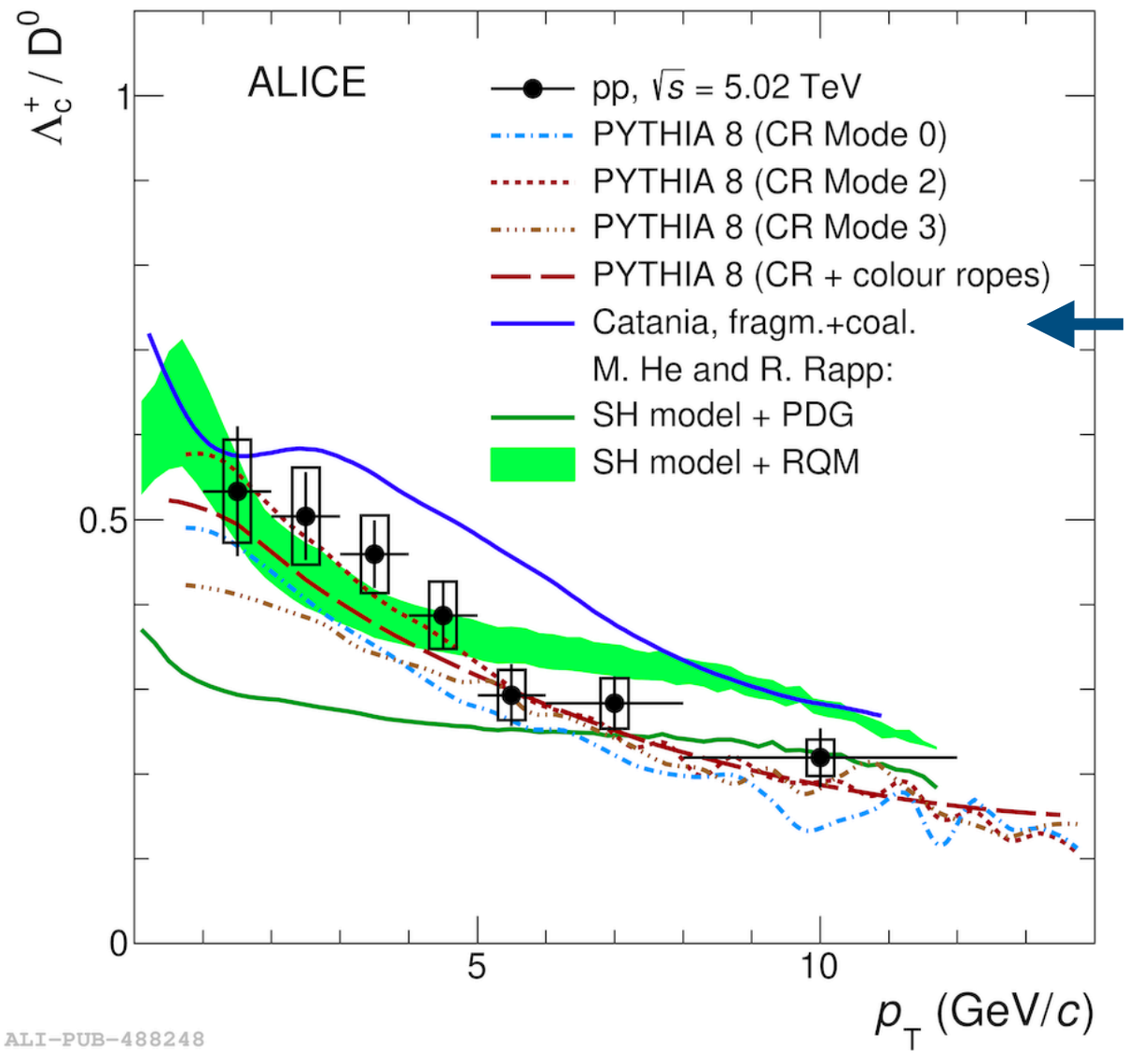
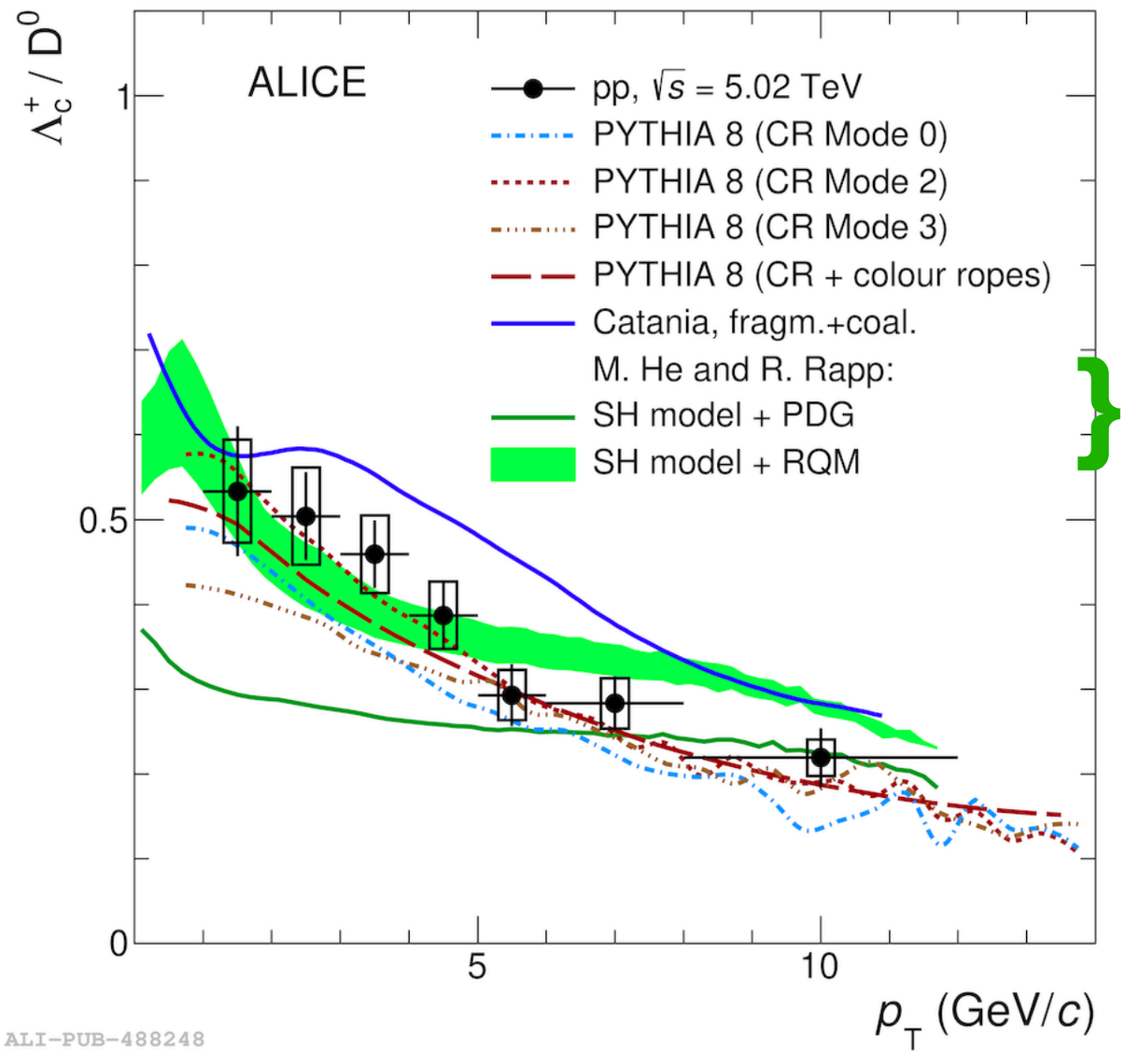


- Better description of Λ_c^+/D^0 with models which lead to modified baryon production
  - **PYTHIA8 + colour reconnection modes**
  - **Hadronisation via coalescence plus fragmentation**
    - Charm quarks can recombine (coalesce) with light quarks from the underlying event
- $p_T^{\text{hadron}} = \sum p_T^{\text{quark}}$: enhancement of low-pT baryons w.r.t mesons
- Quarks not coalescing will hadronise via fragmentation

V. Minissale, S. Plumari, V. Greco: arXiv:2012.12001

Λ_C^+/D^0 Baryon-to-meson ratio vs models

arXiv:2011.06078
arXiv:2011.06079



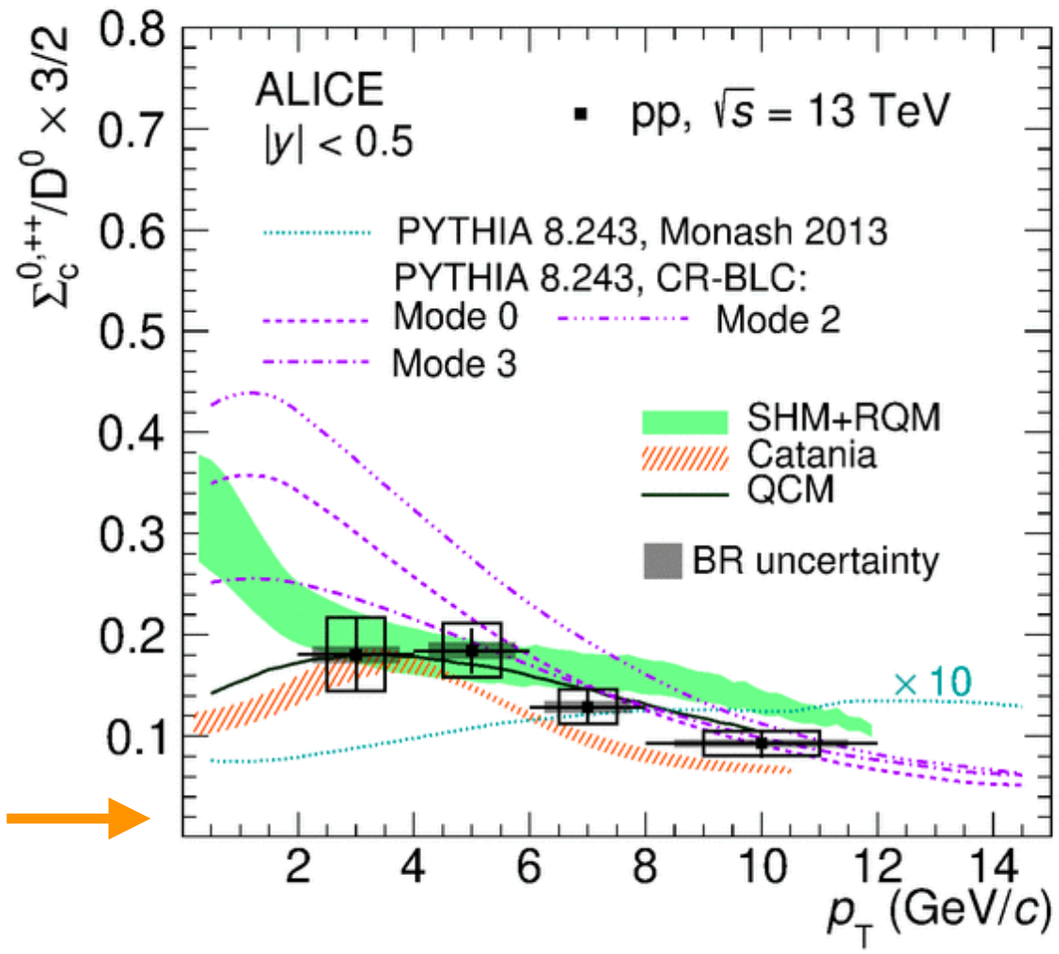
- Better description of Λ_c^+/D^0 with models which lead to modified baryon production
  - **PYTHIA8 + colour reconnection modes**
  - **Hadronisation via coalescence plus fragmentation**
  - **Statistical hadronisation plus additional baryon states**
    - Hadron yields determined through Statistical Hadronisation model
    - Different hypotheses for underlying baryon resonant spectrum:
      - **PDG:** 5 Λc(I=0) , 3 Σc(I=1), 8 Ξc (I=1/2), 2 Ωc(I=0)
      - **RQM: strong feed-down from additional (yet-unobserved) excited charm baryons:** 18 extra Λc, 42 extra Σc, 62 extra Ξc, 34 extra Ωc (supported by lattice QCD)

M. He, R. Rapp: Phys. Lett. B, 795 (2019), p. 117

Charmed baryon production 'spectroscopy': $\Sigma_c^{0,+,++}$

$\Sigma_c^{0,+,++}/D^0$ **ratio**

arXiv:2106.08278



From Belle:

$\Sigma_c^{0,+,++}/D^0 \sim 0.02$

~x10 enhancement!

Phys. Rev. D 97, 072005 (2018)

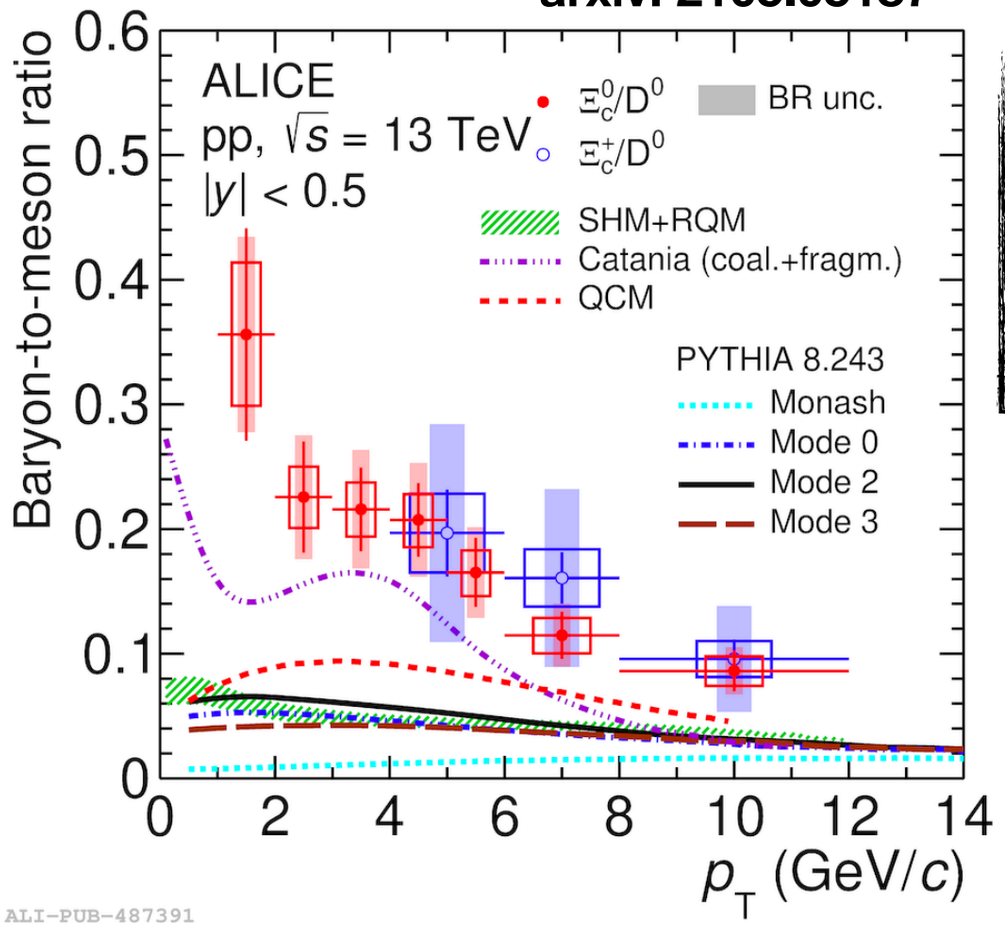
- Isospin *I*=1 partner of singlet *I*=0 Λ_c^+ baryon
- $\Sigma_c^{0,+,++}$ decays strongly to Λ_c^+ - **access to heavier baryonic contribution to Λ_c^+ yield**

- **Significantly larger $\Sigma_c^{0,+,++}/D^0$ than measured in e^+e^- collisions + PYTHIA8** (tuned on e^+e^-)
  - **Described well** by models which modify baryon production
- **→enhanced Λ_c^+ production partially comes from enhanced Σ_c feed-down**

Charmed baryon production 'spectroscopy': $\Xi_c^{0,+}$,Ω_c^0

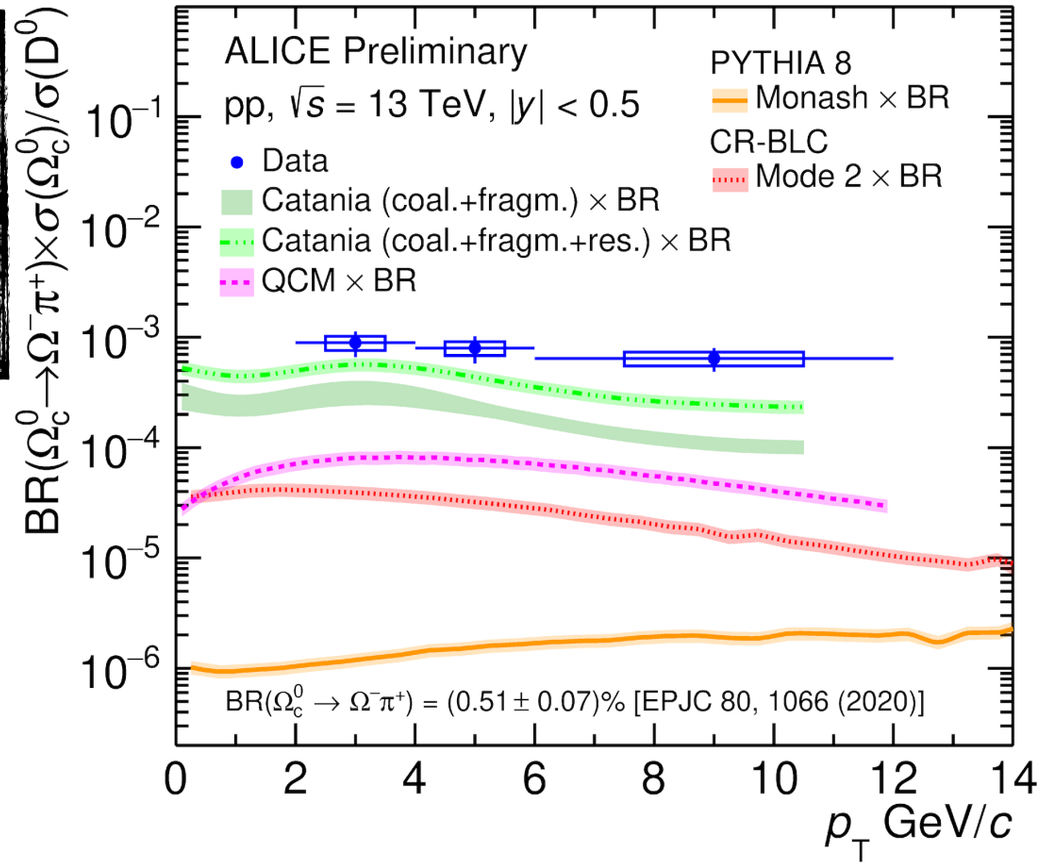
arxiv: 2105.05187

$\Xi_c^{+,0}/D^0$ ratio



Ω_c^0/D^0 ratio

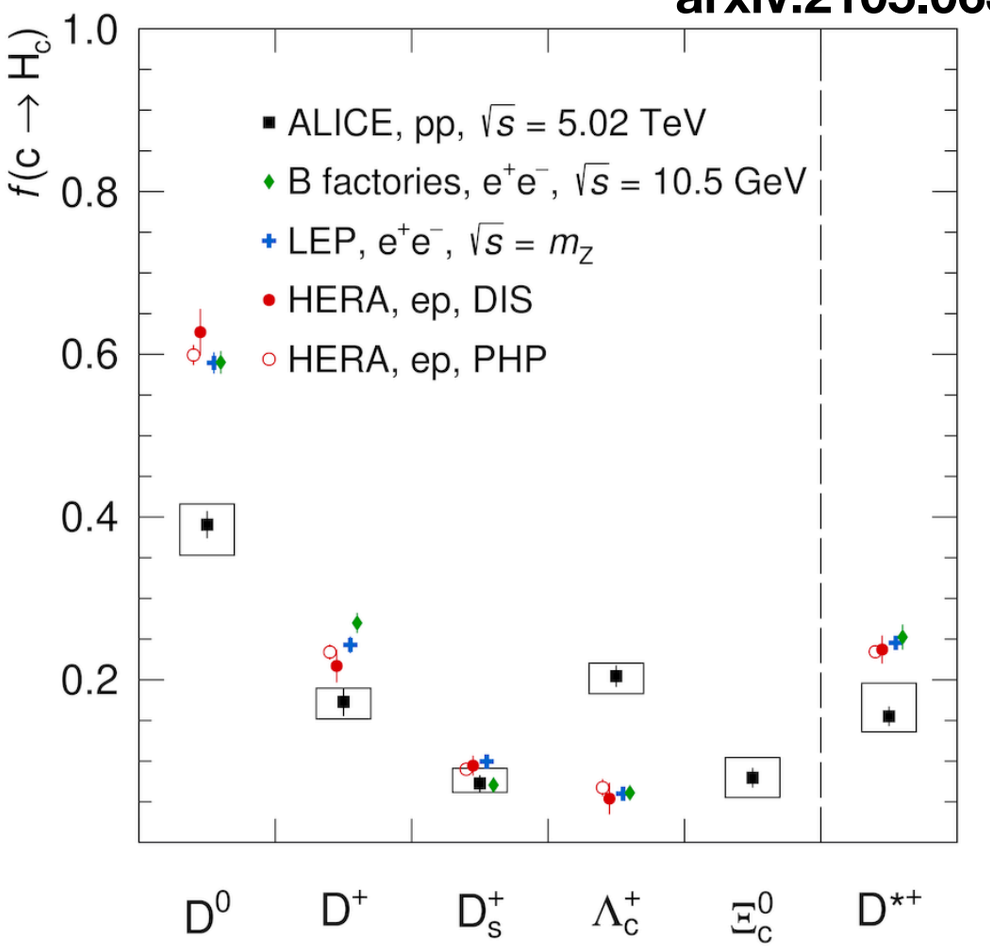
BR not measured but taken from theory



- $\Xi_c^+ = usc, \Xi_c^0 = dsc, \Omega_c^0 = ssc \rightarrow$ access to charm-strange baryons
- **PYTHIA8 Monash tune significantly underestimates $\Xi_c^{0,+}/D^0$ ratio** (by factor x20-40)
  - Models which enhance baryon production also underestimate $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0 ratio → something missing in models.
    - strangeness contribution not enough?
- Ω_c^0 yield ~of the order of the Ξ_c^+ yield

Charm-quark fragmentation fractions and production cross section

arxiv:2105.06335



- Note: Ξ_c **and** Ω_C^0 **production poorly studied at e⁺e⁻ collisions** - previous fragmentation fraction calculations using e^+e^-/ep data use assumption:
  $\frac{f(s \to \Xi^-)}{f(s \to \Lambda)} = \frac{f(s \to \Xi_c^+)}{f(s \to \Lambda_c^+)}$ ~ 0.005 and
  $\frac{f(s \to \Omega^-)}{f(s \to \Lambda)} = \frac{f(s \to \Omega_c^0)}{f(s \to \Lambda_c^+)}$ ~ 0.06

  M. Lisovyi, A. Verbytskyi, O. Zenaiev: EPJ C 76 (2016) no.7, 397

  OPAL Collaboration: Z.Phys. C72, 1 (1996).

- p_T-integrated fragmentation fractions confirm that **fragmentation fractions not universal across collision systems**

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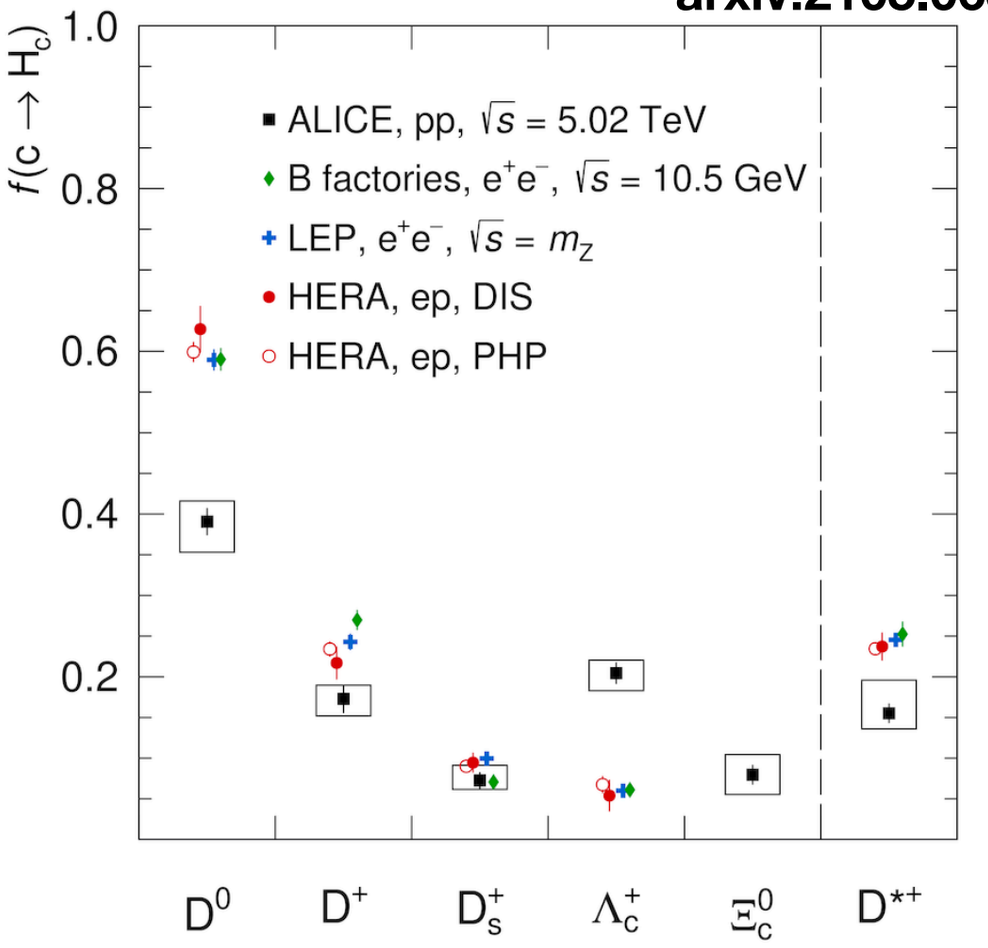

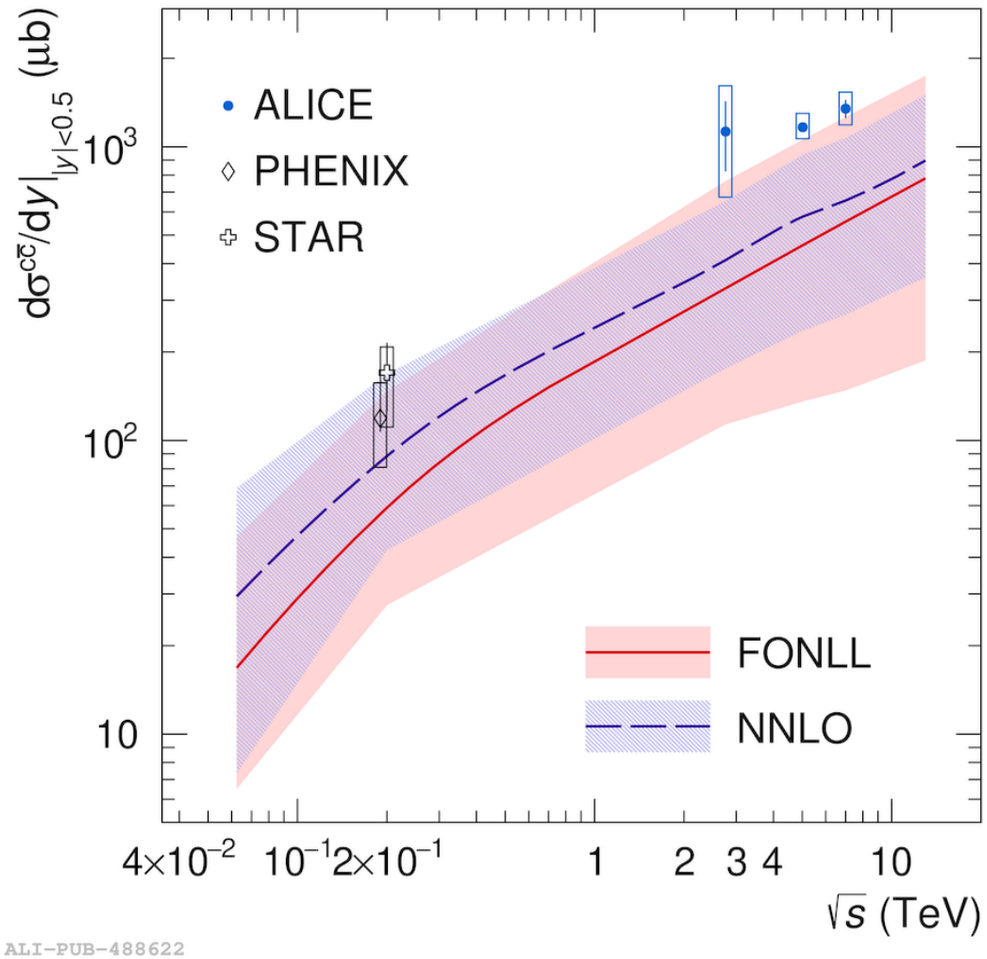

- p_T-integrated fragmentation fractions confirm that **fragmentation fractions not universal across collision systems**
- Total baryonic contribution included in charm production cross section at mid rapidity at $\sqrt{s} = 5.02$ TeV

$$d\sigma^{c\bar{c}}/dy\,|_{|y|<0.5} = 1165 \pm 44\ (\text{stat.})\ ^{+134}_{-101}\ (\text{syst.})\ \mu b$$

- Updated previous calculations at $\sqrt{s} = 2.76{,}7$ TeV which assumed universal fragmentation: **~40% increase**

Beauty baryon production

http://pdg.lbl.gov/2015/reviews/rpp2015-rev-b-meson-prod-decay.pdf

Pre-LHC: at Tevatron, b-baryon fragmentation in pp collisions **over 2x that in e^+e^-** (though uncertainties large)

Table 1: Fragmentation fractions of b quarks into weakly-decaying b-hadron species in $Z \to b\bar{b}$ decay, in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

b hadron	Fraction at Z [%]	Fraction at $\bar{p}p$[%]
B^+, B^0	40.4 ± 0.9	33.9 ± 3.9
B_s	10.3 ± 0.9	11.1 ± 1.4
b baryons	8.9 ± 1.5	21.2 ± 6.9

Beauty baryon production

- Λ_b^0 production at the LHC shows consistent picture:
  - Λ_b^0 cross section **steeper-falling** and **underestimated by pQCD (POWHEG) at low p_T**
  - Baryon-to-meson ratio indicates **clear decreasing trend vs p_T**

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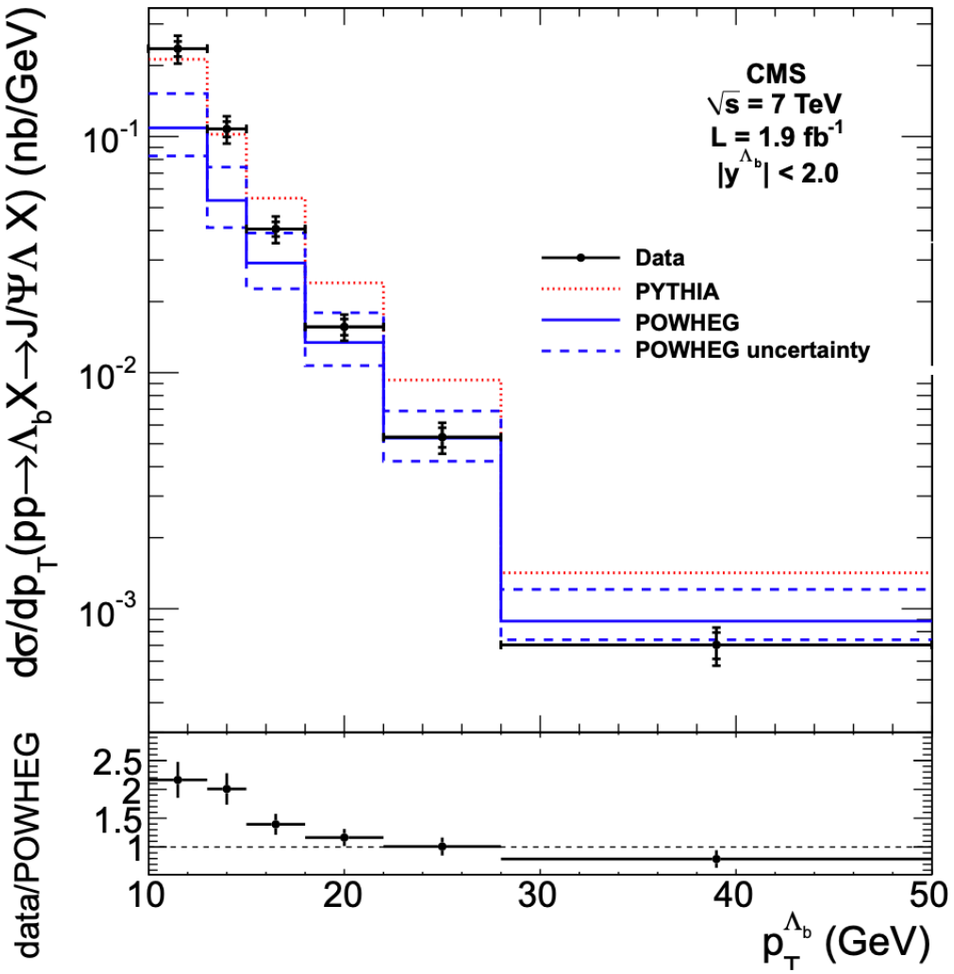
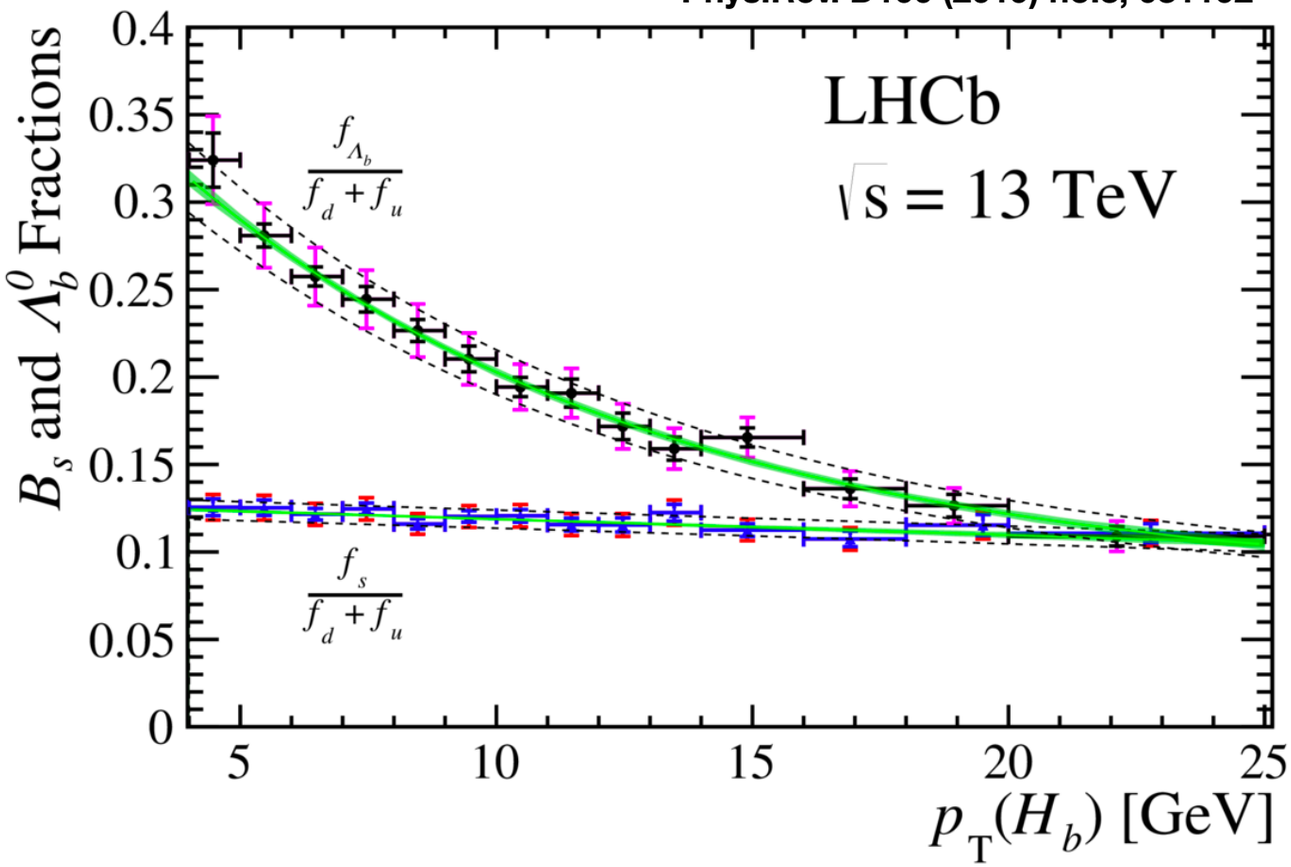
Phys. Lett. B 714 (2012) 136



Phys.Rev. D100 (2019) no.3, 031102



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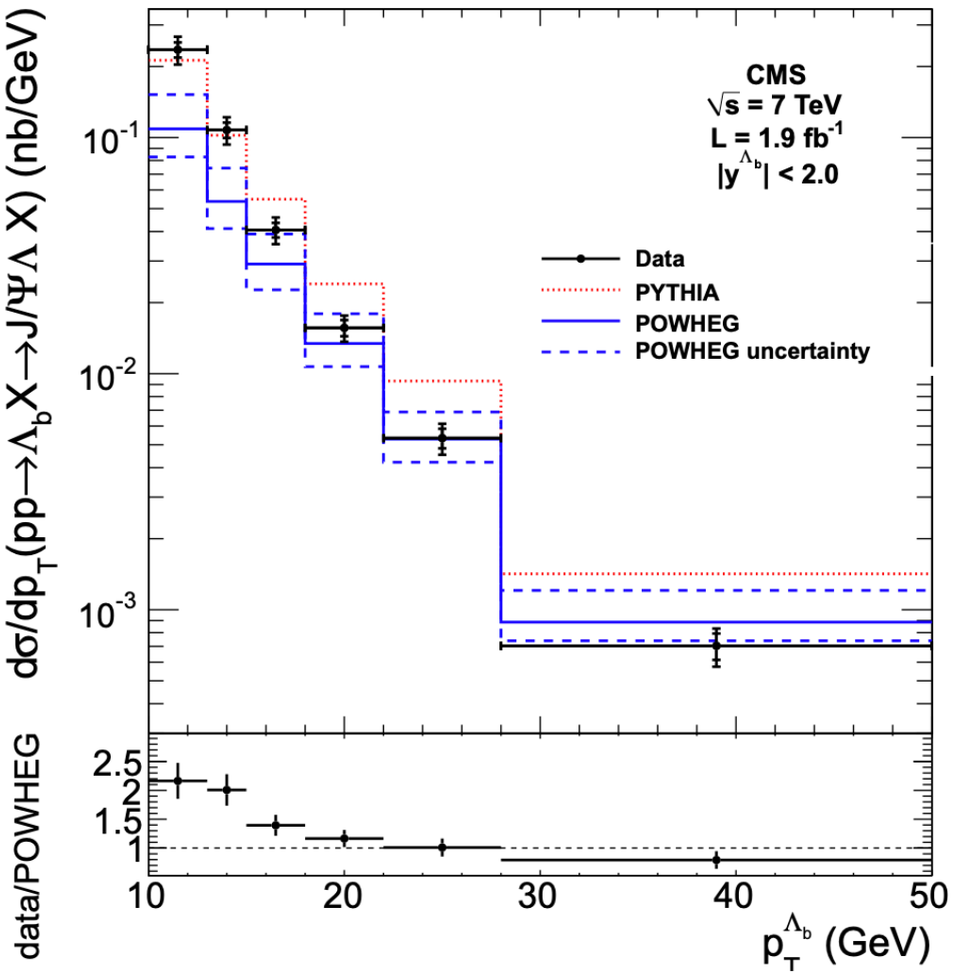

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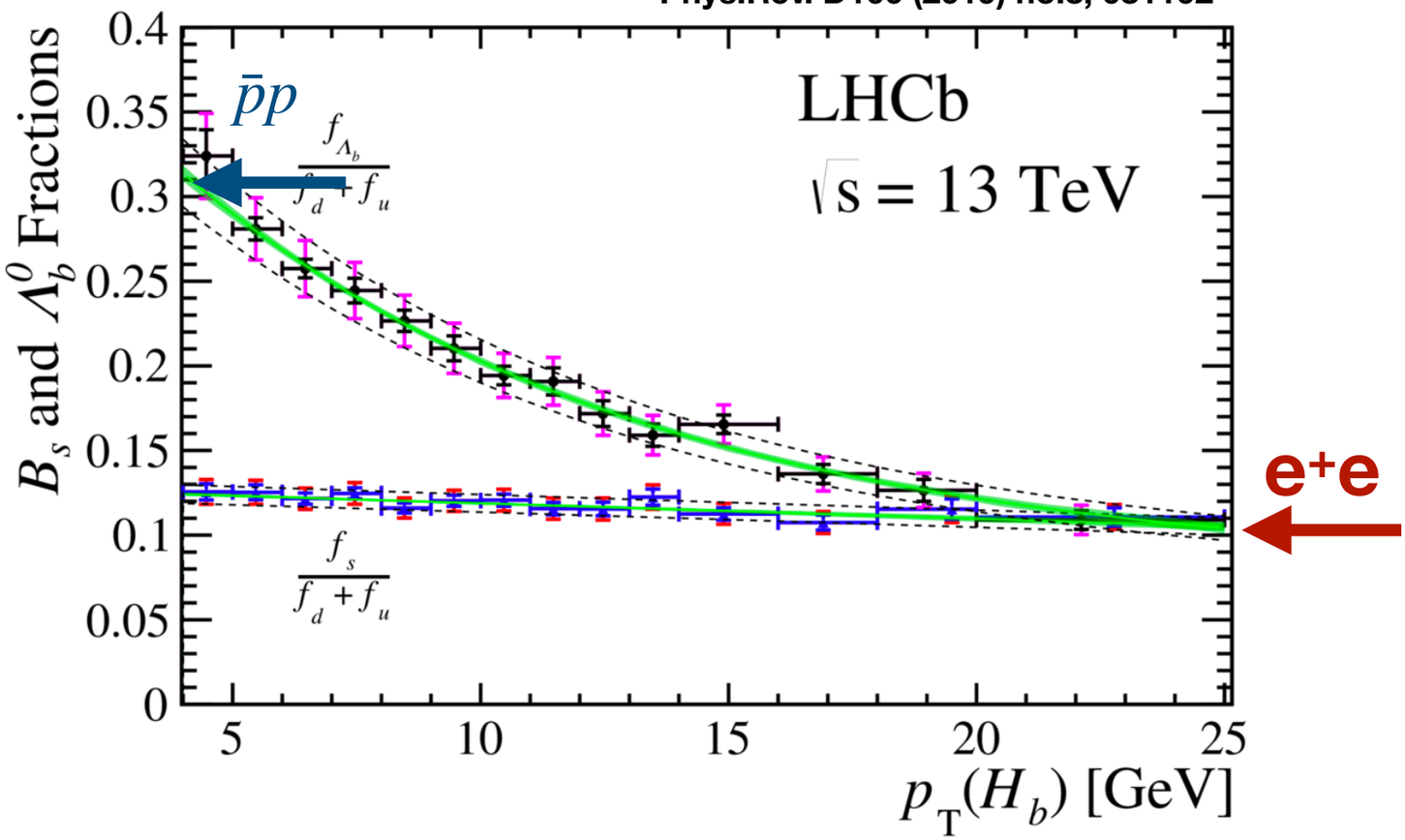
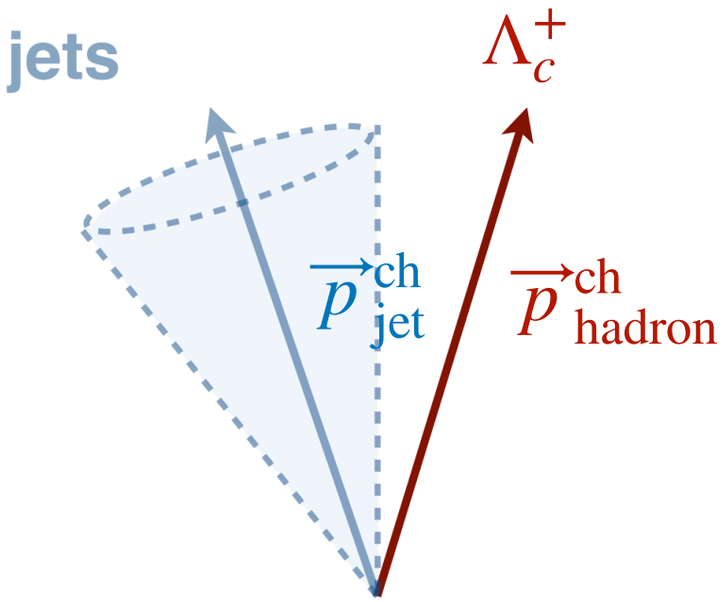
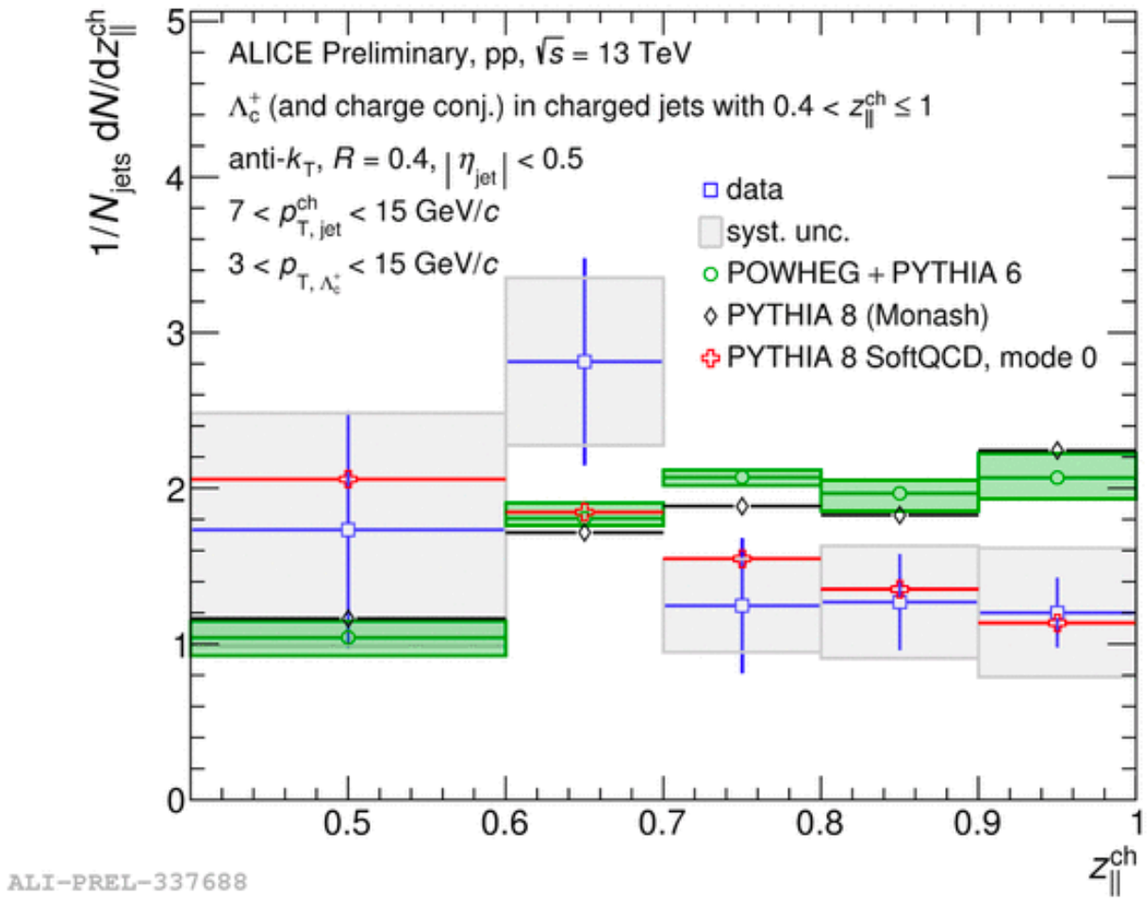


→ **Similar mechanisms leading to low p_T Λ_c^+ and Λ_b^0 baryon enhancement?**

Probing Λ_c^+ fragmentation: Λ_c^+ in jets



$$z_{||}^{\mathrm{ch}} = \frac{\overrightarrow{p}^{\,\mathrm{ch}}_{\mathrm{jet}} \cdot \overrightarrow{p}^{\,\mathrm{ch}}_{\mathrm{hadron}}}{\overrightarrow{p}^{\,\mathrm{ch}}_{\mathrm{jet}} \cdot \overrightarrow{p}^{\,\mathrm{ch}}_{\mathrm{jet}}}$$

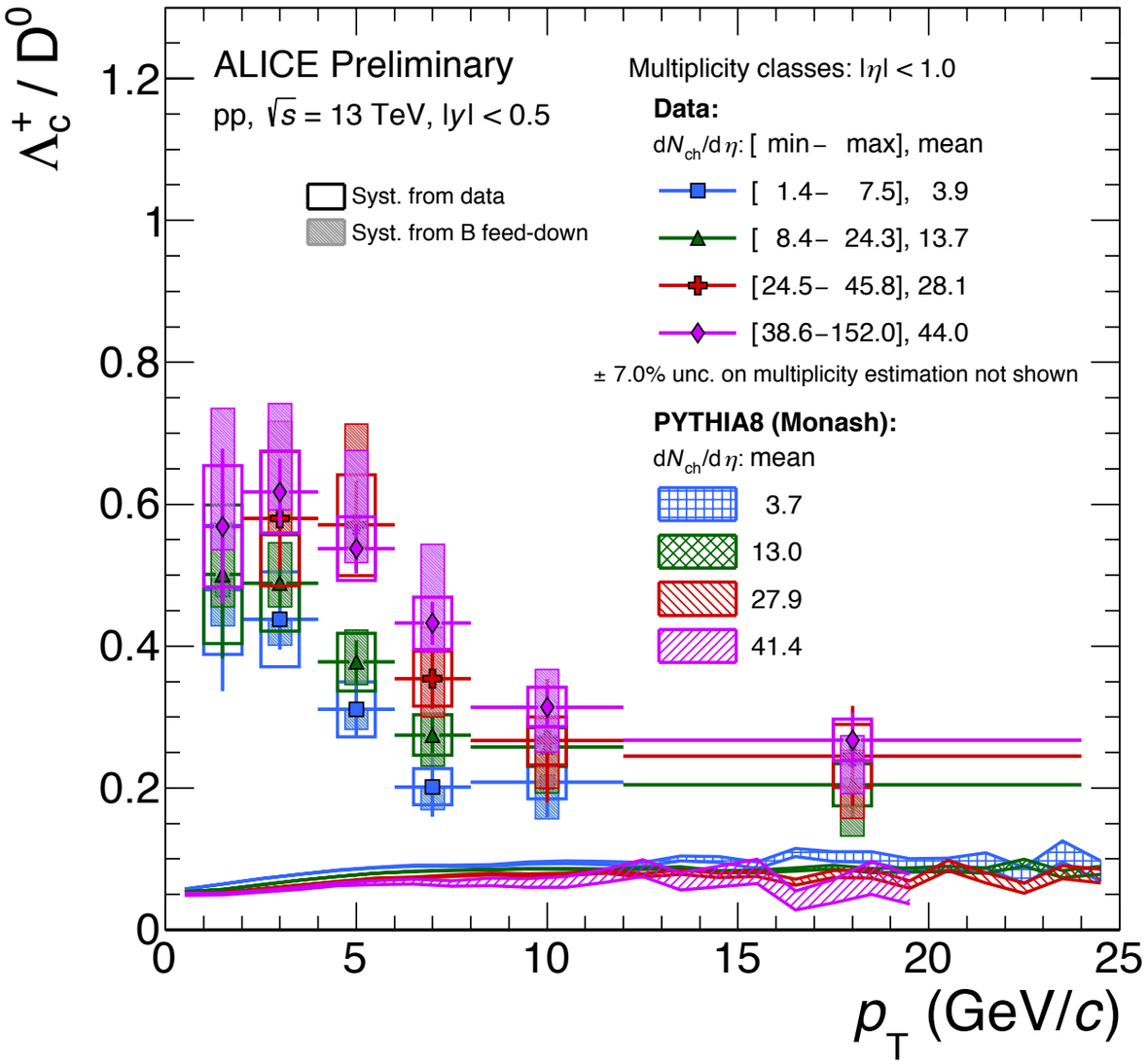


- $z_{||}^{\mathrm{ch}}$ sensitive to Λ_c^+ fragmentation function
  - 'soft' $z_{||}^{\mathrm{ch}}$ - PYTHIA requires colour reconnection modes to reproduce measurement
  - Softer fragmentation with respect to D mesons would explain p_T-dependence of Λ_c^+ ratio
- **More differential studies of heavy-flavour baryon production promising way to further probe fragmentation…**

Heavy-flavour baryon production as a function of system size (from pp → Pb-Pb collisions)

- Heavy-flavour baryons have been proposed for some time as a sensitive test of hadronisation in heavy-ion collisions
  - Expected enhancement if hadronisation via coalescence(recombination) has large role to play
  - At what point (system/energy density/multiplicity) do ‘traditional’ heavy-ion effects take hold?
- Could heavy baryon production be described with ‘unified’ picture going from pp → Pb-Pb collisions?

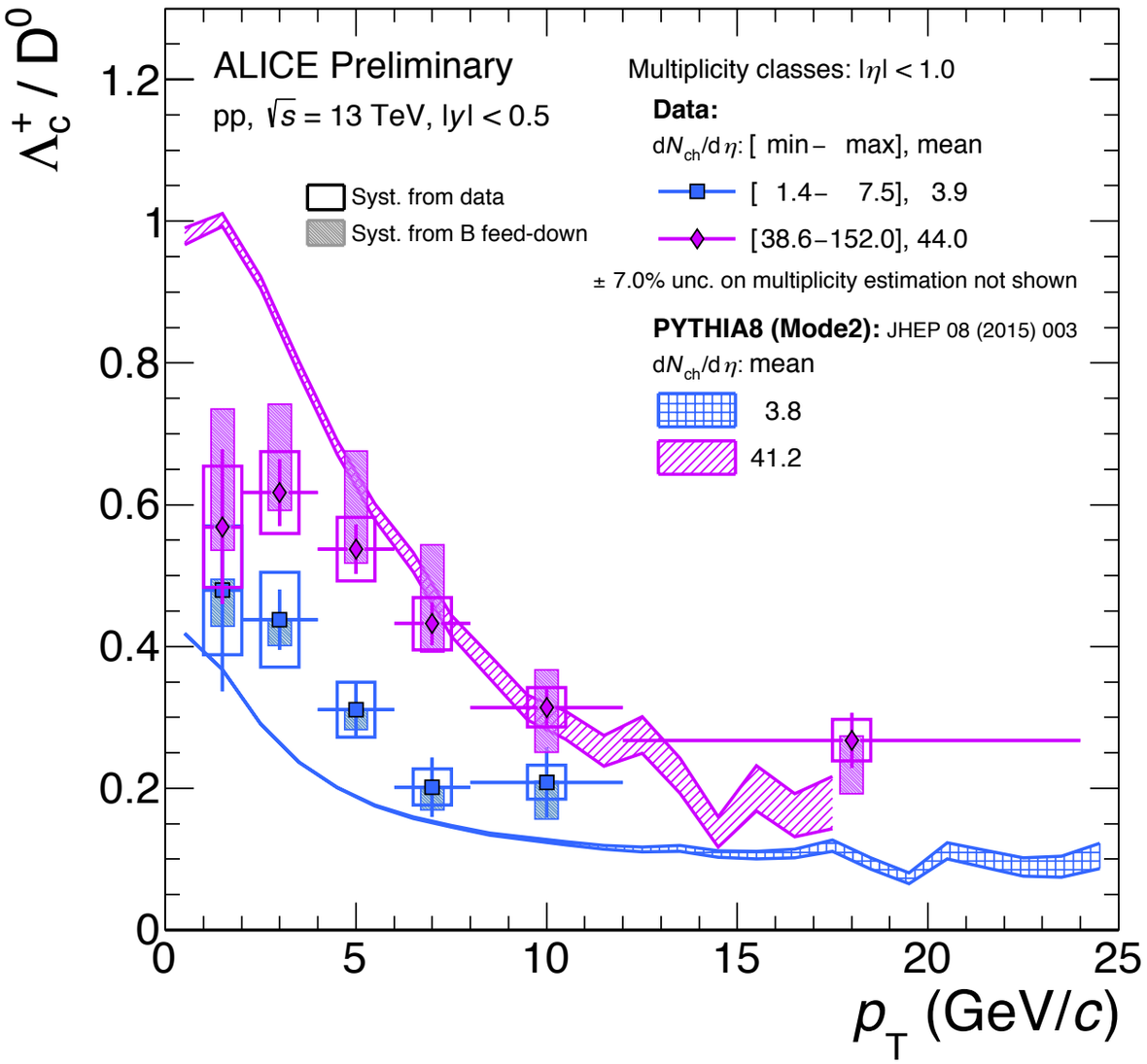
multiplicity-dependence of Λ_c^+ production in pp collisions



Multiplicity measured at mid-rapidity: $dN_{ch}/d\eta$ in ALICE Silicon Pixel Detector

- **Significant enhancement** in high-multiplicity Λ_c^+/D^0 ratio with respect to low multiplicity

multiplicity-dependence of Λ_c^+ production in pp collisions



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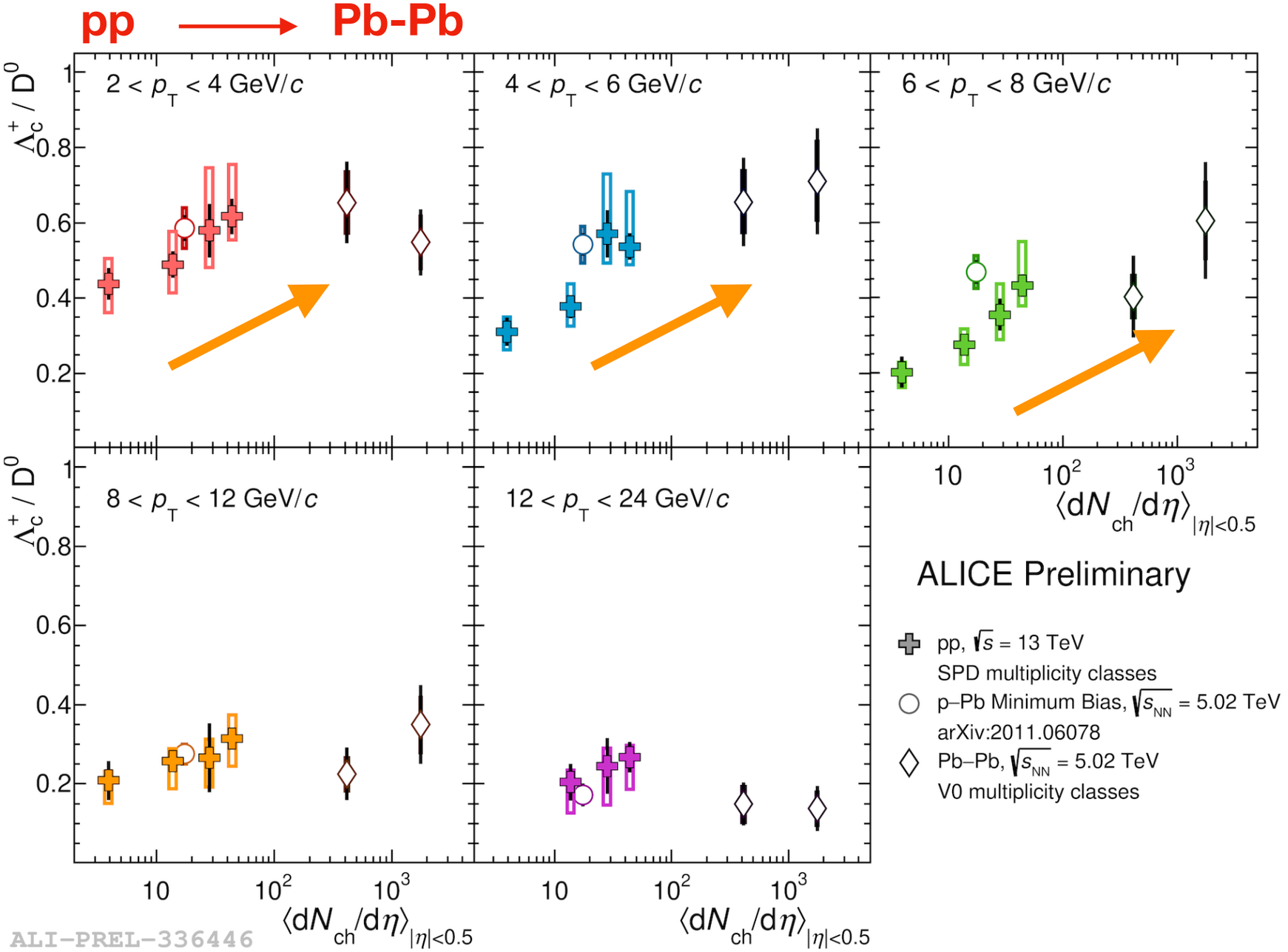
- **Significant enhancement** in high-multiplicity Λ_c^+/D^0 ratio with respect to low multiplicity
- Multiplicity-dependence reproduced with PYTHIA Colour Reconnection modes
  - Increased baryon production due to higher energy density

Λ_c^+/D^0 vs multiplicity



- Λ_c^+/D^0 shows smooth evolution of enhancement vs multiplicity across pp, p-Pb and Pb-Pb collisions
- **Underlying processes which lead to heavy flavour hadron production similar in different hadronic collision systems?**

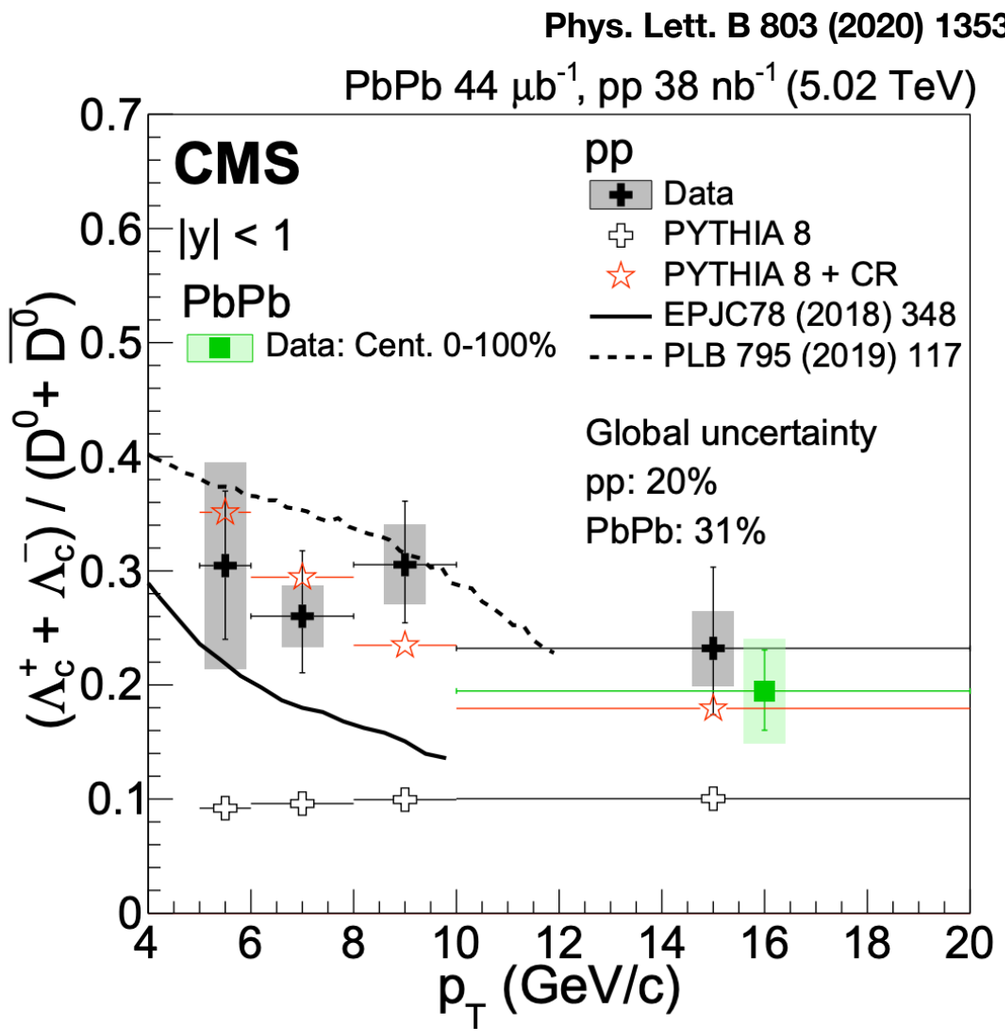
Summary and outlook

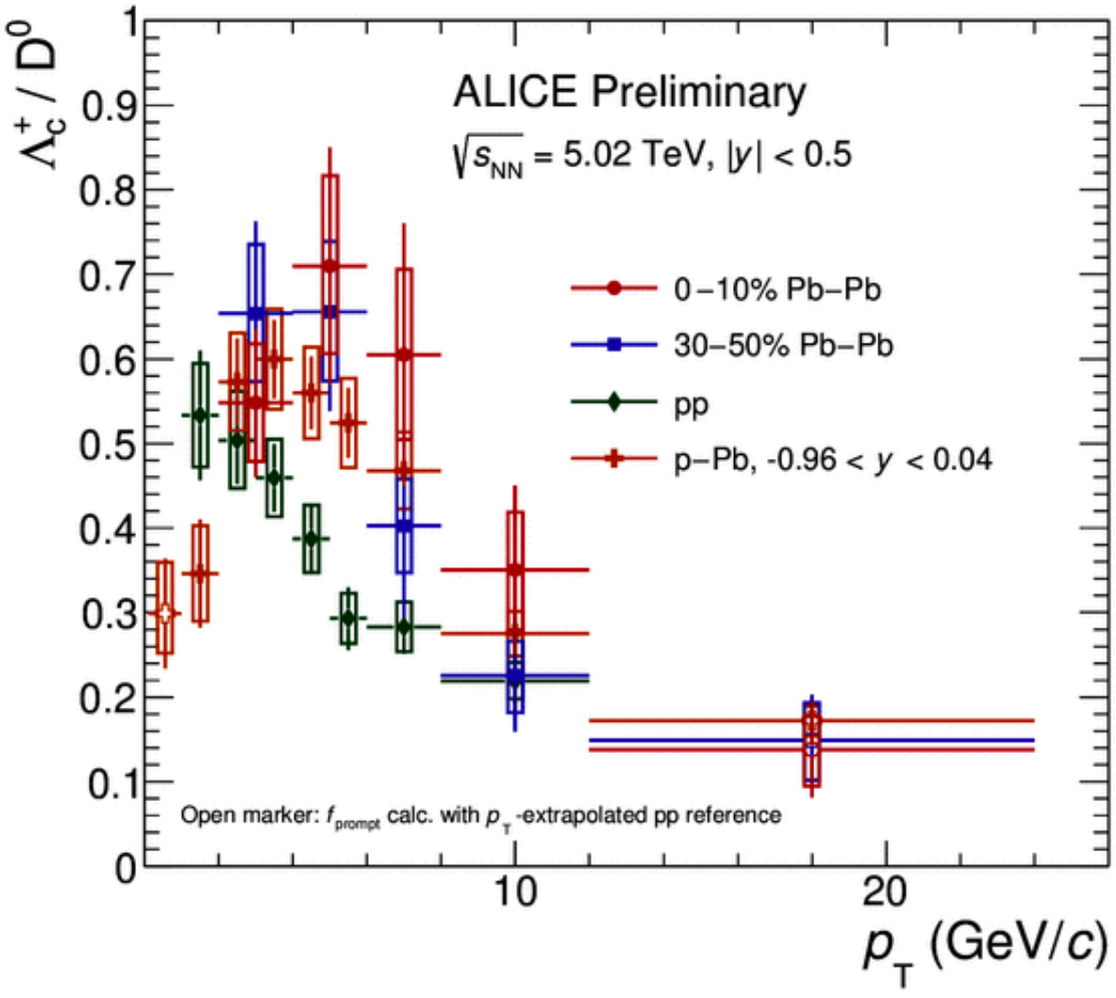
- Heavy-flavour baryon production measurements offer important insights into hadronisation in hadronic collisions
- **Indication that factorisation theorem with universal parton-to-hadron fragmentation is no longer valid**
  - Colour reconnection between uncorrelated partons? Hadronisation via coalescence? Yet-unobserved baryon states?
    - Some models describe relative production of Λ_c^+ and Σ_c baryons w.r.t mesons, plus multiplicity-dependence of Λ_c^+ production… Though still generally underestimate Ξ_c and Ω_c^0
- **Run 3 and 4 at the LHC:**
  - Major detector upgrades will open new paradigm for studies of heavy-flavour baryon production
    - Production spectroscopy, searches for baryon resonances, high/low multiplicity in small systems, precision heavy baryon fragmentation measurements…
    - OO and pO runs will provide new opportunities to study baryon production vs system size
- **Future Electron-Ion collider** would offer unique opportunity to probe hadronisation going from e^+e^- to heavy-ion collisions

arXiv:2102.08337

Backup

Λ_c^+ production in Pb-Pb collisions





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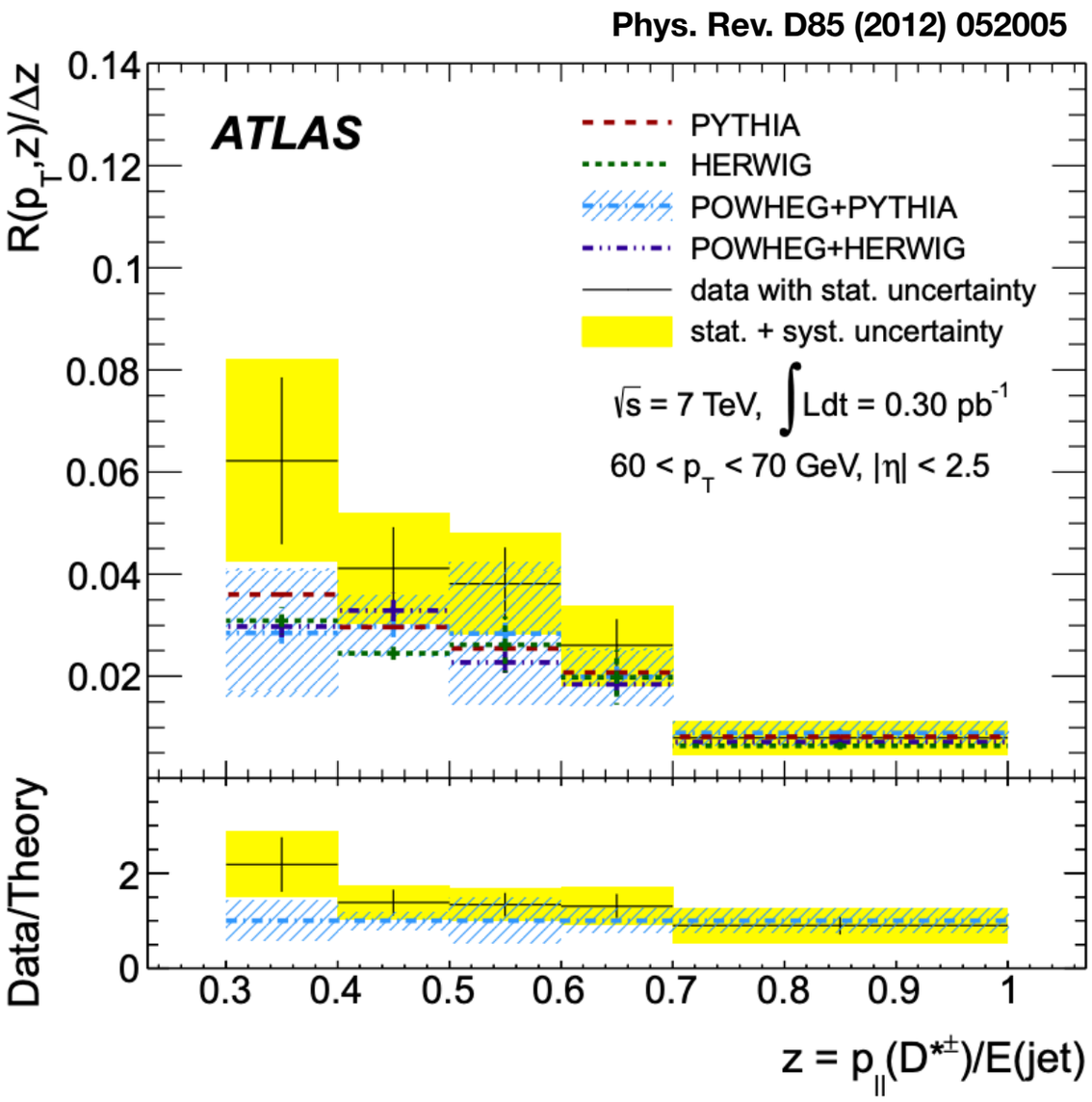
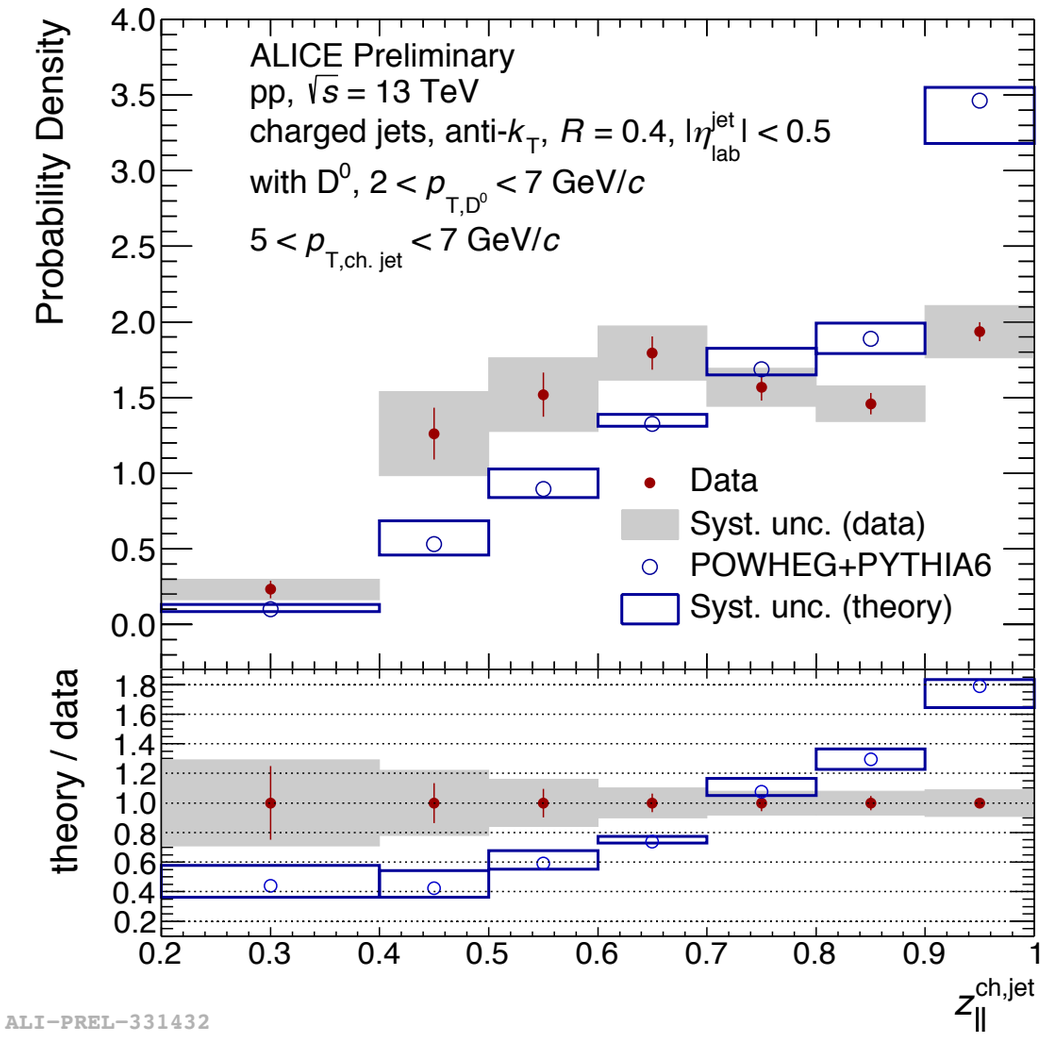
- High p_T (p_T > 10 GeV/c): Λ_c/D^0 ratio consistent within uncertainties - fragmentation dominant
- Mid-p_T (3 < p_T < 8 GeV/c): evolution of Λ_c/D^0 ratio vs multiplicity?

D-jet measurements

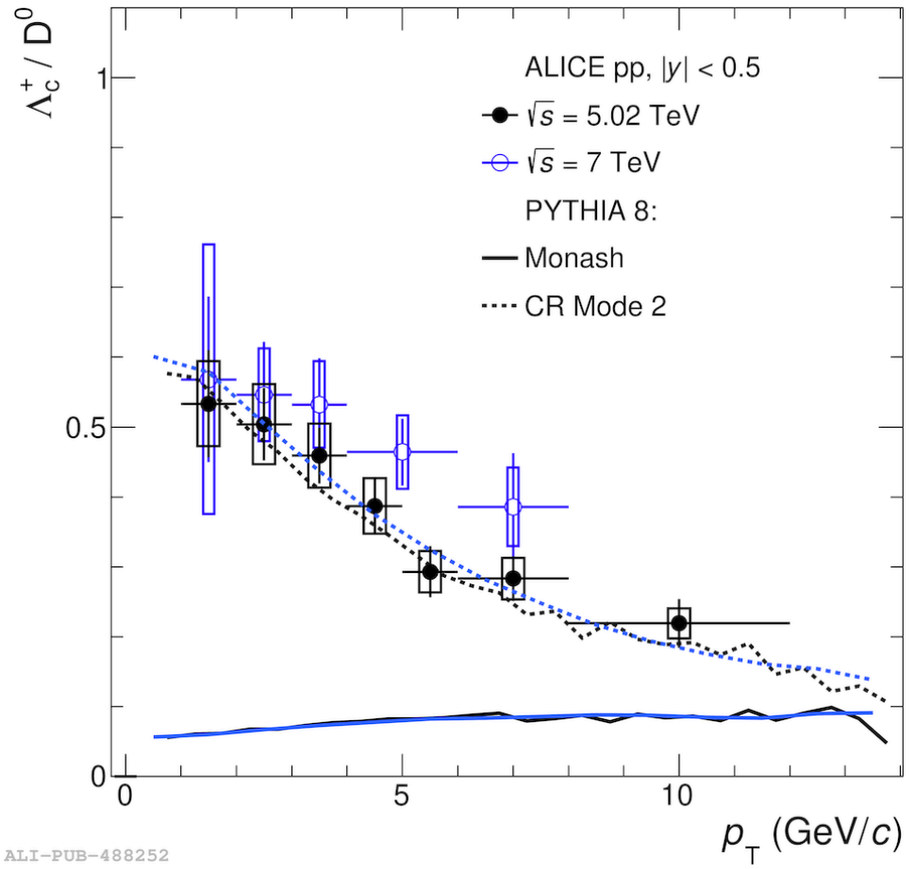




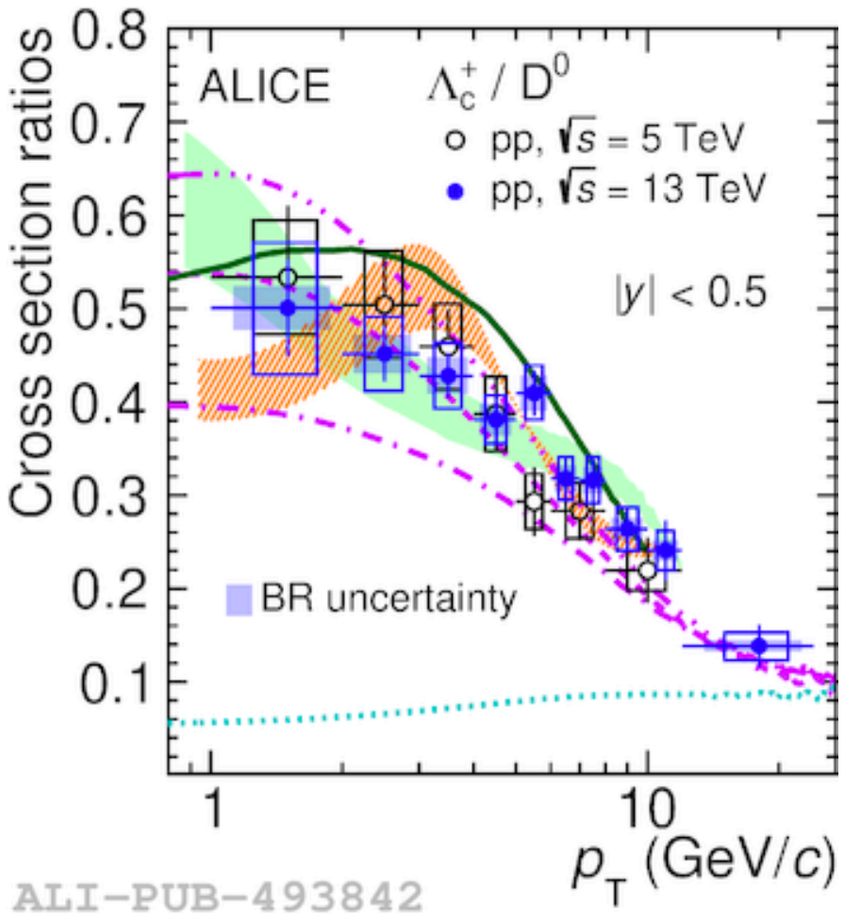
- Low-p_T charm jet fragmentation to D mesons not described well by MC generators

Baryon-to-meson ratios vs collision energy

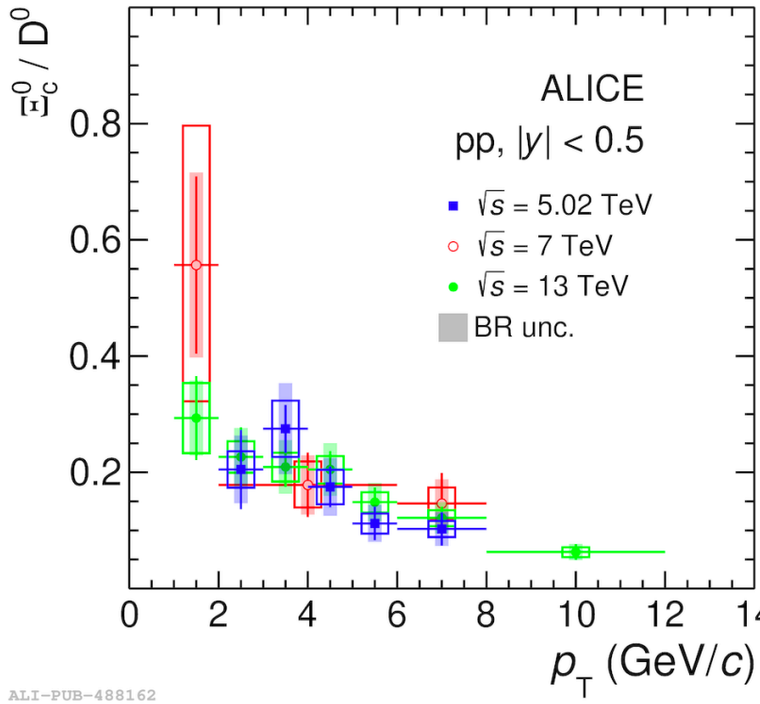
arXiv:2011.06078
arXiv:2011.06079



arXiv:2106.08278



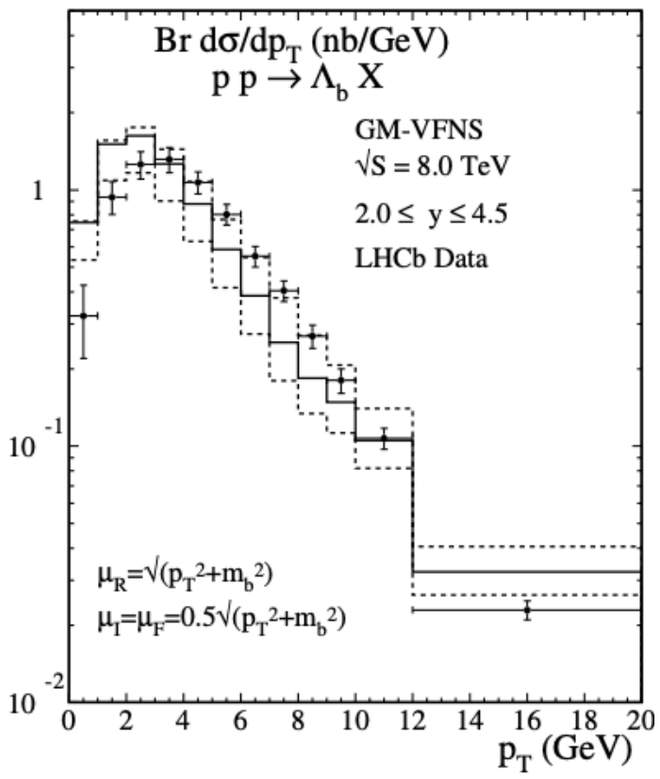
arXiv:2105.05616

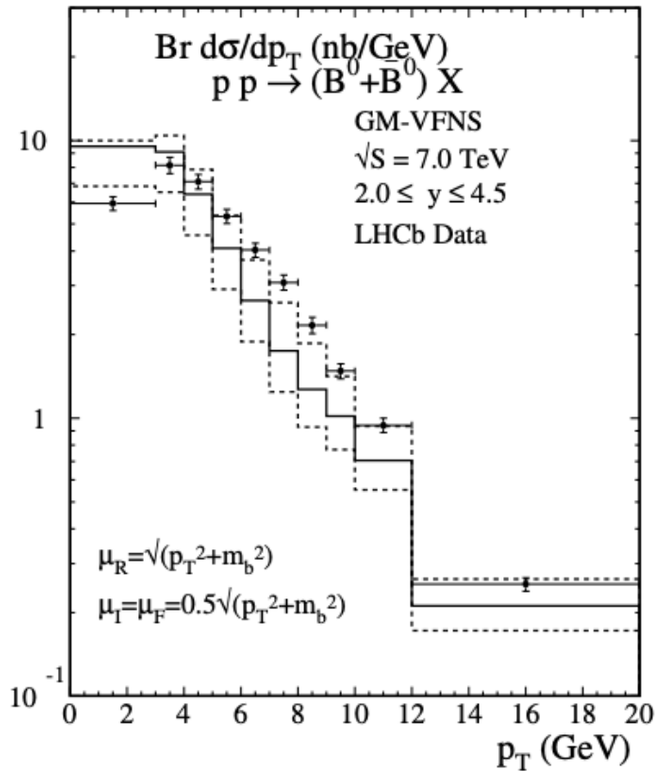


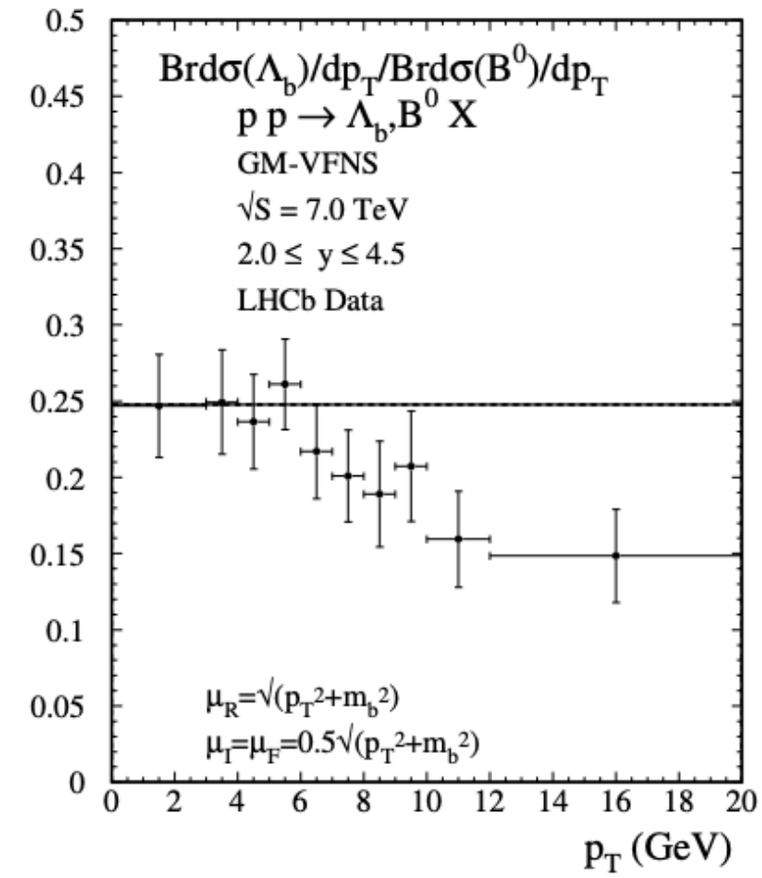
- Λ_c^+/D^0 ratio consistent vs collision energy (5.02 TeV → 13 TeV)
- Ξ_c^0/D^0 ratio consistent vs collision energy (5.02 TeV → 13 TeV)

Beauty baryon production in GM-VFNS

arxiv:1803.11103





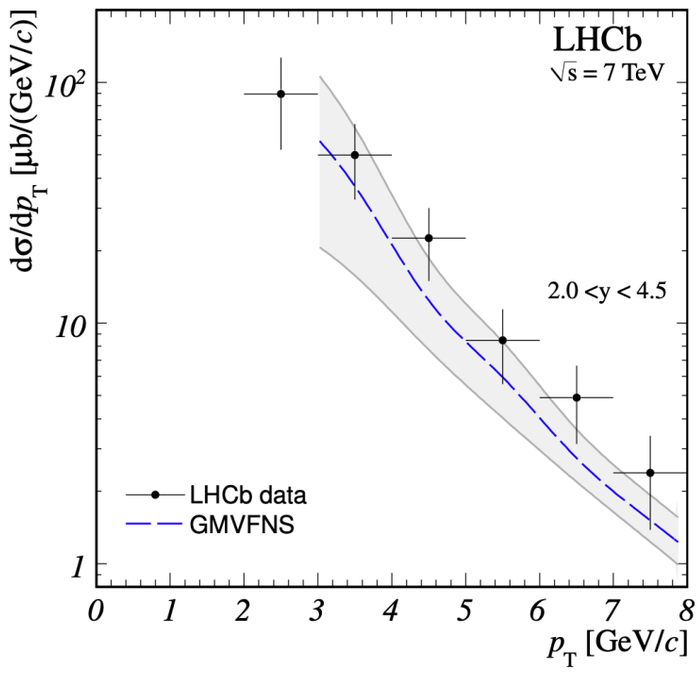


- Beauty baryon production in GM-VFNS:
  - Common fragmentation functions for mesons and baryons
  - Comparison with data indicates that fragmentation functions need to be modified

Λ_C^+/D^0 tension at mid-rapidity/forward rapidity?

- Tension in Λ_c^+ production measurement from LHCb in pp collisions at 7 TeV
  - Λ_c^+ production cross section in good agreement with pQCD (GM-VFNS)
  - Flat rapidity trend predicted by models not reproduced by LHCb
- Λ_c^+/D^0 in p-Pb collisions measured by the LHCb experiment shows a flatter trend with rapidity

Nuclear Physics, Section B 871 (2013), pp. 1-20



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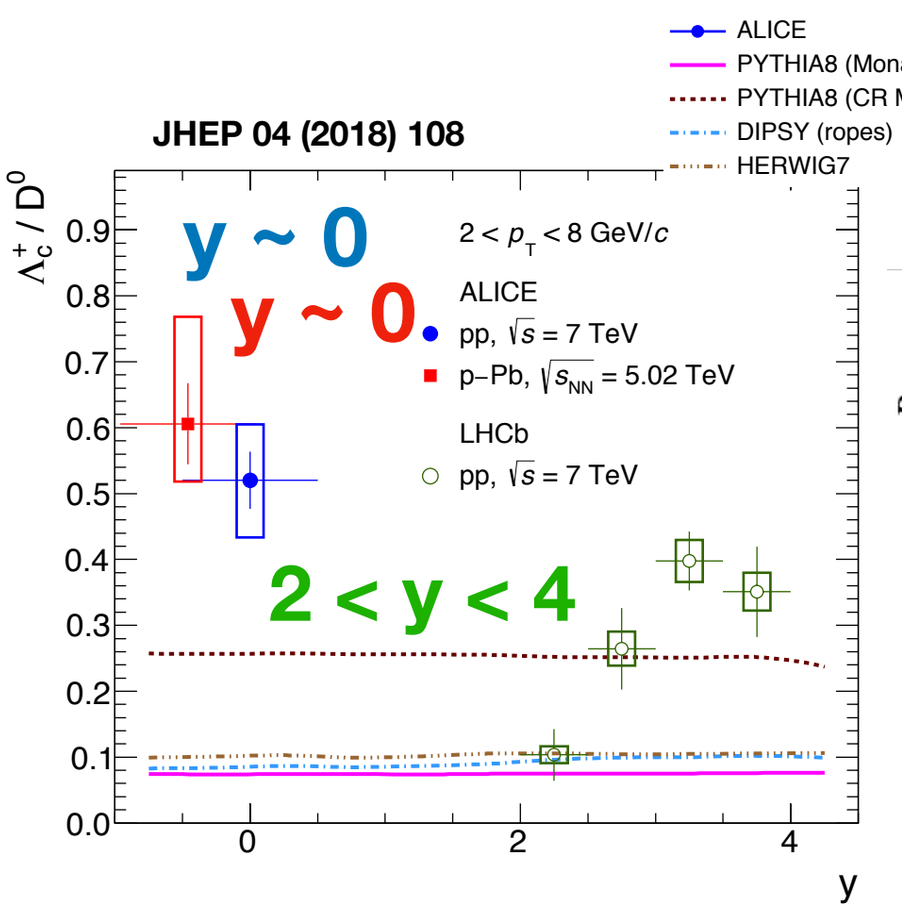

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