UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

STRONG 2020

ALICE

New insights into heavy-quark hadronisation with charm and beauty hadrons in hadronic collisions with ALICE

ANNALENA KALTEYER, GSI DARMSTADT, UNIVERSITÄT HEIDELBERG

ON BEHALF OF THE ALICE COLLABORATION

28.03.2023

11th International Conference on hard and electromagnetic probes of high-energy nuclear collisions

Heavy-flavour production

$$\frac{d\sigma^{\mathrm{pp}\to H_q}}{dp_{\mathrm{T}}} = f_i(x_1,\mu_f^2) f_j(x_2,\mu_f^2) \times \frac{d\sigma^{ij\to q}}{dp_{\mathrm{T}}}(x_1,x_2,\mu_f^2) \times D_{q\to H_q}\left(z_q=\frac{p_{H_q}}{p_q},\mu_f^2\right)$$

Parton distribution functions (PDFs)

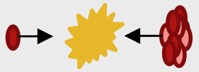
Hard scattering cross section (pQCD)

Fragmentation function (hadronisation)

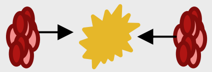
Test pQCD-based calculations and study hadronisation with heavy-flavour (HF) hadron production measurements

- Cross section of charm- and beauty-hadron production is typically calculated in a factorization approach
  - Fragmentation functions are constrained from $\mathrm{e^+e^-}$ and $\mathrm{e^-p}$ measurements
  - Typical assumption: fragmentation functions apply universally across $\mathrm{e^+e^-}$, $\mathrm{e^-p}$, pp, p–Pb and Pb–Pb collision systems
- **Yield ratios of charm/beauty hadrons are sensitive to heavy-quark hadronisation**

- **Reference for Pb–Pb**
- **Test of pQCD**
- **Study hadronisation**



- **Study cold nuclear matter (CNM) effects**
  - Modification of PDFs in nuclei



- **Investigate fundamental properties of strongly interacting hot matter (QGP)**
  - Energy loss
  - Collectivity
  - Hadronisation

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Heavy-flavour production

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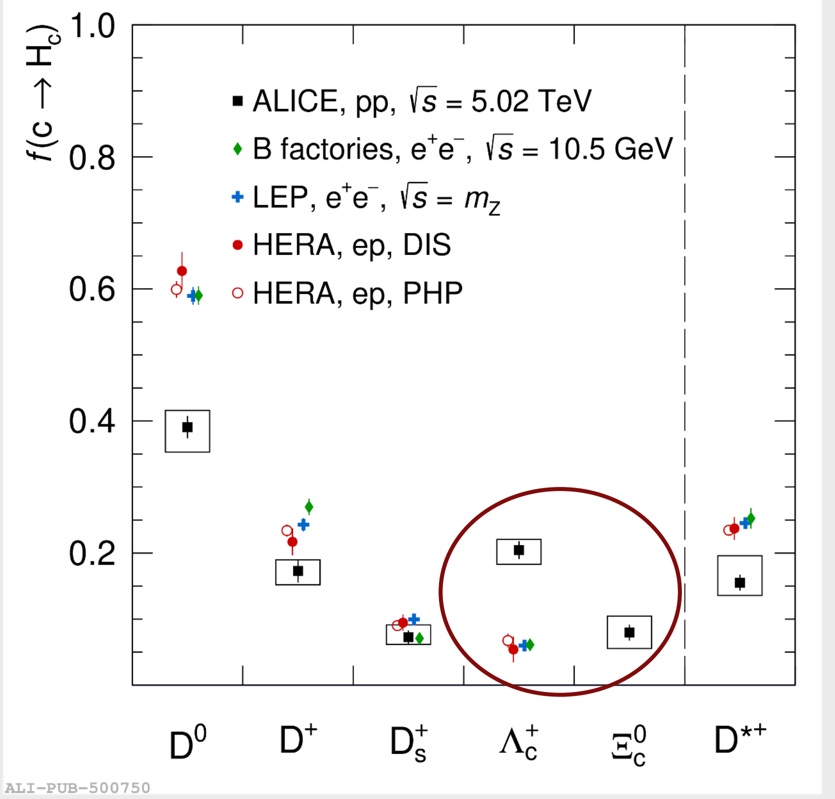


PRD 105, L011103 (2022)

Significant baryon enhancement in pp with respect to e^+e^- and e^-p collisions

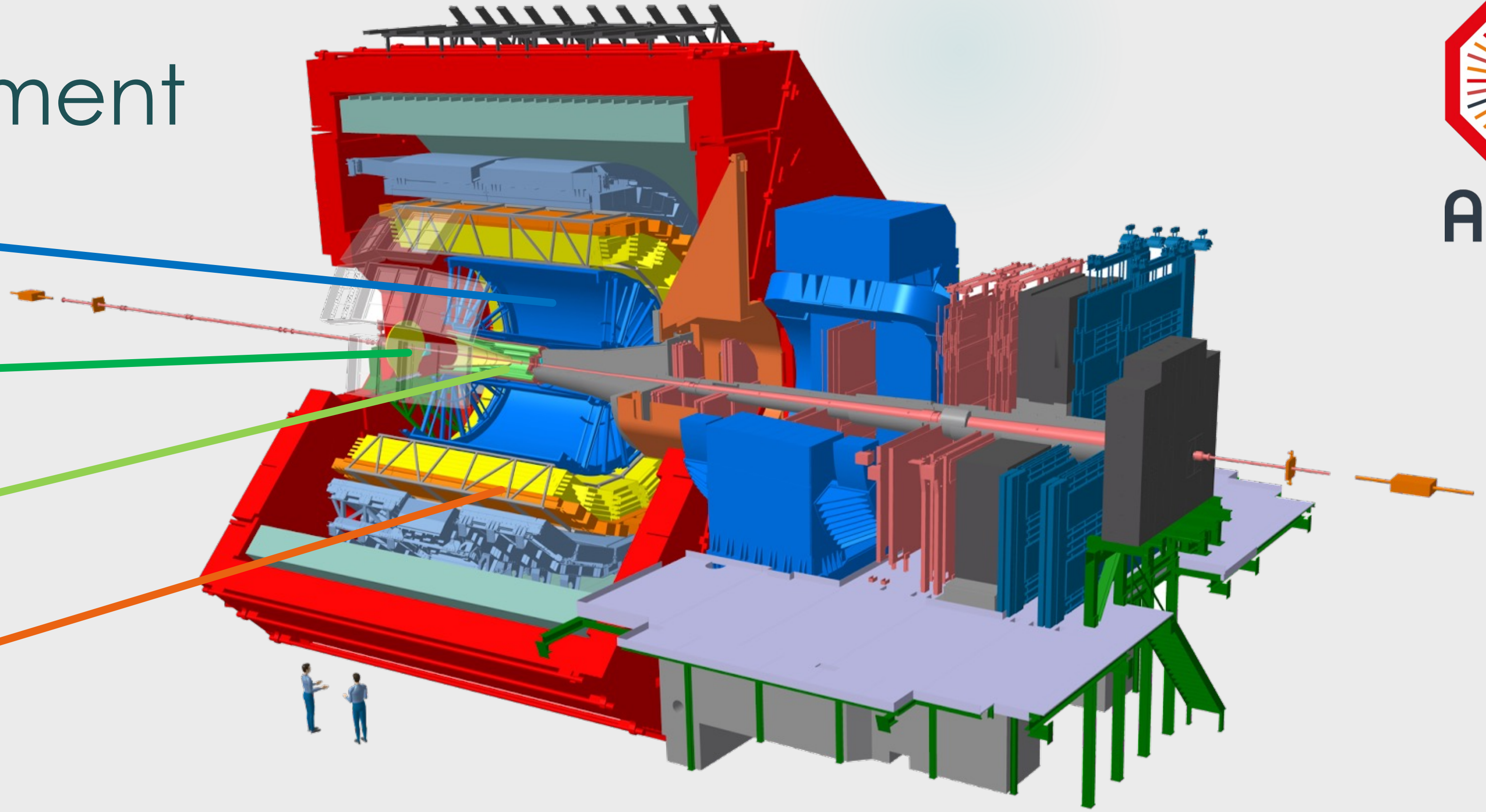
The ALICE experiment

Time Projection Chamber (TPC):
Tracking, PID via dE/dx

V0 detector
Triggering

Inner Tracking System (ITS):
Tracking and vertexing

Time-of-Flight (TOF) detector:
PID via time of flight



$D^0(\bar{u}c) \rightarrow K^-\pi^+$

$D^+(\bar{d}c) \rightarrow K^-\pi^+\pi^+$

$D^{*+}(\bar{d}c) \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$

$D_s^+(\bar{s}c) \rightarrow \Phi\pi^+ \rightarrow K^-\pi^+\pi^+$

$D_{s1}^+(\bar{s}c) \rightarrow D^{*+}K_s^0 \rightarrow D^0\pi^+\pi^-\pi^+$

$D_{s2}^{*+}(\bar{s}c) \rightarrow D^+K_s^0 \rightarrow D^0\pi^+\pi^-\pi^+$

Λ_c^+ (udc) $\rightarrow pK^-\pi^+, pK_s^0$

$\Sigma_c^{0,++}$ (ddc, uuc) $\rightarrow \Lambda_c^+\pi^{-,+}$

Ξ_c^0 (dsc) $\rightarrow \Xi^-e^+\nu_e, \Xi^-\pi^+$

Ξ_c^+ (usc) $\rightarrow \Xi^-\pi^+\pi^+$

Ω_c^0 (ssc) $\rightarrow \Omega^-\pi^+$

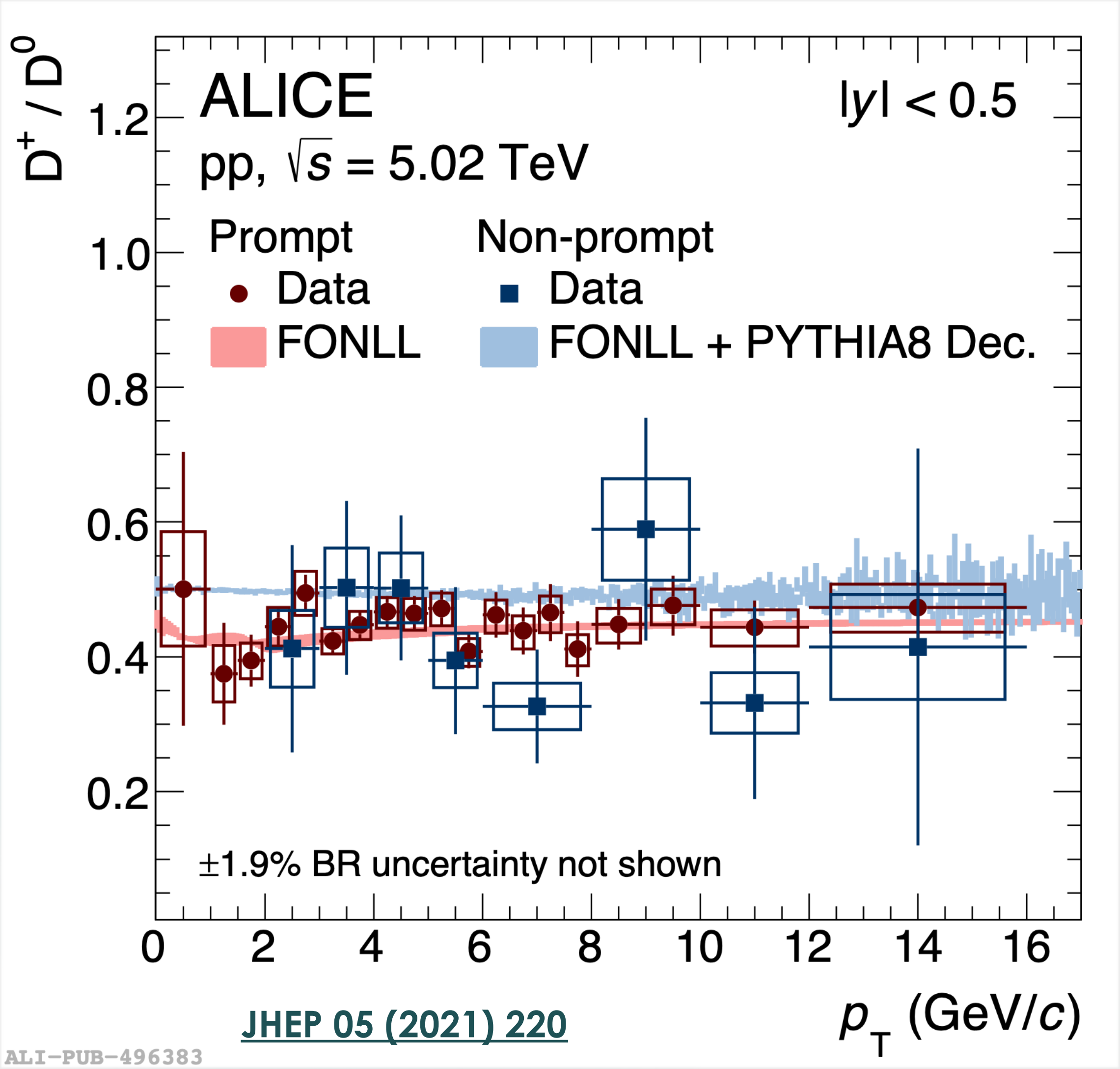
pp: $\sqrt{s} = 5.02$ TeV $\rightarrow \mathcal{L}_{int} \sim 19\ nb^{-1}$
pp: $\sqrt{s} = 13$ TeV $\rightarrow \mathcal{L}_{int} \sim 32\ nb^{-1}$
p–Pb: $\sqrt{s_{NN}} = 5.02$ TeV $\rightarrow \mathcal{L}_{int} \sim 287\ \mu b^{-1}$

Talk: Stefano Politano 29.03. 10:00

Charm and beauty meson production

c, b

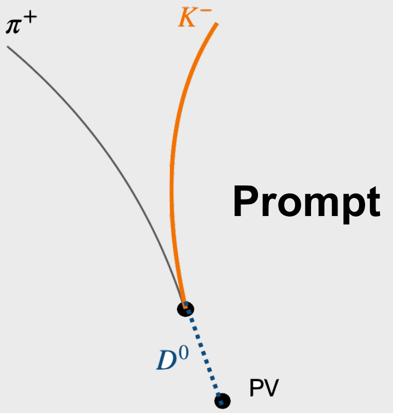
D^+, D^0

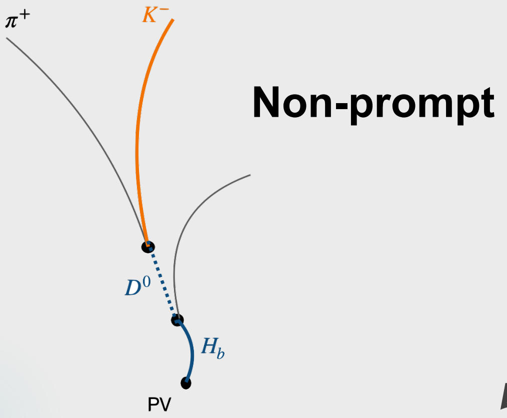


Meson-to-meson yield ratio:

- D^+/D^0 yield ratios are independent of meson p_T for prompt and non-prompt measurements
- Charm and beauty meson-to-meson yield ratios are well described by model calculations, based on the factorization approach assuming fragmentation functions from e^+e^- collisions

FONLL: JHEP 05 (1998) 007 $f_c \rightarrow D$: Eur. Phys. J. C75 (2015) 19





Strange charm meson production

b

D^+, D^0, D_s^+

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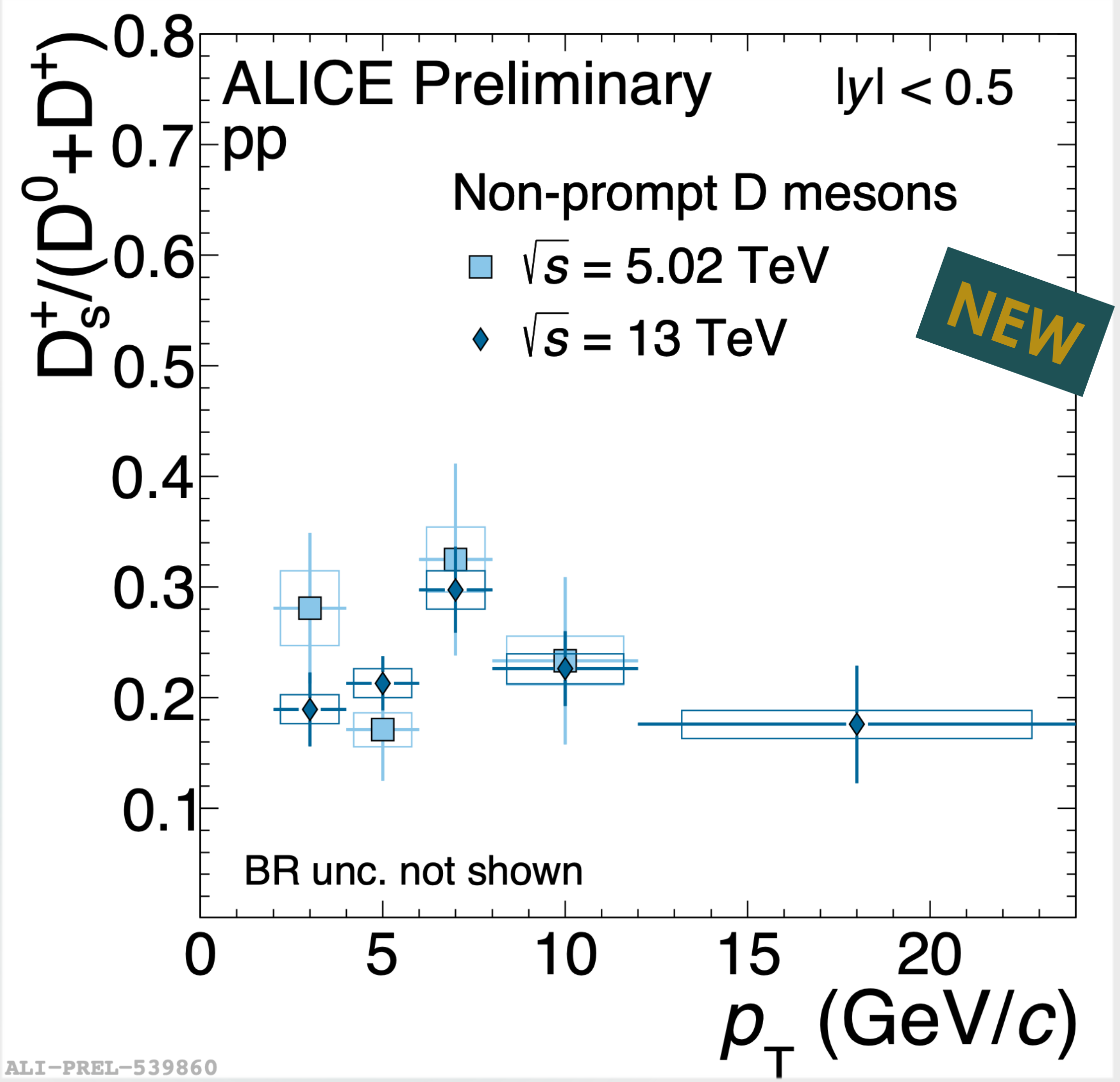

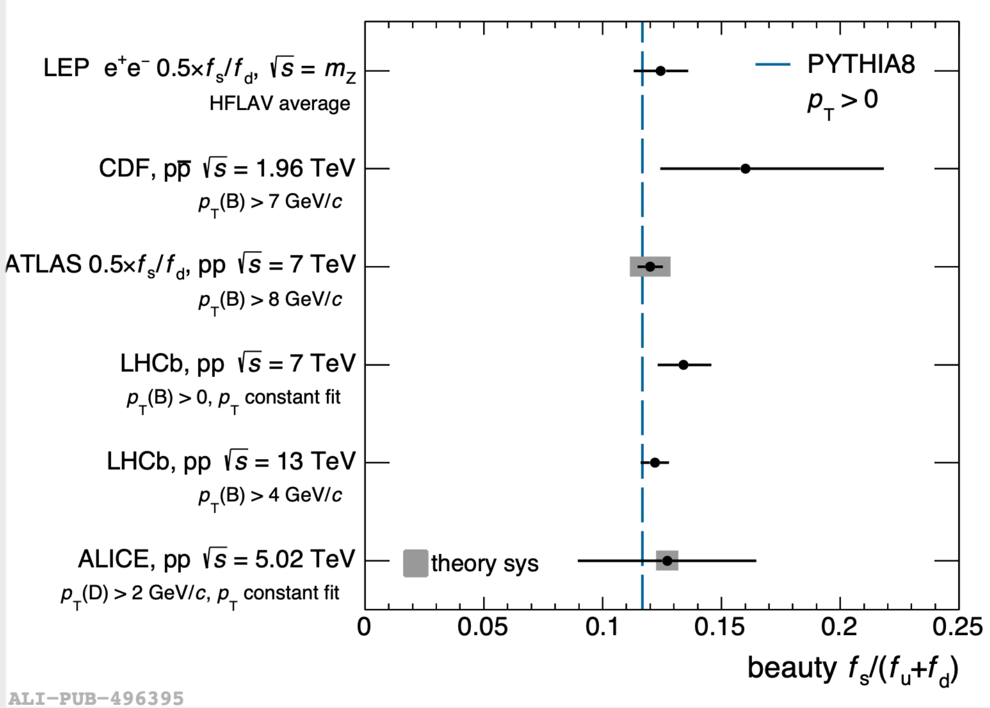

Meson-to-meson yield ratio:

- $D_s^+/(D^0 + D^+)$ yield ratios are also independent of meson p_T
- Consistency between center-of-mass energies
- $f_s/(f_u + f_d)$ ratio for non-prompt is found to be the same as beauty in e^+e^- results

Charm baryon-to-meson yield ratio

c Λ_c^+/D^0

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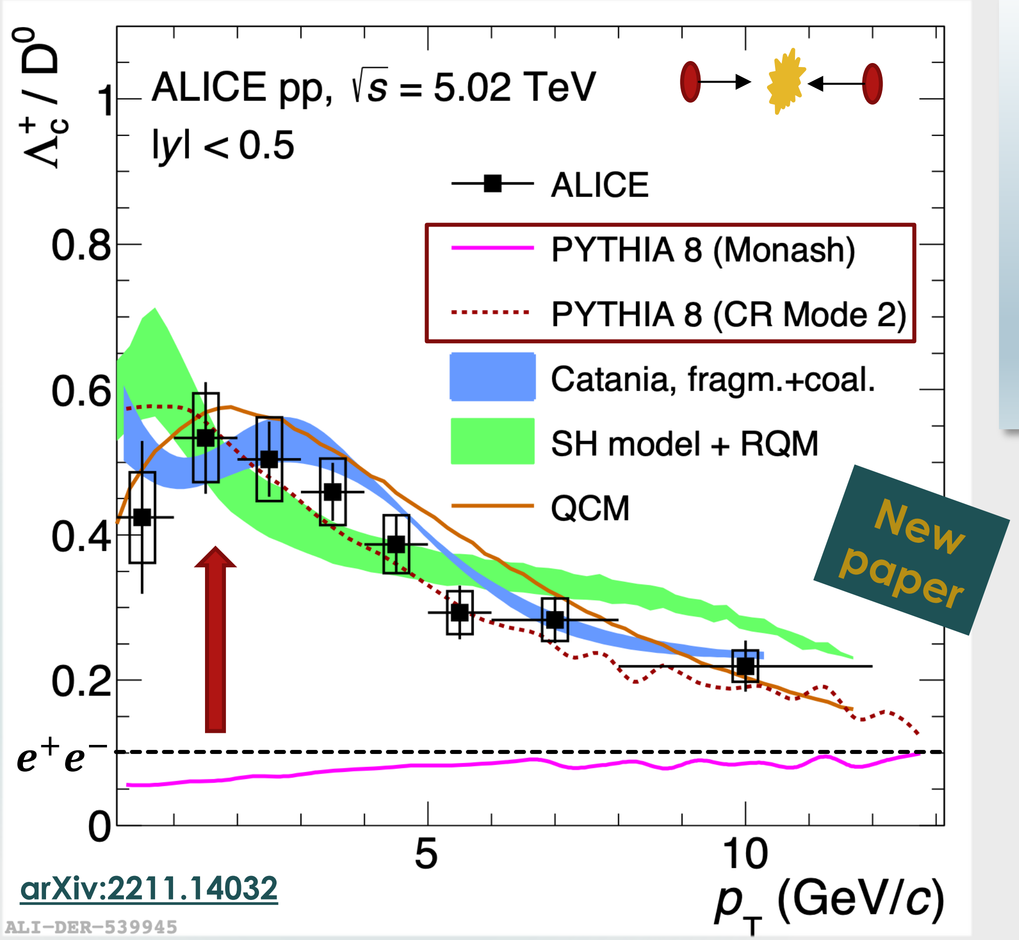
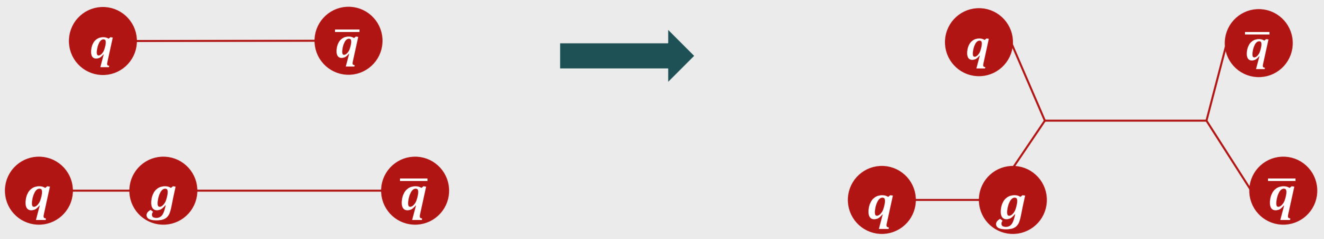


LEP average: $(0.113 \pm 0.013 \pm 0.006)$

PYTHIA 8 — J.P. Christiansen, P. Z. Skands: JHEP 1508 (2015) 003

- Models based on **fragmentation functions from e^+e^-** collisions underestimate the data (PYTHIA 8 Monash)
- Models including **color reconnection** beyond leading color describe the data (PYTHIA 8 CR Mode 2)

Allowing **"junction"** topologies in multiparton interactions, which enhance the charm baryon production.



Significant baryon enhancement w.r.t models tuned on e^+e^- collisions

Charm baryon-to-meson yield ratio

c Λ_c^+/D^0

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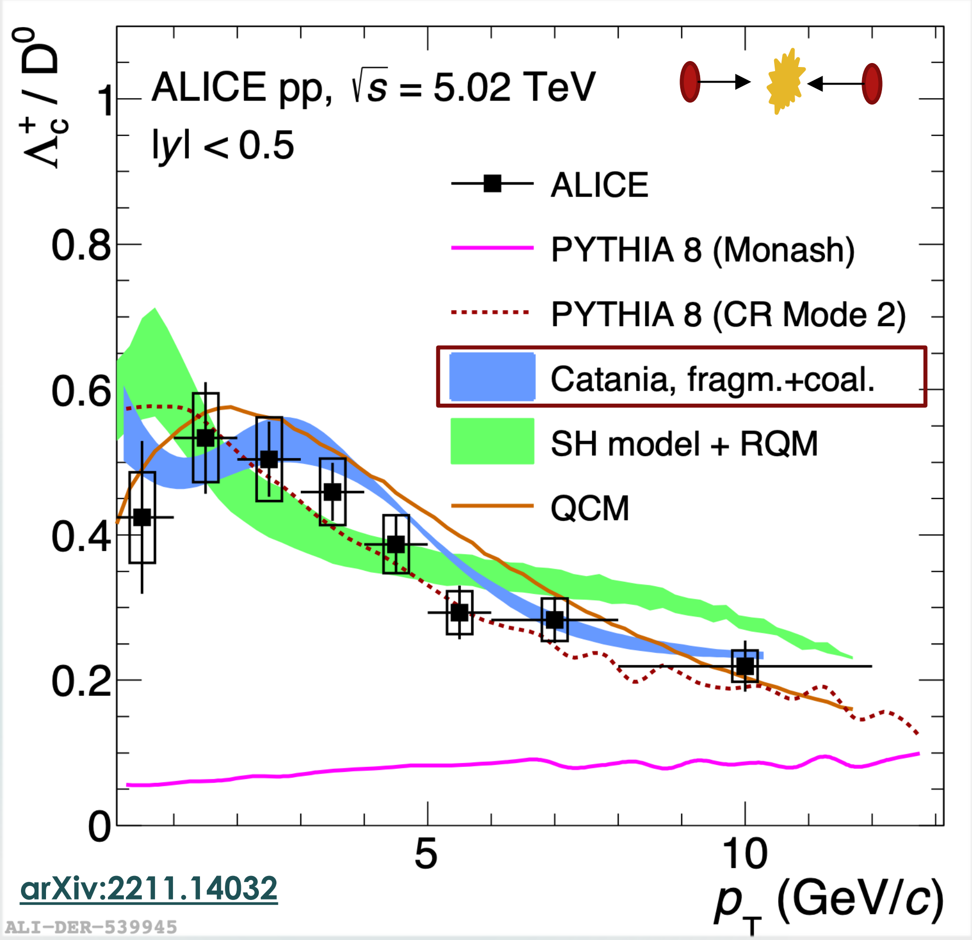
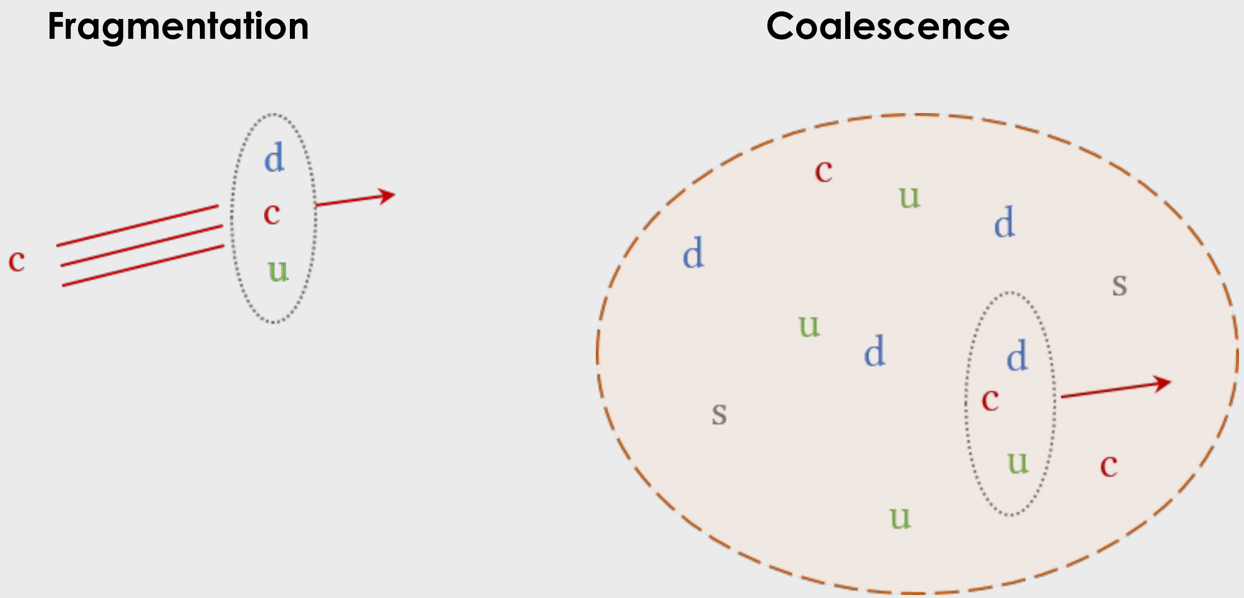


arXiv:2211.14032

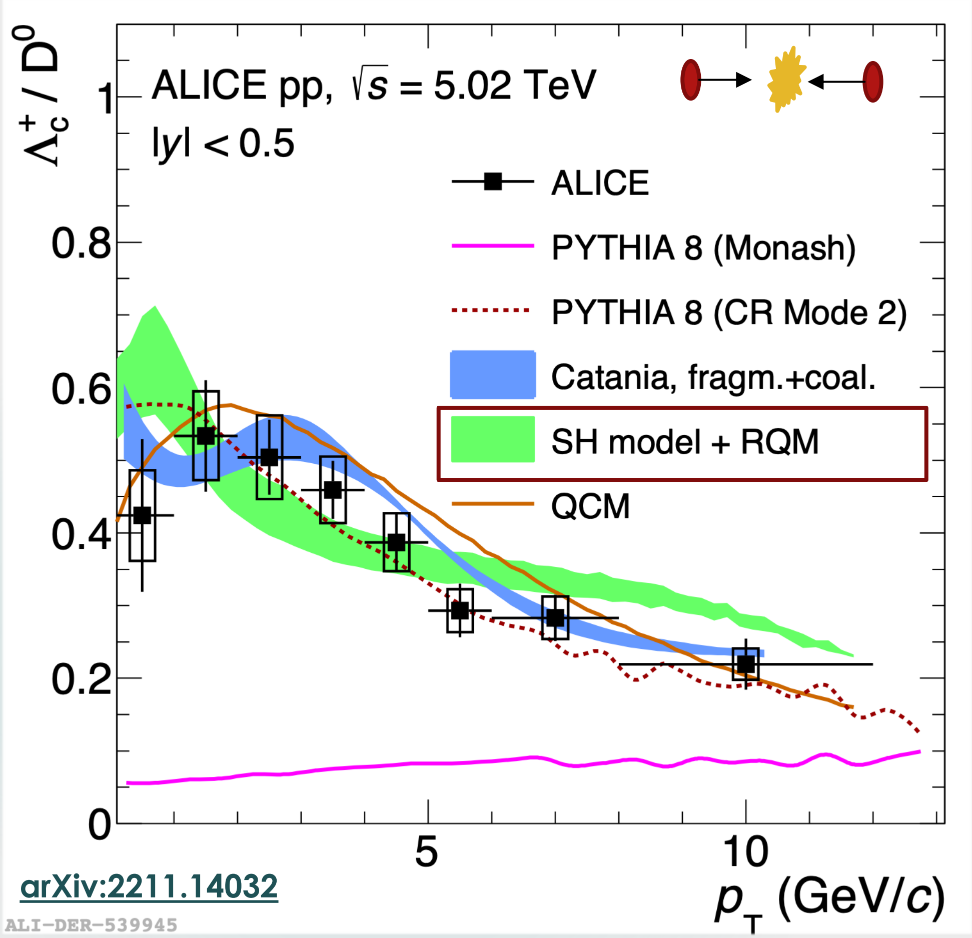
Catania V. Minissale et. Al.: PLB 821 (2021) 136622

Thermalised system of gluons, light quarks and antiquarks (QGP). Hadronisation via **coalescence and fragmentation.**



Charm baryon-to-meson yield ratio

c Λ_c^+/D^0



arXiv:2211.14032

M. He, R. Rapp: PLB 795 (2019) 117-121

Statistical Hadronisation Model

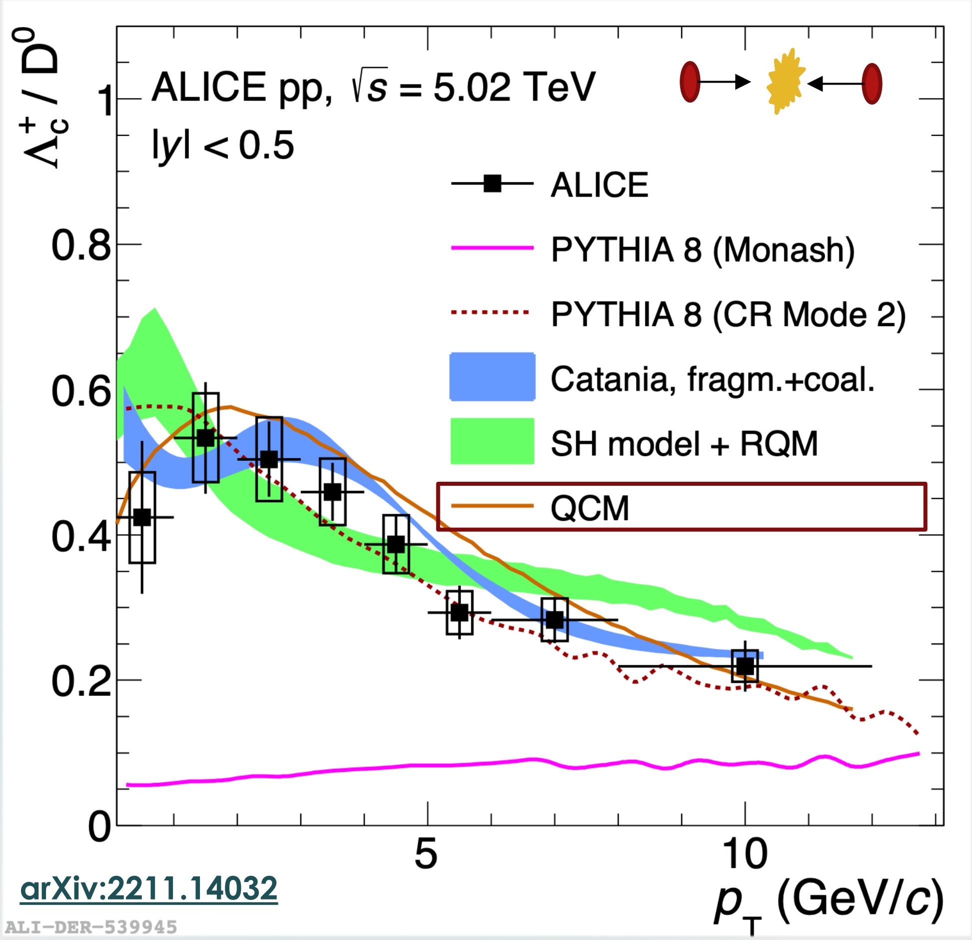
Replaces complexity of hadronisation by **thermo-statistical weights,** governed by the masses of hadrons at a universal hadronisation "temperature".

Feed-down from an augmented set of excited charm baryons necessary to describe $\frac{\Lambda_c^+}{D^0}$

- PDG states: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
- RQM states: additional 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c

Charm baryon-to-meson yield ratio

c Λ_c^+/D^0



arXiv:2211.14032

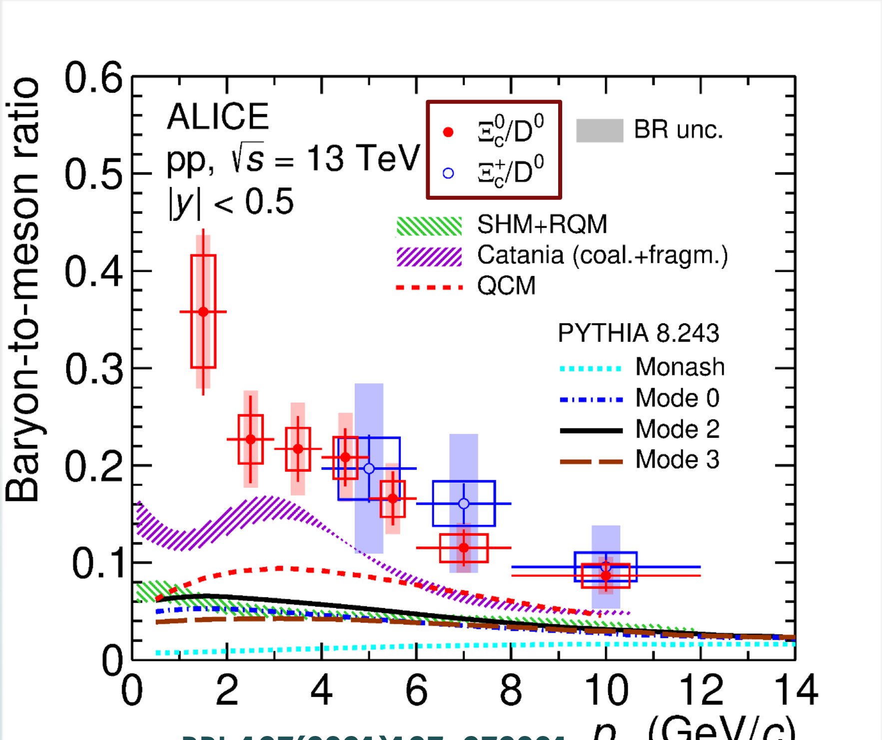
H. Li et. Al.: PRC 97 (2018) 064915

Quark (re)combination mechanism

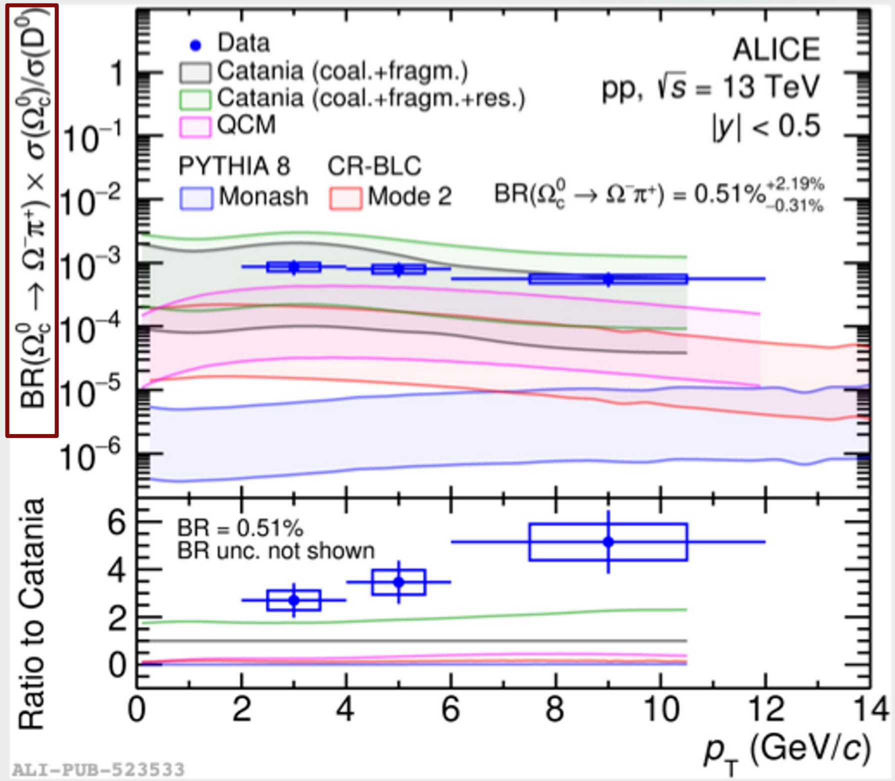
Charm is **combined with co-moving light antiquark or two quarks**. Abundances of charm baryon species are determined by thermal weights.

Strange charm baryon production

c $\Xi_c^{0,+}$, Ω_c^0



PRL 127(2021)127, 272001



Charm-strange sector not yet fully understood.

Baryon-to-meson yield ratio

In the charm-strange sector the enhancement is even larger

- PYTHIA with Monash tune and CR-BLC, QCM, and the SHM+RQM underestimate $\Xi_c^{0,+}/D^0$ yield ratio
- Catania describes the $\Xi_c^{0,+}/D^0$ shape down to $p_T \approx 2$ GeV/c
- Catania describes the Ω_c^0/D^0 yield ratio best, when including higher mass resonance decays (*)

* $BR(\Omega_c^0 \to \Omega^-\pi^+)$ is not measured → use calculation for scaling of theory curves

Y. Hsiao et al. EPJC 80, 1066 (2020)

Modification of p_T spectra from pp to p–Pb?

c Λ_c^+, Ξ_c^0

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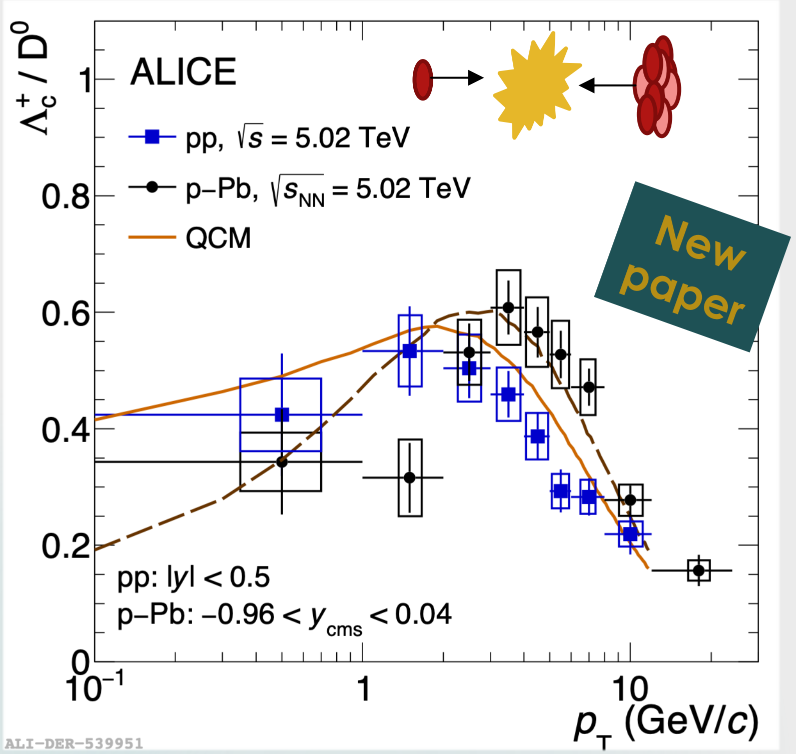
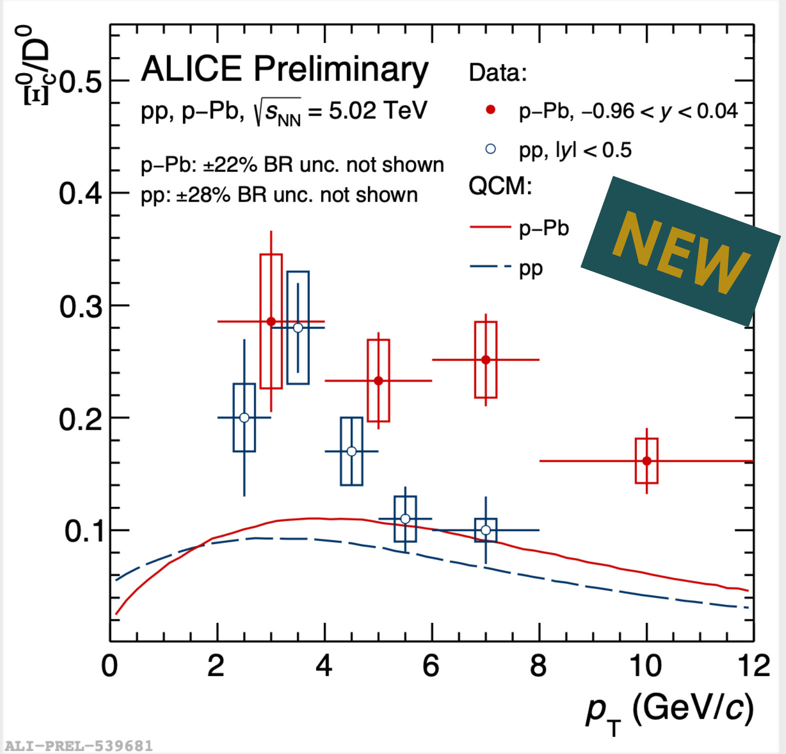




arXiv:2211.14032

- For p_T > 3 GeV/c Λ_c^+/D^0 larger in p–Pb collisions than in pp collisions, for p_T < 2 GeV/c tendency for lower ratio
- Confirmed by 3.7σ higher $\langle p_T \rangle$ of Λ_c^+
- QCM underpredicts the Ξ_c^0/D^0 yield ratio, although it can describe the Λ_c^+/D^0 yield ratio, as it was seen also in pp collisions

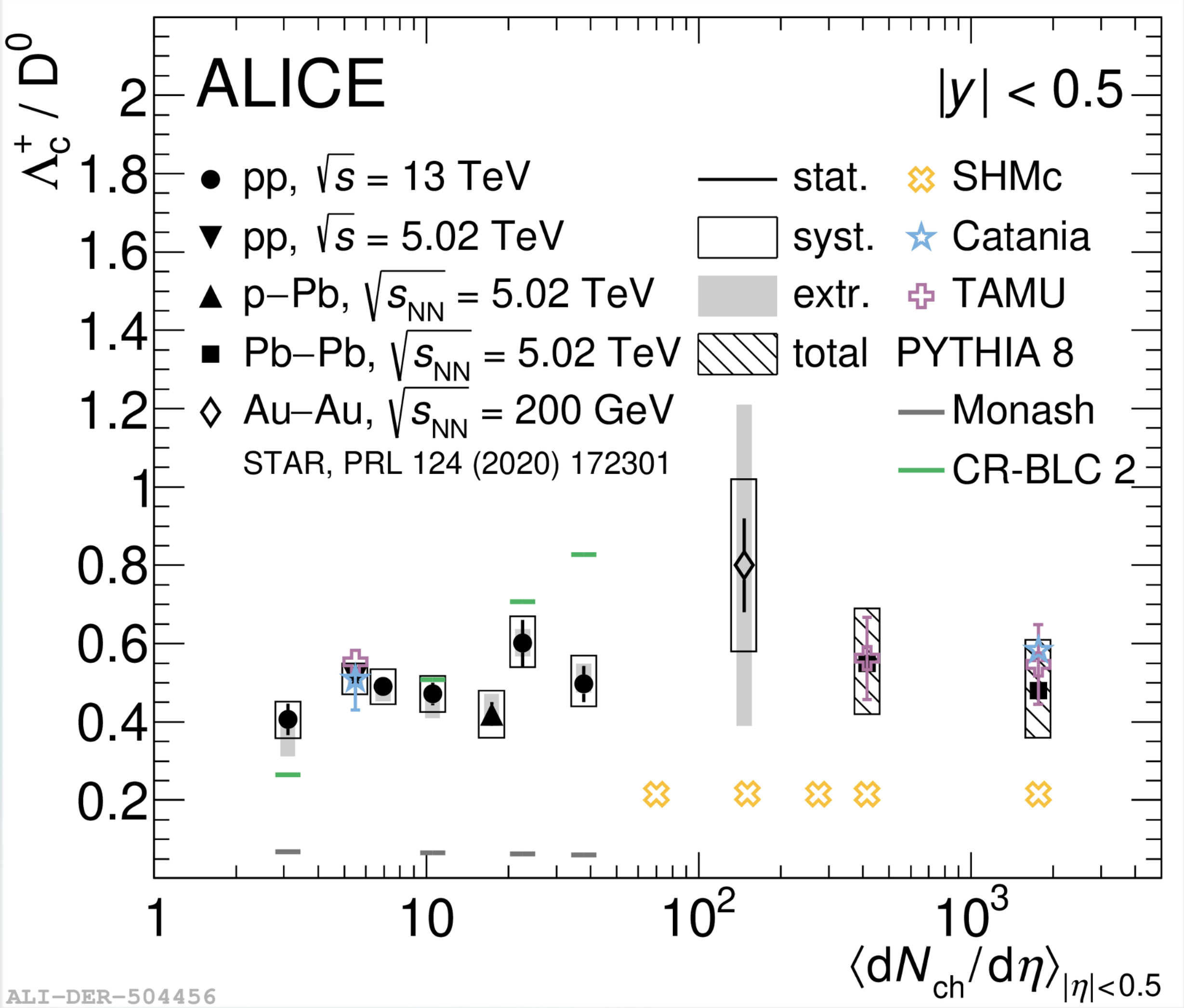
	$\langle p_T \rangle$ (GeV/c)	
	pp	p–Pb
D^0	2.06 ± 0.03 (stat.) ± 0.03 (syst.)	2.07 ± 0.02 (stat.) ± 0.04 (syst.)
Λ_c^+	1.86 ± 0.06 (stat.) ± 0.03 (syst.)	2.29 ± 0.06 (stat.) ± 0.06 (syst.)

Hardening of p_T spectra w.r.t pp is predicted in the presence of a medium (QCM) for Λ_c^+ and Ξ_c^0

p_T-integrated yields from pp to Pb–Pb

c Λ_c^+/D^0

ALICE



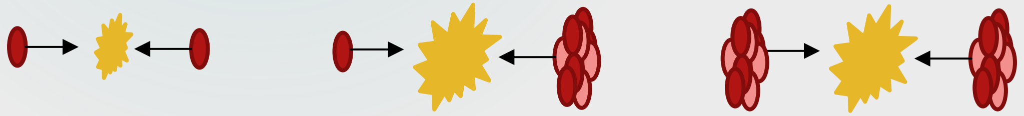
p_T-integrated Λ_c^+/D^0 :

- No significant variation of p_T-integrated Λ_c^+/D^0 as a function of multiplicity or collision system within the uncertainties

Hypothesis:

- Difference between collision systems is due to momentum redistribution, no modification of the overall yield.

Models including coalescence describe the data, as well as the SHM when including additional charm baryon states.



pp (13 TeV), pp (5.02 TeV), p–Pb (5.02 TeV), Au–Au (200 GeV), Pb–Pb (5.02 TeV)

SHMc, Catania, TAMU, Monash, CR-BLC Mode 2

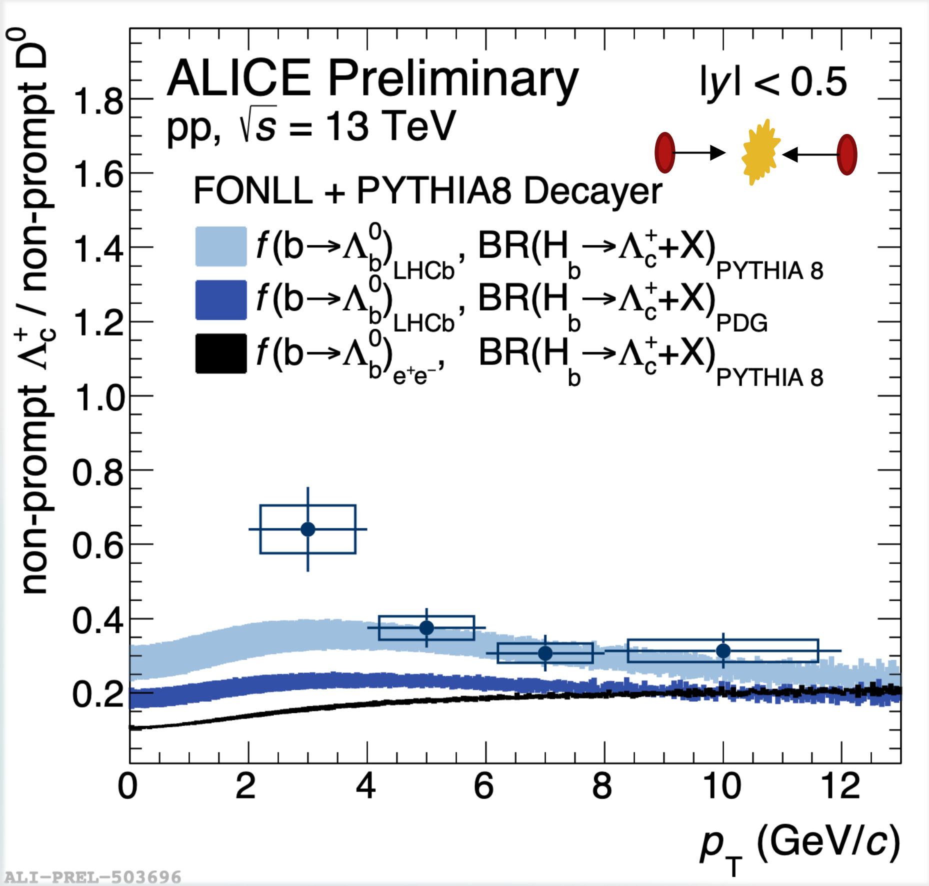
Beauty baryon-to-meson yield ratio

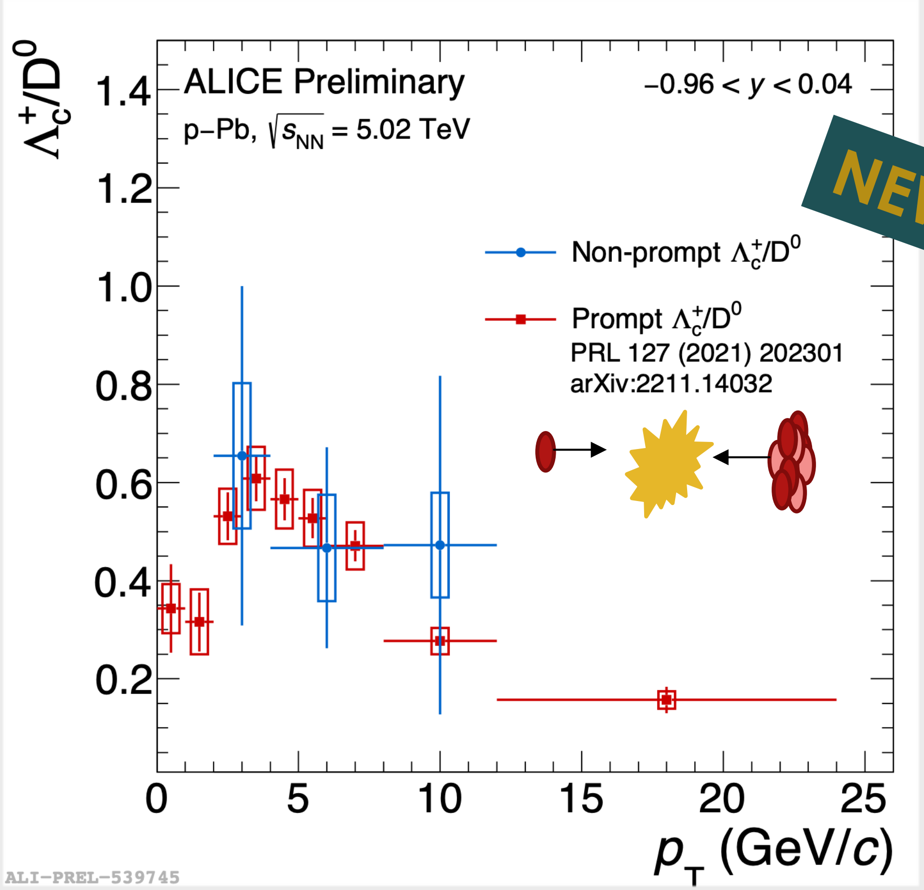
c, b

Λ_c^+/D^0

ALICE

Poster: Mingyu Zhang





- Agreement between prompt and non-prompt Λ_c^+/D^0 in pp and p–Pb collisions within the uncertainties
- Choice of BR and fragmentation fraction matters

FONLL calculations for beauty quark production (FONLL: JHEP 05 (1998) 007)

$f(b \to \Lambda_b^0)$, LHCb (PRD 100 (2019) no.3, 031102)

$BR(H_b \to \Lambda_c^+ + X)$, PYTHIA 8 (arXiv:1410.3012)

Non-prompt Λ_c^+ and D^0 are well described by model calculations within the uncertainties

Nuclear modification factor

c | Λ_c^+, Ξ_c^0

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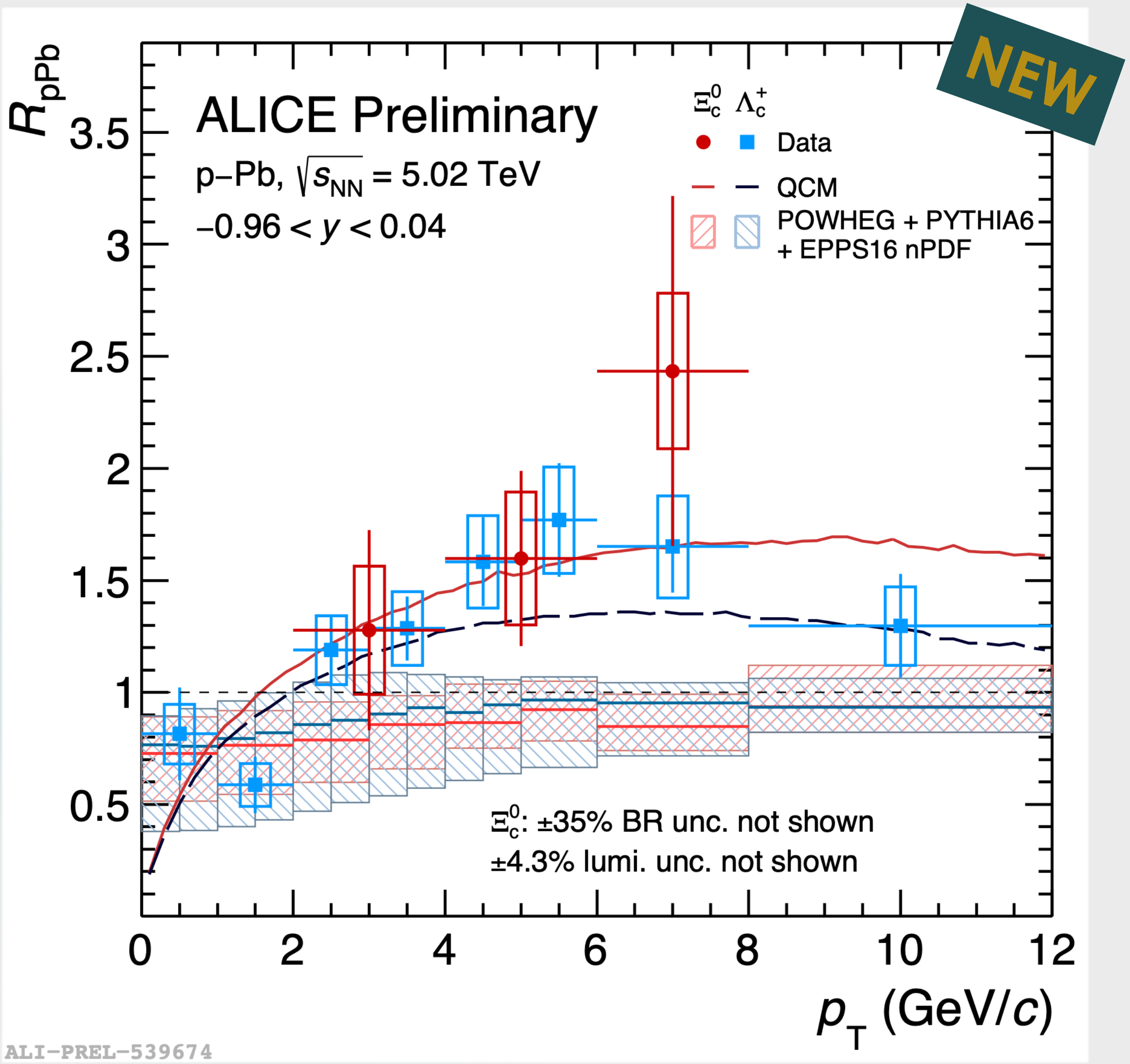
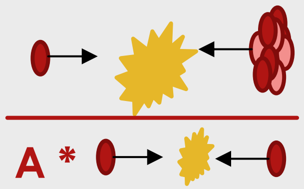


Nuclear modification factor

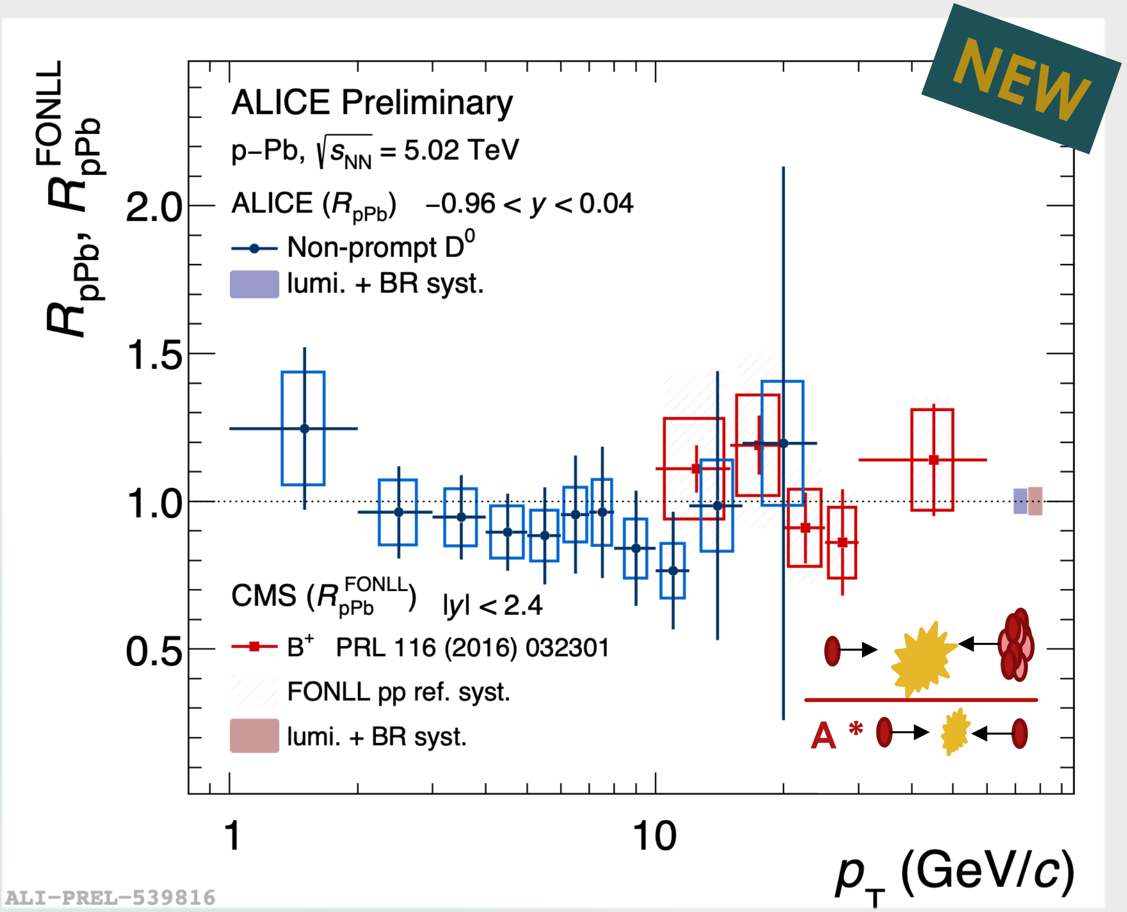
- $R_{pPb} = 1$: No modification in p–Pb with respect to pp collisions
- Disentangle cold nuclear matter effects from final state effects

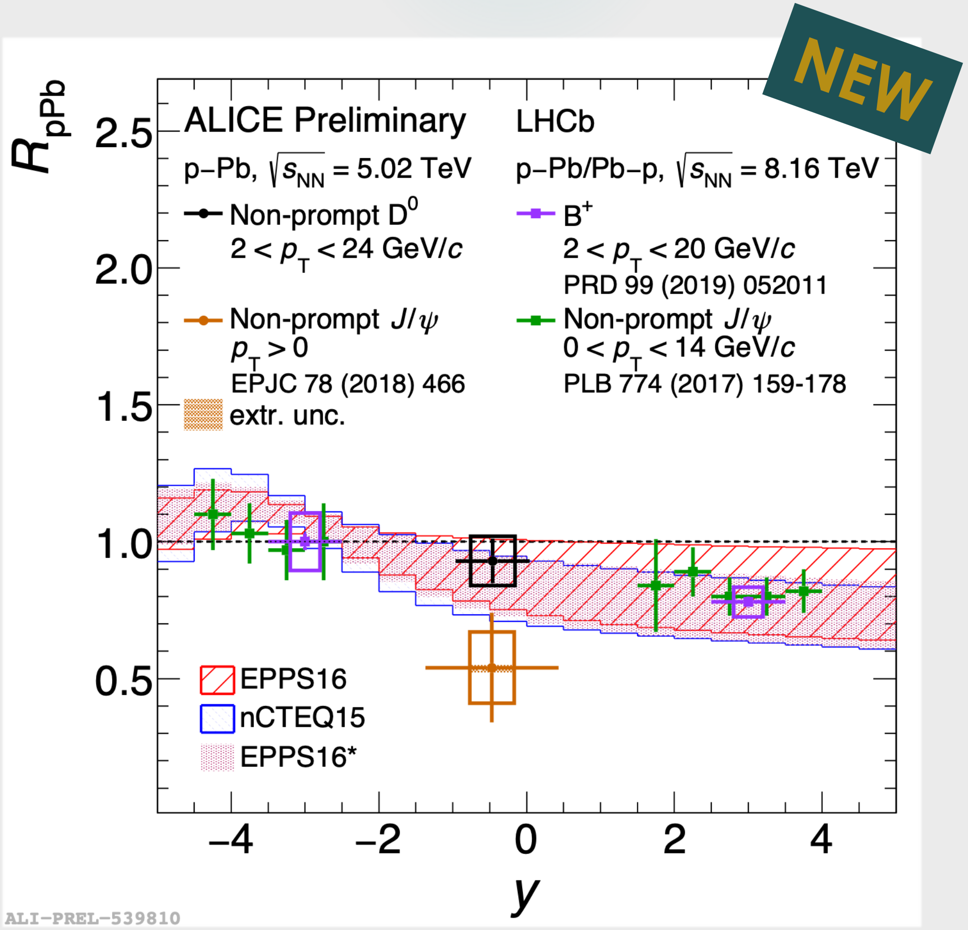


- R_{pPb} of Λ_c^+ and Ξ_c^0 are in agreement within the uncertainties
- R_{pPb} of $\Lambda_c^+ < 1$ at low p_T and > 1 at intermediate p_T, as also observed in the strange sector (CMS: Phys. Rev. C 101, 064906)
- QCM prediction agrees with Ξ_c^0 measurement

Non-prompt R_{pPb}

b D^0 ALICE





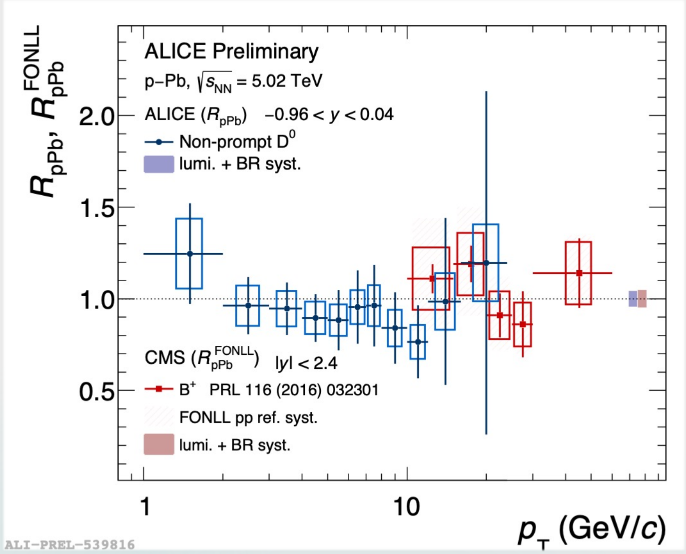
Nuclear modification factor

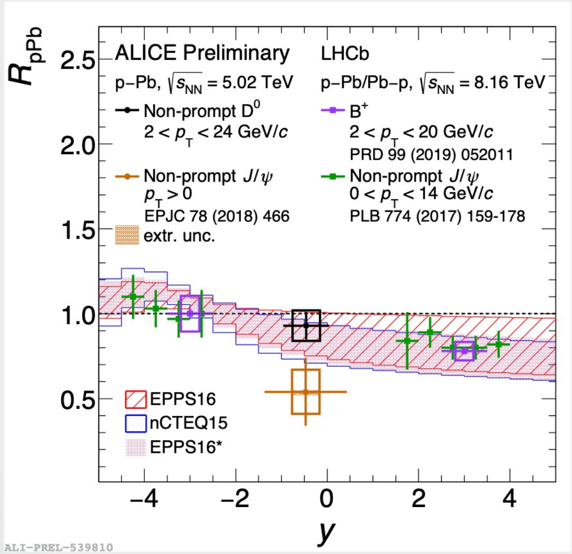
- Non-prompt D^0 R_{pPb} is in agreement with measurement of B^+ from CMS
- p_{T}-integrated non-prompt D^0 R_{pPb} is in agreement with measurement of B^+, and non-prompt J/ψ from LHCb

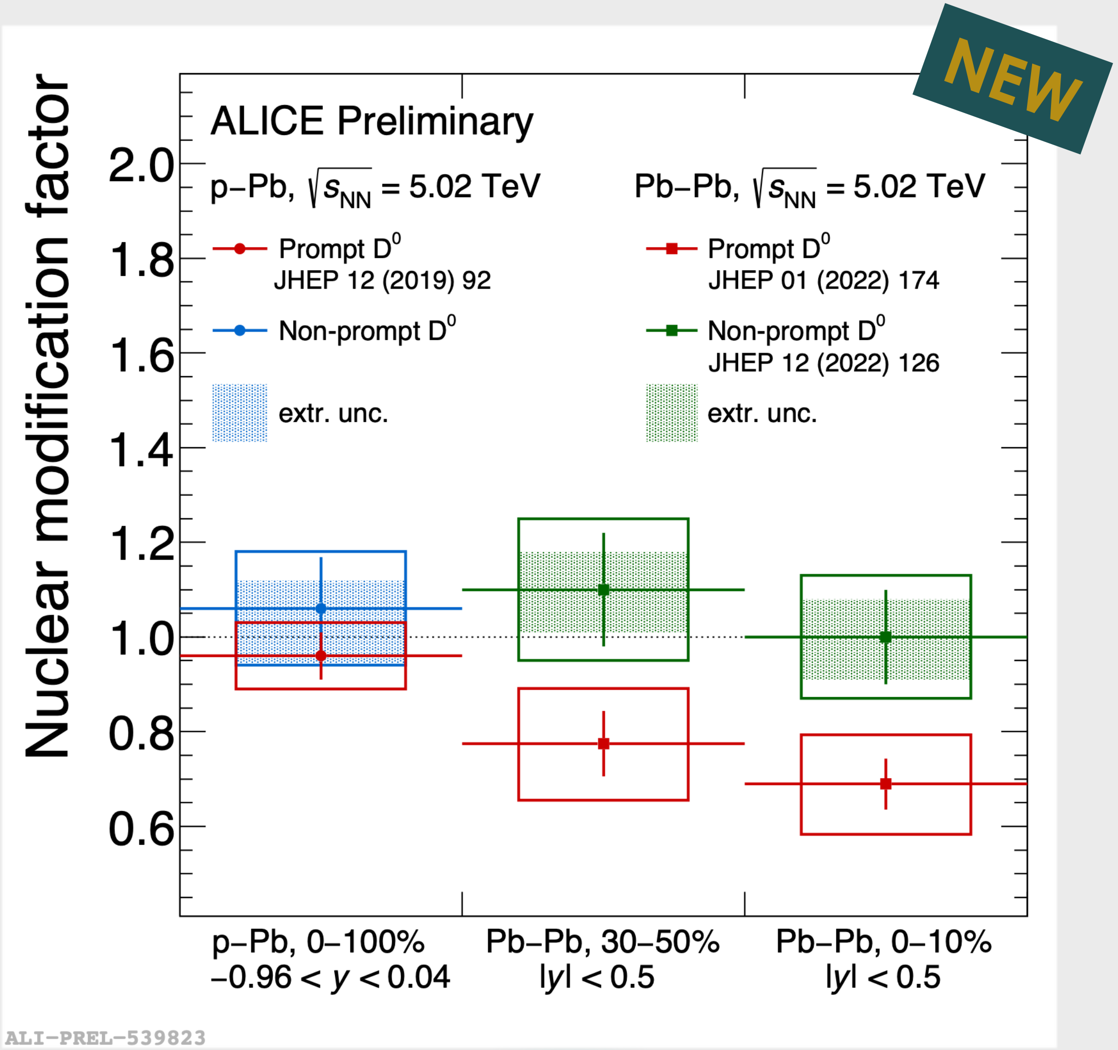
Non-prompt R_{pPb}

c, b

D^0



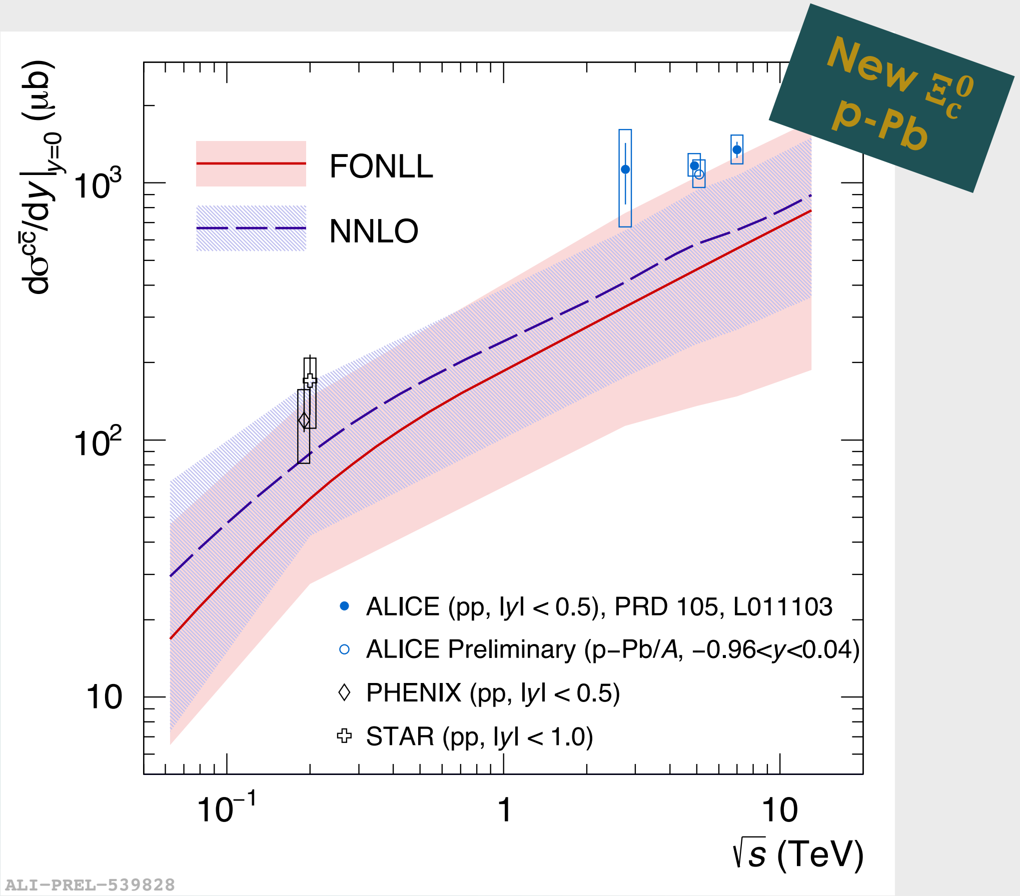


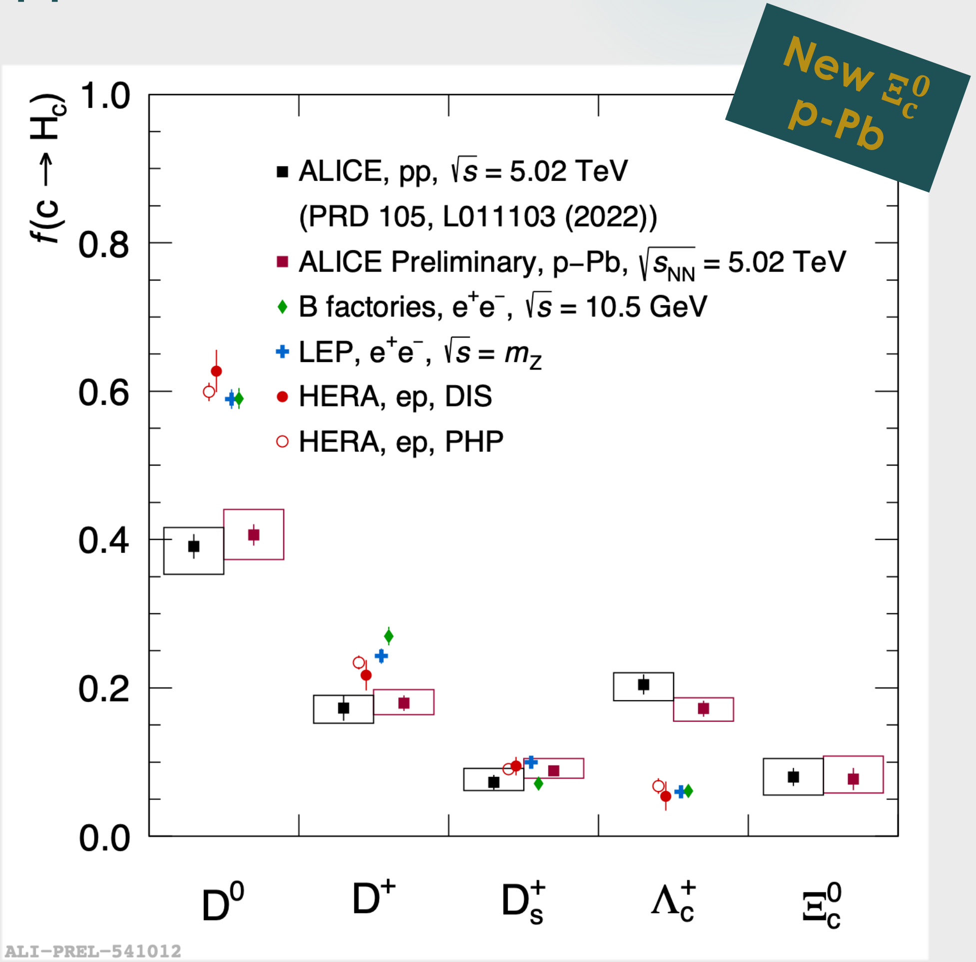


Nuclear modification factor

- Non-prompt D^0 R_{pPb} is in agreement with measurement of B^+ from CMS
- p_T–integrated non-prompt D^0 R_{pPb} is in agreement with measurement of B^+, and non-prompt J/ψ from LHCb
- **Study shadowing for beauty and for charm**

Total charm cross section





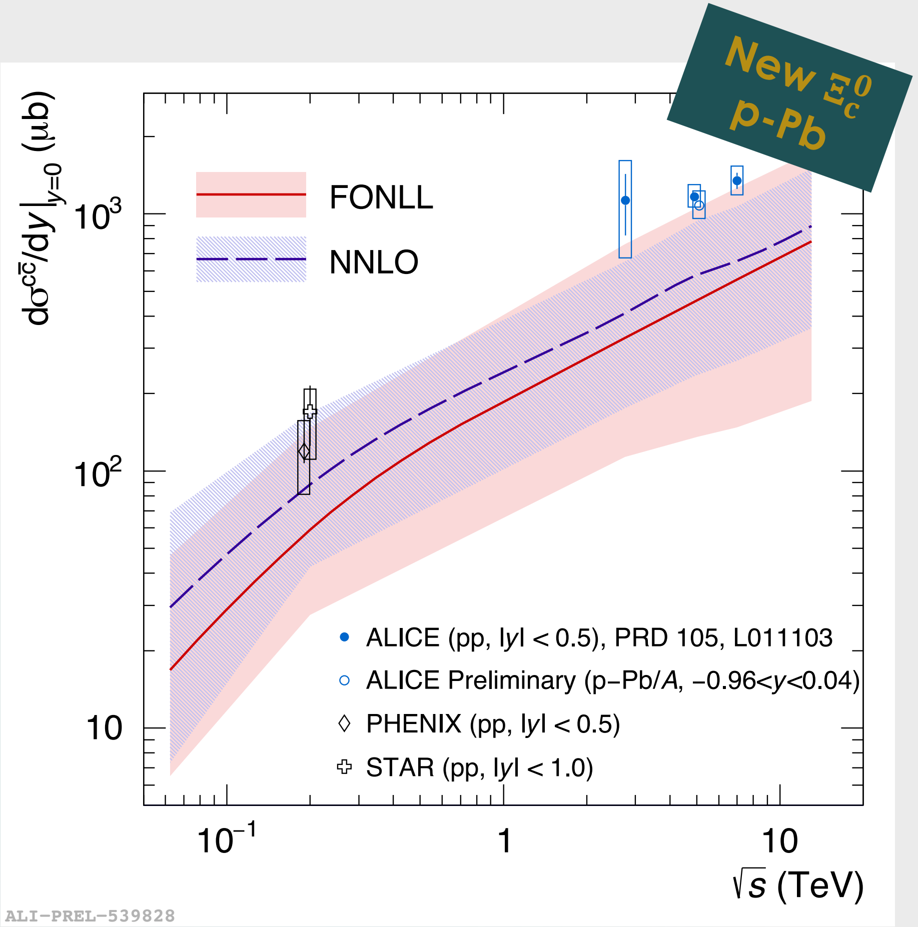
Results are on the upper edge of FONLL and NNLO calculations

PRD 105, L011103 (2022)

Measured at midrapidity as a sum of ground state charm hadron cross sections

- pp and p–Pb results are compatible
- Significant baryon enhancement in pp and p–Pb w.r.t. e^+e^- and e^-p collisions

Total charm cross section



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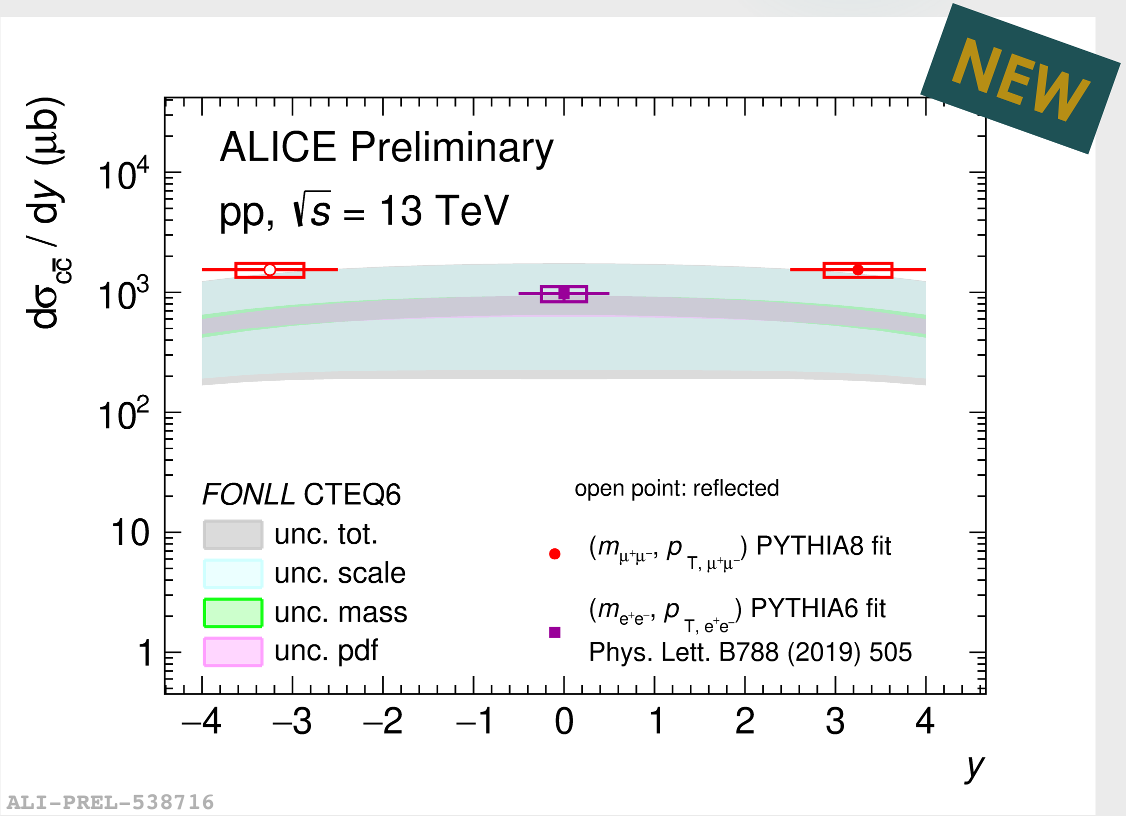
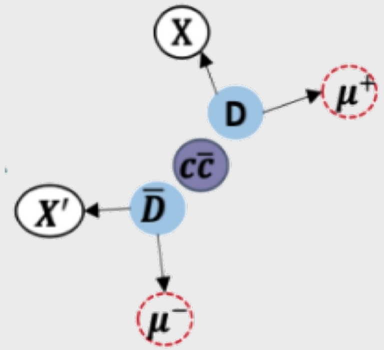


Dielectron: PLB 788 (2019) 505

Poster: Michele Pennisi

Results are on the upper edge of FONLL and NNLO calculations

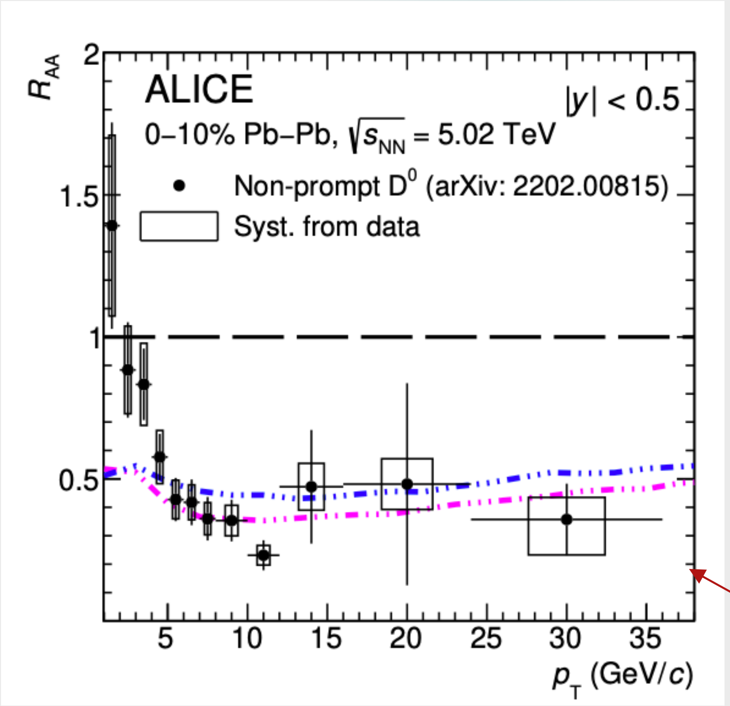


- New measurement of $c\bar{c}$ and $b\bar{b}$ cross section at forward rapidity via dilepton spectra at $m_{\mu\mu} > 4\,\frac{\text{GeV}}{c^2}$
- Update of $c, c \rightarrow e^+e^-$ will be released soon, with an updated BR

Summary

Heavy flavour hadrons

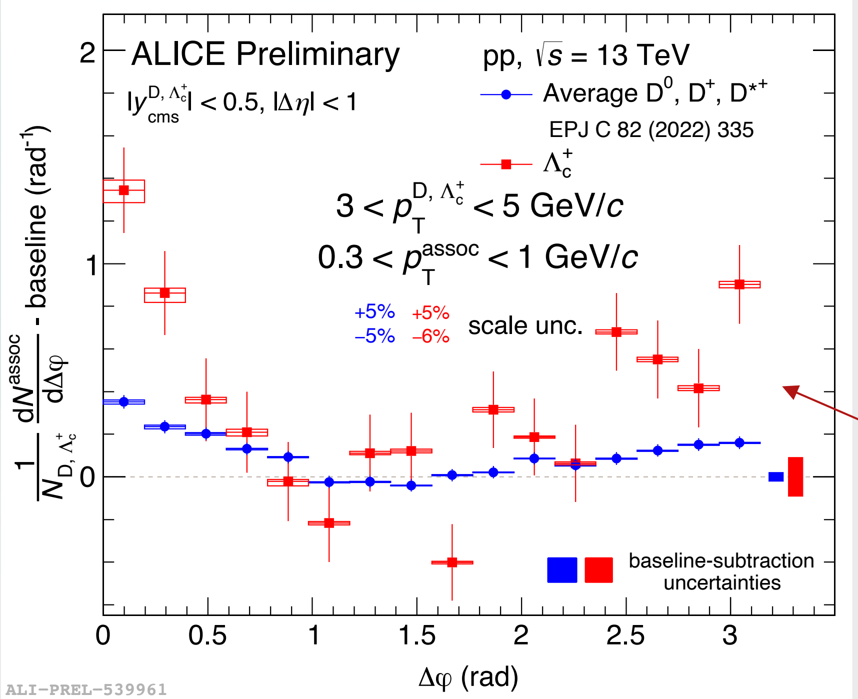
- Modified hadronisation mechanisms could be needed w.r.t. the vacuum string fragmentation picture to describe the heavy-flavour baryon measurements
- Or additional charm baryon states should be considered



JHEP 12 (2022) 126

Talk: Martin Völkl 29.03. 09:00

Non-prompt D mesons to investigate beauty-quark interaction in the QGP



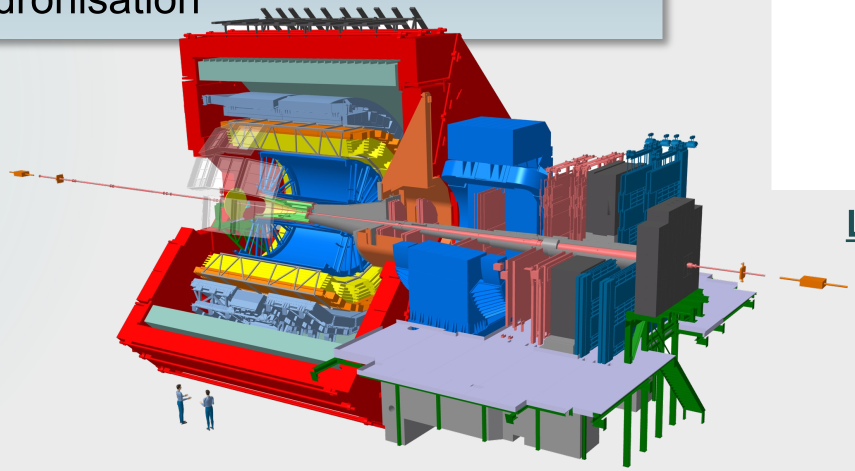
Talk: Antonio Palasciano 29.03. 14:40

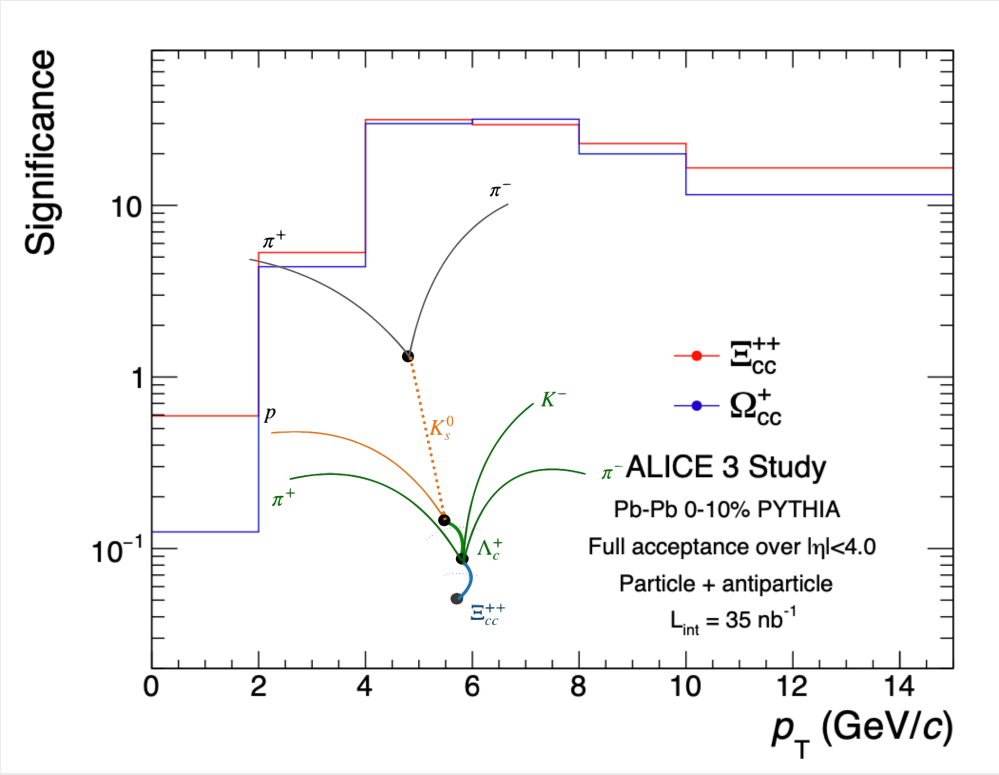
Additional information on charm hadronisation by studying Λ_c^+-h correlation measurements in comparison to D-h correlations.

Outlook

LHC Run 3, 4 and beyond

- Higher data taking rate and upgraded TPC and ITS
- Direct reconstruction of beauty mesons and baryons
- Measurement of charm and beauty cross section and fragmentation fractions from pp to Pb–Pb
- Reconstruction of complex decays like Ξ_{cc}^{++}
- Better constraints to theoretical models of the strongly interacting medium and hadronisation





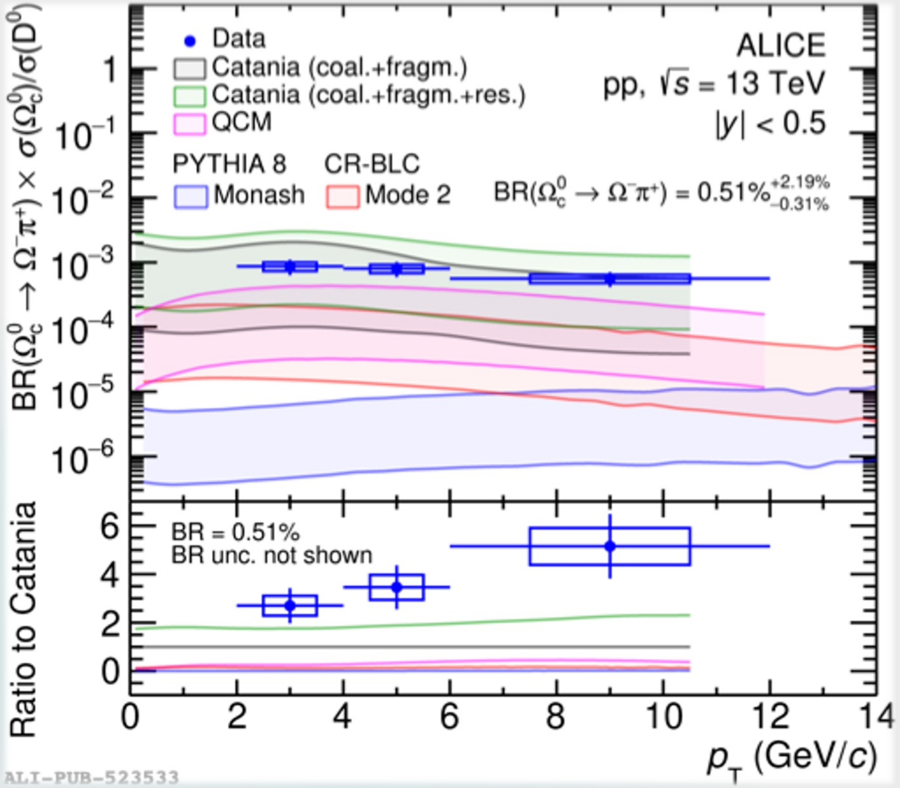
LoI ALICE 3: arXiv:2211.02491

Backup

Doubly strange charmed baryon production

Ω_c^0/D^0

ALICE



$$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+)\times\Omega_c^0/D^0$$

* $\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+) = (0.51 \pm 0.07)\%$ is not measured → use calculation for scaling Y. Hsiao et al. EPJC 80, 1066 (2020)

Ratio	ALICE (pp 13 TeV) $2 < p_T < 12$ GeV/c	Belle (e^+e^- 10.52 GeV) visible
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+)\times\sigma(\Omega_c^0)/\sigma(\Lambda_c^+)$	$(1.96 \pm 0.42 \pm 0.13)\times 10^{-3}$	$(2.24 \pm 0.29 \pm 0.16)\times 10^{-4}$
$\mathrm{BR}(\Omega_c^0 \to \Omega^-\pi^+)\times\sigma(\Omega_c^0)/\sigma(\Xi_c^0)$	$(3.99 \pm 0.96 \pm 0.96)\times 10^{-3}$	$(8.58 \pm 1.15 \pm 1.98)\times 10^{-4}$

Belle: PRD 97, 072005 (2018)

fragmentation fraction ~7%

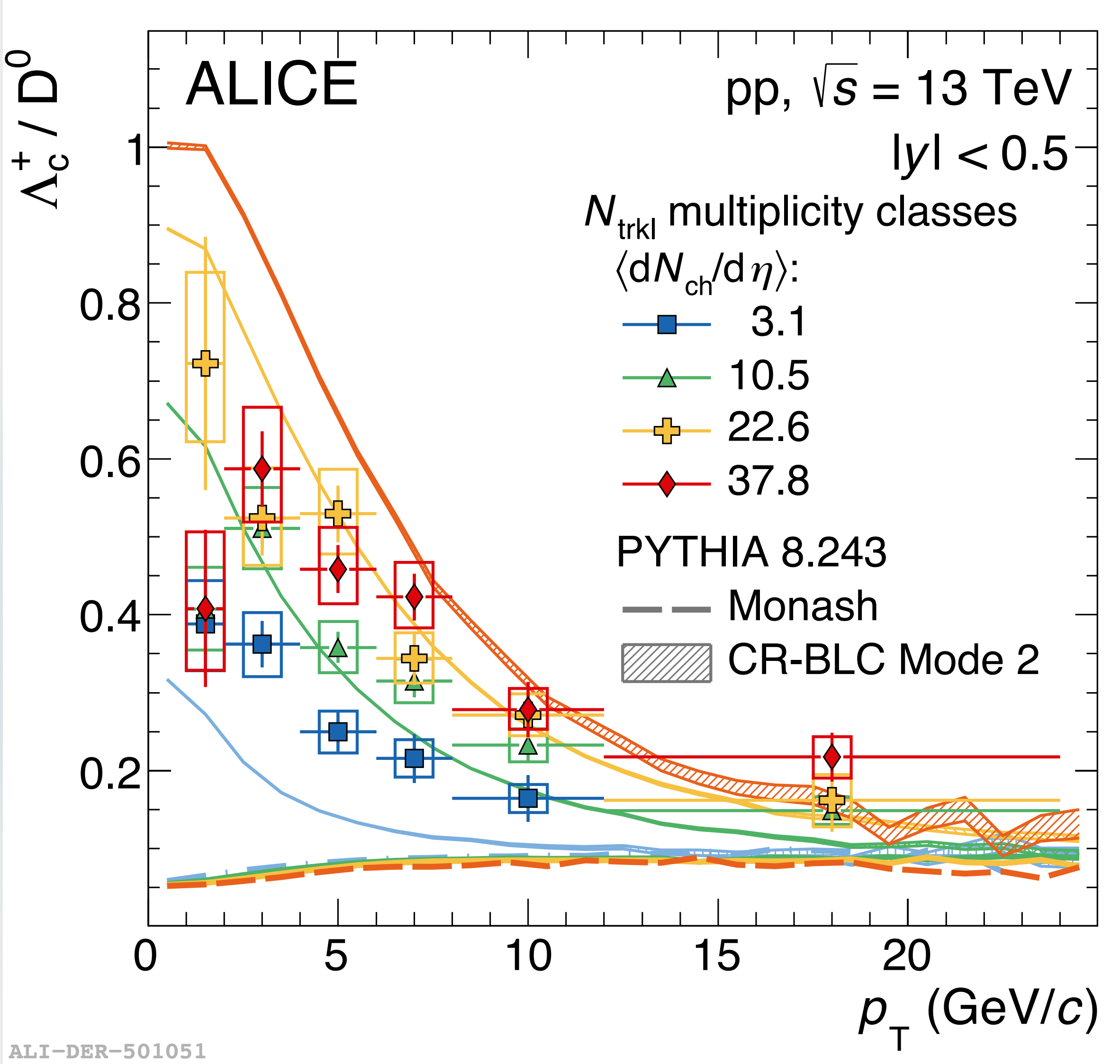
- **Catania comes closest to data** and describes baryon-to-meson yield ratio when including higher mass resonance decays

Sizable Ω_c^0 contribution to charm production at LHC energies?

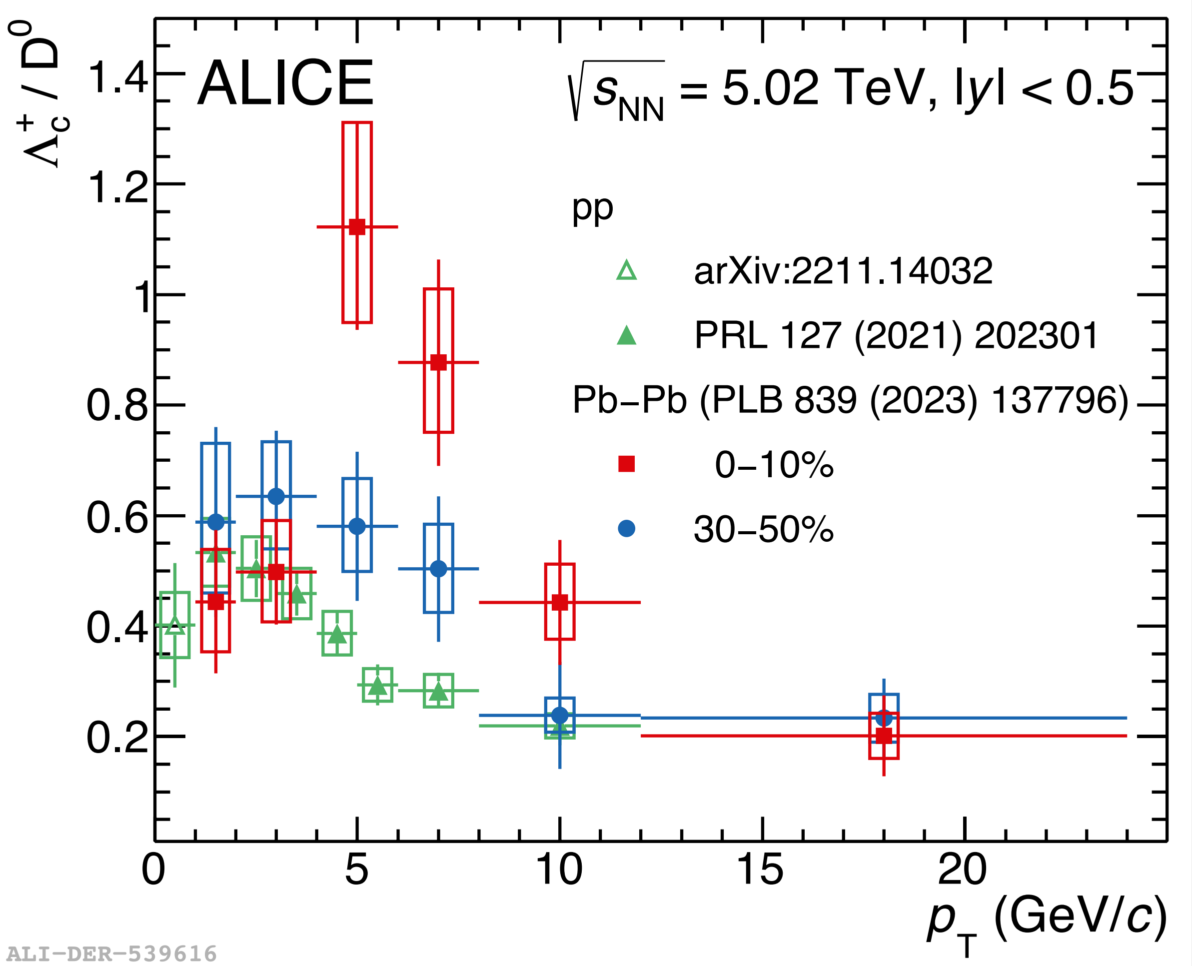
Charm baryon-to-meson yield ratio

c Λ_c^+/D^0

ALICE

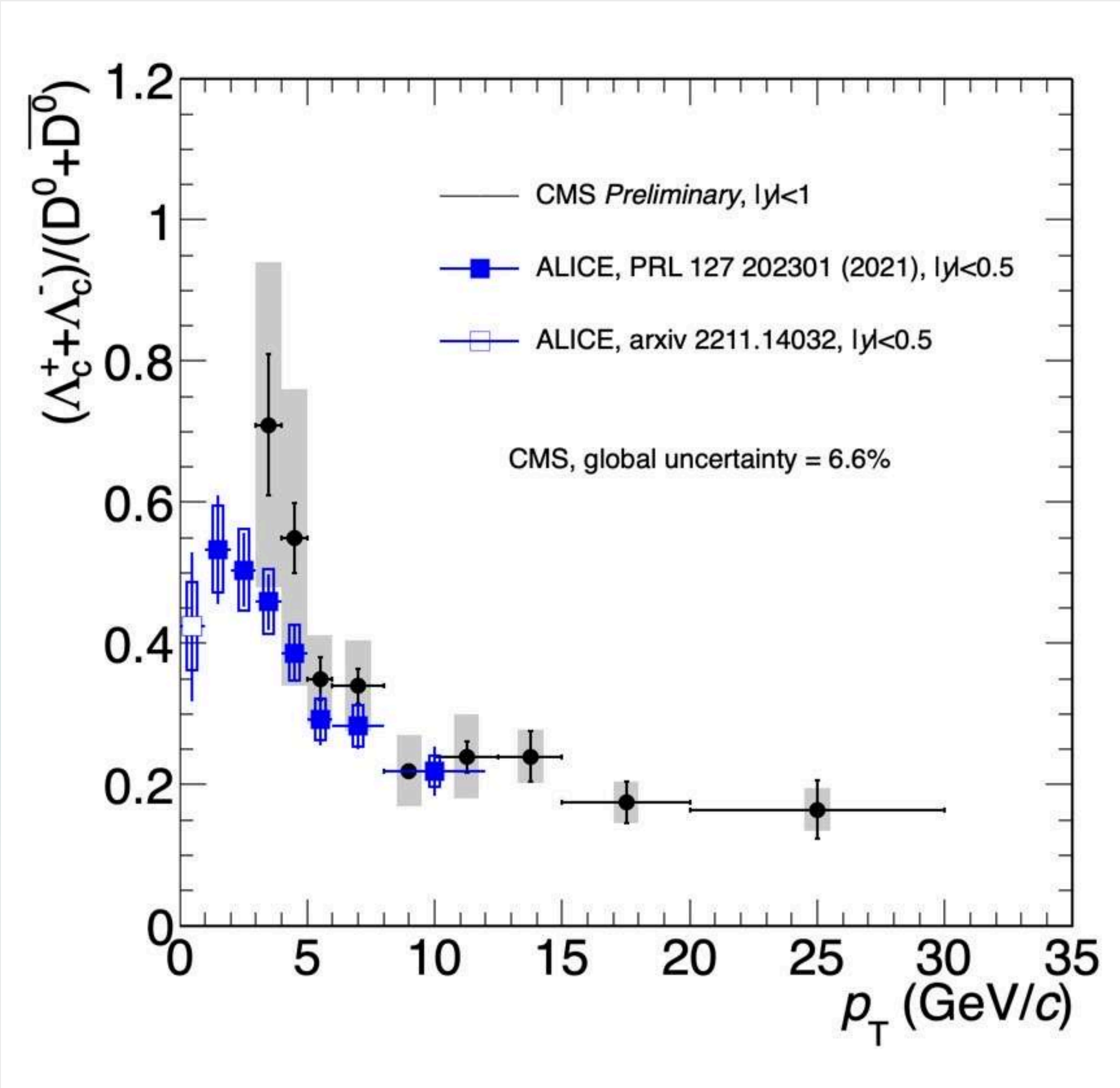


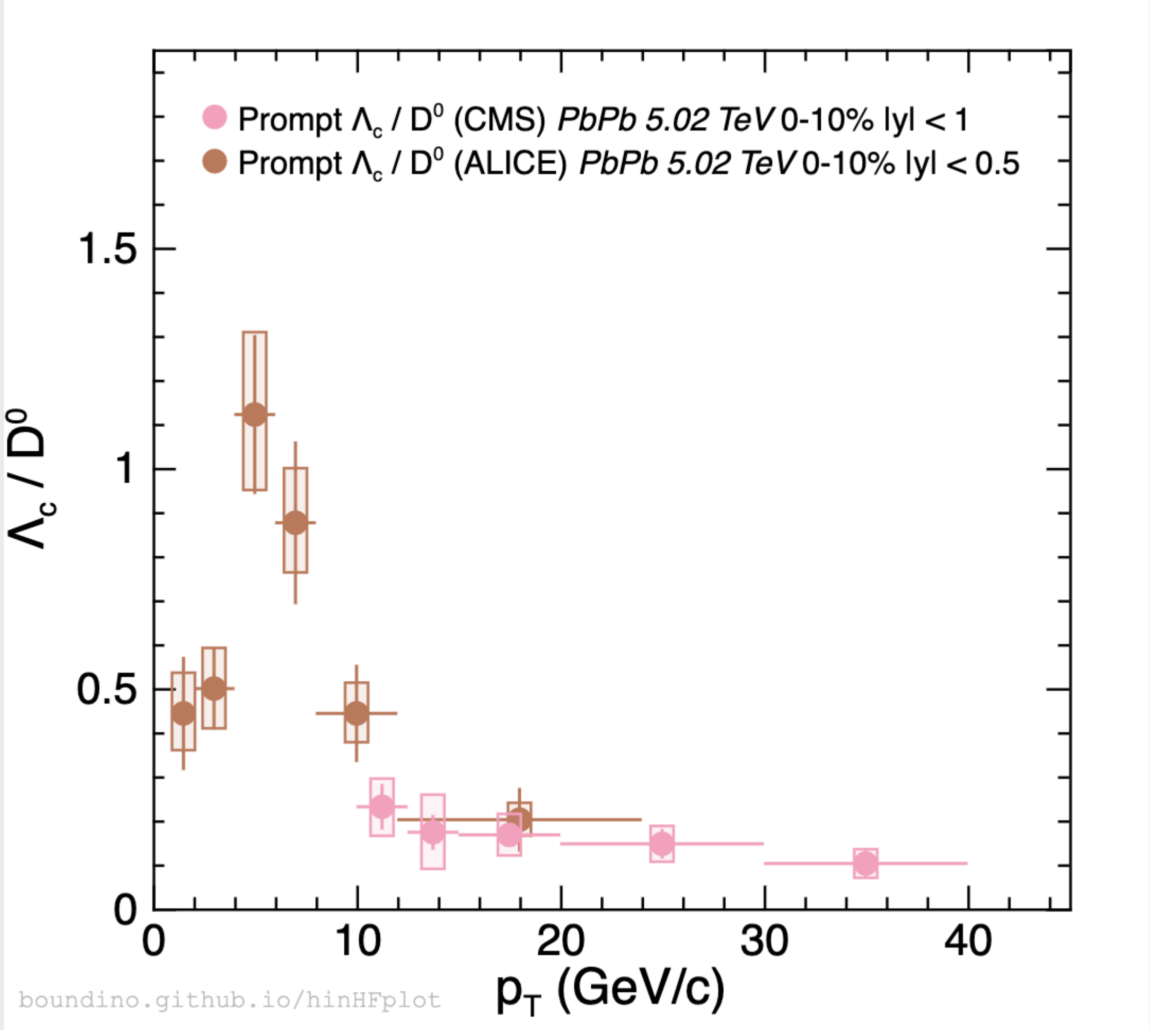
➢ Λ_c^+/D^0 as a function of p_T for different multiplicities



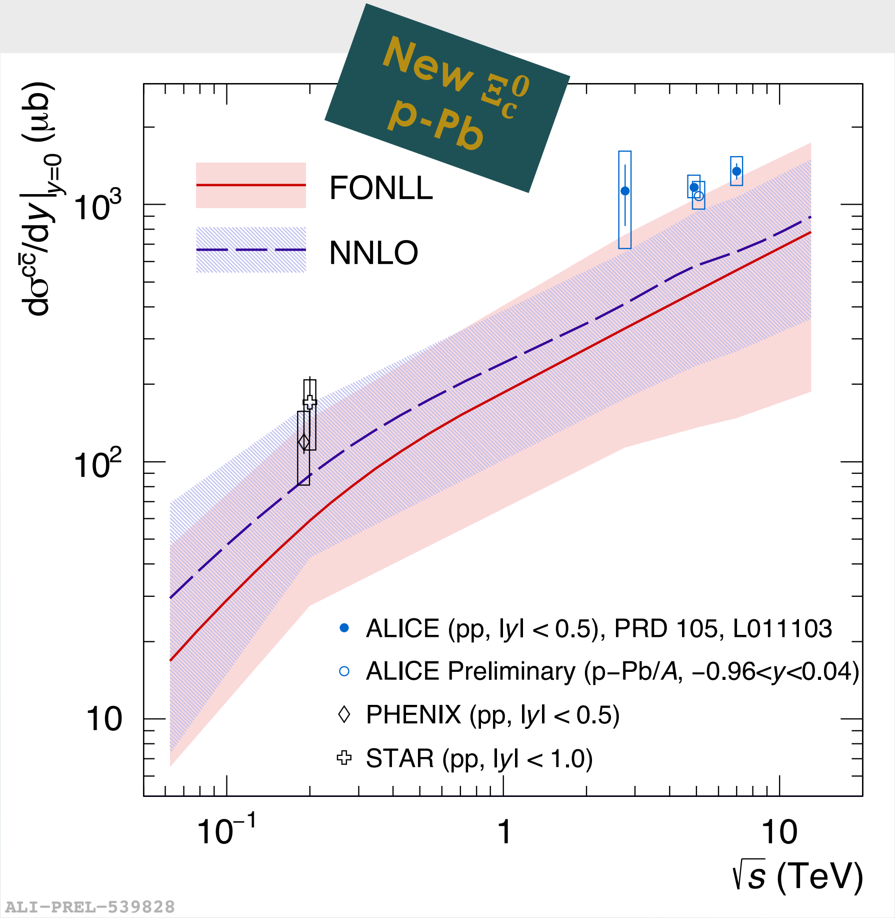
Charm baryon-to-meson yield ratio

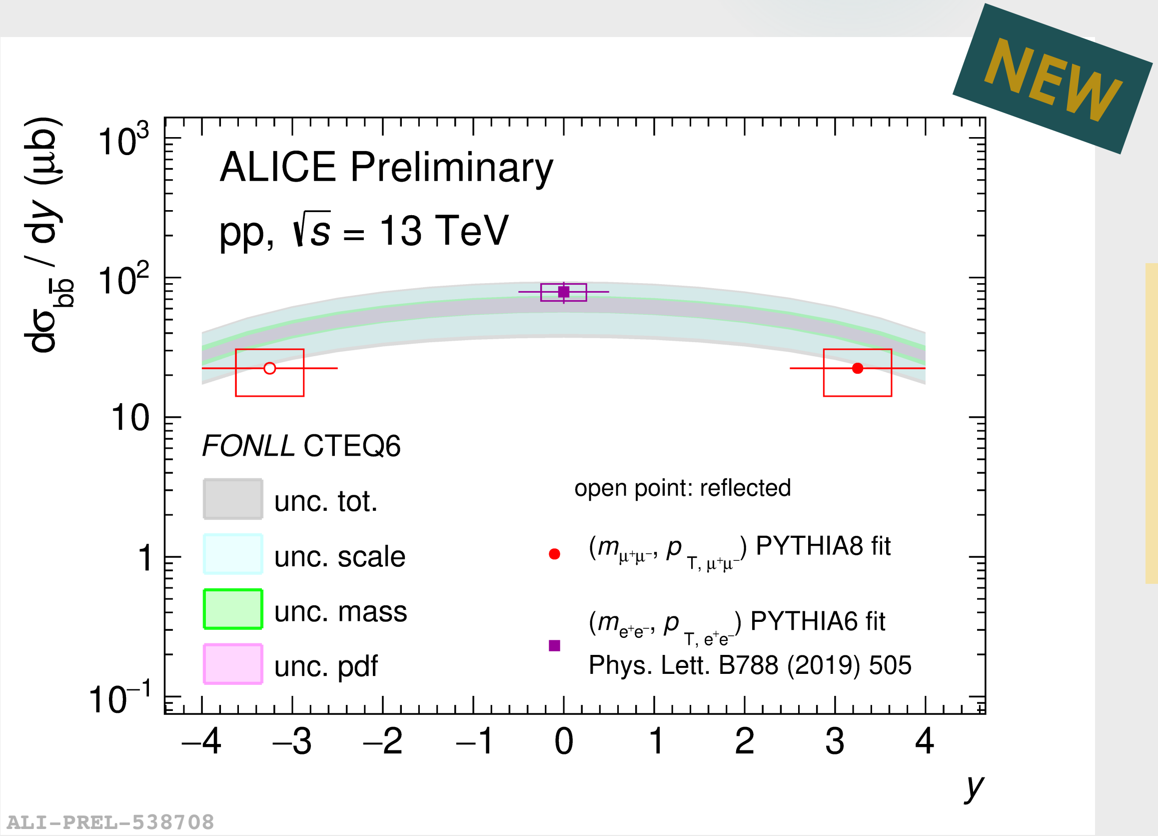
c Λ_c^+/D^0



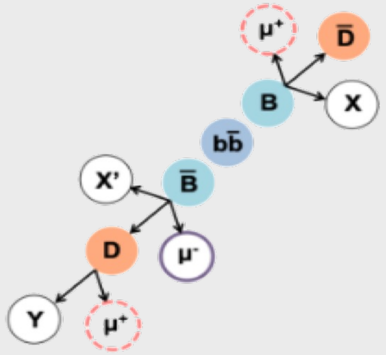


Total charm and beauty cross section





Results are on the upper edge of FONLL and NNLO calculations

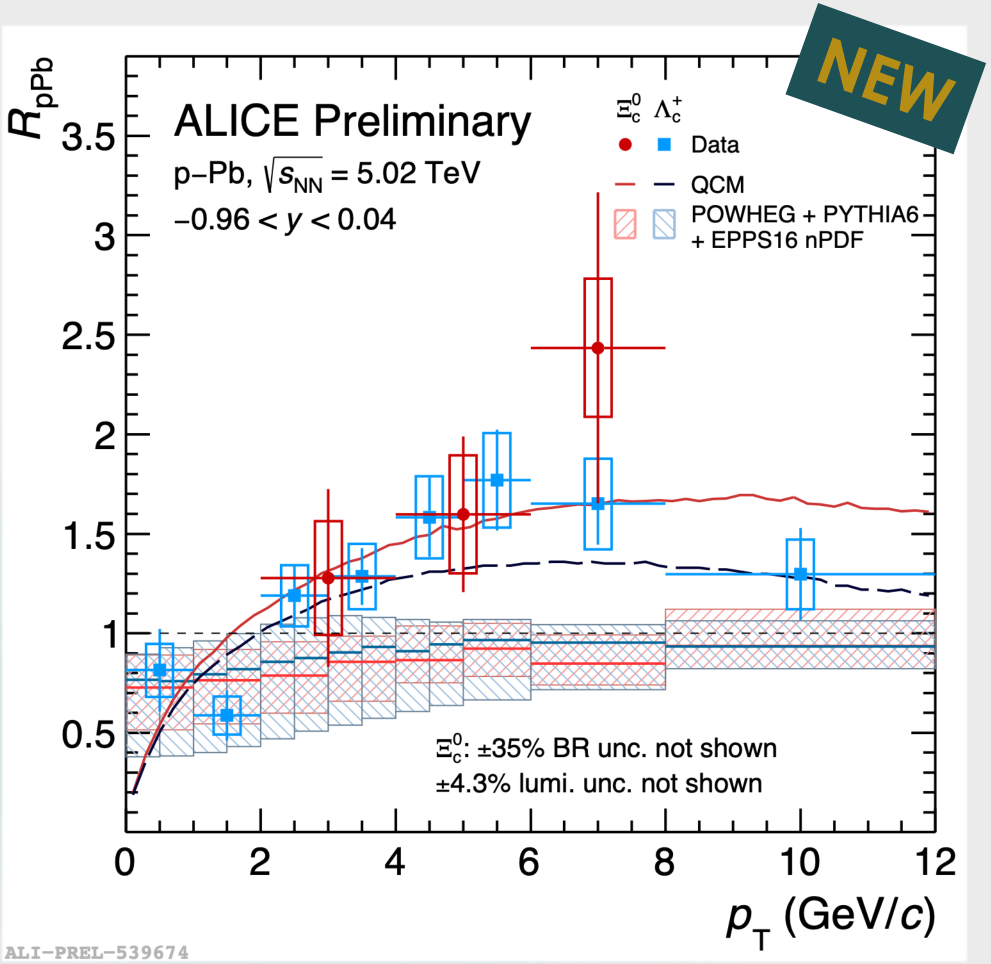


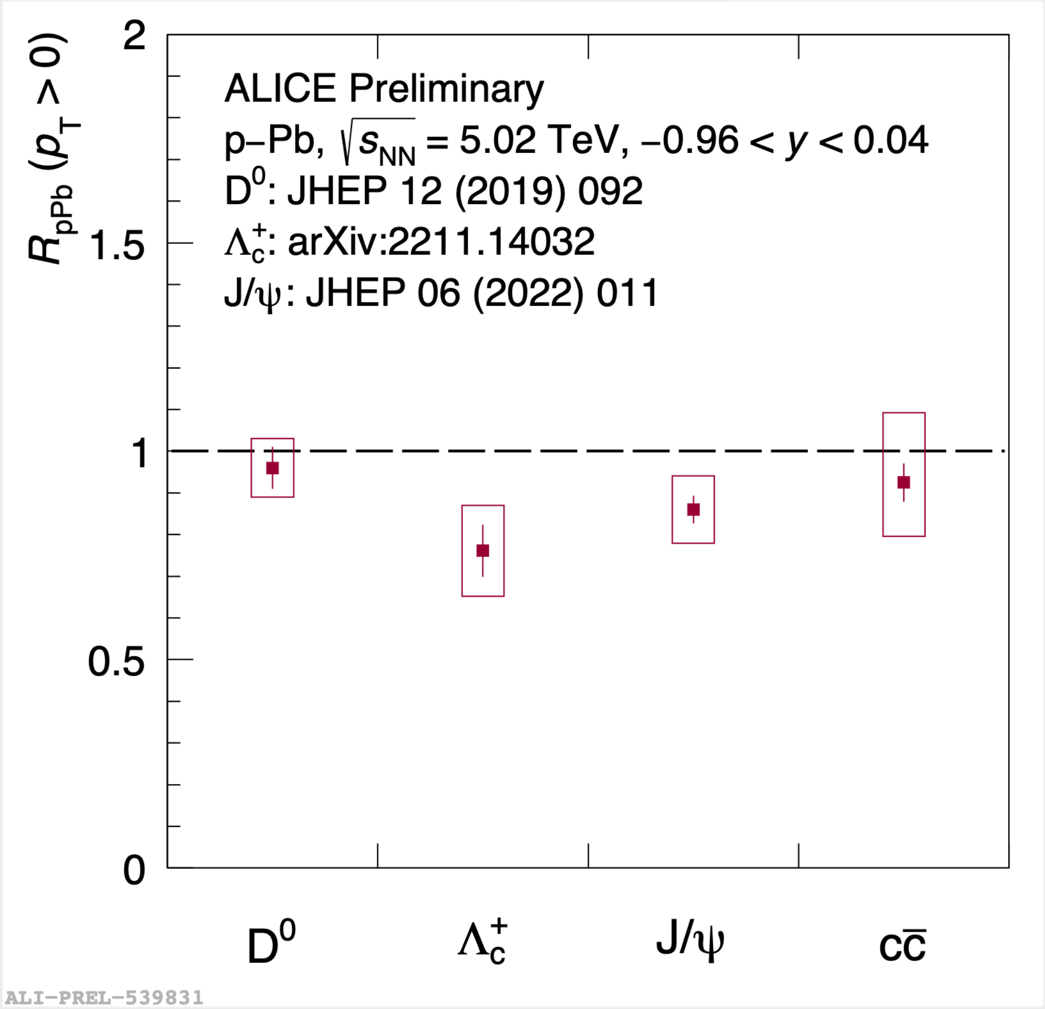
Measured at midrapidity as a sum of ground state charm hadron cross sections

New measurement of $c\bar{c}$ and $b\bar{b}$ cross section at forward rapidity via dilepton spectra at $M_{\mu\mu} > 4\mathrm{GeV}/c$

Nuclear modification factor

c | Λ_c^+, Ξ_c^0





- Total charm R_{pPb} is in agreement with unity
- **Goal:** Study modifications also in Pb–Pb collisions