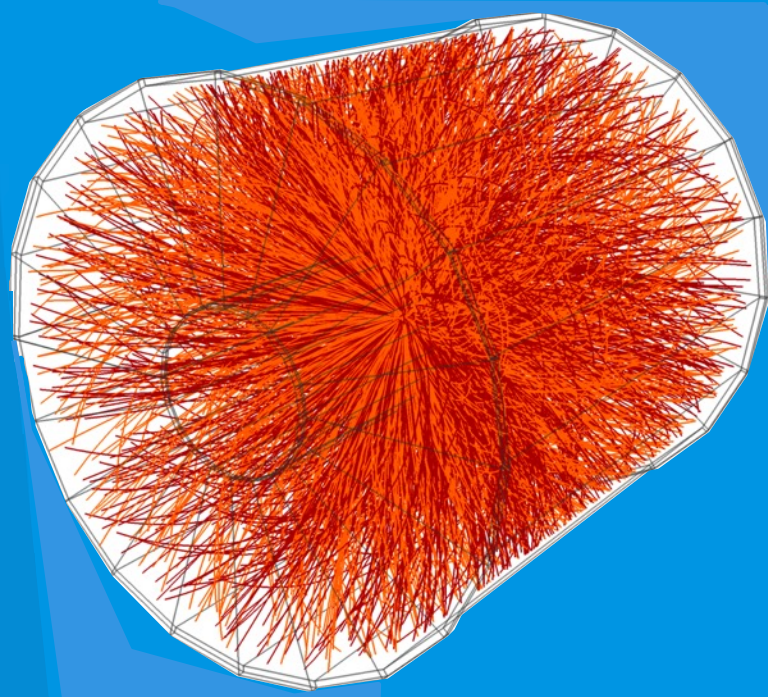
Experimental results on heavy quark hadronisation



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Torino
16/07/2022

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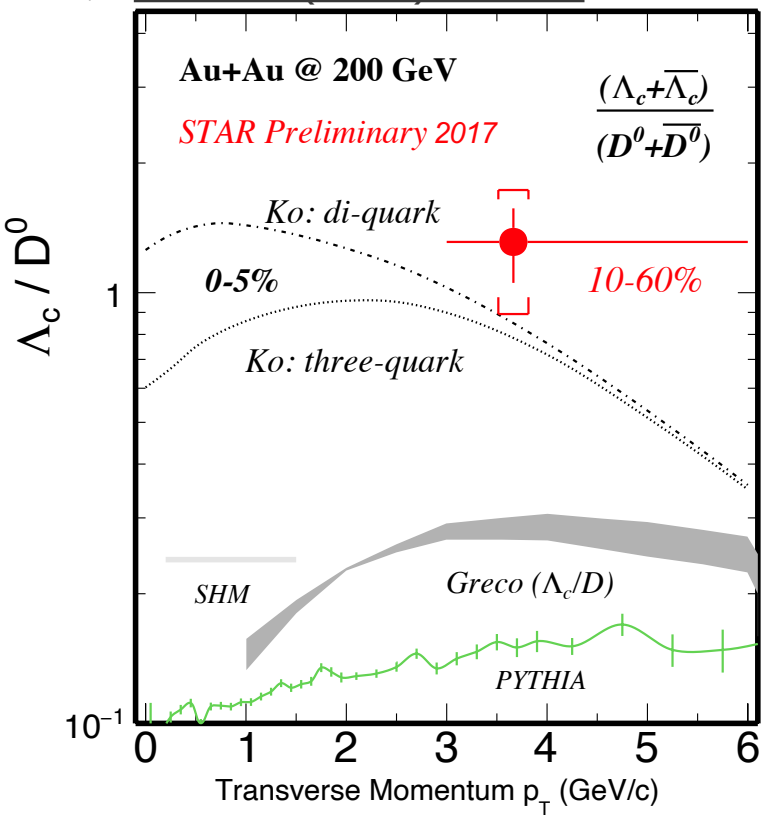
Heavy-quark hadronisation

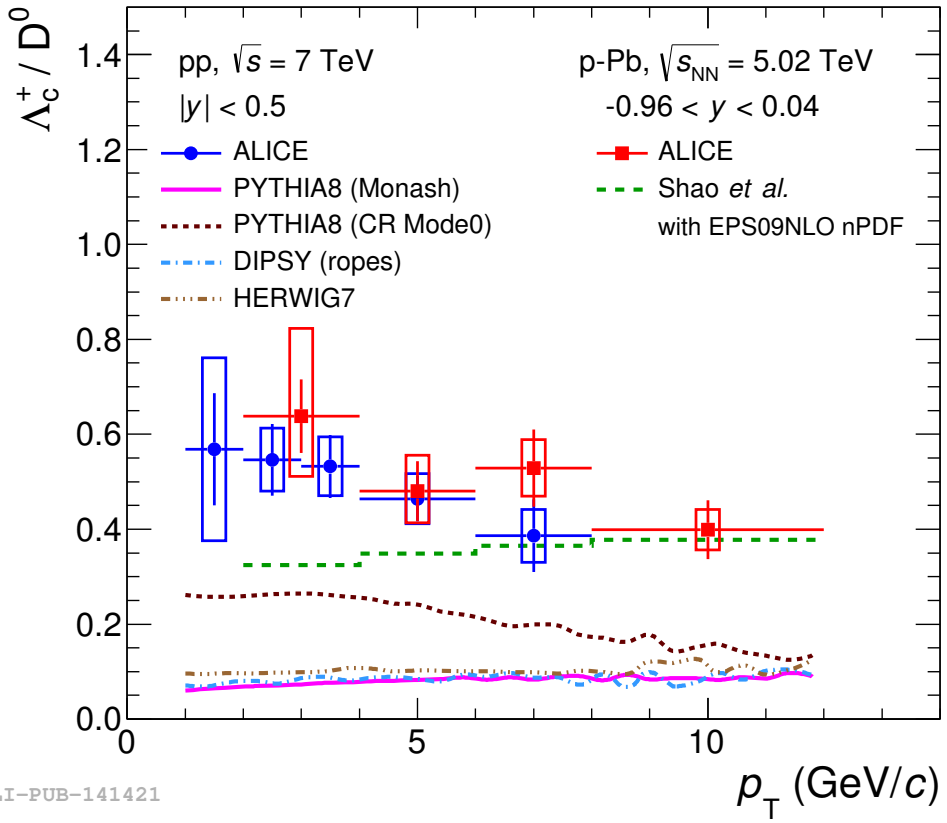
Interest in heavy-quark hadronisation recently (re)started

- $<$ **QM17:** Only appeared as one of the model ingredients
- $\geq$ **QM17:** Investigated after STAR and ALICE pioneering Λ_c^+ measurements
- $=$ **QM22:** 6x "heavy-flavour hadronisation" in contribution titles

Extended and published in:
PRL 123 (2020) 172301



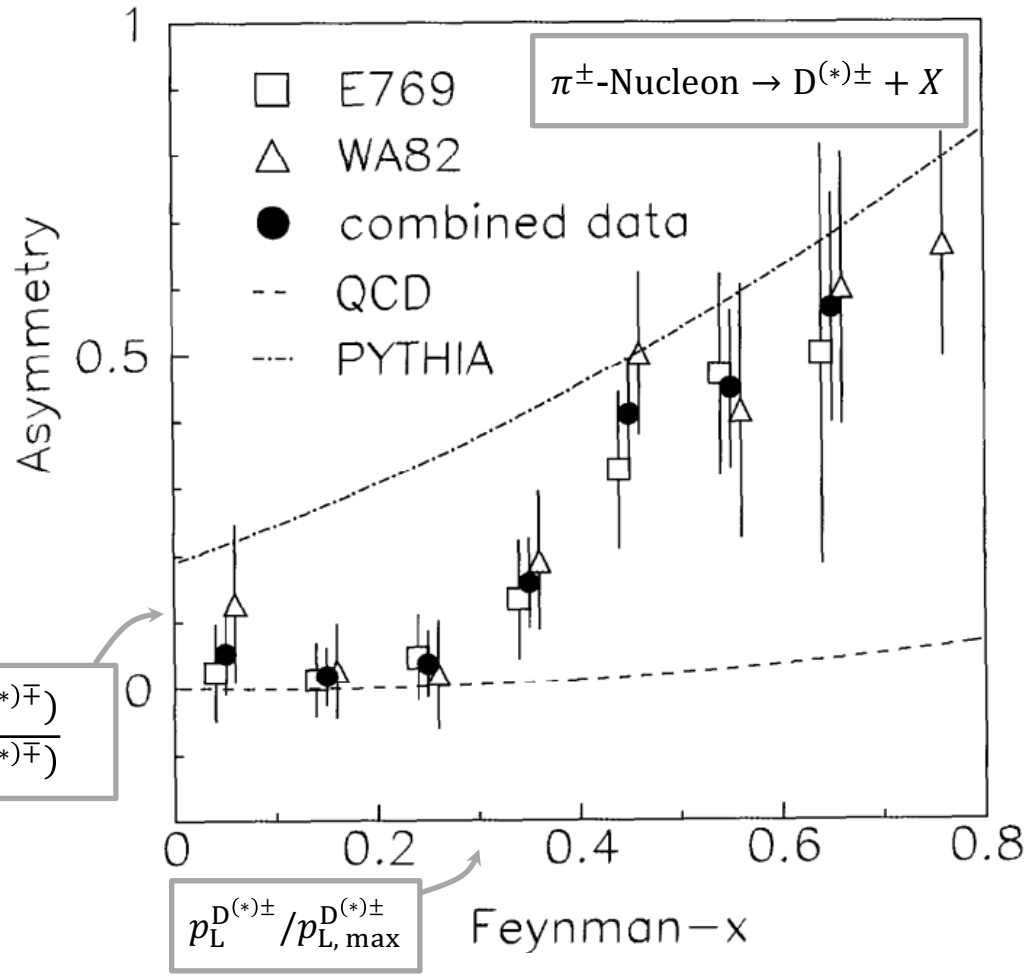
JHEP 04 (2018) 108



When the experimental effort actually began

"The leading particle effect": An observed asymmetry in charm-hadron production in case the light quark is in common with the beam particle

- Not described by models → **Modified hadronisation mechanisms** proposed (recombination)



$$\frac{N(D^{(*)\pm}) - N(D^{(*)\mp})}{N(D^{(*)\pm}) + N(D^{(*)\mp})}$$

$$p_L^{D^{(*)\pm}} / p_{L,\,max}^{D^{(*)\pm}}$$

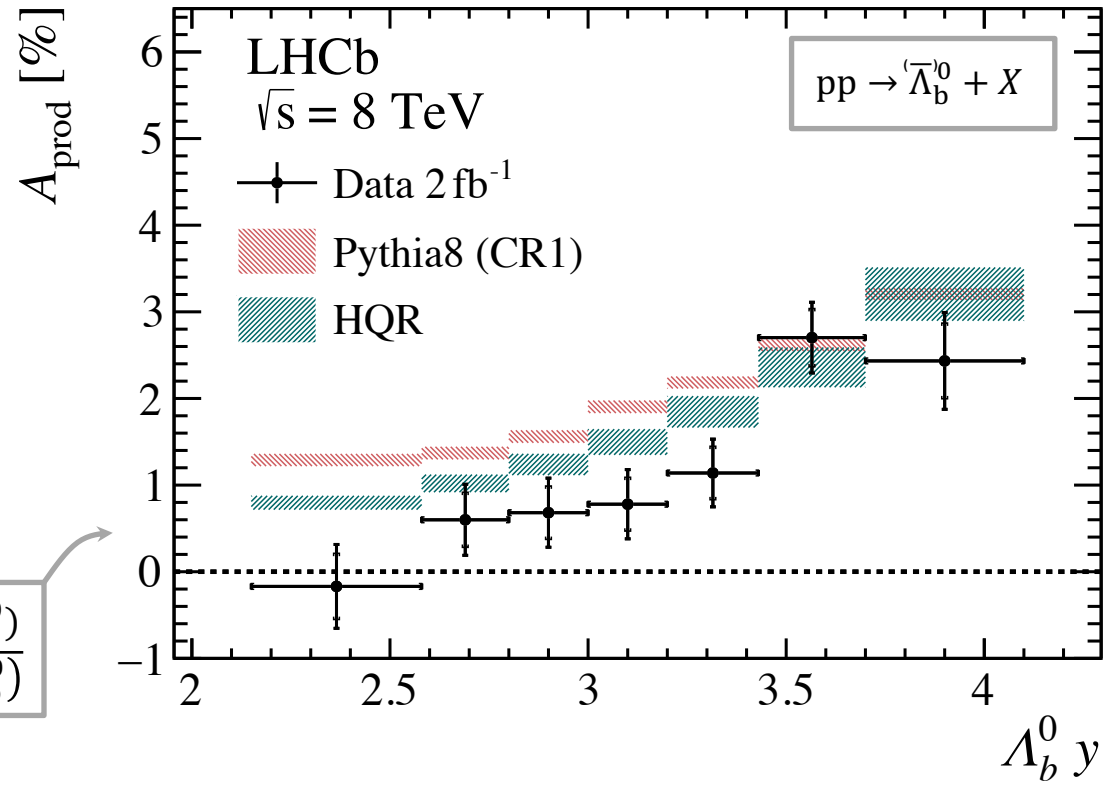
- [LEBC-EHS] Phys. Lett. B 122 (**1983**) 312
- [NA27] Phys. Lett. B 161 (**1985**) 400
- [LEBC-EHS] Zeit. Phys. C 31 (**1986**) 491
- [ACCMOR] Zeit. Phys. C 49 (1991) 555
- [WA82] Phys. Lett. B 305 (1993) 402
- [E769] Phys. Rev. Lett. 72 (1994) 1946
- [E791] Phys. Lett. B 371 (1996) 157
- [E791] Phys. Lett. B 411 (1997) 230
- [WA89] Eur. Phys. J. C 8 (1999) 593
- [SELEX] Phys. Lett. B 528 (2002) 49

Recent progress on HF production asymmetry

LHCb studied the hadronisation process via the production asymmetry for HF hadrons

- Crucial to improve the precision of *CP*-violation measurements
- y- and p_T-differential Λ_b^0 data at 8 TeV **favour** a (~pQCD) heavy-quark **recombination model**

[E. Braaten et al.] Phys. Rev. D 66 (2002) 034003



$$\frac{\sigma(\Lambda_b^0) - \sigma(\overline{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\overline{\Lambda}_b^0)}$$

- [LHCb] Phys. Lett. B 713 (2012) 186
- [CMS] Phys. Lett. B 714 (2012) 136
- [LHCb] Phys. Lett. B 718 (2013) 902
- [LHCb] Phys. Lett. B 739 (2014) 218
- [D0] Phys. Rev. D 91 (2015) 072008
- [LHCb] Chin. Phys. C 40 (2016) 011001
- [LHCb] Phys. Lett. B 774 (2017) 139
- **[LHCb]** JHEP 10 (2021) 060

[CR1, J. Christiansen et al.] JHEP 08 (2015) 003
[HQR, W. K. Lai et al.] Phys. Rev. D 91 (2015) 054022

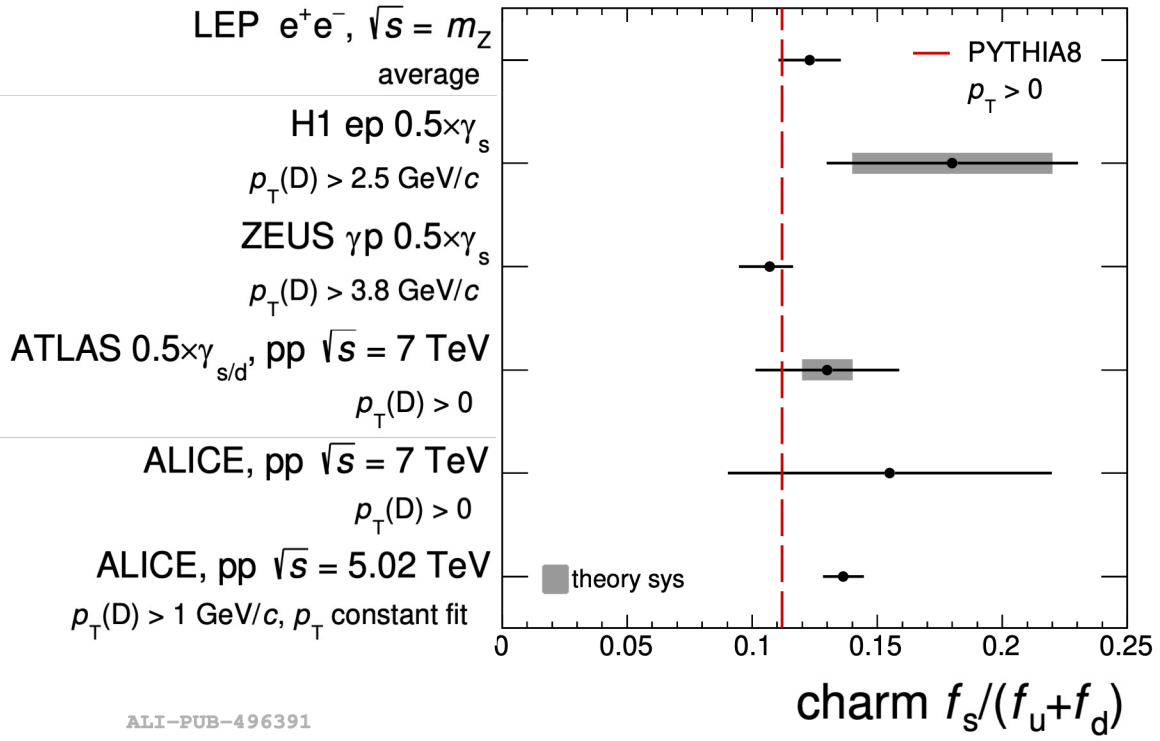
Meson fragmentation fraction ratios in pp

Improved precision on HF fragmentation fractions (**strangeness suppression factor**)

- Compatible with previous measurements (pp, γp, ep, e^+e^-) and PYTHIA 8 simulations
- LHCb observes a **significant dependence on √s** and p_T

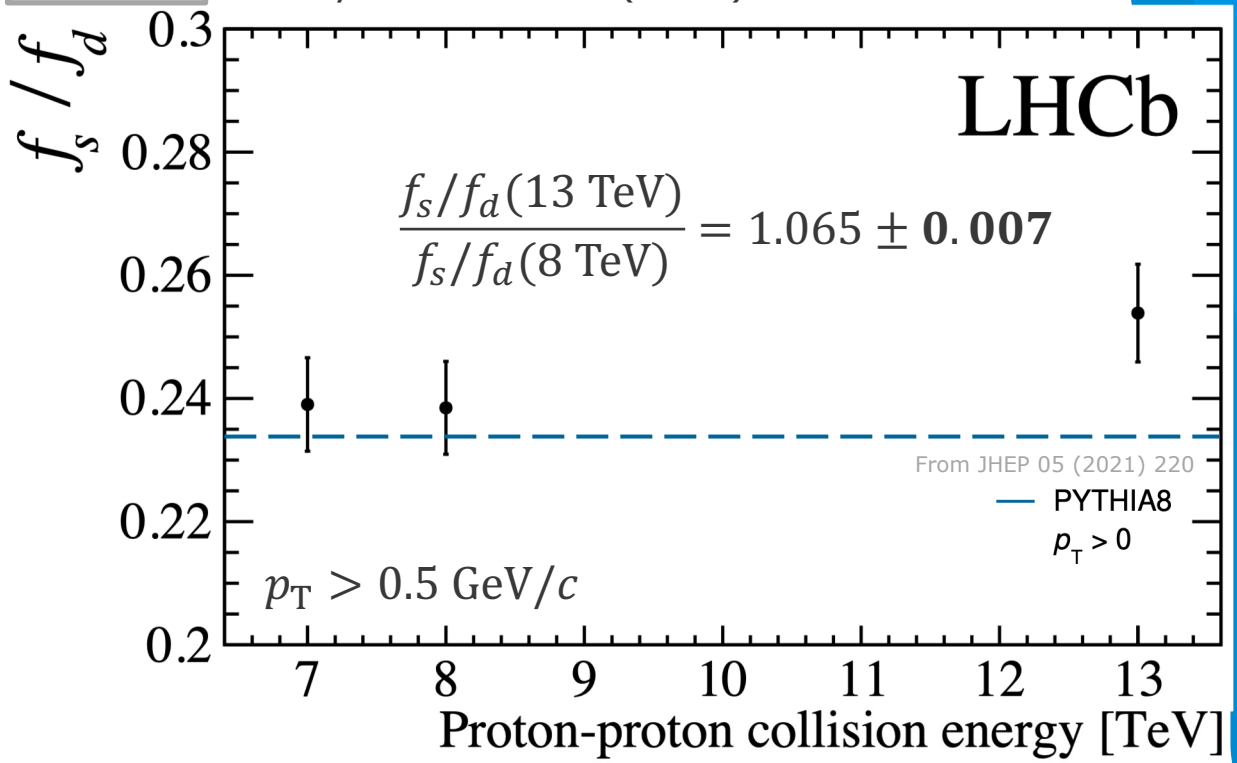
charm

[ALICE] JHEP 05 (2021) 220



beauty

Phys. Rev. D 104 (2021) 032005

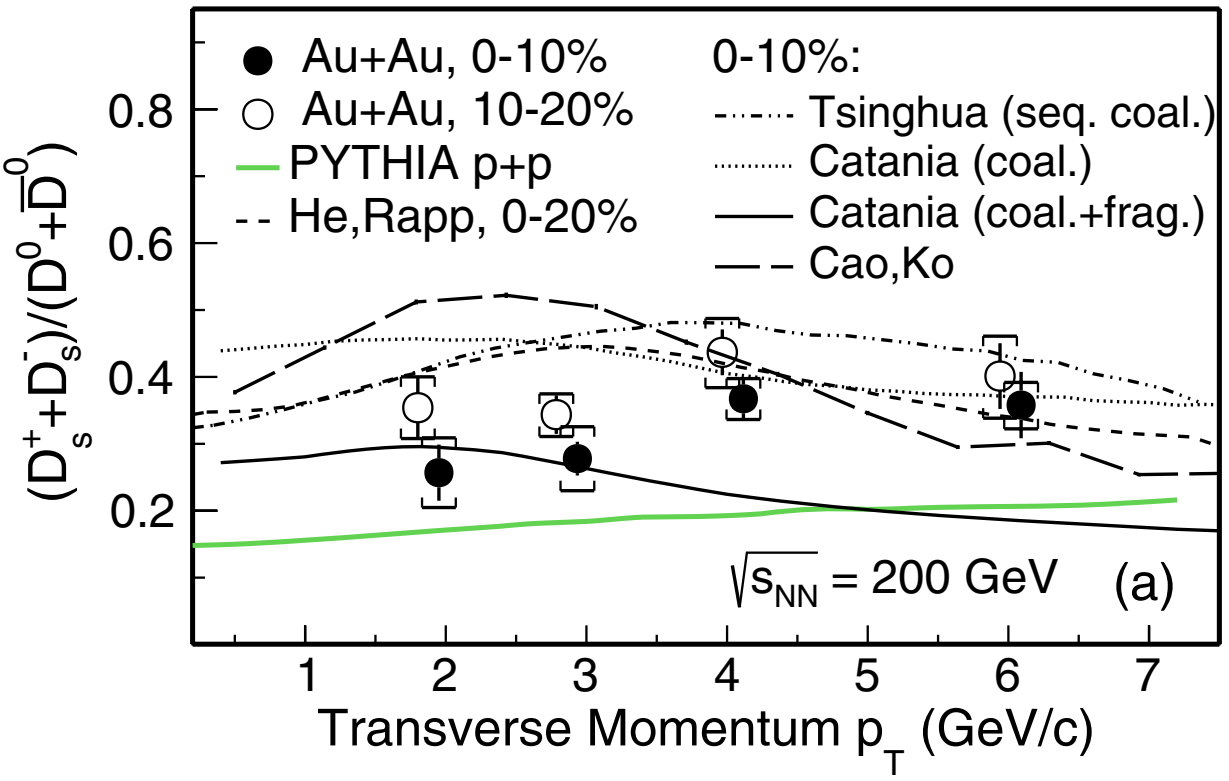


Charm-strange mesons in A–A

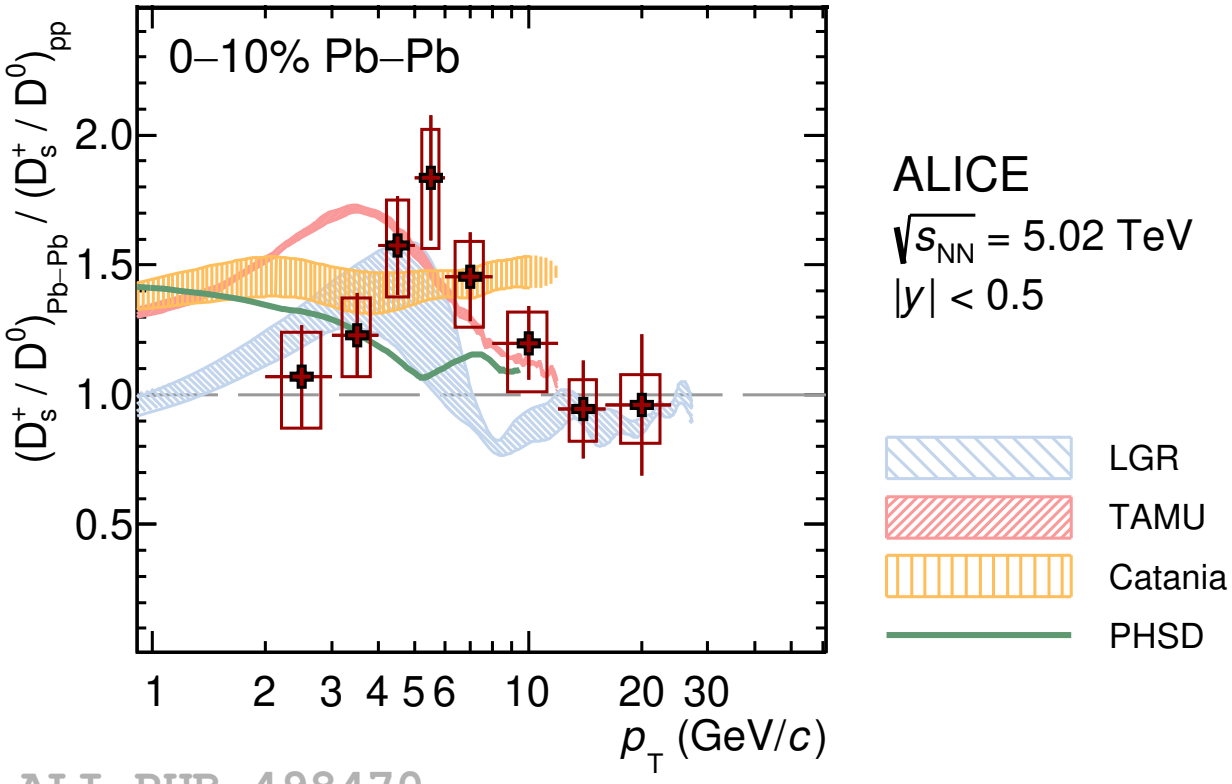
The D_s^+/D^0 ratio for p_T < 8 GeV/c in A–A is larger than the measured/predicted ratio in pp

- ALICE 0–10% Pb–Pb by **2.3σ**, STAR 10–60% Au–Au by **>5σ**
- Qualitatively captured by models including **recombination** and strangeness enhancement

[STAR] PRL 127 (2021) 092301



PLB 827 (2022) 136986



ALI-PUB-498470

[TAMU] PRL 124 (2020) 042301 [Tsinghua] arXiv:1805.10858 [LGR] EPJC 80 (2020) 671
[Catania] PRC 96 (2017) 044905 [Cao/Ko] PLB 807 (2020) 135561 [PHSD] PRC 93 (2016) 034906

The baryon sector in pp

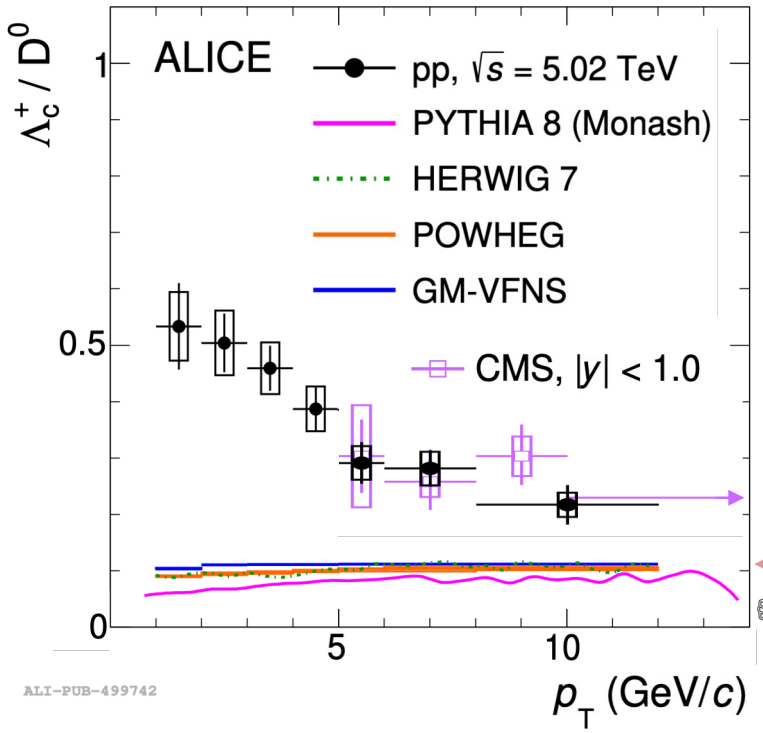
Strong p_T dependence observed in the heavy-flavour baryon-to-meson ratios

- Ratio **significantly higher** at low and intermediate p_T than **e^+e^- and ep** collision data
- pQCD(-inspired) and e^+e^--tuned **calculations underpredict data**

charm

[ALICE] PRL 127 (2021) 202301

[CMS] PLB 803 (2020) 135328

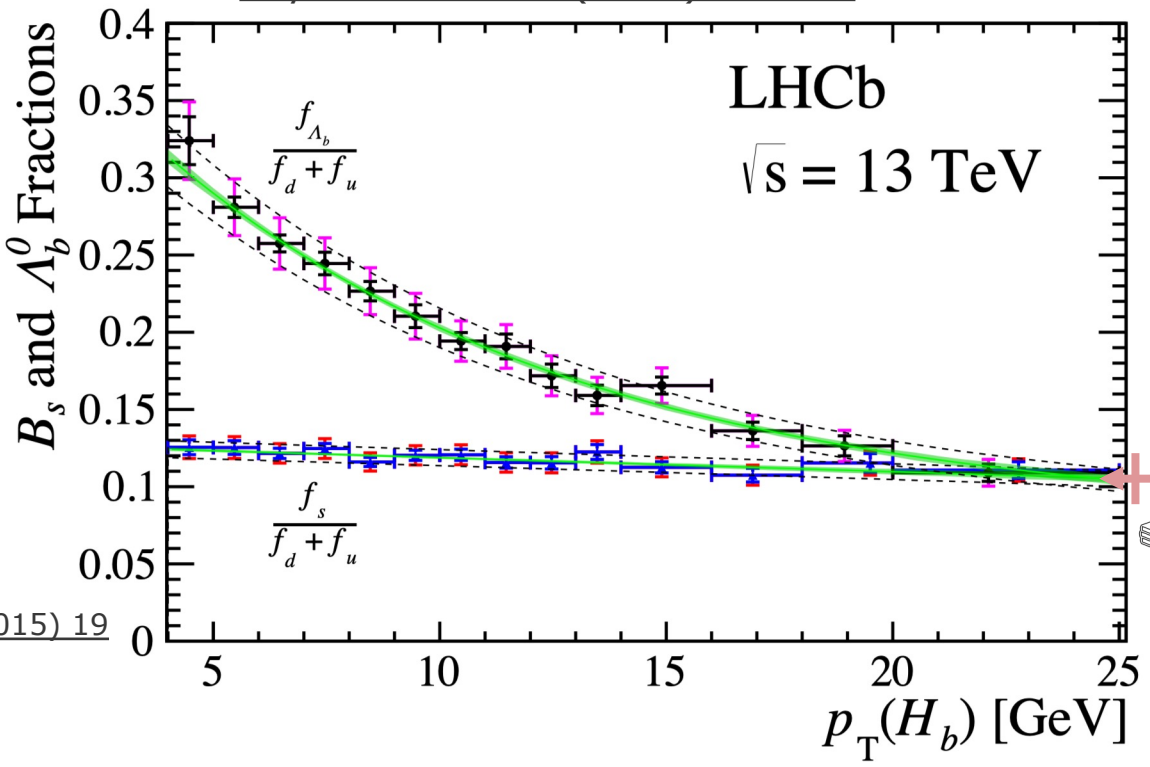


e^+e^-

EPJC 75 (2015) 19

beauty

Phys. Rev. D 100 (2019) 031102



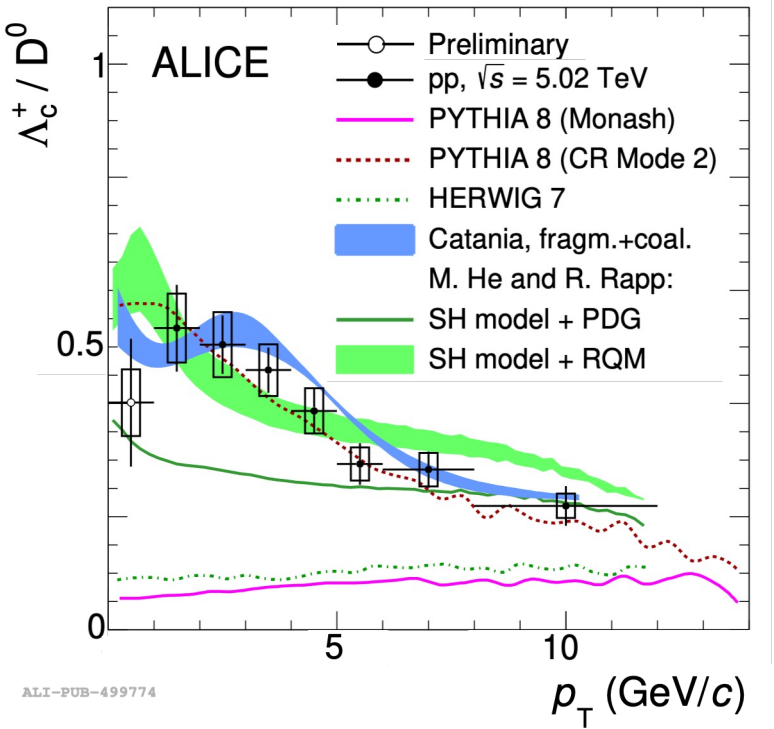
e^+e^-

EPJC 81 (2021) 226

Charm baryons in pp vs models

ALICE measured many charm baryons: Λ_c^+, $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, and Ω_c^0

PRL 127 (2021) 202301



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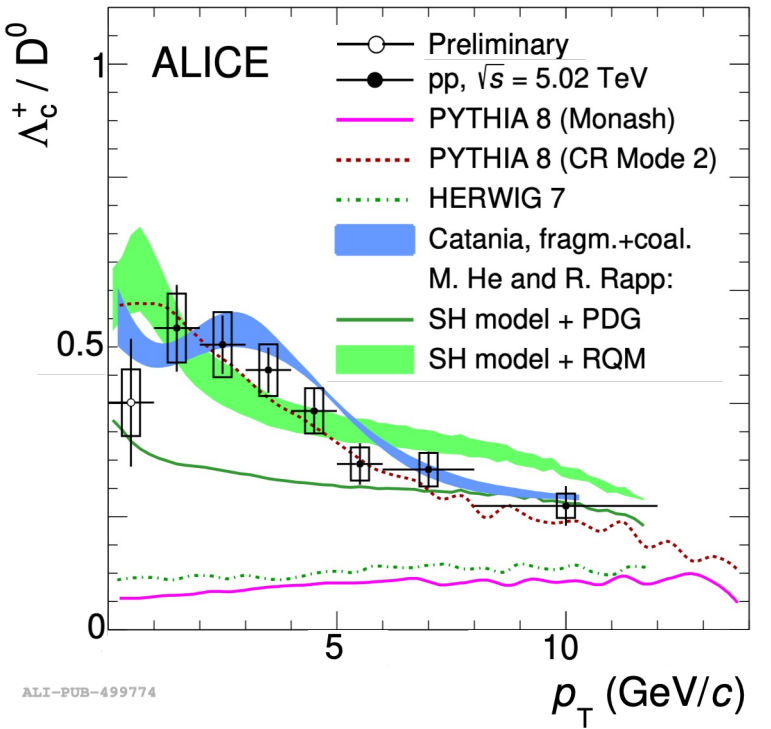
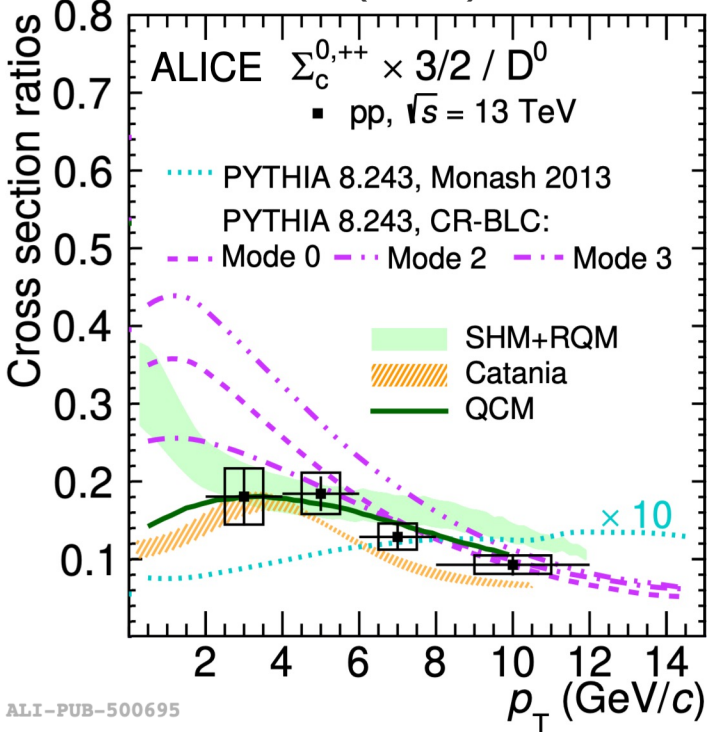
PRL 127 (2021) 202301



PRL 128 (2022) 012001



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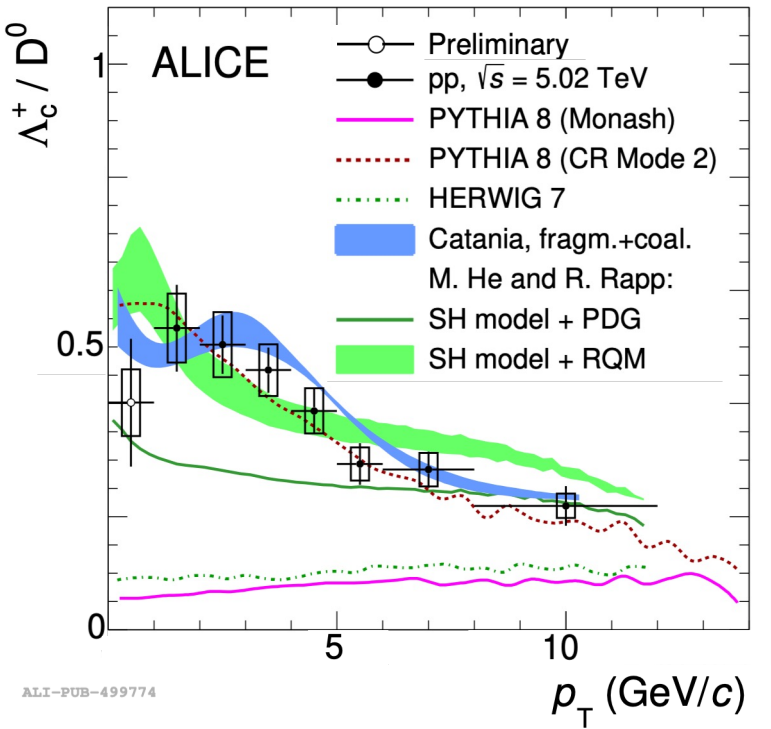
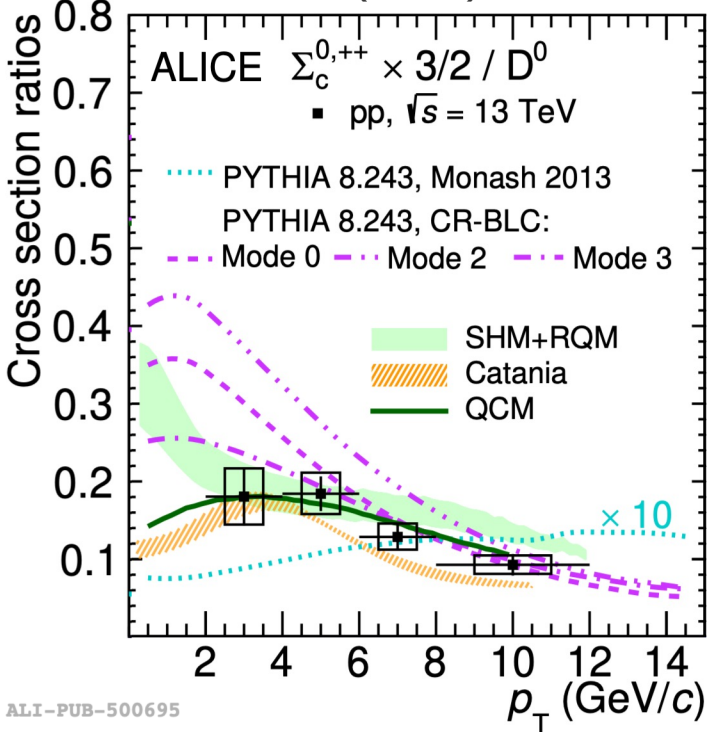
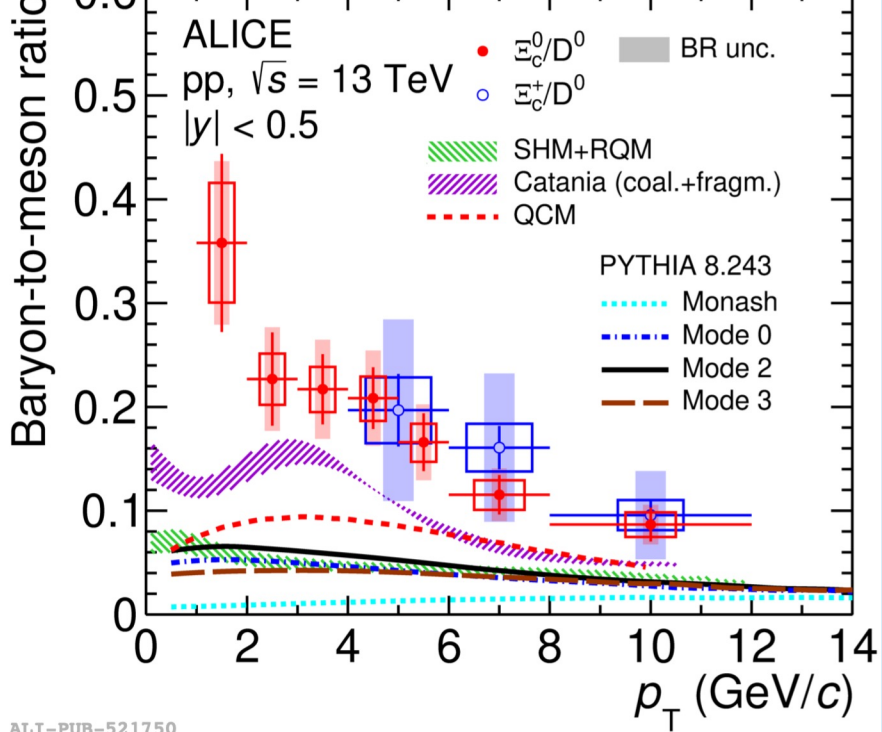
PRL 127 (2021) 202301



PRL 128 (2022) 012001



PRL 127 (2021) 272001



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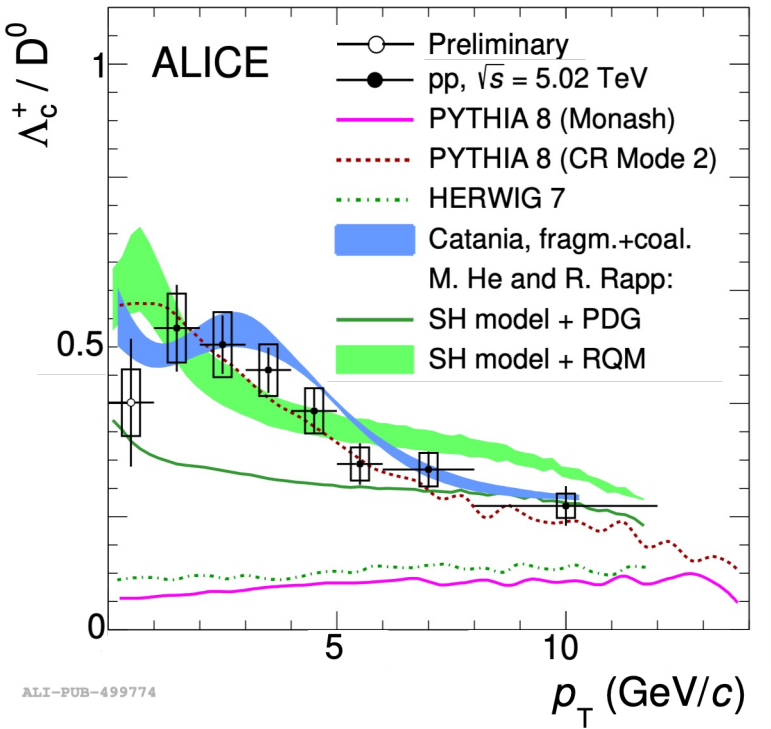
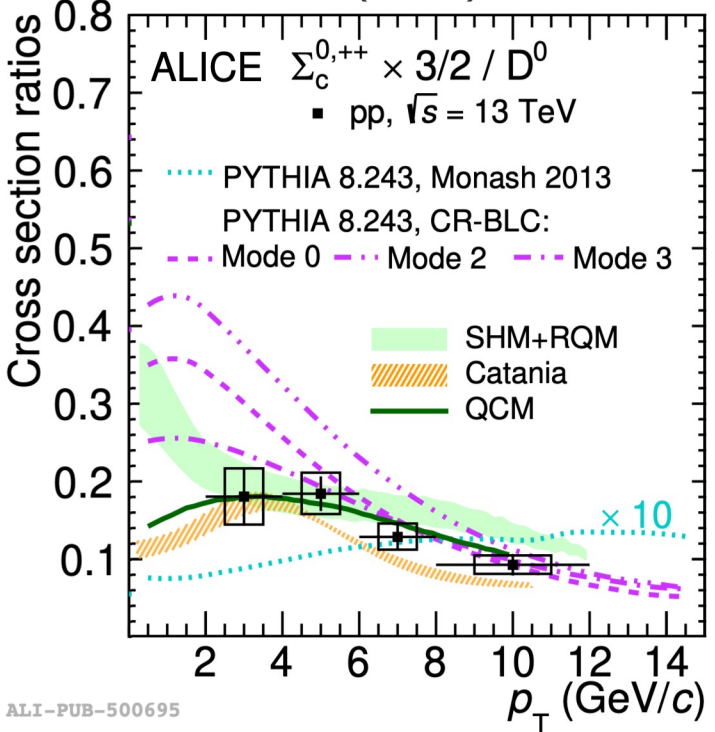
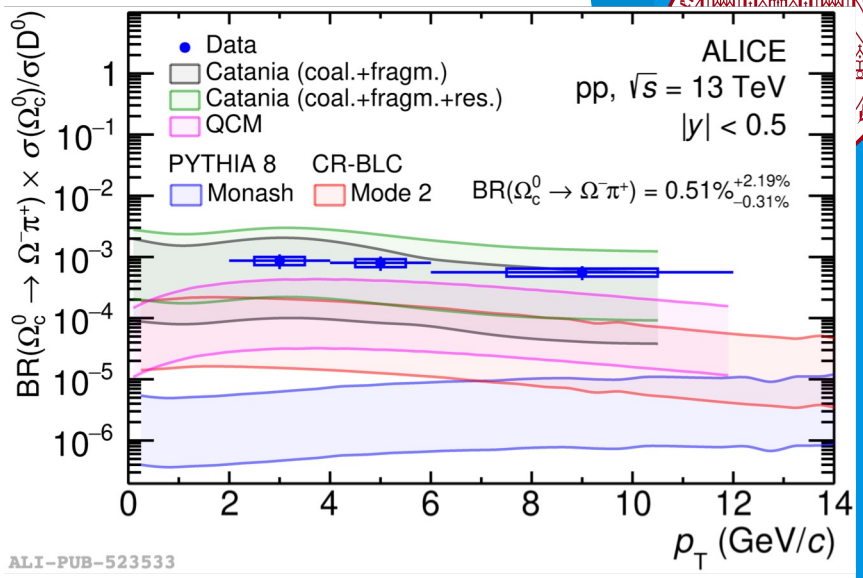
PRL 127 (2021) 202301



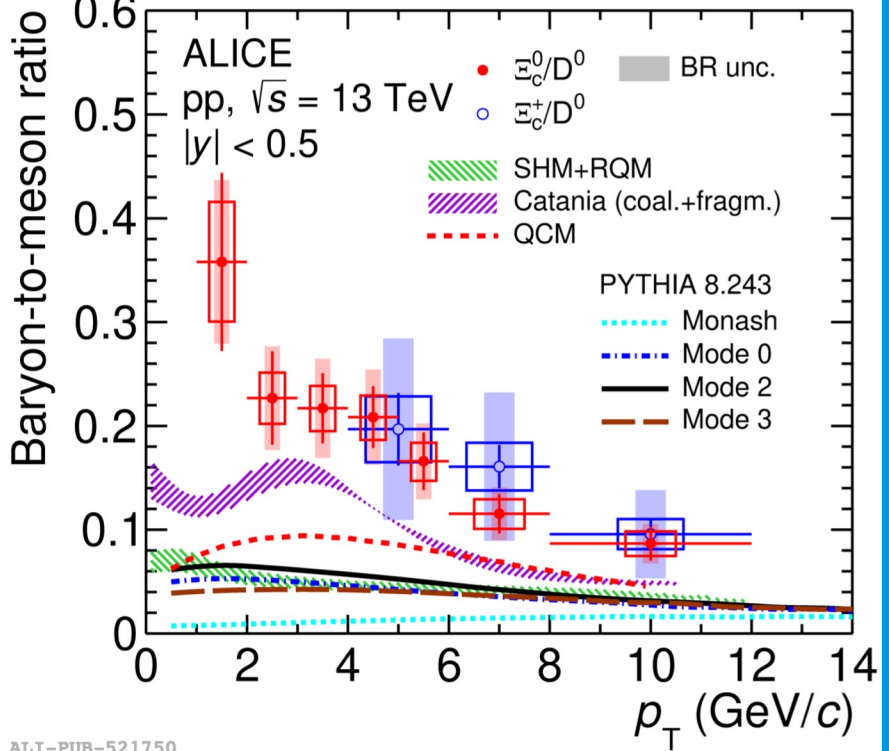
PRL 128 (2022) 012001



arXiv:2205.13993



PRL 127 (2021) 272001

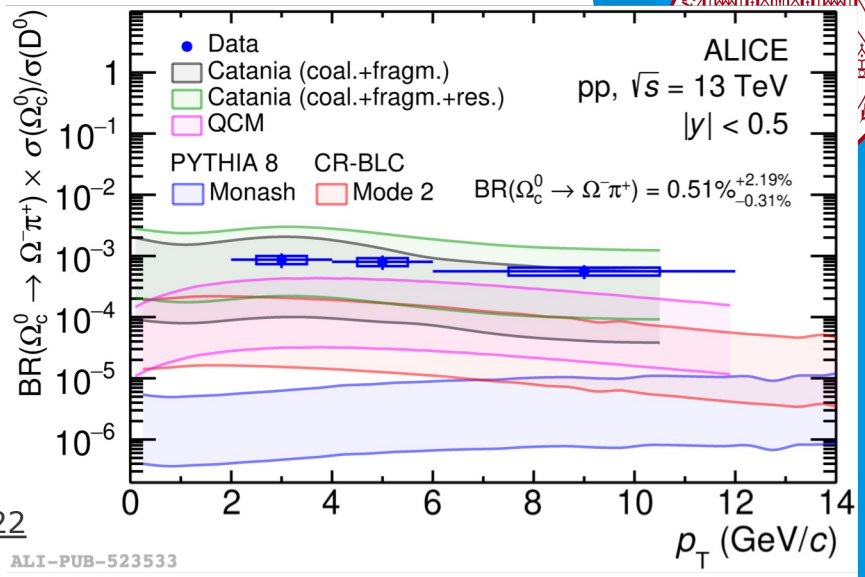


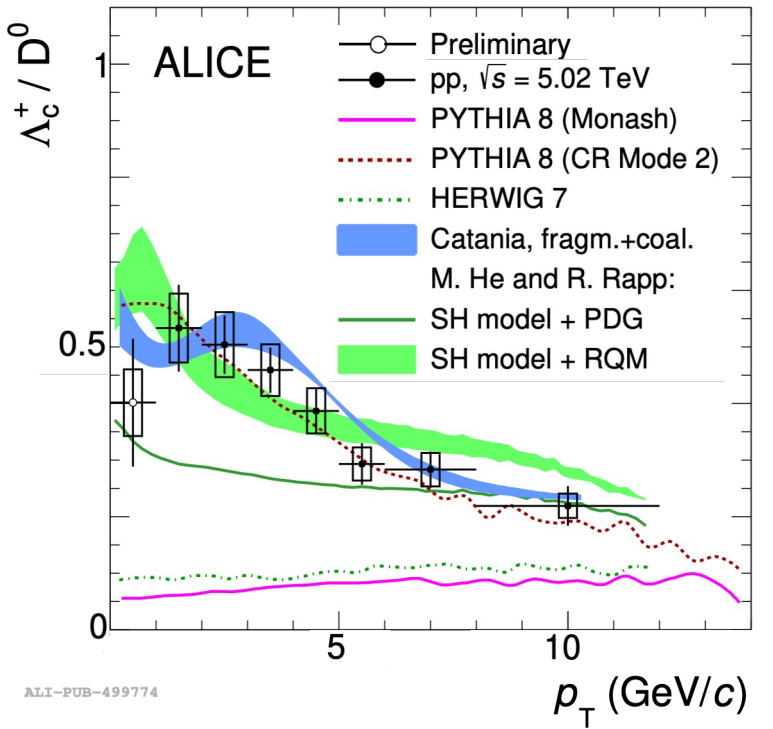
Charm baryons in pp vs models

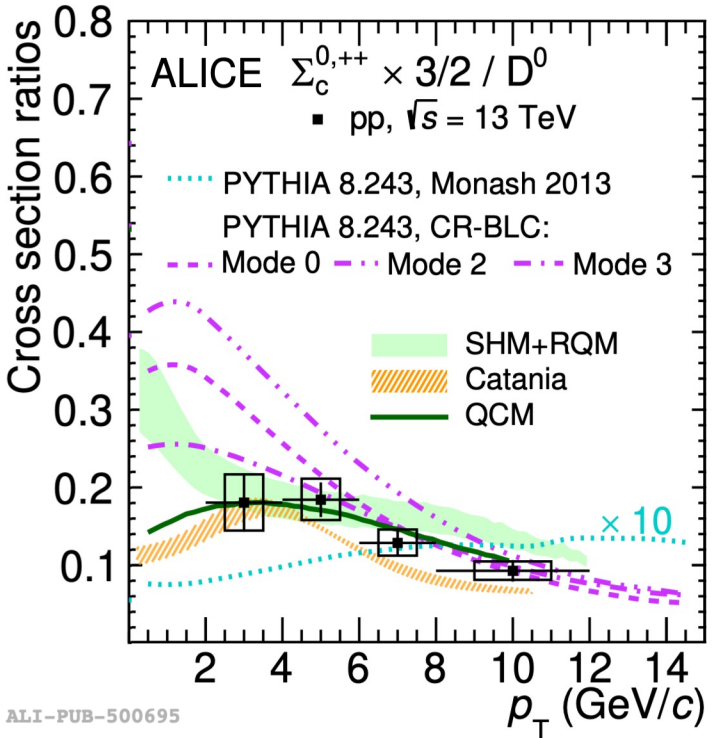
ALICE measured many charm baryons: Λ_c^+, $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, and Ω_c^0

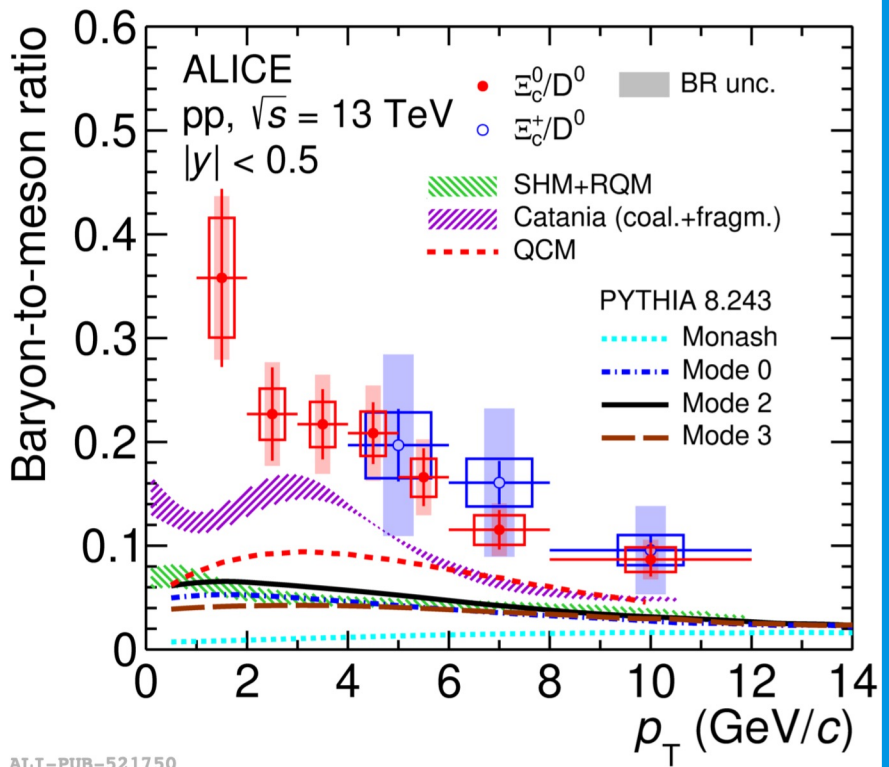
- Theoretical effort ongoing to describe them all

	Λ_c^+/D^0 (no s)	$\Sigma_c^{0,++}/D^0$ (no s)	$\Xi_c^{0,+}/D^0$ (s)	Ω_c^0/D^0 (ss)	
Monash	❌	❌	❌	❌	EPJC 74 (2014) 3024
CR-BLC	✅	✅	❌	❌	JHEP 08 (2015) 003
SHM+RQM	✅	✅	❌	–	PLB 795 (2019) 117
Catania	✅	✅	~	~	PLB 821 (2021) 136622
QCM	✅	✅	❌	❌	EPJC 78 (2018) 344

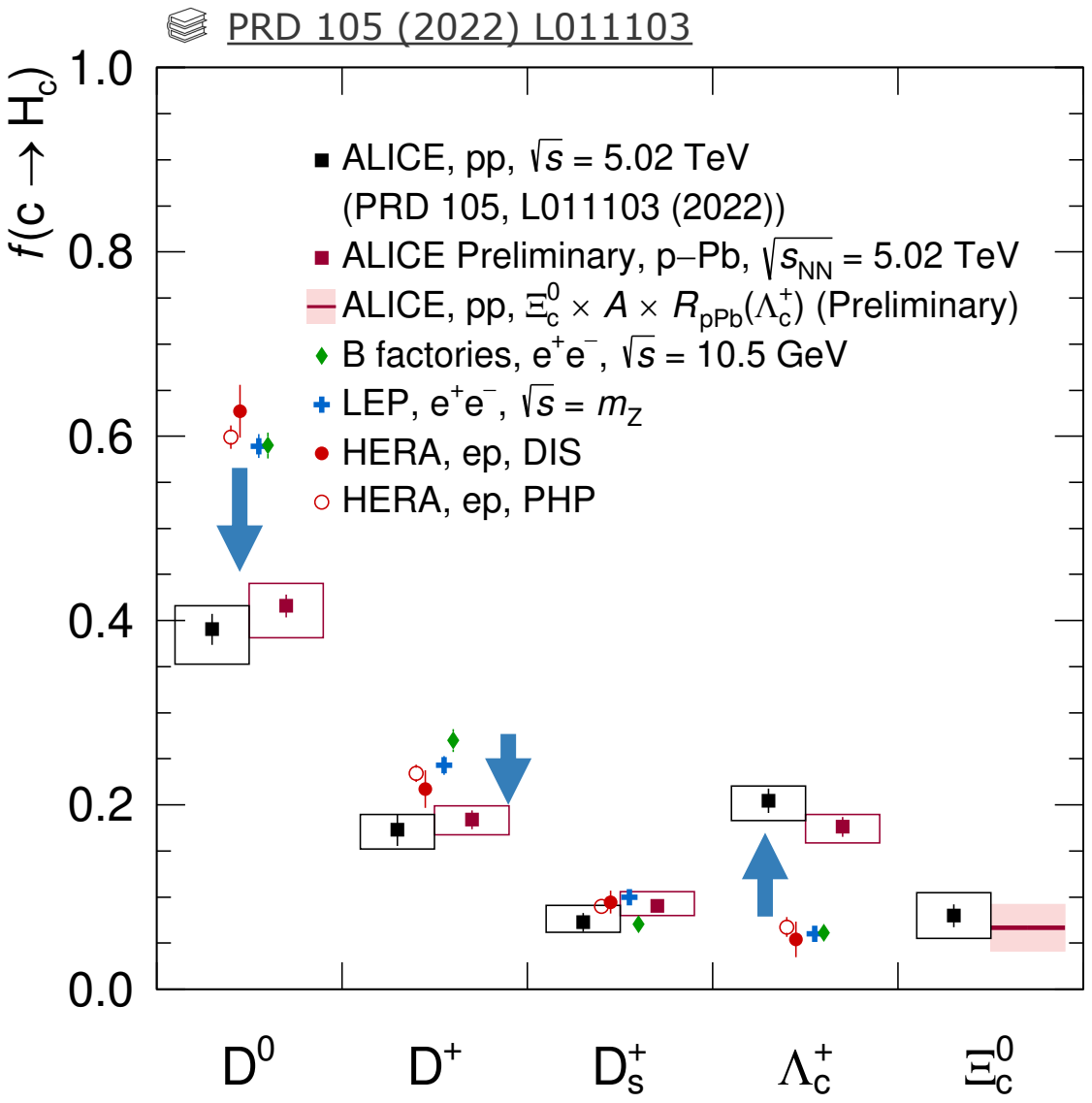








Charm fragmentation fractions in pp & p–Pb



ALI-PREL-503055

Fragmentation fractions $f(c \to H_c)$ estimated by ALICE and found to be not universal

→ significant baryon enhancement in hadronic collisions

	$f(c \to H_c)$ in pp
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$
Ξ_c^0, Ξ_c^+	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$
(D^{*+})	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$

Heavy-flavour production vs multiplicity in pp

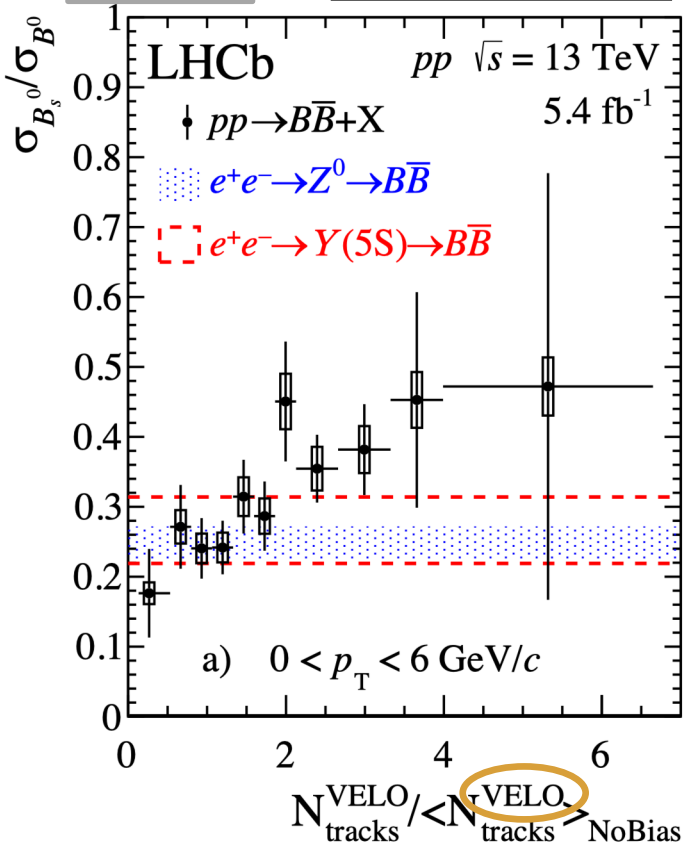
LHCb observes an **increase** in the $\mathbf{B_s^0/B^0}$ ratio **with multiplicity** below 6 GeV/*c* (**3.4σ**)

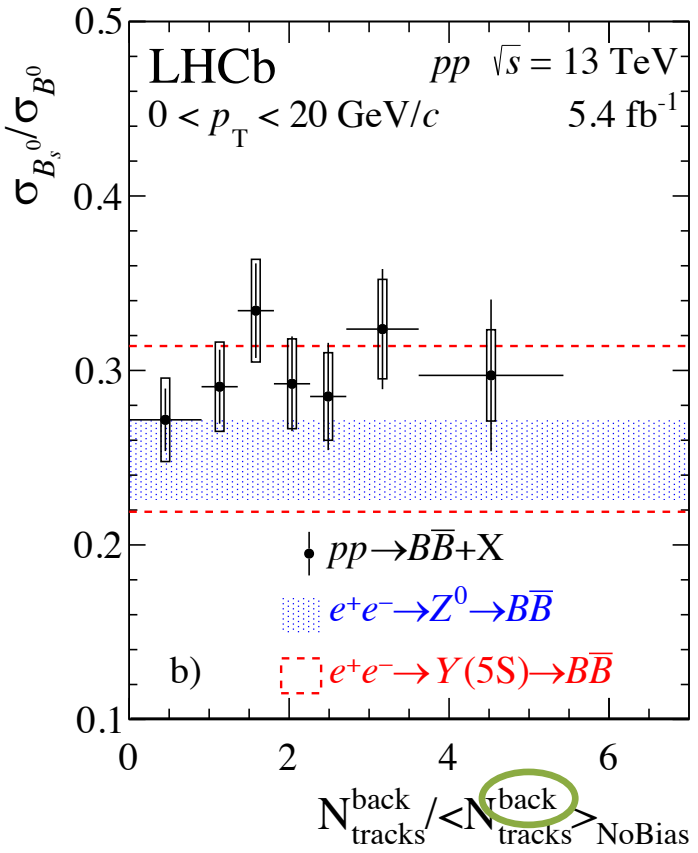
- NB: disappears when multiplicity is sampled in different phase-space region

ALICE finds a significant enhancement in the $\mathbf{\Lambda_c^+/D^0}$ ratio with multiplicity (**5.3σ**, midrapidity)

meson

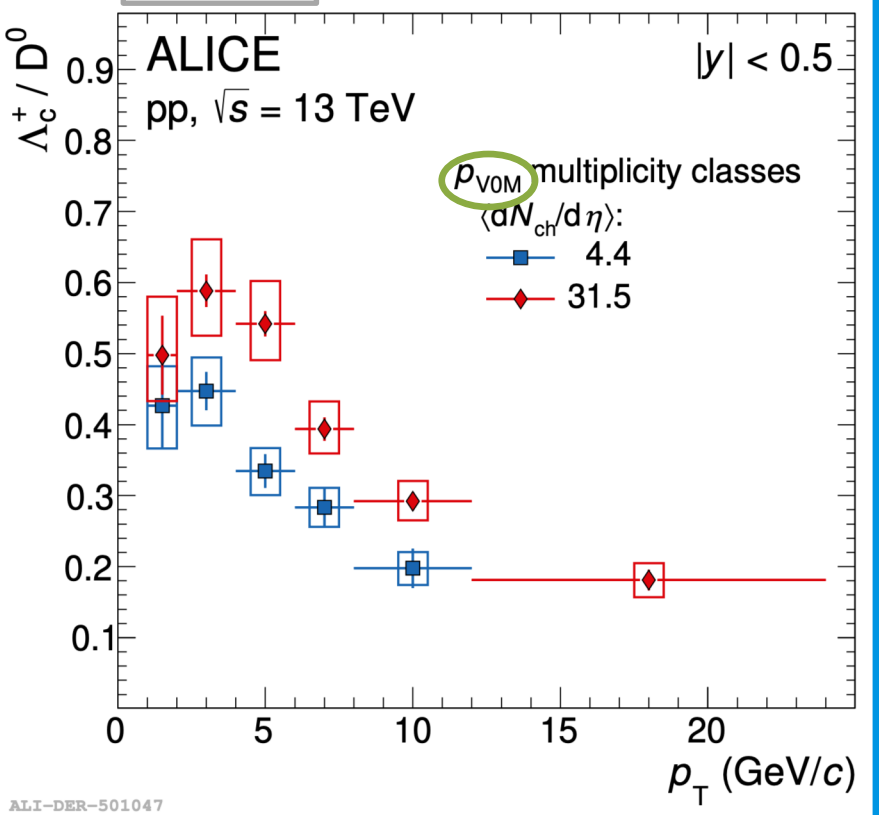
arXiv:2204.13042





baryon

PLB 829 (2022) 137065



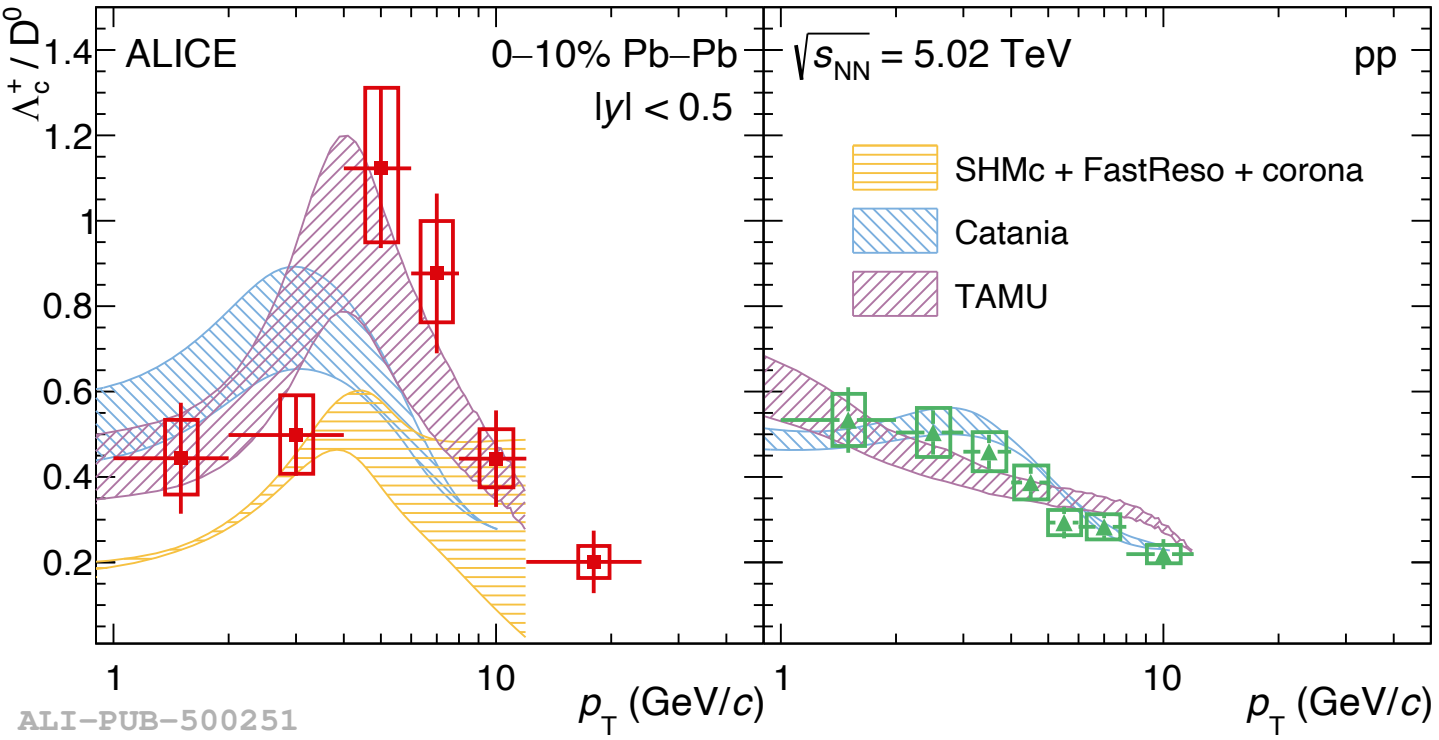
Charm baryons in A–A

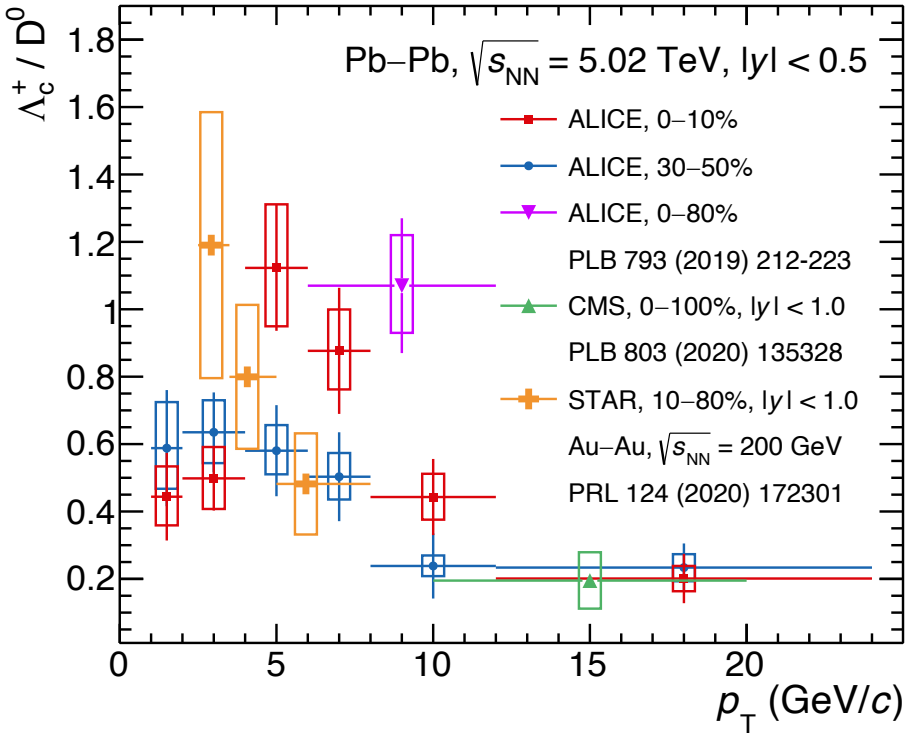
ALICE observes an **enhanced** Λ_c^+/D^0 in central Pb–Pb wrt pp collisions by **3.7σ**

- As for STAR, data described by the fragm+recomb TAMU and Catania models
- CMS ratio, in 10 < p_T < 20 GeV/c, compatible with pp → recomb. minimal effect

[ALICE] arXiv:2112.08156
[ALICE] PLB 793 (2019) 212
[CMS] PLB 803 (2020) 135328
[STAR] PRL 124 (2020) 172301

arXiv:2112.08156 PRL 127 (2021) 202301





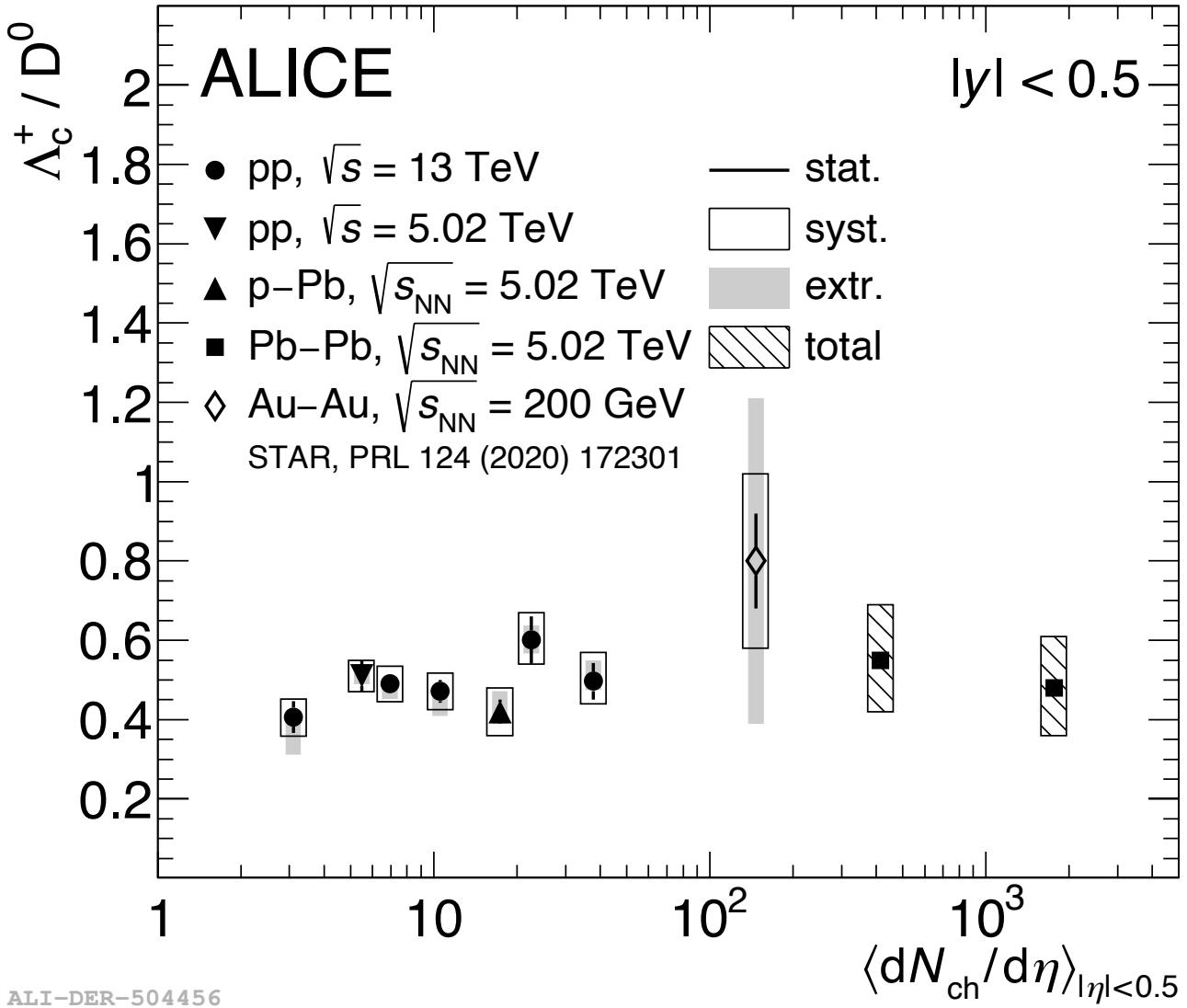
[TAMU] PRL 124 (2020) 042301
[Catania] PRC 96 (2017) 044905
[SHMc] JHEP 07 (2021) 035

p_T-integrated Λ_c^+/D^0 ratio

[ALICE] PLB 829 (2022) 137065
[ALICE] PRL 127 (2021) 202301
[ALICE] arXiv:2112.08156
[STAR] PRL 124 (2020) 172301

The Λ_c^+ and D^0 yields extrapolated to $p_T > 0$

- New and precise estimates by ALICE at low and high multiplicities
- Hint of a **flat trend with multiplicity**



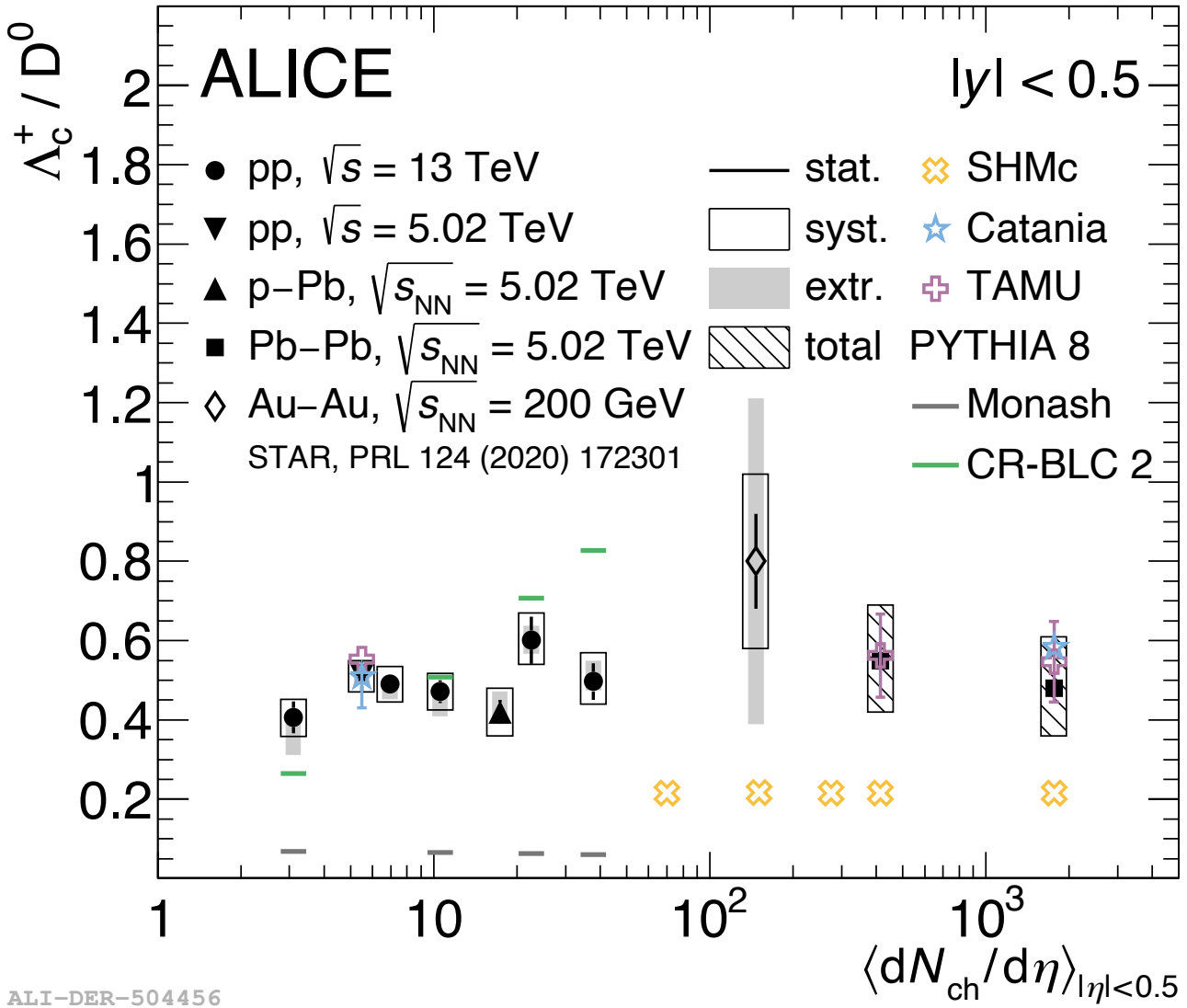
p_T-integrated Λ_c^+/D^0 ratio

The Λ_c^+ and D^0 yields extrapolated to $p_T > 0$

- New and precise estimates by ALICE at low and high multiplicities
- Hint of a flat trend with multiplicity

Reproduced by the **fragm+recomb** and SHM predictions (in case new, not yet observed, charm-baryon states are assumed)

- **Tension with CR-BLC** PYTHIA predictions that show an enhancement with multiplicity



[TAMU] PRL 124 (2020) 042301
[Catania] PRC 96 (2017) 044905
[CR-BLC] JHEP 08 (2015) 003
[SHMc] JHEP 07 (2021) 035

p_T-integrated Λ_c^+/D^0 ratio

The Λ_c^+ and D^0 yields extrapolated to $p_T > 0$

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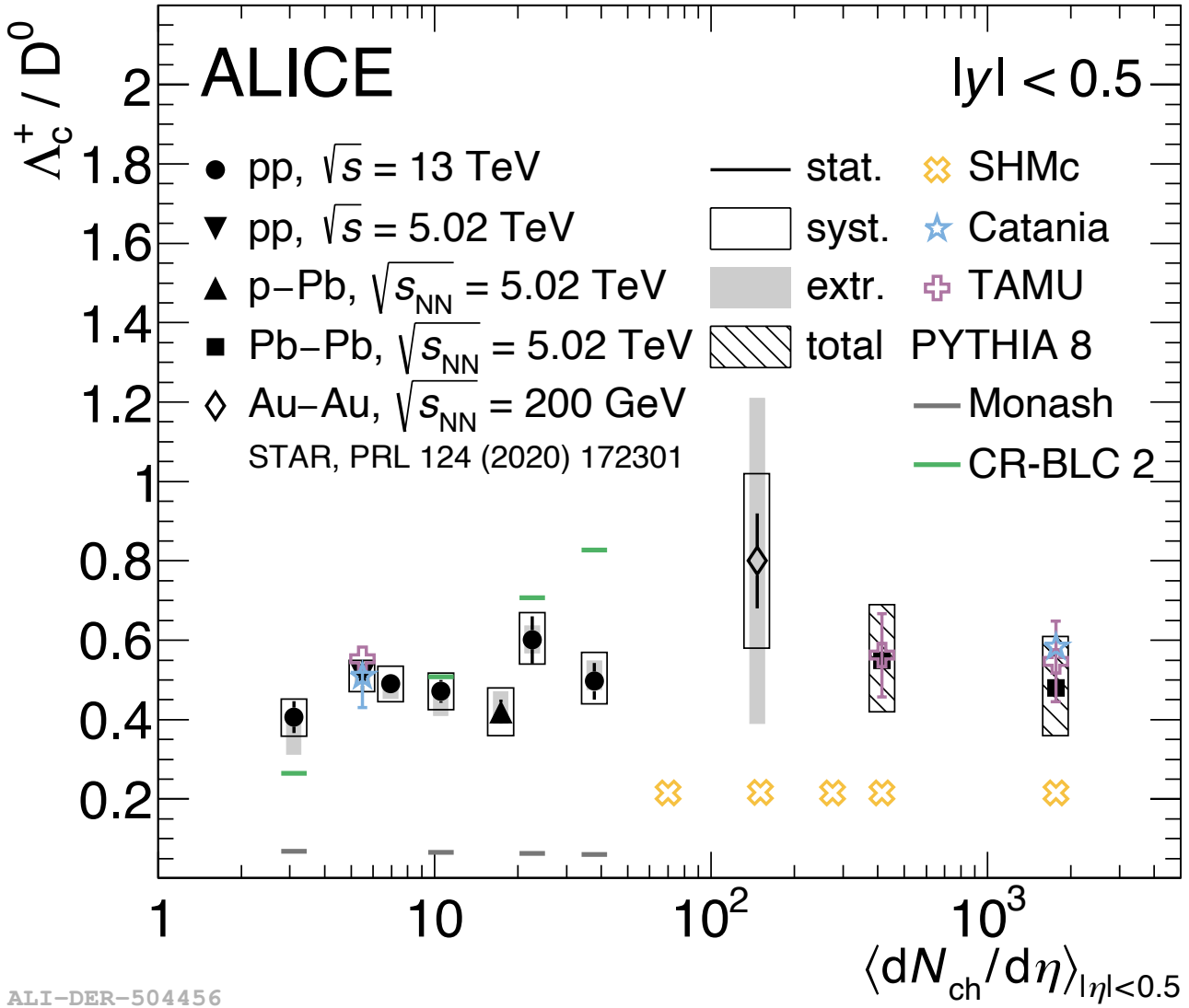
Reproduced by the fragm+recomb and SHM predictions (in case new, not yet observed, charm-baryon states are assumed)

- Tension with CR-BLC PYTHIA predictions that show an enhancement with multiplicity

Similarities with the light-flavour sector

- Is the p_T differential Λ_c^+/D^0 enhancement just a **consequence of radial flow and recomb?**



Outlook: beauty-strange and -charm mesons

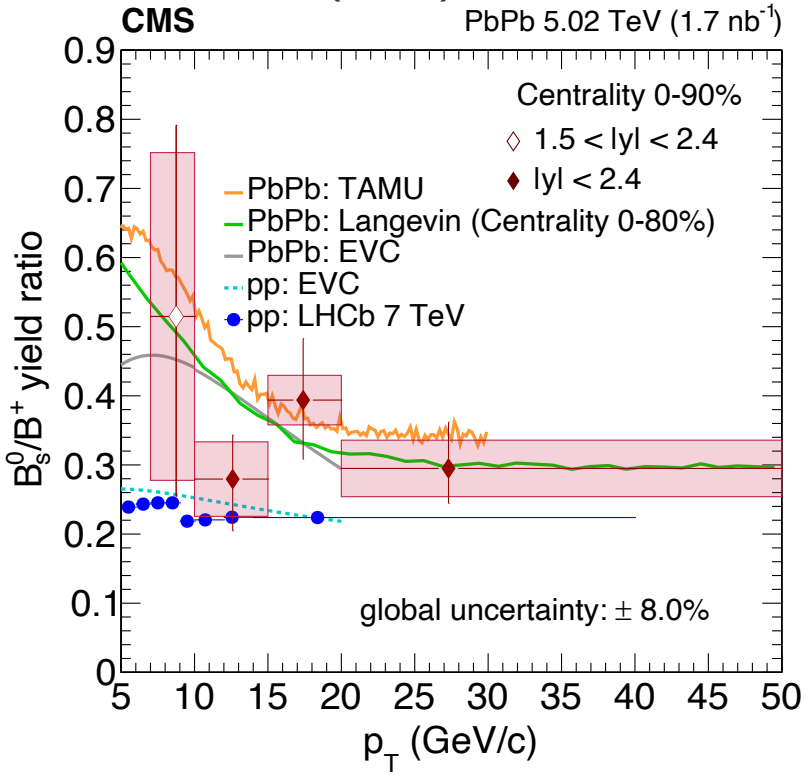
B_s^0, B_c^+, and $X(3872)$ production also accessed in pp (LHCb, ATLAS, CMS) and Pb–Pb (CMS)

- Current uncertainties still relatively large → **outlook for LHC Run 3 and 4**

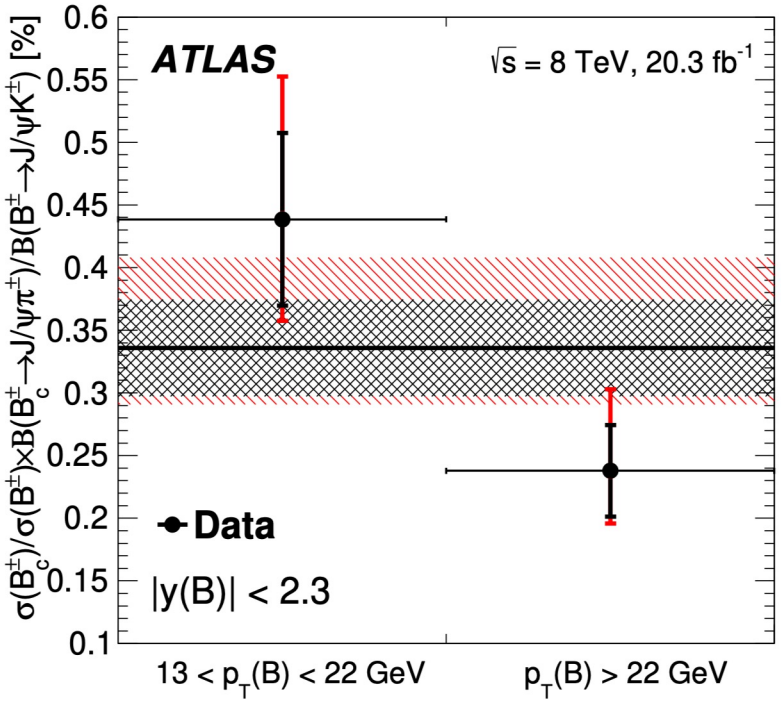
In addition, future **double-** or **triple-charm baryon** measurements in A–A of large interests

- So far only Ξ_{cc}^{++} accessed by LHCb in various decay channels in pp JHEP 05 (2022) 038

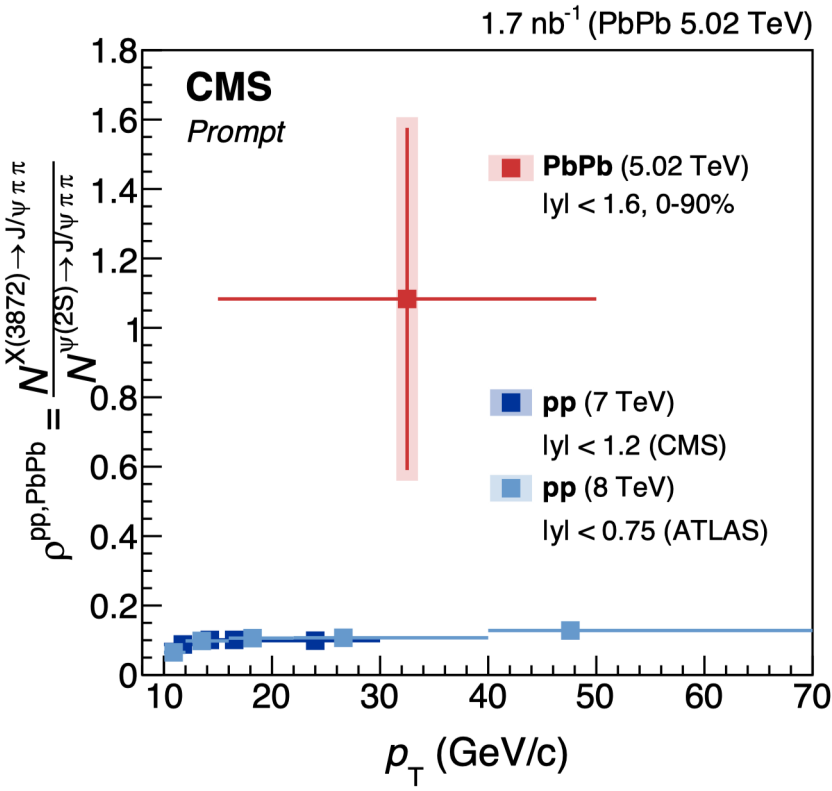
PLB 829 (2022) 137062



PRD 104 (2021) 012010



PRL 128 (2022) 032001



Concluding words

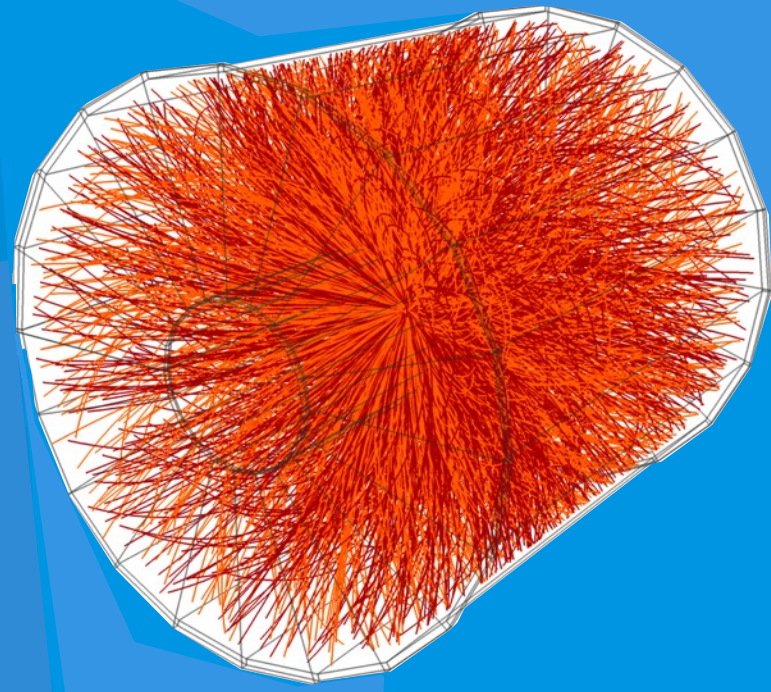
HQ hadronisation is a very active field (again since ~5 years)

Many recent **experimental** measurements shown today

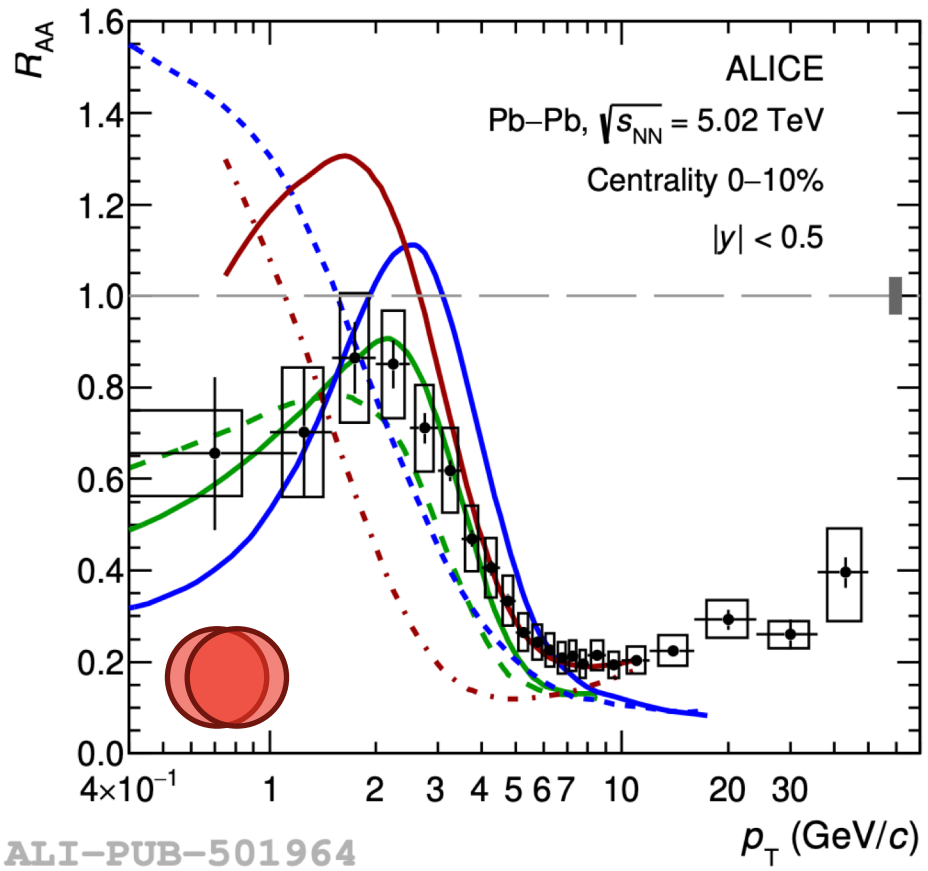
with a personal bias to open heavy flavour production, sorry if I missed your favourite measurement

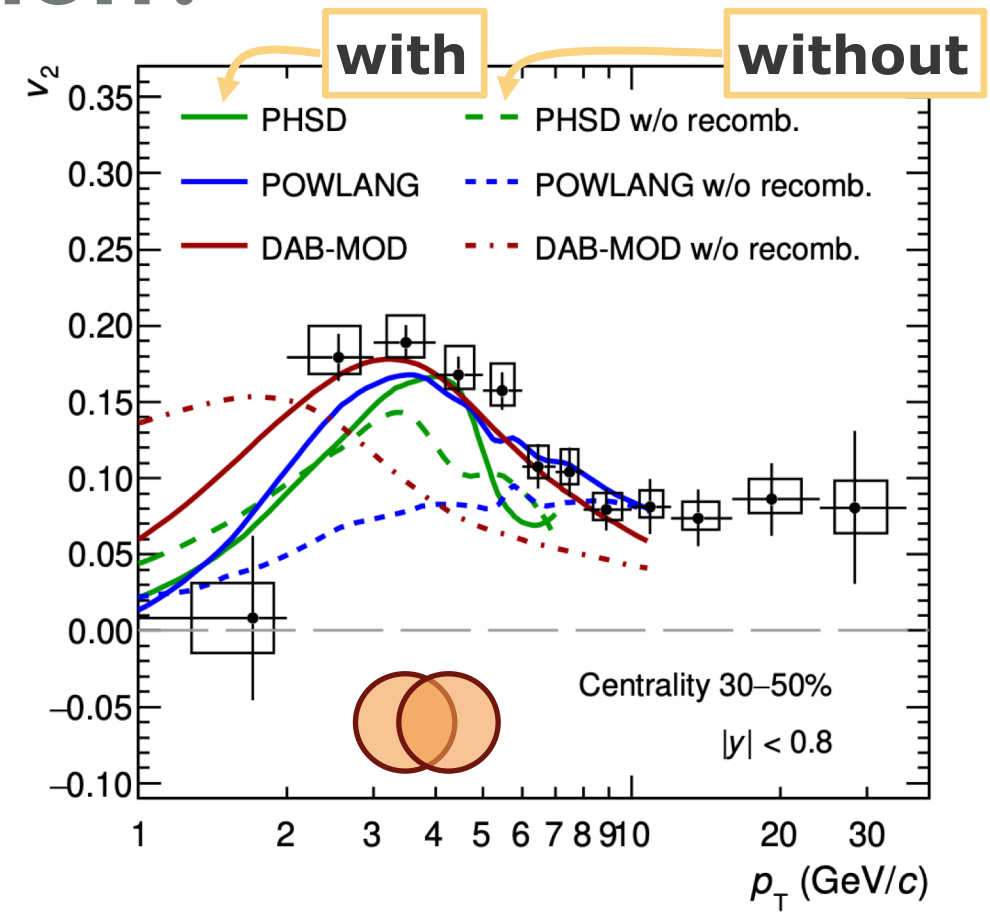
Coming up: Salvatore Plumari, “Heavy quark hadronization (**theory**)”

Additional slides



What does recombination?





Hadronisation via recombination important to describe low and intermediate p_T

→ D meson "picks up" the v_2 of the light quark

PHSD: PRC 93, 034906 (2016)
POWLANG: EPJC 75 (2015) 3, 121
DAB-MOD: PRC 96, 064903 (2017)

R_{AA}: JHEP 01 (2022) 174
v_2: PLB 813 (2021) 136054

Statistical hadronisation of charm

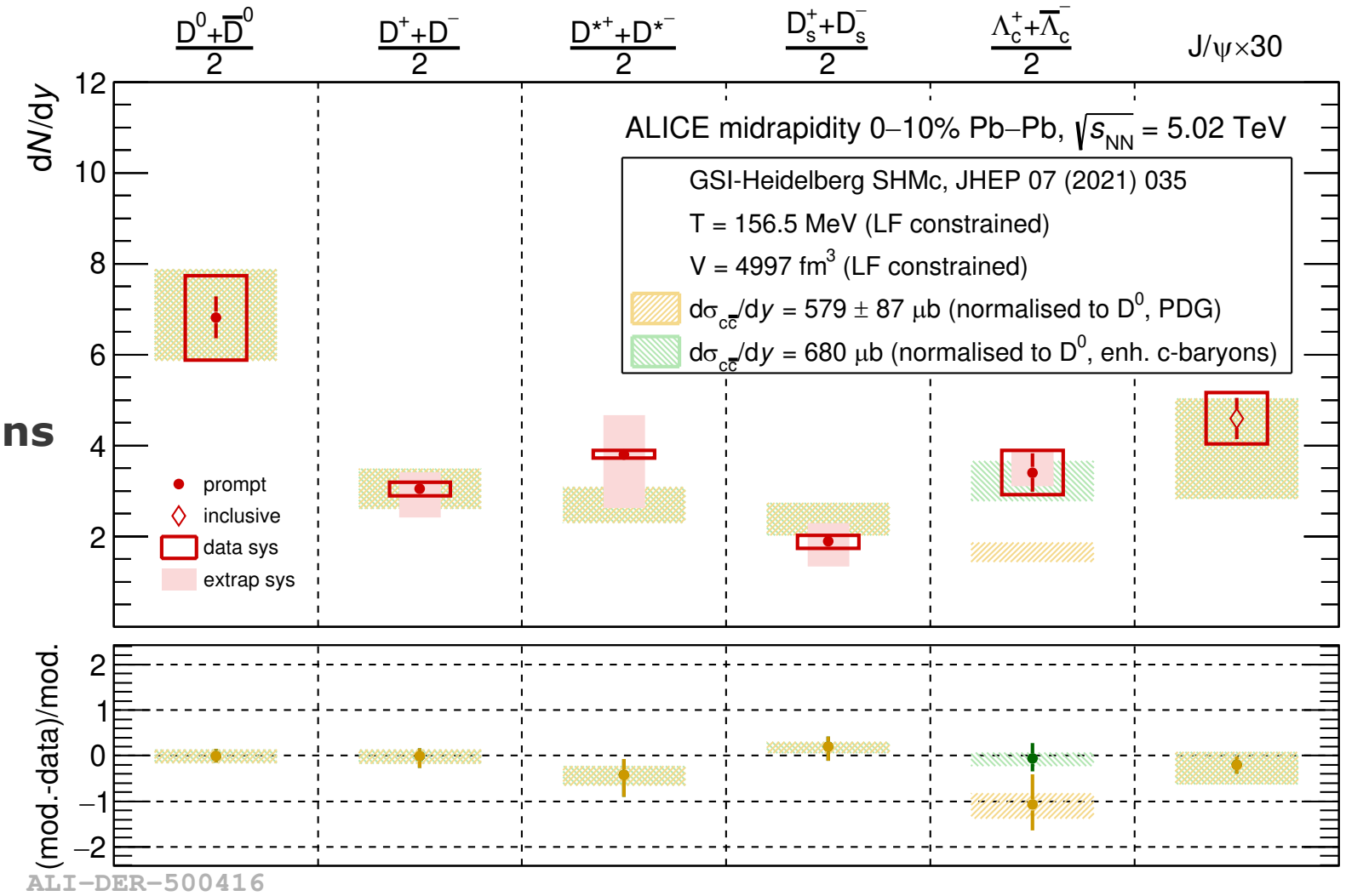
SHMc (charm quarks fully thermalised in the QGP)

→ Distributed into hadrons at phase boundary according to **thermal weights**

Measured yields of **open-charm mesons compatible** with SHMc

Measured yield of Λ_c^+ **underestimated**

→ Described in case of an enhanced charm-baryon resonance spectrum



SHMc: JHEP 07 (2021) 035

Charm-quark transport models: ingredients

	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
TAMU	✅	❌	✅	✅	✅
LIDO	✅	✅	✅	✅	✅
PHSD	✅	❌	✅	✅	✅
DAB-MOD	✅	✅	✅	✅	❌
Catania	✅	❌	✅	✅	✅
MC@sHQ+EPOS	✅	✅	✅	✅	✅
LBT	✅	✅	✅	✅	✅
POWLANG+HTL	✅	❌	✅	✅	✅
LGR	✅	✅	✅	✅	✅

But more importantly: different **implementations** and **input parameters**.