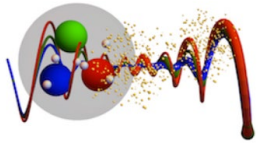
Open and hidden heavy-flavour production in small systems with ALICE



Fabio Colamaria,
INFN Bari

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ALICE

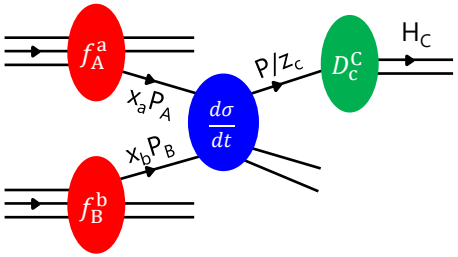
PHYSICS MOTIVATIONS

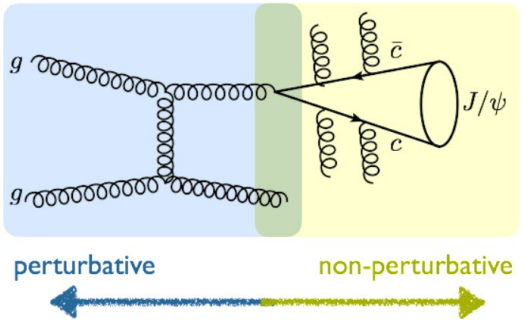
Heavy quarks produced in **hard-scattering processes** in the collision early stages

- Large Q^2 transfer → perturbative process → **test of pQCD** calculations
- Open heavy-flavour hadron production cross section calculated using the **factorisation approach**
  - **Fragmentation functions** assumed **universal** across different collision systems

$$E_C \frac{d^3\sigma}{dp_C^3}(AB \to CX) \propto \sum_{abcd} \int_0^1 dx_a \int_0^1 dx_b \; f_A^a(x_a, Q^2) f_B^b(x_b, Q^2) \; \frac{d\sigma}{dt}(ab \to cd) \; D_c^C(z_c, Q^2)$$

PDF — Partonic x-section — Fragmentation function





Quarkonium production involves different scales

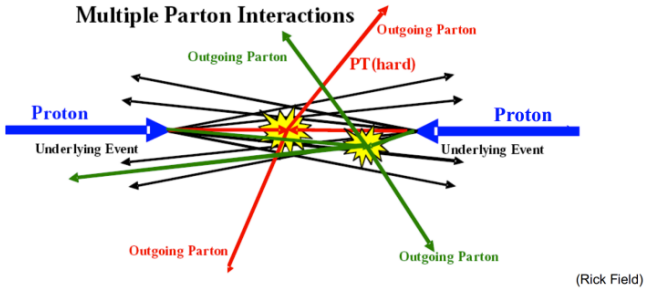
- **Hard scale**: heavy-quark production from hard scattering
- **Soft scale**: binding of $Q\bar{Q}$ pairs into a colorless final state

Different models of quarkonium formation: e.g. Colour Evaporation Model (CEM), Non-Relativistic QCD (NRQCD)

PHYSICS MOTIVATIONS

Ratio of particle species (baryon-to-meson, strange-to-non-strange):

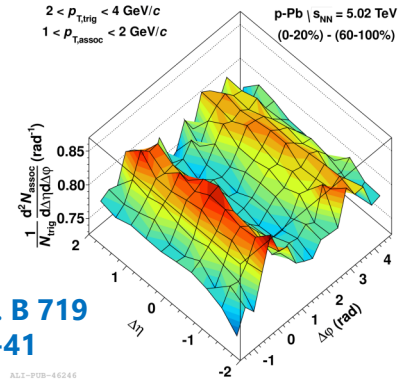
- Observables sensitive to **heavy-quark hadronisation**
- **FF universality questioned** by recent LHC measurements, several explanations proposed by theorists
  - More precise/additional data can discriminate among the different theoretical models



(Rick Field)

Measurements of HF as a function of event multiplicity:

- Understand the **interplay** of **hard and soft processes** in particle production
- Investigate the role of **multiple-parton-interaction** (**MPI**) on heavy-flavour production



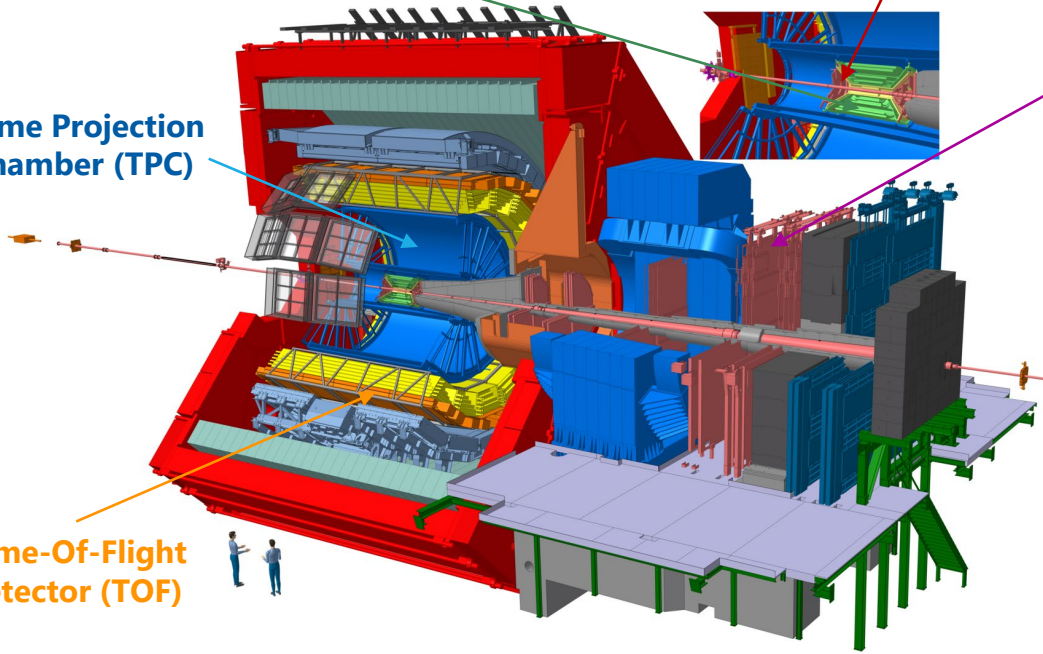
For high-multiplicity pp and p-Pb events, hints of collective behaviour:

- Study **similarities** in small systems and Pb-Pb collisions
- Understand the behaviour across system size via multiplicity-dependent analyses
- Investigate the **source** of collective-like effects (initial or final state?)

Phys. Lett. B 719 (2013) 29-41

THE ALICE EXPERIMENT

A multi-purpose experiment at the LHC, with excellent PID capabilities and tracking down to ≈100 MeV/*c*
Main focus on heavy-ion studies, but rich physics programme also for small systems



HF mesons

$D^0 \to K^- \pi^+$
$D^+ \to K^- \pi^+ \pi^+$
$D^{*+} \to D^0 \pi^+$
$D_s^+ \to \phi \pi^+ \to K^- \pi^+ \pi^+$
$J/\psi \to e^- e^+$
$J/\psi, \psi(2S) \to \mu^- \mu^+$
$\Upsilon(1S, 2S, 3S) \to \mu^- \mu^+$
$D \to e(\mu) X$
$B \to e(\mu) X$

HF baryons

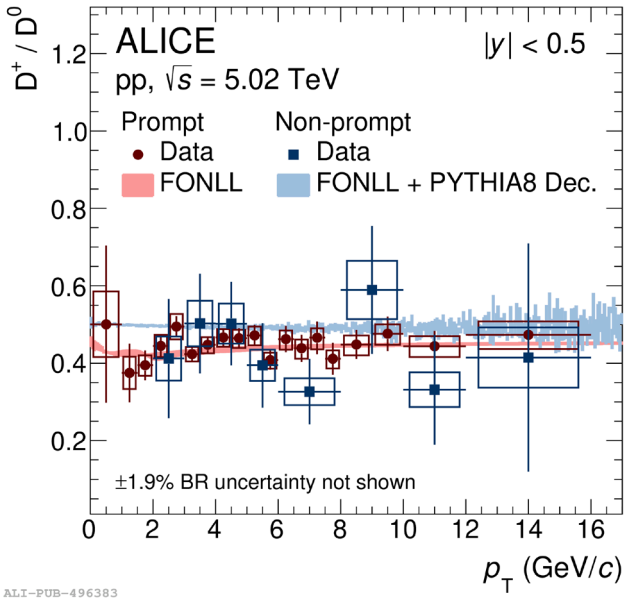
$\Lambda_c^+ \to K_S^0 p$
$\Lambda_c^+ \to \pi^+ K^- p$
$\Xi_c^0 \to \Xi^- e^+ \nu_e$
$\Xi_c^0 \to \Xi^- \pi^+$
$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$
$\Omega_c^0 \to \Omega^- \pi^+$
$\Sigma_c^{0,++} \to \Lambda_c^+ \pi^{-,+}$

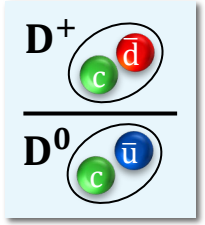
HEAVY-QUARK HADRONIZATION STUDIES

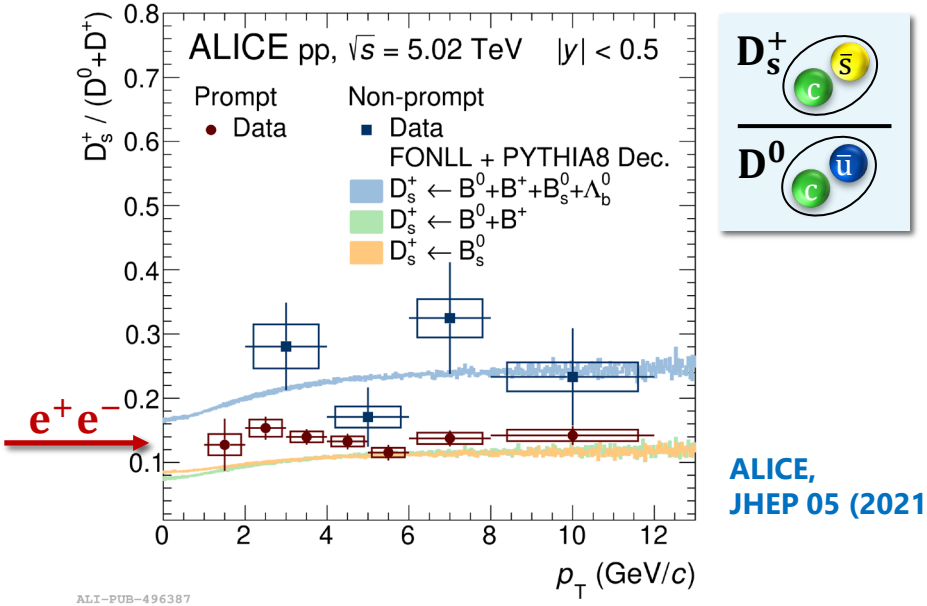
Open and hidden heavy-flavour production in small systems with ALICE

13th MPI@LHC - 17/11/2022

D-MESON YIELD RATIOS IN pp COLLISIONS





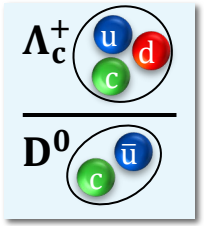


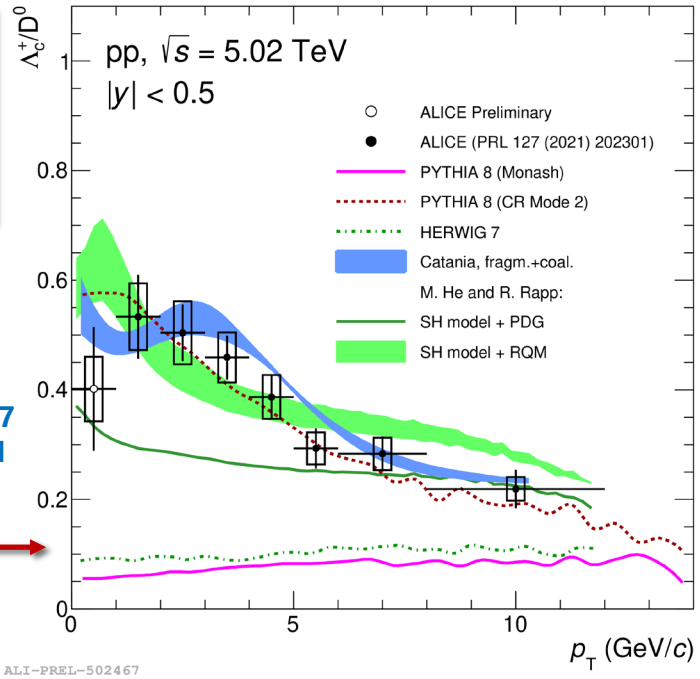
ALICE, JHEP 05 (2021) 220

- **FONLL calculations** (pQCD) correctly **describe** the data
  - Using fragmentation functions evaluated from e^+e^-, e^-p measurements
- Meson-to-meson ratios **independent of p_T** and collision system
- Higher $D_s^+/(D^0+D^+)$ ratios for non-prompt mesons, due to relevant contribution to D_s^+ from B^0, B^+ decays

FONLL: M. Cacciari et al, JHEP 10 (2012) 137
PYTHIA 8 :P. Skands, et al., EPJC 74 (2014) 3024

PROMPT Λ_c^+/D^0 YIELD RATIOS IN pp COLLISIONS





p_T>1 GeV/c: ALICE, PRL 127 (2021) 202301

e^+e^-

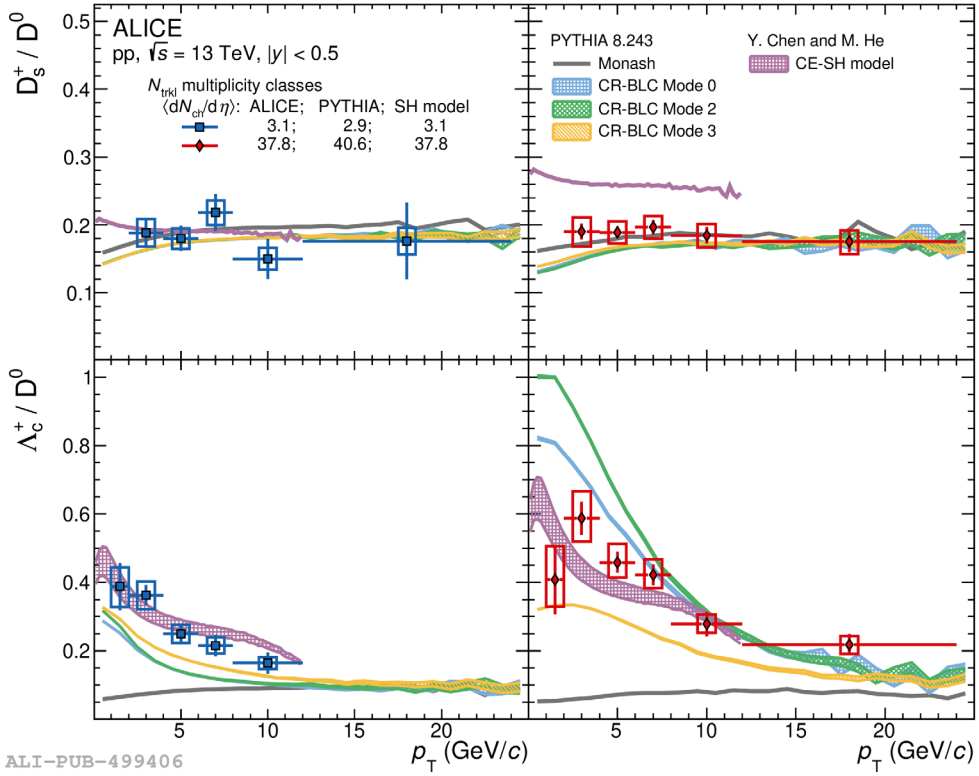
- First Λ_c^+ measurement down to $p_T = 0$
- Ratio **significantly higher** than in e^+e^- and e^-p collisions

LEP average value: **0.113 ± 0.013 ± 0.006**
(L. Gladilin, EPJC 75 (2015) 19)

- **Strong p_T dependence**, as for baryon-over-meson ratios in light-flavour sector
- Ratio **underestimated** by models with **FF tuned on e^+e^-, e^-p** collisions (**PYTHIA 8 Monash**, **Herwig 7**)
- Proper description by models with modified fragmentation or augmented feeddown from higher-mass states:
  - **PYTHIA 8 with updated CR modelling** → "Junction" topologies enhance charm-baryon production
  - **Catania model** → Thermalised system of light quarks and gluons, hadronization via coalescence+fragmentation
  - **Statistical Hadronization Model + Relativistic Quark Model** → large feed-down contribution from augmented set of excited charm baryons, not yet observed

PYTHIA 8 Monash: P. Skands, et al., EPJC 74 (2014) 3024
PYTHIA 8 CR Tunes: J. Christiansen, et al., JHEP 08 (2015) 003
Herwig: Eur.Phys.J. C76 (2016) no.4, 196
SHM: M. He and R. Rapp, PLB 795 (2019) 117-121
RQM: D. Ebert, et al., PRD 84:014025, 2011
Catania: V. Minissale, et al., PLB 821 (2021) 136622

PROMPT Λ_c^+/D^0 YIELD RATIOS VS MULTIPLICITY



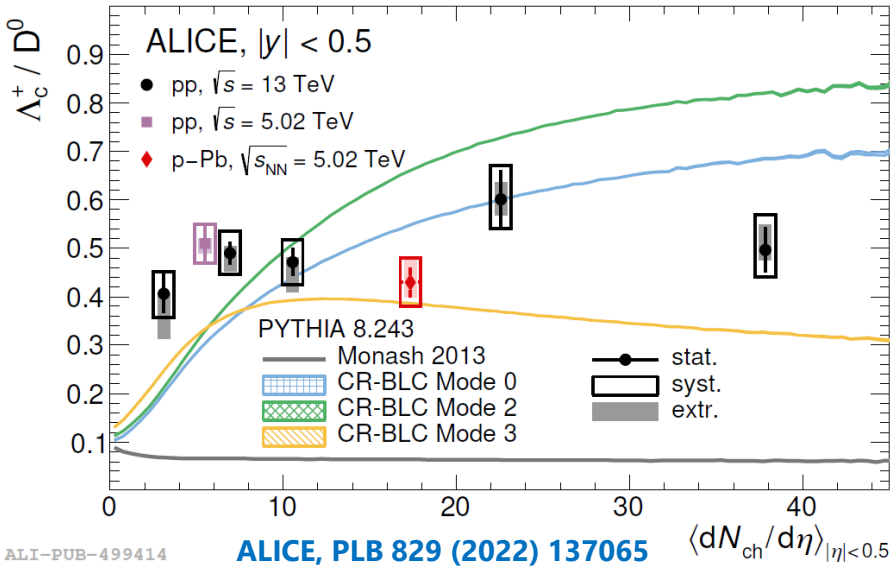
ALICE, PLB 829 (2022) 137065

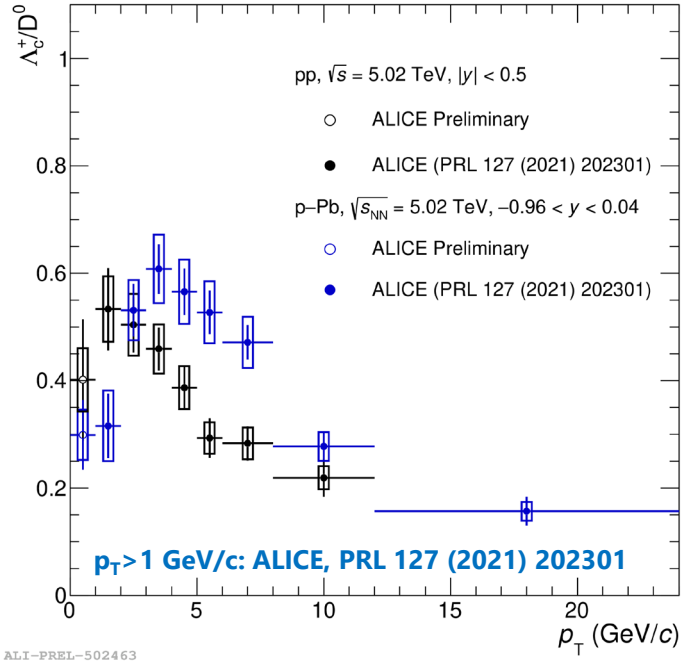
Does this feature evolve with event multiplicity?

- Λ_c^+/D^0 ratios at intermediate p_T larger for highest multiplicity than for lowest multiplicity
  - **5.3σ significance** for $1 < p_T < 12$ GeV/c
- p_T and multiplicity dependence qualitatively described by:
  - **PYTHIA with colour reconnection** beyond leading-colour approximation (CR-BLC)
  - **CE-SH,** a statistical hadronization model with particle set from RQM
- No multiplicity dependence for D_s^+/D^0 ratios

PYTHIA 8 Monash: P. Skands, et al., EPJC 74 (2014) 3024
PYTHIA 8 CR Tunes: J. Christiansen, et al., JHEP 08 (2015) 003
CE-SH: Phys. Lett. B 815 (2021) 136144

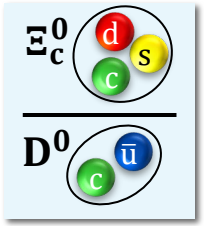
PROMPT Λ_c^+/D^0 YIELD RATIOS IN DIFFERENT SYSTEMS

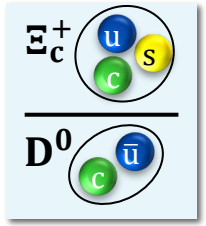


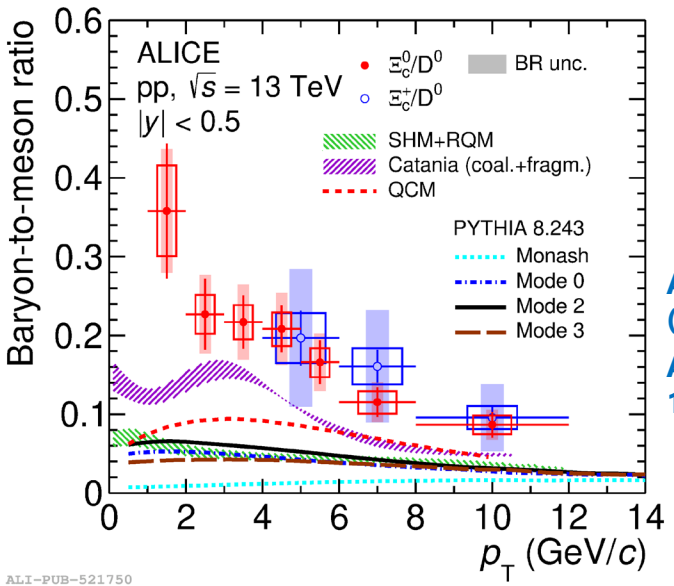


- p_T-integrated Λ_c^+/D^0 ratios **independent of multiplicity**
  - Different p_T redistribution between baryons and mesons rather than overall baryon yield enhancement
- In p-Pb collisions, **larger Λ_c^+/D^0 ratios** for **p_T > 3 GeV/c** (different p_T spectrum)
  - Possible contribution from collective-like effects (as radial flow)?

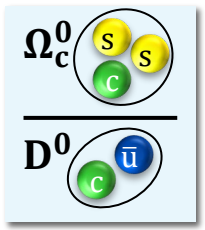
HEAVIER BARION YIELD RATIOS TO D⁰ IN pp COLLISIONS







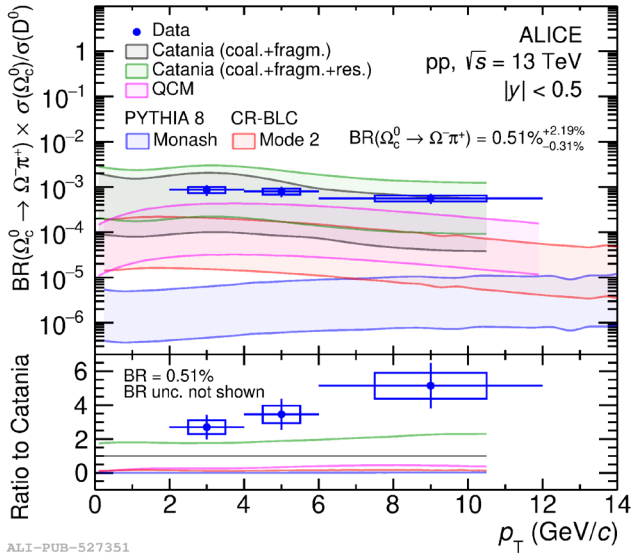
QCM: J. Song, et al., EPJC (2018) 78: 344



ALICE, PRL 127 (2021) 271001

ALICE, JHEP 10 (2021) 159

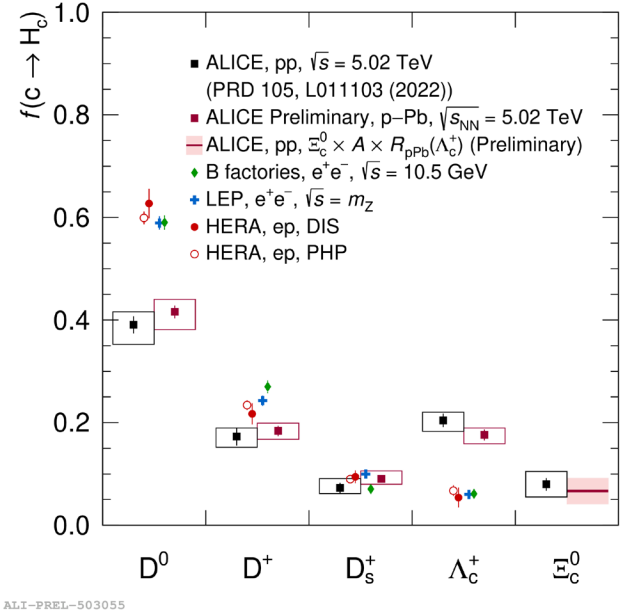
ALICE, arXiv:2205.13993

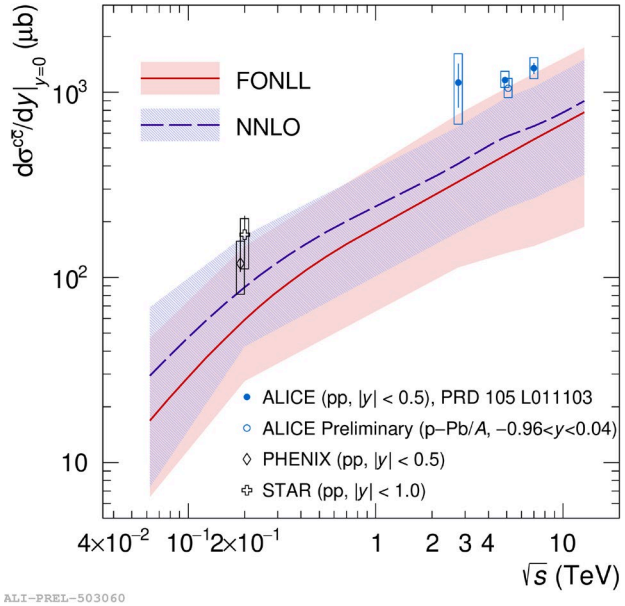


BR($\Omega_c^0 \rightarrow \Omega^-\pi^+$) from theory calculations

- Heavier baryon-to-meson ratios **underestimated by PYTHIA8 Monash** by several orders of magnitude
- **PYTHIA 8 with CR-BLC** modes and **SHM+RQM** models also not able to correctly reproduce the data
- Coalescence-based models get closer to measurements: **Catania** qualitatively describe the data, **QCM** underestimates them but by a lesser extent

CHARM PRODUCTION AND FF IN SMALL SYSTEMS



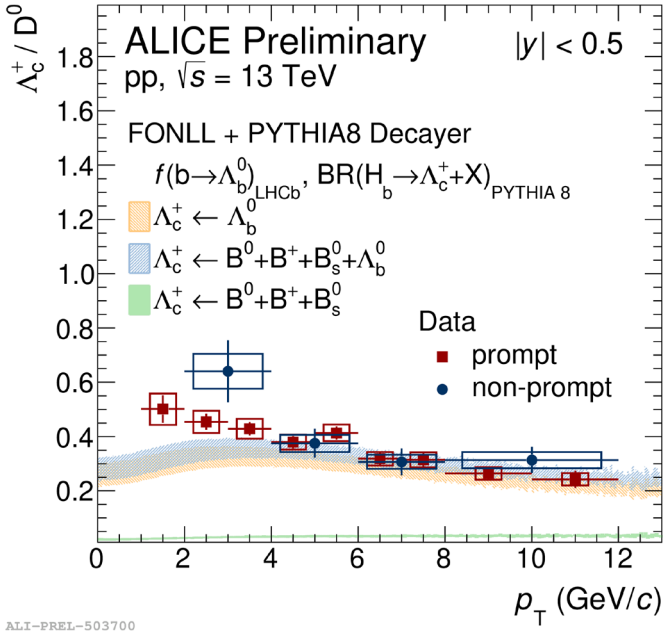


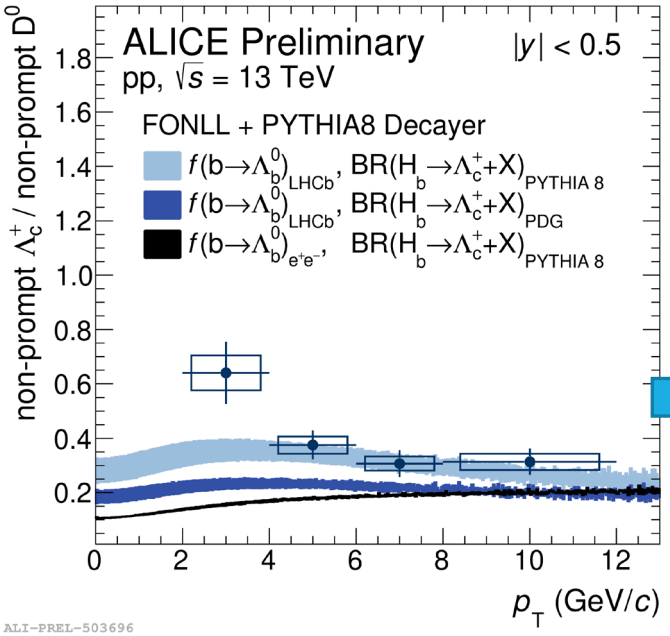
Charm fragmentation fractions:

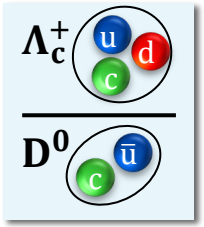
- pp collisions at $\sqrt{s}$ = 5.02 TeV:
  - Published in PRD 105 (2022) 1, L011103
- p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV:
  - **D^0**, **Λ_c^+**: measured from p_T = 0
  - **D^+**, **D_s^+**: extrapolated to p_T = 0 using POWHEG+PYTHIA
  - **Ξ^0_c**: not measured yet:
    - $\sigma_{pp}(\Xi^0_c) \times 208 \times R_{pPb}(\Lambda^+_c)$

- **Compatibility** between **pp and p-Pb** fragmentation fractions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - Significant baryon enhancement w.r.t. e^+e^- and e^-p: **charm fragmentation functions are not universal!**
- **$c\bar{c}$ production cross section** in $|y| < 0.5$ in pp at $\sqrt{s}$ = 5.02 TeV measured by summing all charm ground states
  - Updated results at $\sqrt{s}$ = 2.76 TeV, 7 TeV, all points on **upper edge of pQCD calculations**

NON-PROMPT Λ_c^+/D^0 YIELD RATIOS IN pp COLLISIONS







Dominant contribution to non-prompt Λ_c^+ from Λ_b^0 decays

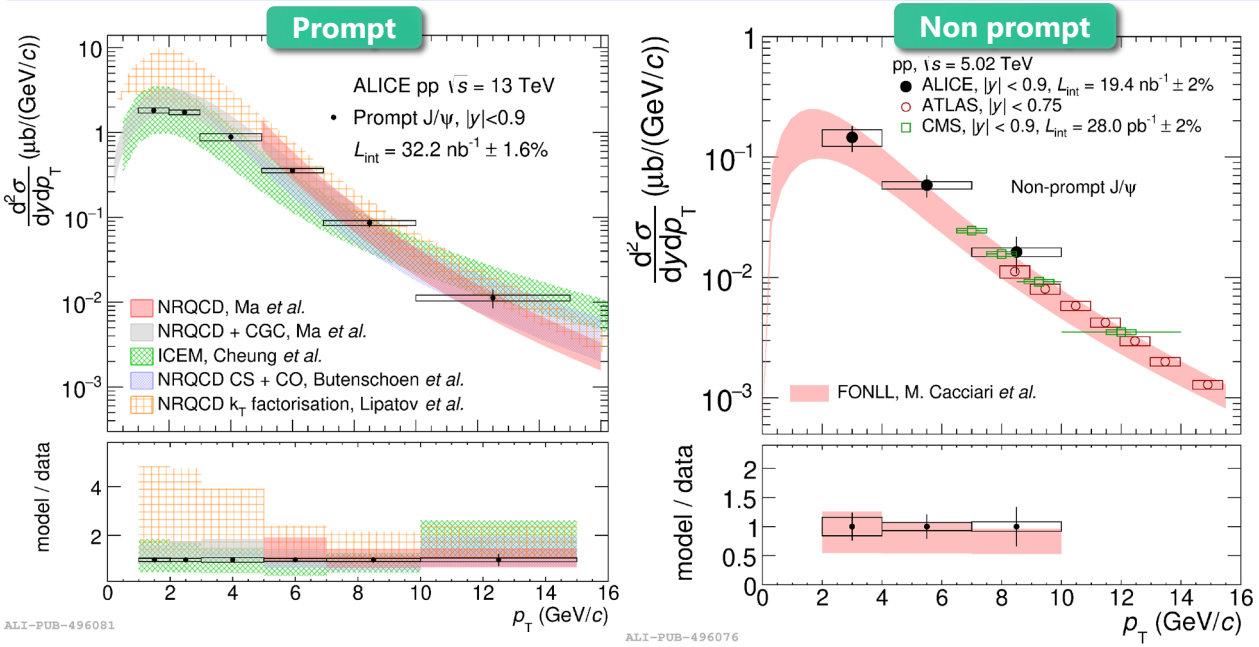
- Provides access to the fragmentation of beauty quarks
- **Enhanced beauty-baryon production** w.r.t. e+e- collisions → **suggests non-universality also of $f(b \to H_b)$**
  - Ratio well described by FONLL using LHCb FF and PYTHIA8 decay table for p_T > 4 GeV/c
- Similar p_T dependence for prompt and non-prompt Λ_c^+/D^0 ratios

HEAVY-FLAVOUR PRODUCTION AND MULTIPLICITY DEPENDENCE

Open and hidden heavy-flavour production in small systems with ALICE

13th MPI@LHC - 17/11/2022

J/Ψ PRODUCTION AT MIDRAPIDITY



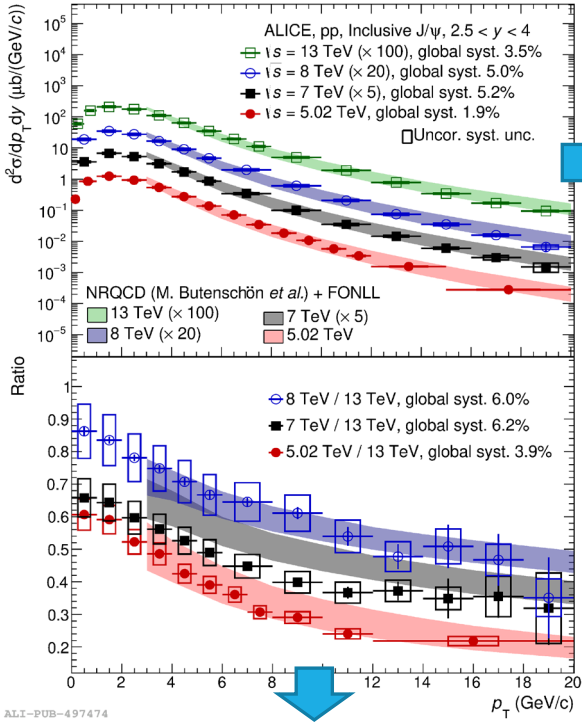
- **Prompt** and **non-prompt J/Ψ** production cross section measured at midrapidity from e^+e^- decays:
  - At $\sqrt{s}$ = **13 TeV** for p_T>1 GeV/c
  - At $\sqrt{s}$ = **5.02 TeV** for p_T>2 GeV/c

ALICE, JHEP 03 (2022) 190

NRQCD: PRL 106 (2011) 042002
NRQCD+CGC: PRL 113, 19, (2014) 192301
NRQCD CS+CO: PRL 106 (2011) 022003
NRQCD kT fact: Phys. Rev. D 100, 11, (2019) 114021
ICEM: Eur. Phys. J. C 80 no. 4, (2020) 330

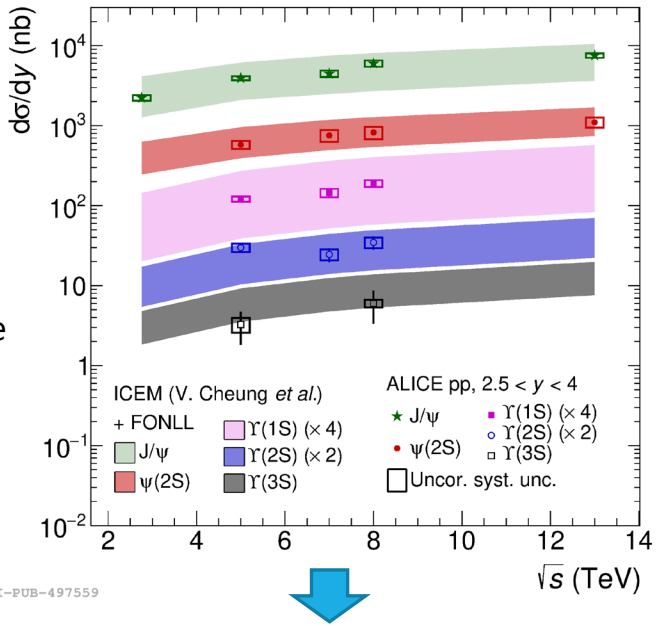
- **Prompt J/Ψ** production cross section: **NRQCD** and **ICEM** models **in agreement** with measurements, NRQCD Lipatov calculations slightly overestimates data at low p_T
- **Non-prompt J/Ψ** production cross section **well described by pQCD** calculations (FONLL)
- Results consistent with CMS and ATLAS measurements in the common p_T range

QUARKONIUM PRODUCTION AT FORWARD RAPIDITY



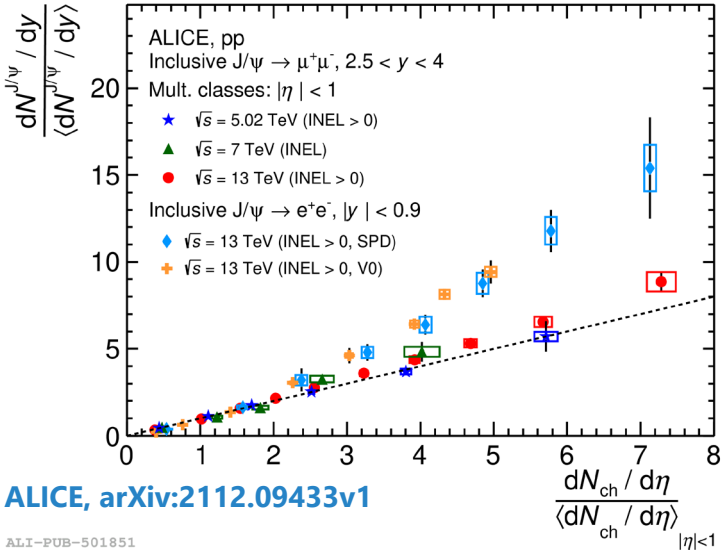
- **Inclusive J/Ψ** production cross section at **forward rapidity** from $\mu^+\mu^-$ decay channel:
  - Down to $p_T = 0$
  - At $\sqrt{s}$ = 5.02, 7, 8, and 13 TeV
- Cross section (and its hardness) increase with increasing collision energy
- **Good description** provided by **NRQCD+FONLL** calculations and **ICEM** (not shown)

ALICE, arXiv:2109.15240



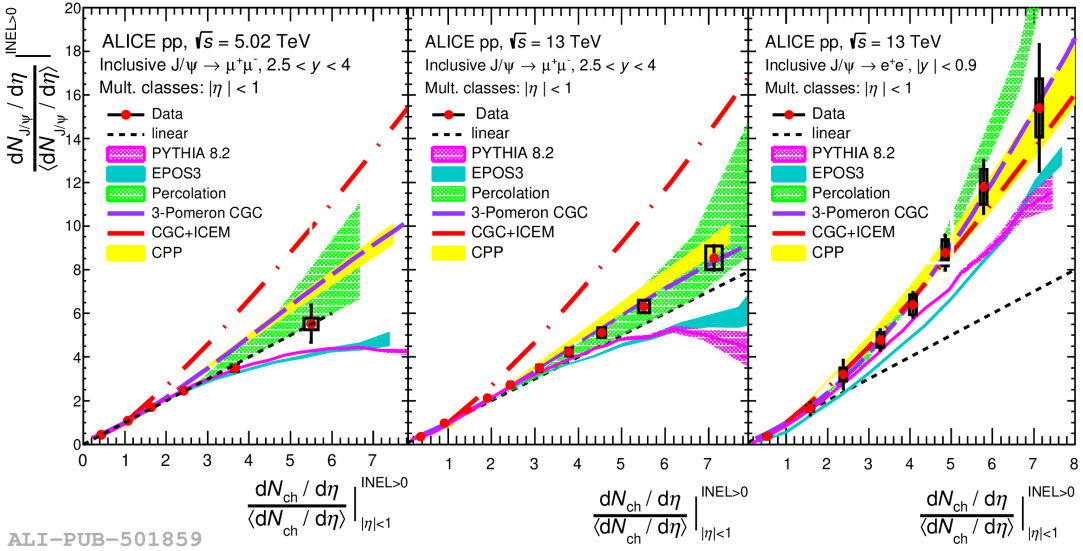
- Cross-section ratios vs p_T well reproduced by NRQCD for 8-to-13 TeV and 5-to-13 TeV, slight overestimation of 7-to-13 TeV ratio
- Behaviour of $q\bar{q}$ **production vs energy well reproduced** by **ICEM** calculations for different quarkonium species

J/Ψ PRODUCTION VS MULTIPLICITY



ALICE, arXiv:2112.09433v1

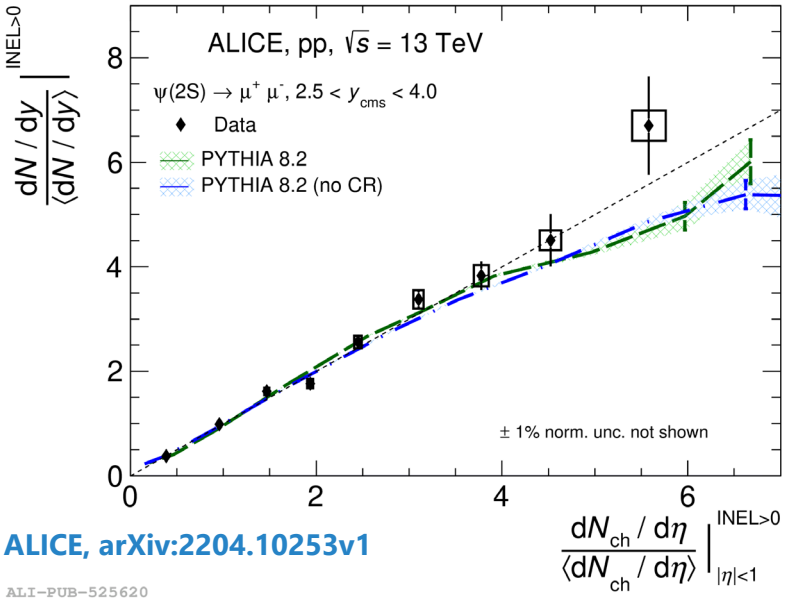
ALI-PUB-501851



ALI-PUB-501859

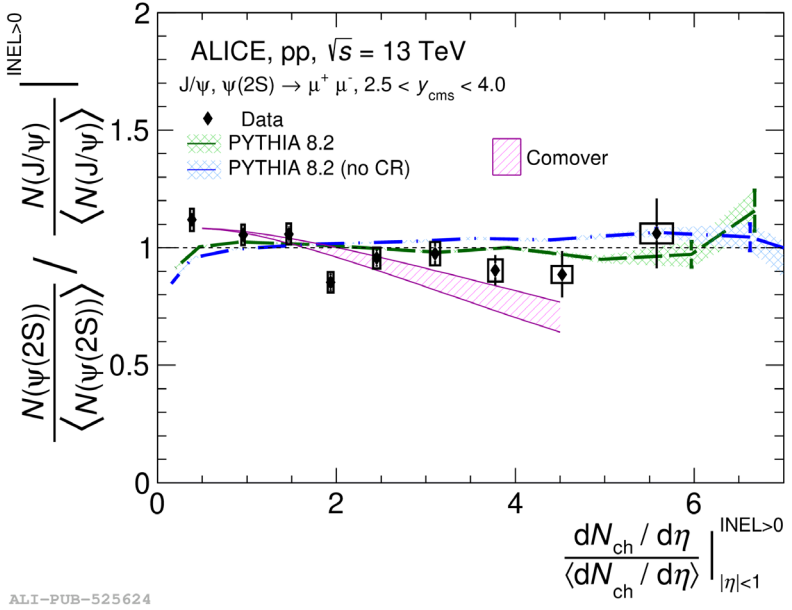
- **Forward-rapidity** J/Ψ production **increasing linearly** with multiplicity (no energy dependence), while **midrapidity** production shows a **faster-than-linear** growth
- **Faster-than-linear increase** at midrapidity predicted by models including different initial- or final-state mechanisms:
  - MPI interactions with color reconnection, gluon saturation, coherent particle production, 3-gluon fusion, percolation
  - CPP, CGC+ICEM, and 3-Pomeron models provide the best description of midrapidity measurements
- CPP and 3-Pomeron models correctly reproduce also the results at forward rapidity, together with percolation model

Ψ(2S) PRODUCTION VS MULTIPLICITY



ALICE, arXiv:2204.10253v1

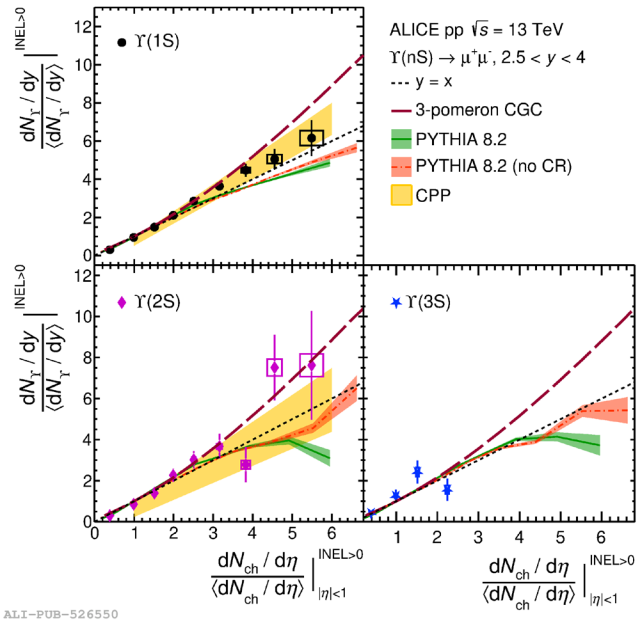
ALI-PUB-525620

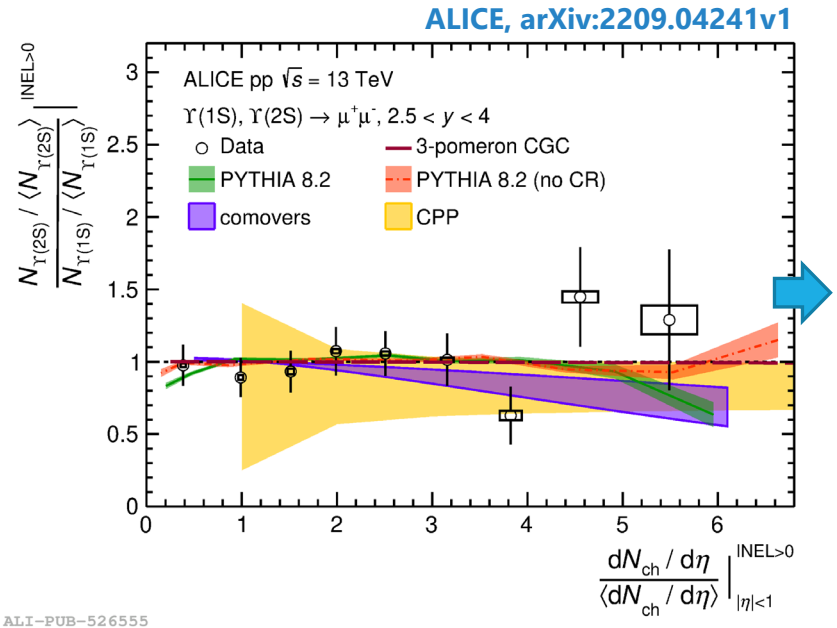


ALI-PUB-525624

- **Inclusive ψ(2S)** production at **forward rapidity** also shows a **linear dependence** with midrapidity multiplicity:
  - Well described by PYTHIA, with/without color reconnection, with some tension at high multiplicity
- **ψ(2S)/J/ψ** double ratio **compatible with unity** → Production at forward rapidity **independent of charmonium state**
  - Comover model in agreement with data within uncertainties, tension with PYTHIA at low multiplicity

BOTTOMONIUM PRODUCTION VS MULTIPLICITY



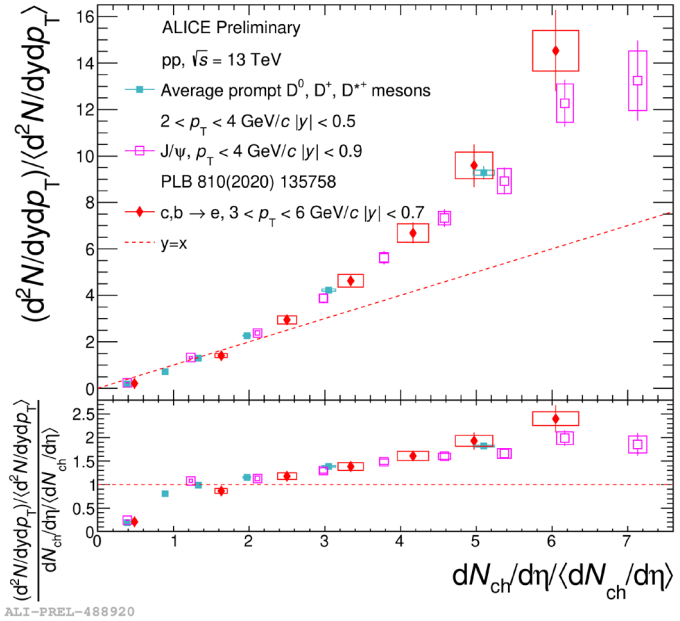


CPP: Eur. Phys. J. C 80 no. 6, (2020) 560
Comovers: Phys. Lett. B 749 (2015) 98–103

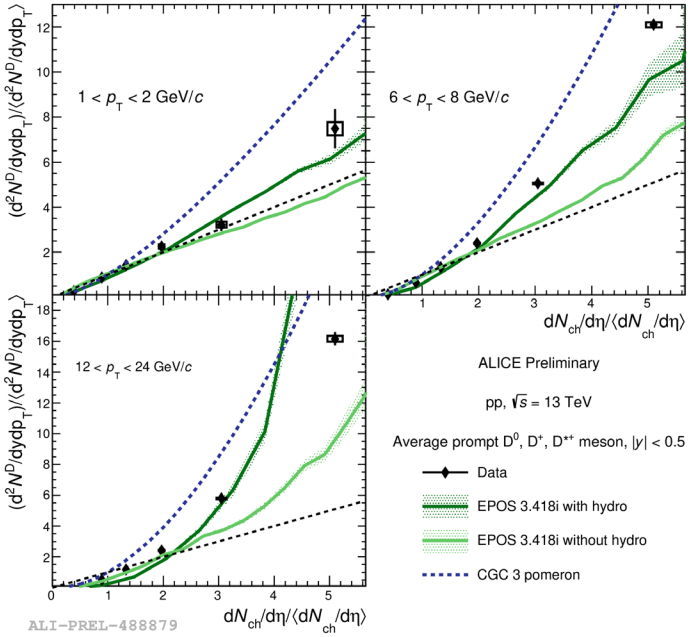
Y(2S)/Y(1S) and Y(3S)/Y(1S) ratios consistent with unity and described by all models within uncertainties

- **Self-normalized Y(1S), Y(2S), Y(3S) yields** and their ratios as a function of event multiplicity, at forward rapidity:
  - Higher-mass states (lower binding energy) **more sensitive** to possible **final-state dissociation** mechanisms
- **Linear increase** of yields with event multiplicity **for all states**
  - Good description of data from all models up to 4·<$dN_{ch}/d\eta$>, models diverge at larger multiplicites

D-MESON PRODUCTION VS MULTIPLICITY



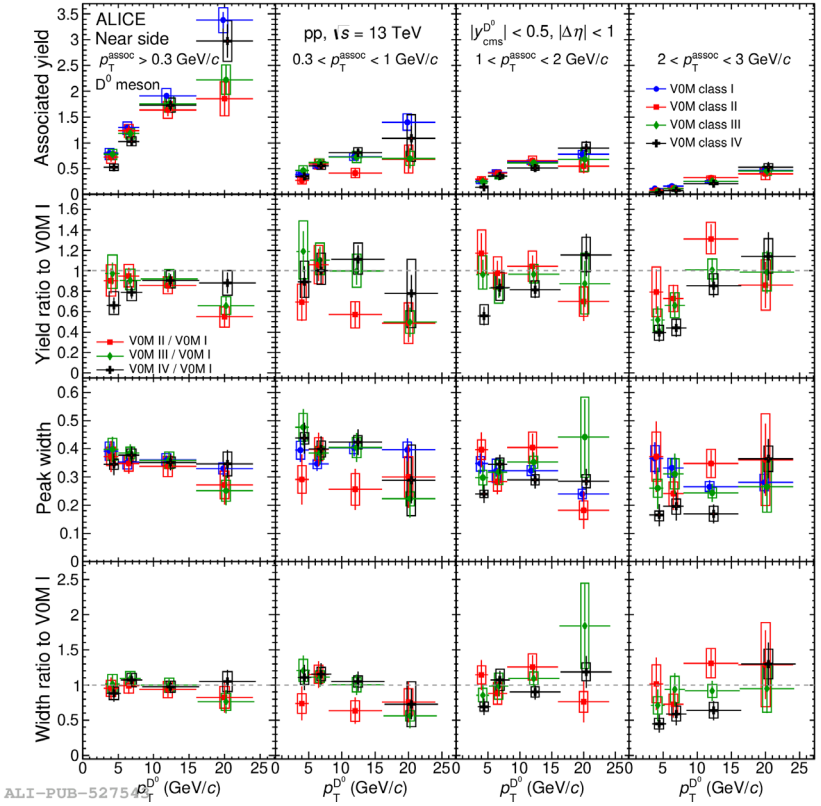
- **Prompt D-meson** self-normalized yields at midrapidity in pp collisions at $\sqrt{s}$ = 13 TeV
- **Faster-than-linear** increase with increasing multiplicity
  - Consistent with other ALICE **open and hidden** HF measurements at $y \approx 0$
  - Points towards a feature of **charm production**, rather than hadronisation



- **EPOS 3** predictions **with hydrodynamic component** reproduce the data trend better than EPOS 3 without hydrodynamics, and Colour Glass Condensate (CGC) with the 3 pomeron mechanism
  - None of the above models provides an optimal description of the measurement

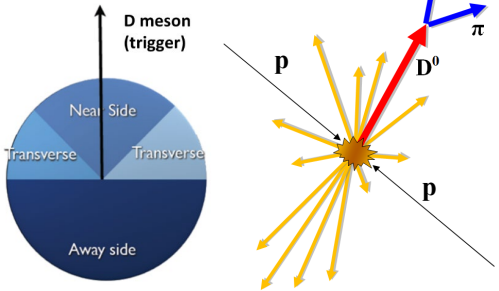
EPOS 3: Phys. Rev. C 89 no. 6, (2014) 064903
CGC: , Eur. Phys. J. C 80 no. 6, (2020) 560

D-h CORRELATIONS VS MULTIPLICITY



V0M classes, I-II-III-IV: higher to lower multiplicities

- What about possible **modifications of charm fragmentation** with multiplicity?
- Measurement of **angular correlations** of prompt D^0 mesons with charged particles in pp collisions at $\sqrt{s}$ = 13 TeV
  - Evaluated near-side peak yields and widths in different forward-rapidity multiplicity ranges
  - **No significant dependence** of peak features with multiplicity observed
- Suggests **similar fragmentation** of charm into hadrons at different event multiplicities, at least when it hadronises to D^0 mesons



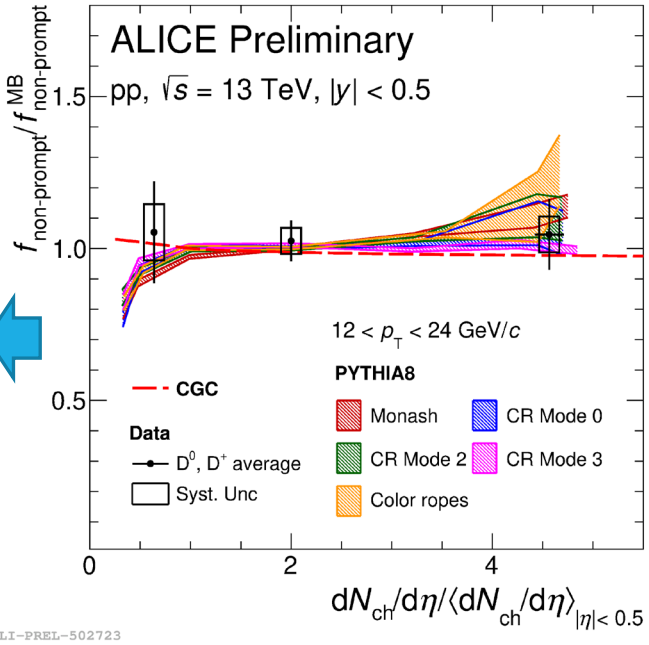
ALICE, Eur. Phys. J. C (2022) 82:335

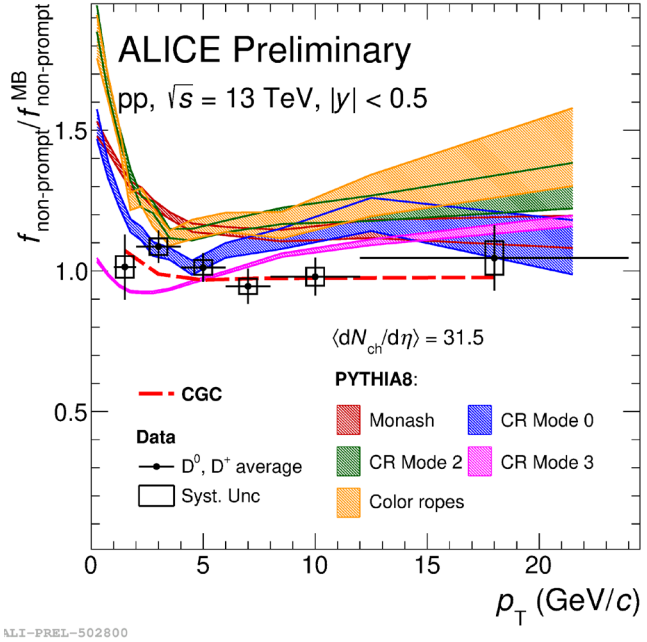
NON-PROMPT D-MESON PRODUCTION VS MULTIPLICITY

What about beauty production dependence on event multiplicity?

$f_{\text{nonprompt}}$: fraction of D-mesons produced from decay of beauty hadrons

PYTHIA 8 Monash: EPJC 74 (2014) 3024
PYTHIA 8 CR Tunes: JHEP 08 (2015) 003
PYTHIA 8, Color ropes: arXiv:2203.11601





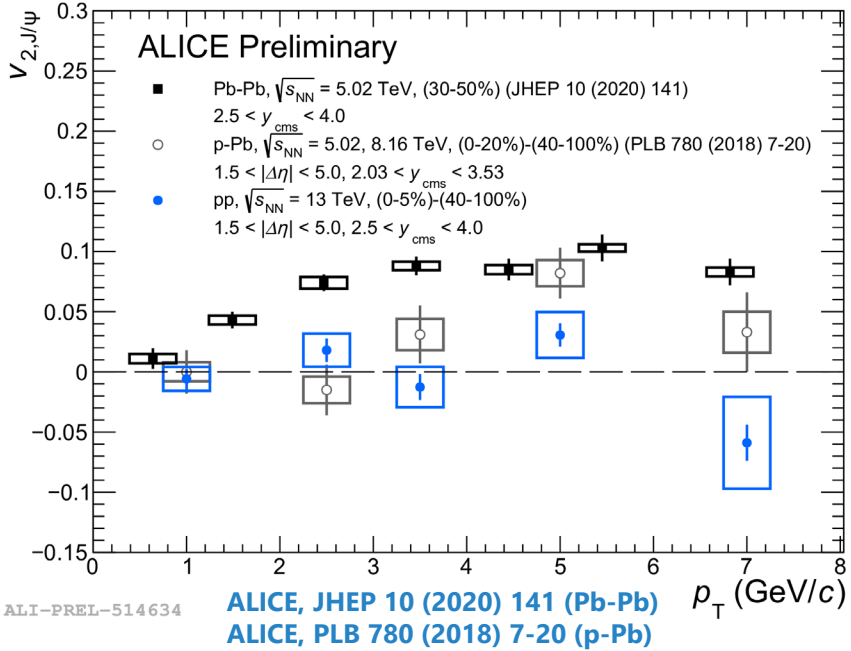
- **No relevant multiplicity dependence** of **non-prompt D-meson fraction** in pp collisions at $\sqrt{s}$ = 13 TeV
- Measurements compatible with CGC framework, qualitative description also provided by PYTHIA 8, with a slight overestimation at high multiplicity by some tunes

COLLECTIVE EFFECTS IN SMALL SYSTEMS

Open and hidden heavy-flavour production in small systems with ALICE

13th MPI@LHC - 17/11/2022

J/Ψ ELLIPTIC FLOW IN SMALL SYSTEMS

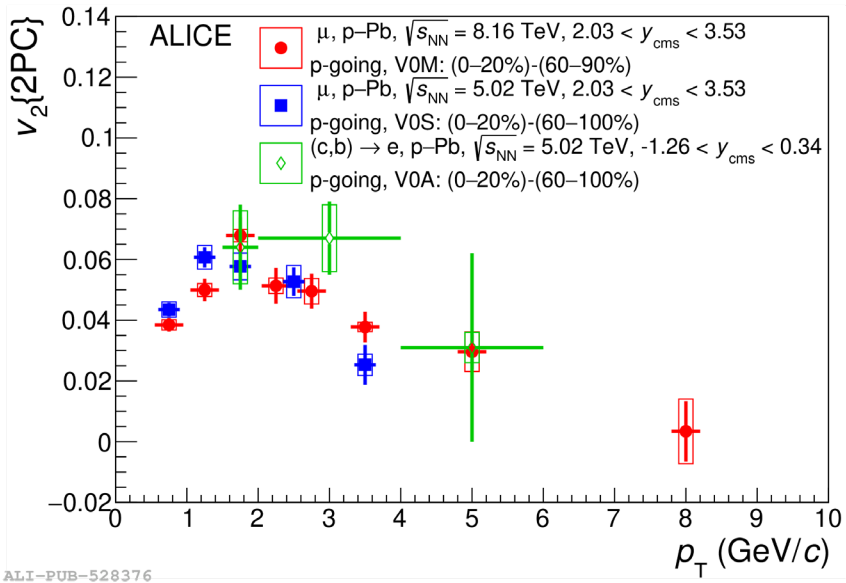


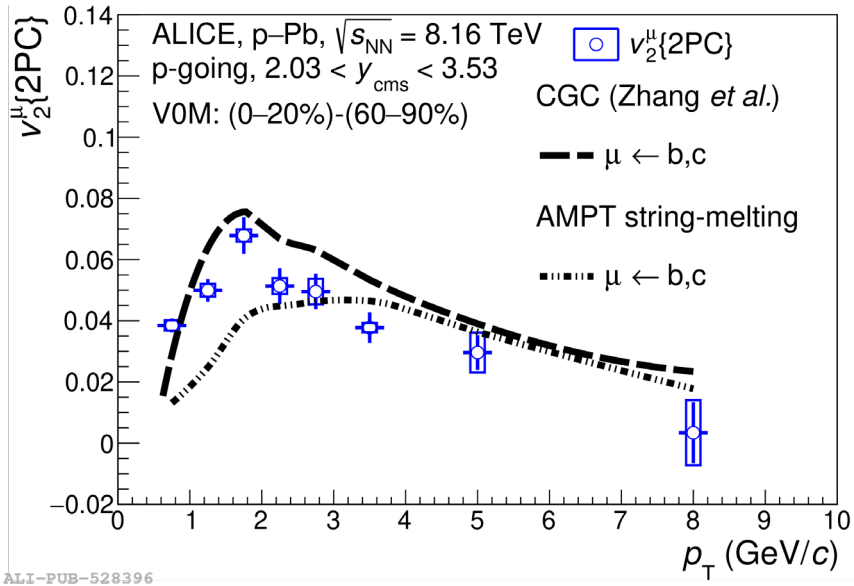
ALICE, JHEP 10 (2020) 141 (Pb-Pb)
ALICE, PLB 780 (2018) 7-20 (p-Pb)

- Investigate the presence of **collective motion** in **high-multiplicity pp and p-Pb** events for J/Ψ, and compare with Pb-Pb results
- **Pb-Pb collisions:**
  - Presence of **strong collective effects**
- **p-Pb collisions:**
  - **Significant flow** for p_T > 3 GeV/c, not explained by transport models
- **pp collisions (new):**
  - **No hints** of collective behaviour observed for J/Ψ within uncertainties

- Presence of **collective behavior** in **p-Pb** and **Pb-Pb**, suggesting a common mechanism at play, still to be understood, with a significant difference w.r.t. pp data
- p-Pb results support what previously observed for open heavy flavour (and light-flavour particles)

OPEN HEAVY-FLAVOUR ELLIPTIC FLOW IN SMALL SYSTEMS

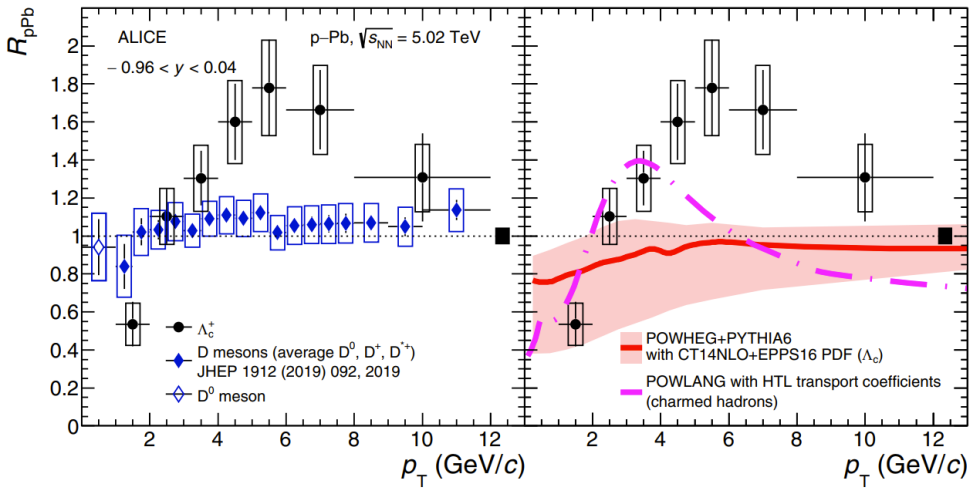


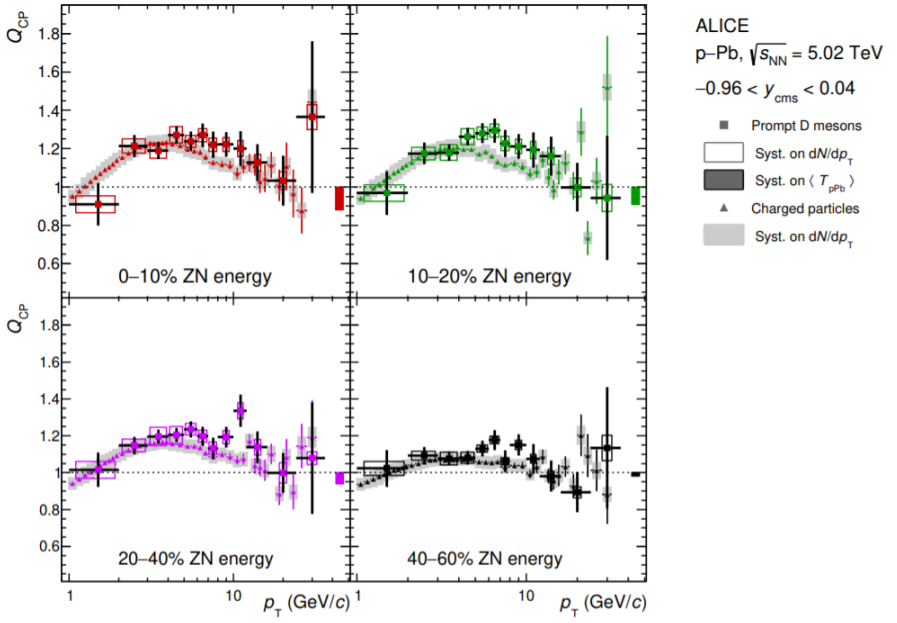


- **Positive v_2** for HF decay **muons** in high-multiplicity p-Pb, consistent with previous HF decay **electron** measurement
  - Feature observed for lower $_{pT}$ than for J/Ψ, but different quark→particle p_T scale + c,b → e,μ decay kinematics
  - Well described by CGC model, and by AMPT from p_T>2 GeV/c
- Collective motion in high-multiplicity p-Pb collisions due to **final-state effects** (QGP droplet)? Or behaviour related to **initial-state effects** (e.g. gluon saturation)?

FURTHER HINTS OF COLLECTIVE EFFECTS IN HF

These observations add up to previous findings of possible collective-like effects in heavy-flavour sector





- R_{pPb} of Λ_c^+ **larger than unity** for $4 < p_T < 8$ GeV/c
  - Potentially also from **radial flow** in p-Pb? Possible effect of **recombination**?
- D-meson $Q_{CP} > 1$, pointing toward possible radial-flow 'push' of D-meson spectra in HM p-Pb
- **Systematic data/theory comparison is needed to understand the source of these features!**
  - Further modellization of HF evolution from small to large systems would be helpful

$$Q_{CP} = \frac{(d^2N^{prompt\,D}/dp_T dy)^{i}_{p-Pb} / \langle T_{pPb} \rangle_i}{(d^2N^{prompt\,D}/dp_T dy)^{60-100\%}_{p-Pb} / \langle T_{pPb} \rangle_{60-100\%}}$$

SUMMARY AND PERSPECTIVES

- Wealth of results released by the ALICE Collaboration exploiting **Run 2 pp and p–Pb** data, providing relevant findings on heavy-flavour behaviour in small systems

- **Open heavy-flavour**:
  - Baryon-to-meson ratios and baryon fragmentation fractions in pp and p-Pb collisions **significantly larger** than in e^+e^-, e^-p collisions
  - **Charm fragmentation fractions are not universal** across the collision systems

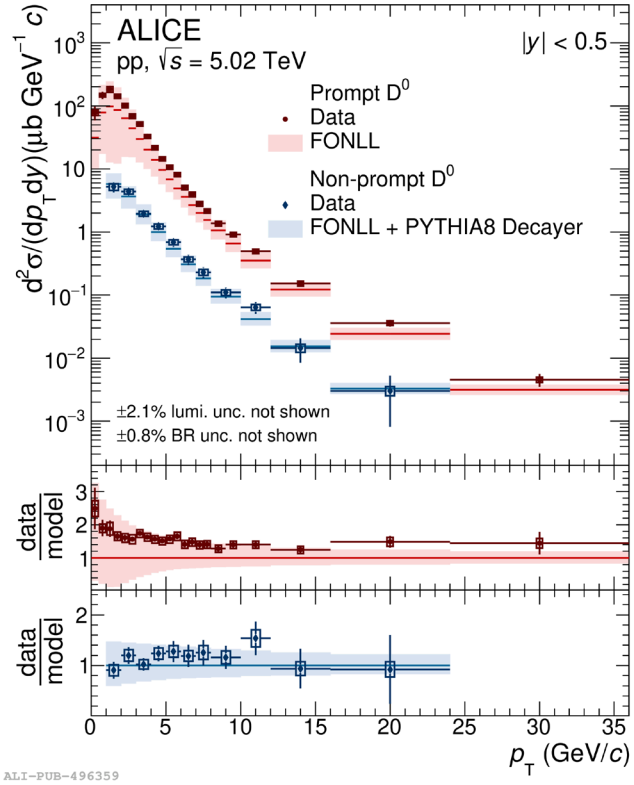
- **Quarkonium**:
  - **Different correlation to event multiplicity** for quarkonium production at **forward** and **midrapidity**
  - Observed **positive elliptic flow** in high multiplicity **p-Pb collisions** (as for open HF), **no evidence** of collective motion in high-multiplicity **pp collisions**

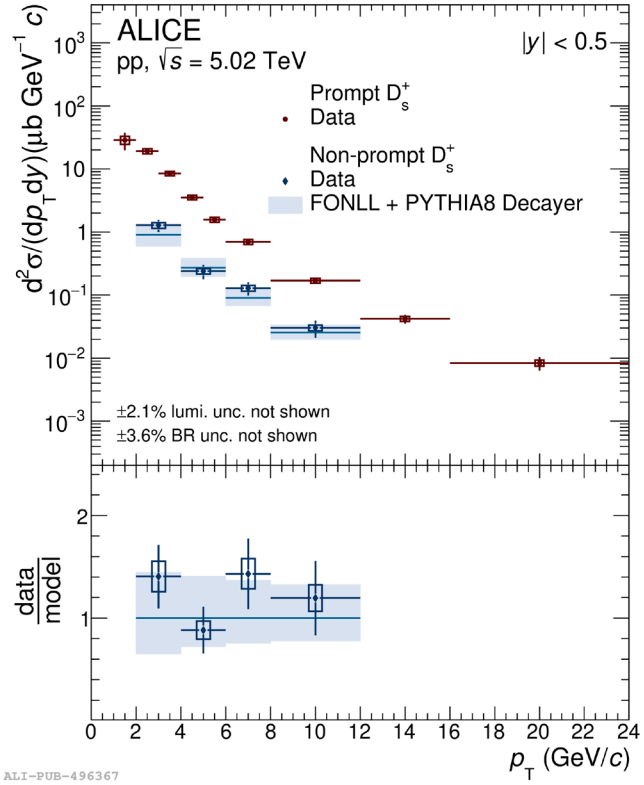
- ALICE Collaboration **ready to analyze Run 3 data** to shed light on the currently open questions

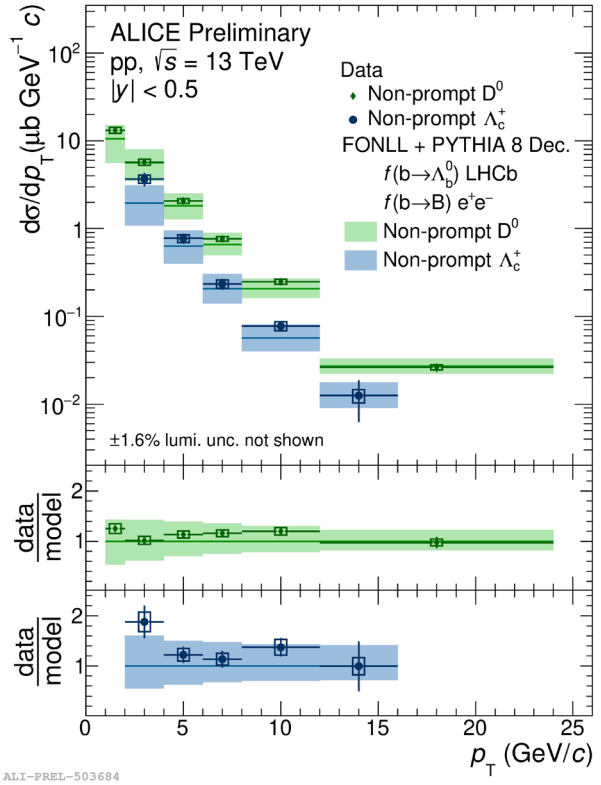
BACKUP SLIDES

BEAUTY PRODUCTION AT MIDRAPIDITY

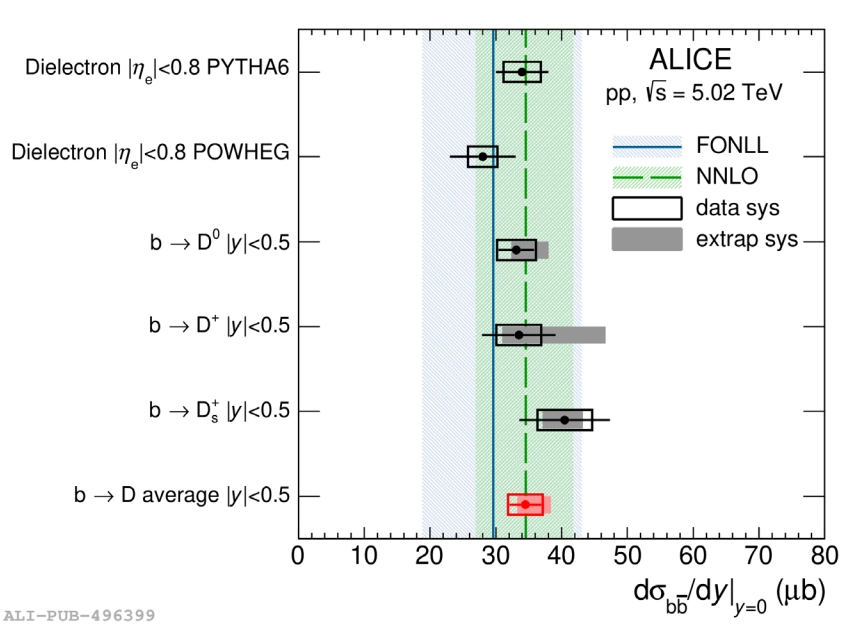
ALICE, JHEP 05 (2021) 220

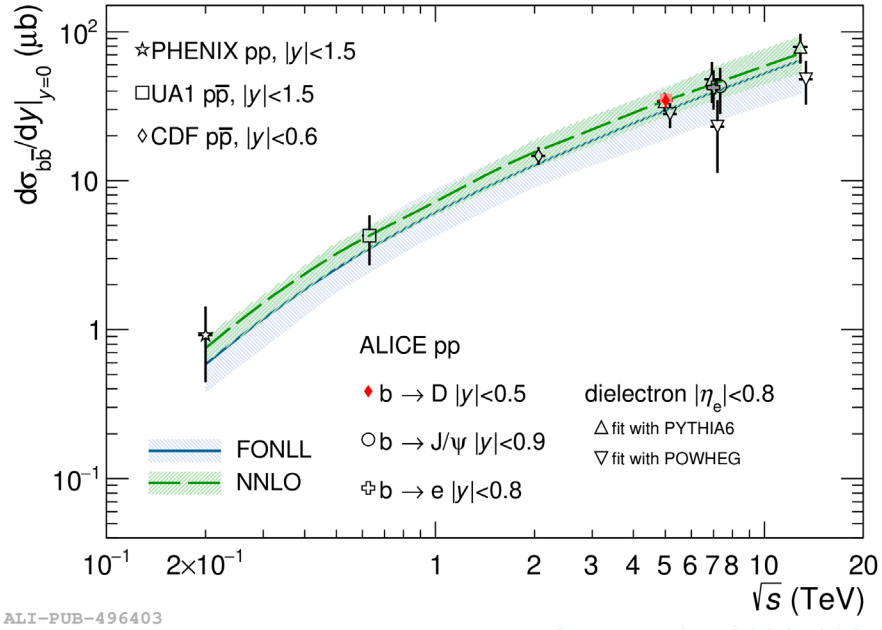






BEAUTY PRODUCTION AT MIDRAPIDITY



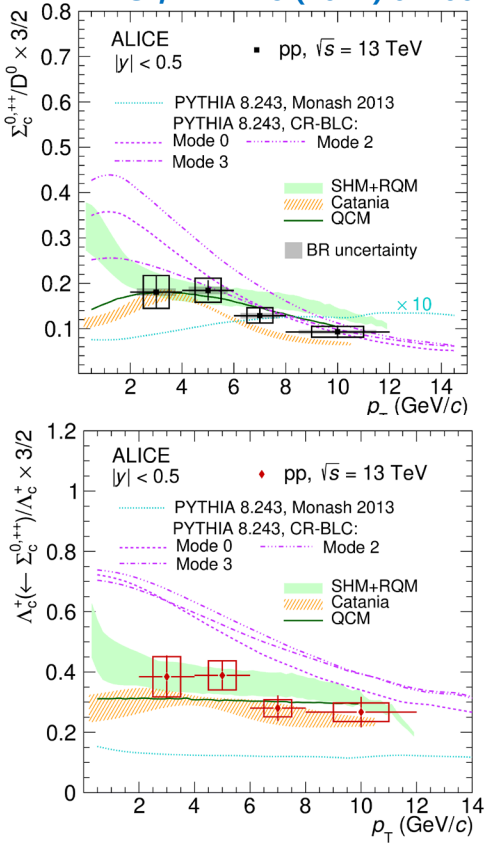


ALICE, JHEP 05 (2021) 220

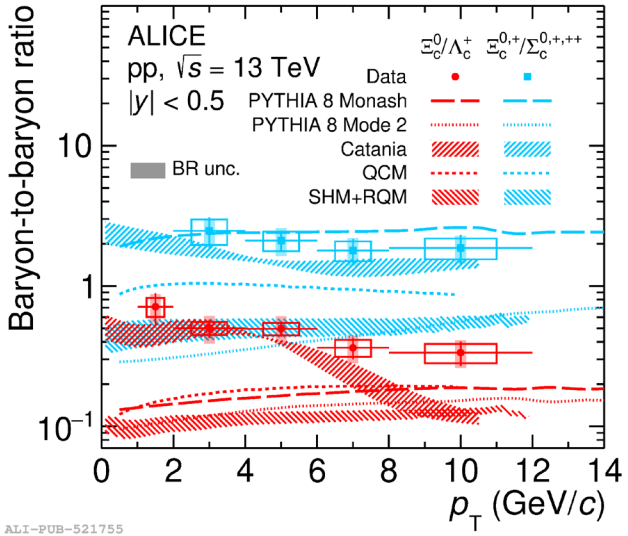
- $b\bar{b}$ production cross section at midrapidity in pp collisions at $\sqrt{s}$ = 5.02 TeV
  - From measurements of non-prompt D^0, D^+, and D_s^+ mesons, extrapolated with FONLL+PYTHIA8
- Consistent with previous measurements, well described by FONLL and NNLO pQCD calculations

HEAVIER CHARM BARYON RATIOS

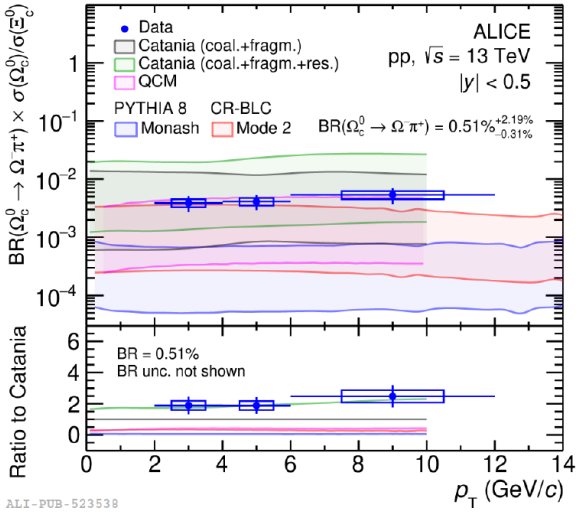
ALICE, PRL 128 (2021) 012001



ALICE, PRL 127 (2021) 271001

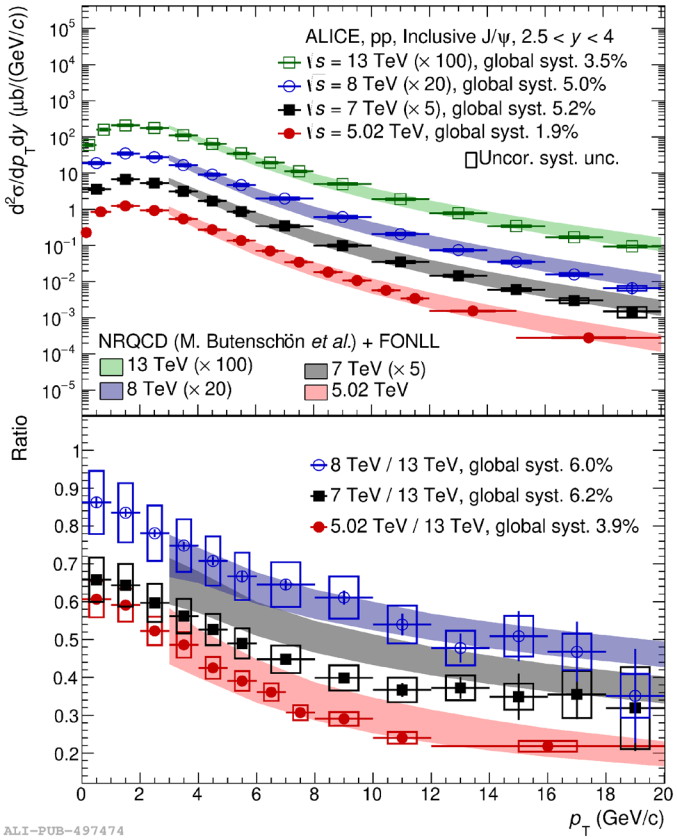


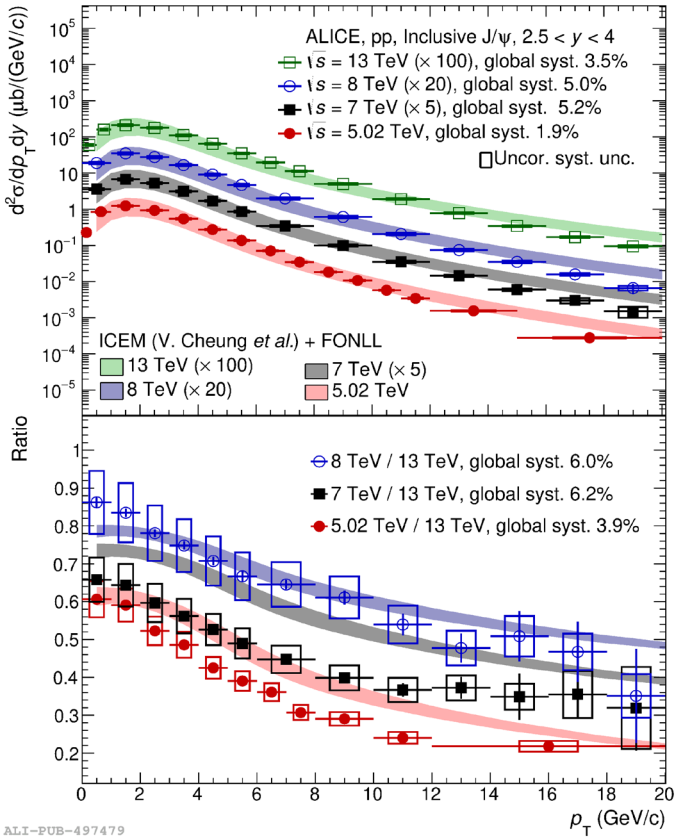
ALICE, arXiv:2205.13993



- $\Sigma^{0,+,++}/D^0$ well described by predictions from SHM+RQM, QCM and Catania
  - ➤ Its enhancement partially accounts for the Λ_c/D^0 enhancement
- $\Xi_c^0/\Sigma^{0,+,++}$ correctly described by Catania, but also by PYTHIA 8
- Ξ_c^0/Λ_c^+ is instead well reproduced only by Catania model
- $\Omega_c^0/\Xi_c^0 \approx 1$: important Ω_c^0 contribution to charm cross section?

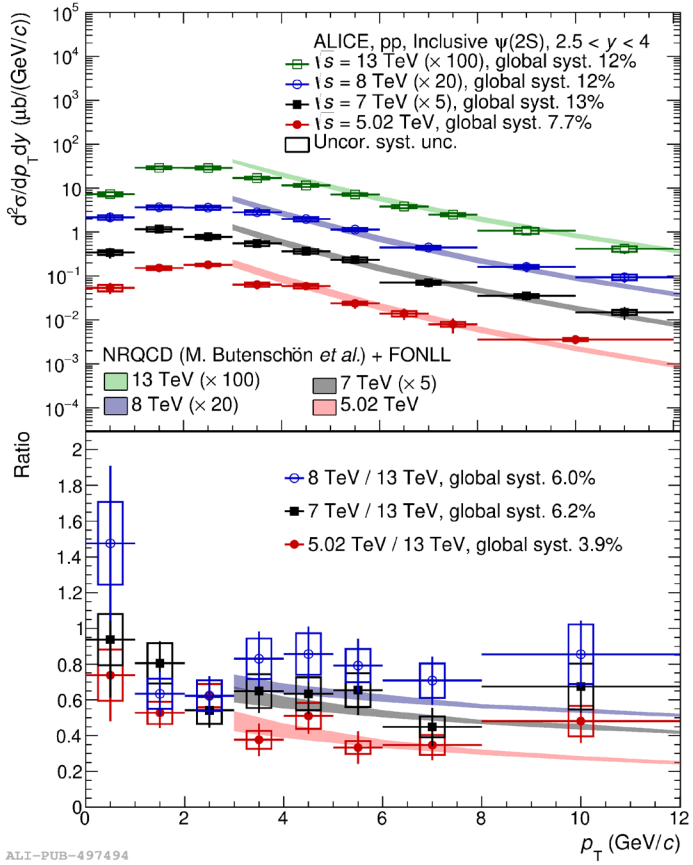
FURTHER J/Ψ DATA/MODEL COMPARISON AT FORWARD RAPIDITY

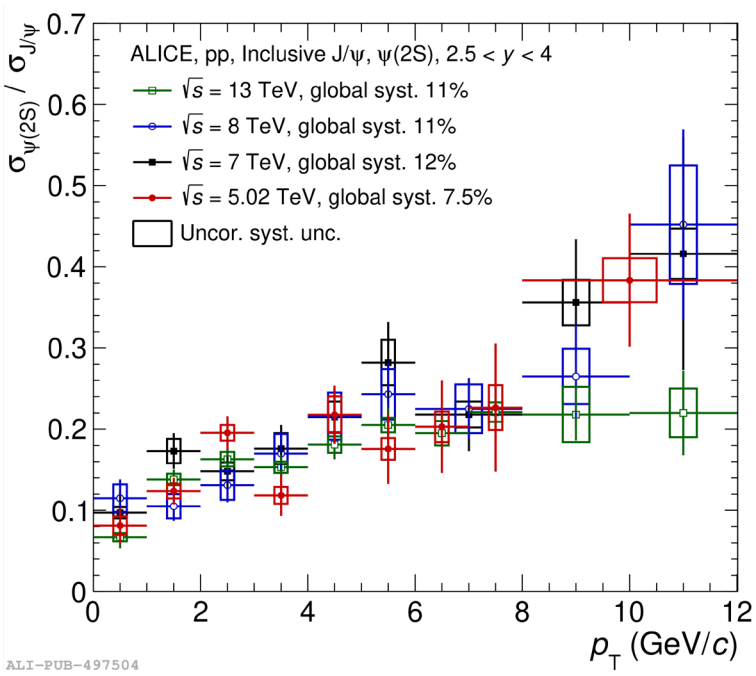




ALICE, arXiv:2109.15240

Ψ(2S) PRODUCTION AT FORWARD RAPIDITY IN pp



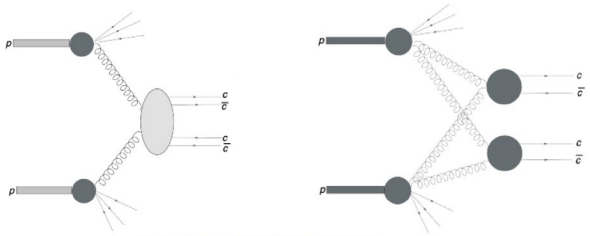


ALICE, arXiv:2109.15240

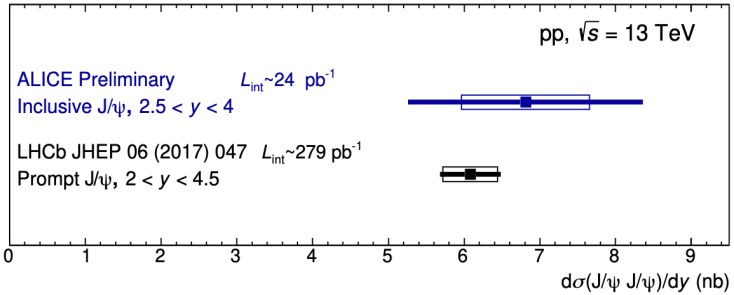
- Ψ(2S) production cross section at forward rapidity in pp collisions well described by NRQCD and ICEM (not shown) at all studied energies
- Ψ(2S)-to-J/Ψ ratio increasing with p_T, consistently for all energies

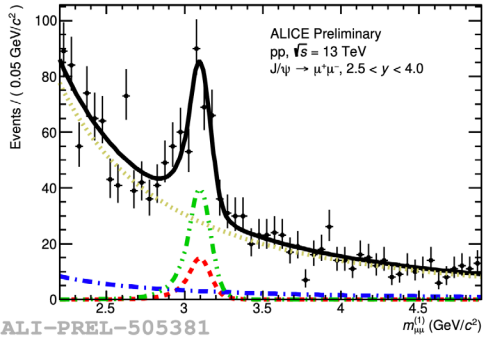
J/Ψ PAIR PRODUCTION

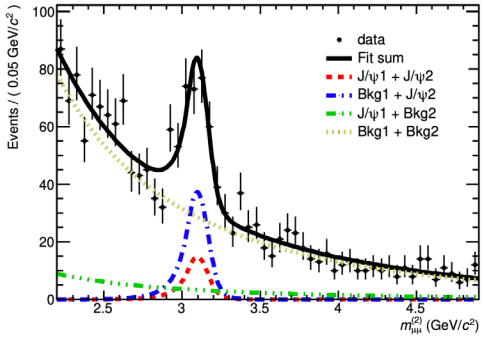
Simultaneous reconstruction of two J/ψ in same event from dimuon decay channel

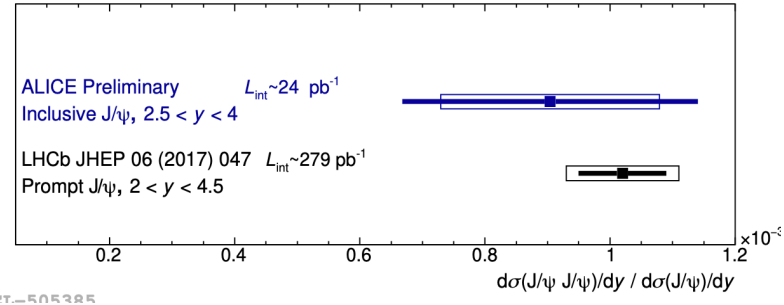


AIP Conf. Proc. 1523 (2013) 1, 255-259









Both results on di-J/ψ and di-J/ψ to single J/ψ cross section are in good agreement with LHCb

Caveats:
- ALICE measures inclusive J/ψ and LHCb prompt J/ψ
- Slightly different rapidity ranges