Heavy-flavor production and hadronization at the LHC : experimental status and perspectives from LHC experiments

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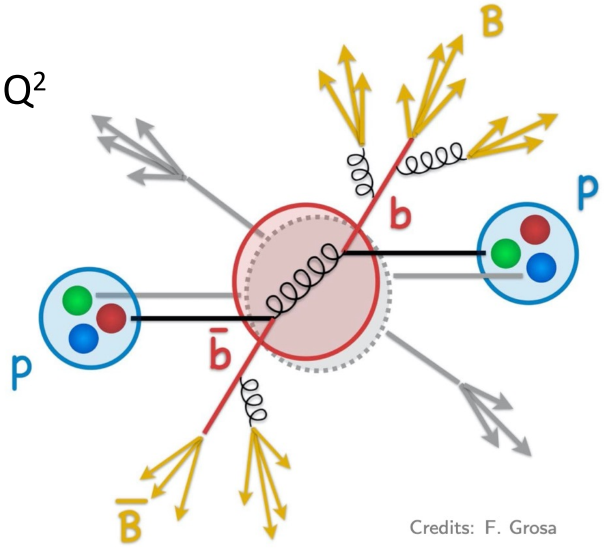
Large Hadron Collider Physics conference 2024

Introduction – Heavy flavors

- Heavy-flavor hadrons contain one heavy c or b quark
- Because of their large masses ($\mathrm{m_b} > \mathrm{m_c} \gg \Lambda_{\mathrm{QCD}}$), they have a short formation time and experience the whole medium evolution
- Heavy quarks are produced in initial hard scattering with moderate to large Q^2
  ➜ their production can be described with perturbative QCD calculations



- The production can be described with the factorization approach :

$$\int \sigma_{(AB\rightarrow CX)} \propto PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{(ab\rightarrow cd)} \otimes D_c^C(z_c, Q^2)$$

- Parton distribution functions (non perturbative)
- Partonic cross section (perturbative)
- Fragmentation functions (non perturbative)

- Fragmentation functions are assumed to be universal across collision systems

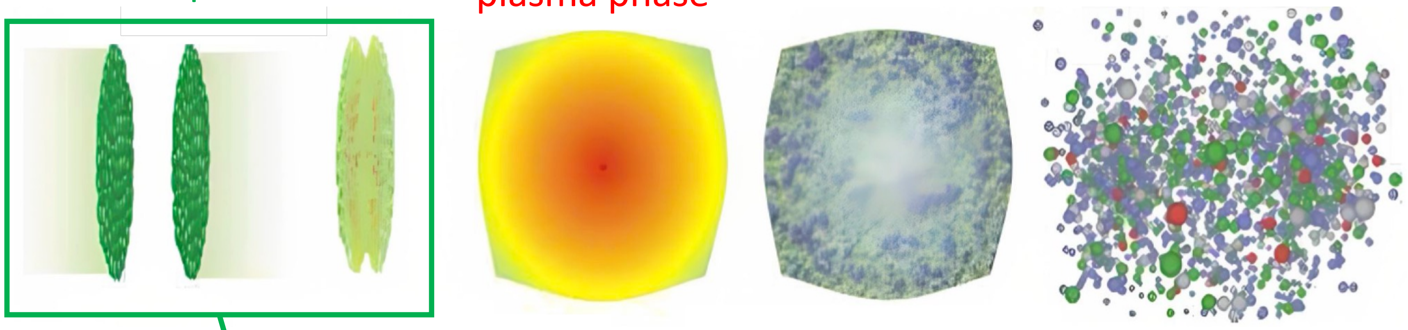
Introduction – What can we measure and learn?

Initial phase

Quark-gluon plasma phase

Hadronisation

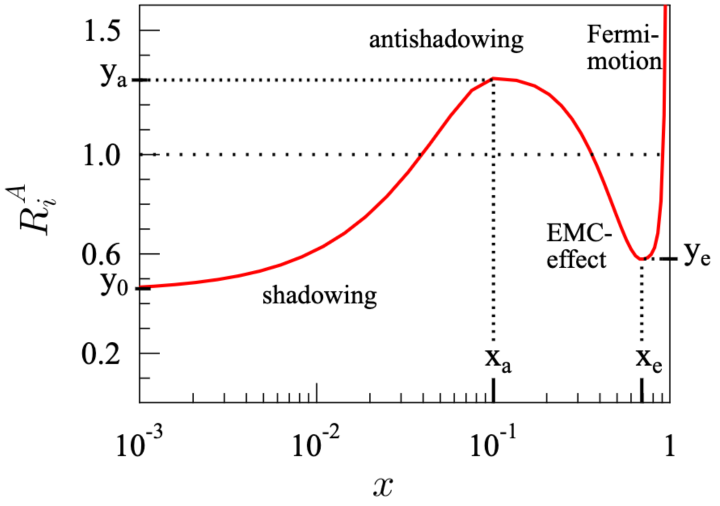
Hadronic phase



Initial State effects :

- Saturation
- Modification of PDFs
- …

JHEP 04 (2009) 065



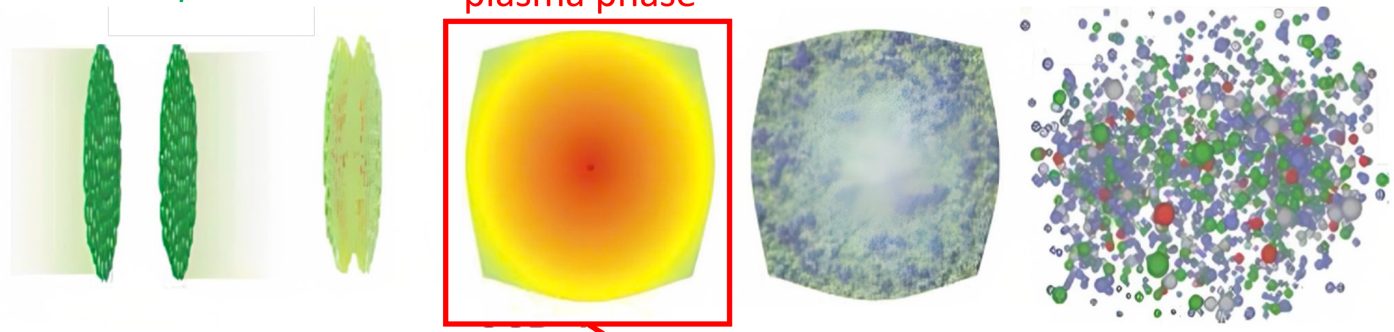
Introduction – What can we measure and learn?

Initial phase

Quark-gluon plasma phase

Hadronisation

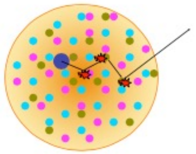
Hadronic phase



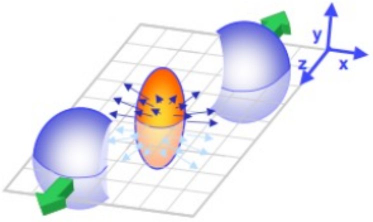
In medium effects :

- Energy loss : Interaction of heavy quarks with the medium

$$R_{\mathrm{AA}} = \frac{Y_{\mathrm{AA}}}{N_{\mathrm{coll}} \cdot Y_{\mathrm{pp}}}$$

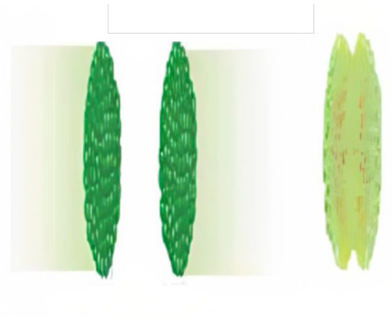


Collectivity: elliptic flow, triangular flow, angular correlations…

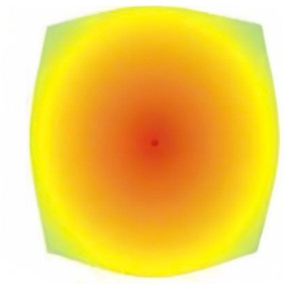


Introduction – What can we measure and learn?

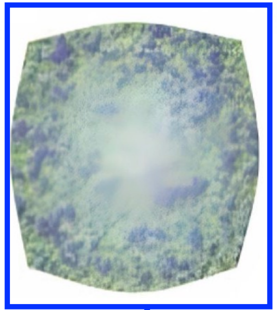
Initial phase



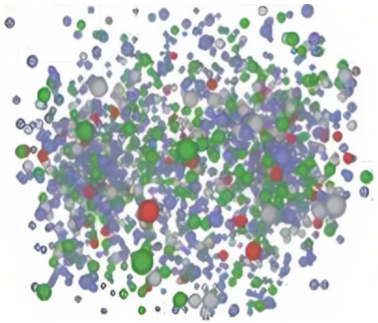
Quark-gluon plasma phase



Hadronisation



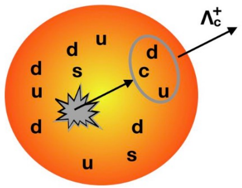
Hadronic phase



Mechanisms

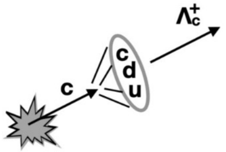
- Coalescence: combination of quarks close in phase space

Coalescence



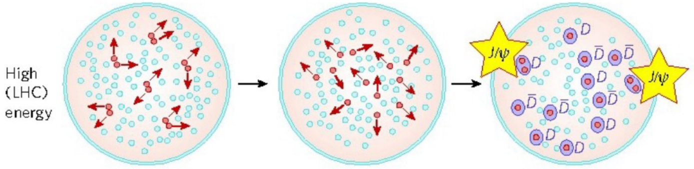
- Fragmentation: "break up" of charm quark

Fragmentation



Models

- Statistical hadronization : charm quarks distributed to hadrons according to thermal weights

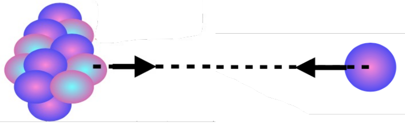


Introduction – Different collision systems

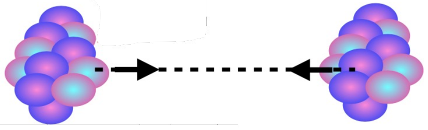
- Measurements in different collision size allow to investigate several properties

- Proton-proton collisions :
  - Measurement of fragmentation fraction
  - Test of pQCD models regarding hadron formation

- Proton-Nucleus collisions :
  - Initial state effects
  - Interplay between soft and hard process

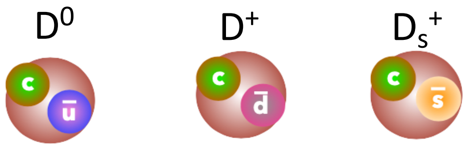


- Nucleus-Nucleus collisions
  - Properties of the quark-gluon plasma (QGP)
  - Final state effects

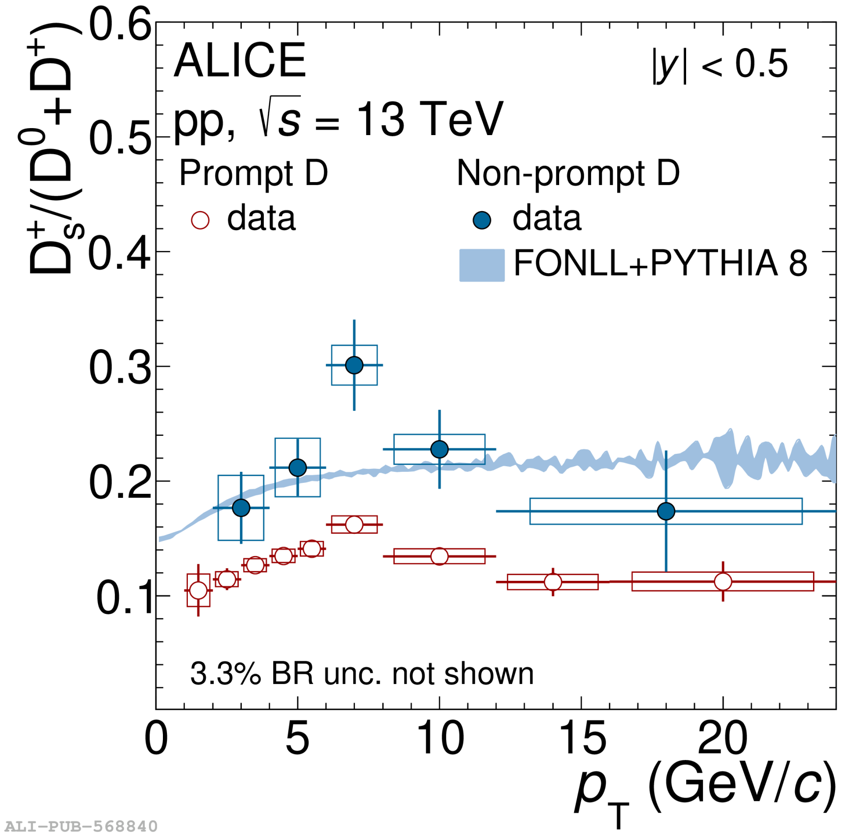


D-meson production in pp collisions

- Understanding the hadronization mechanism is necessary as enhancement in the strangeness is expected in QGP
- Prompt strange-to-non-strange meson ratio exhibit an increasing trend as a function of p_T up to ~8 GeV/c
- No significant trend visible in the non-prompt case
- FONLL calulation describe the data in the p_T range



ALICE, JHEP 12 (2023) 086
ALICE, arxiv:2402.16417

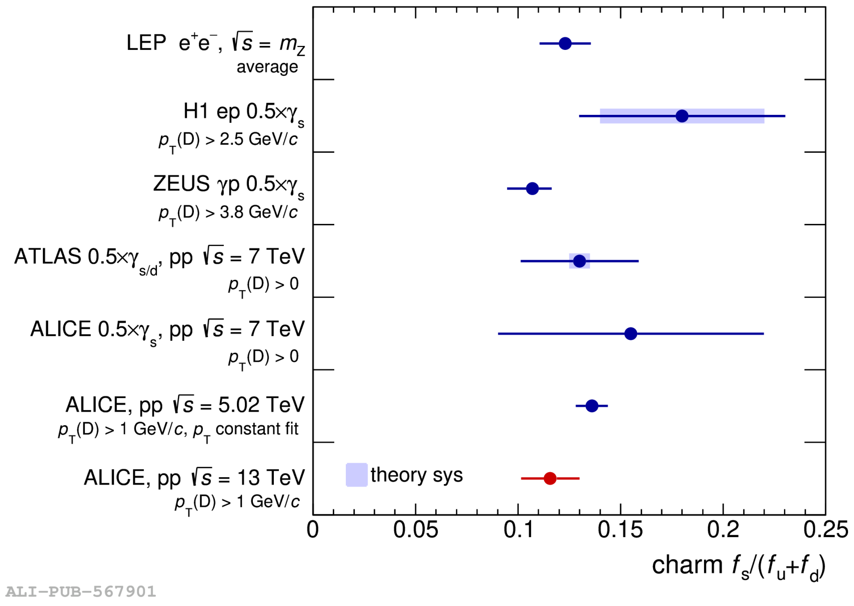


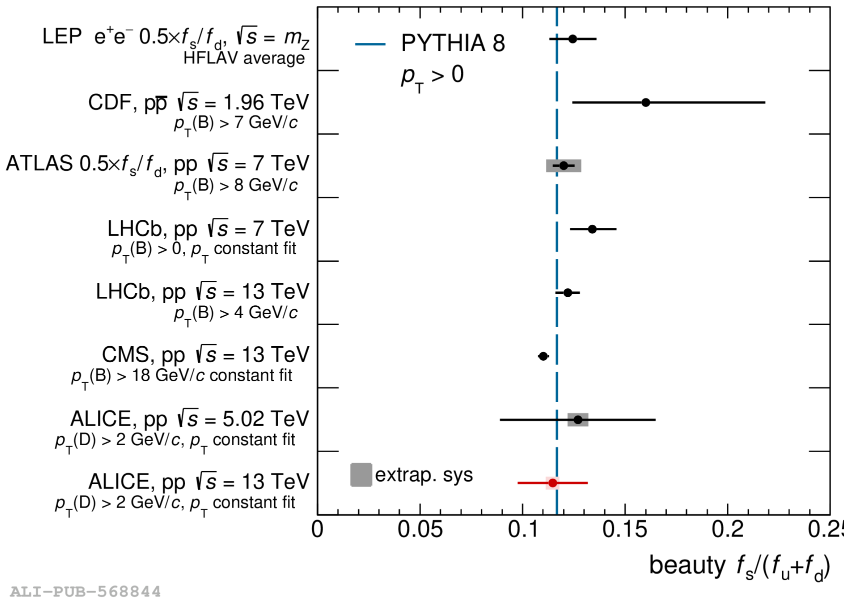
FONLL, JHEP 10 (2012) 137

D-meson production in pp collisions

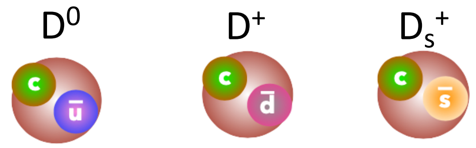
ALICE, JHEP 12 (2023) 086
ALICE, arxiv:2402.16417

- Results are compatible with the values found for e^+e^- collisions
  → Indicates universality of the fragmentation function for mesons





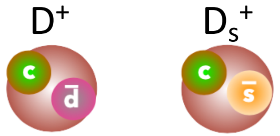
Prompt



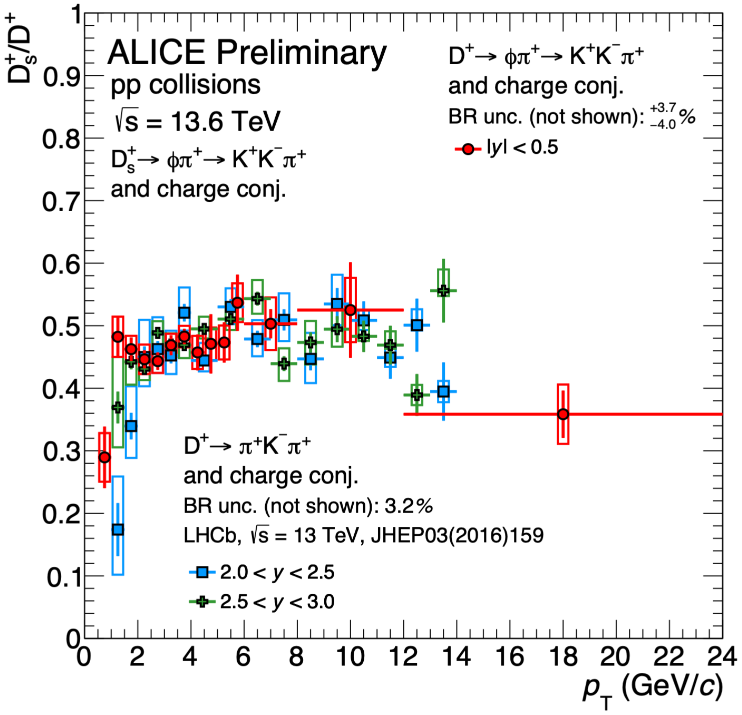
Non-Prompt

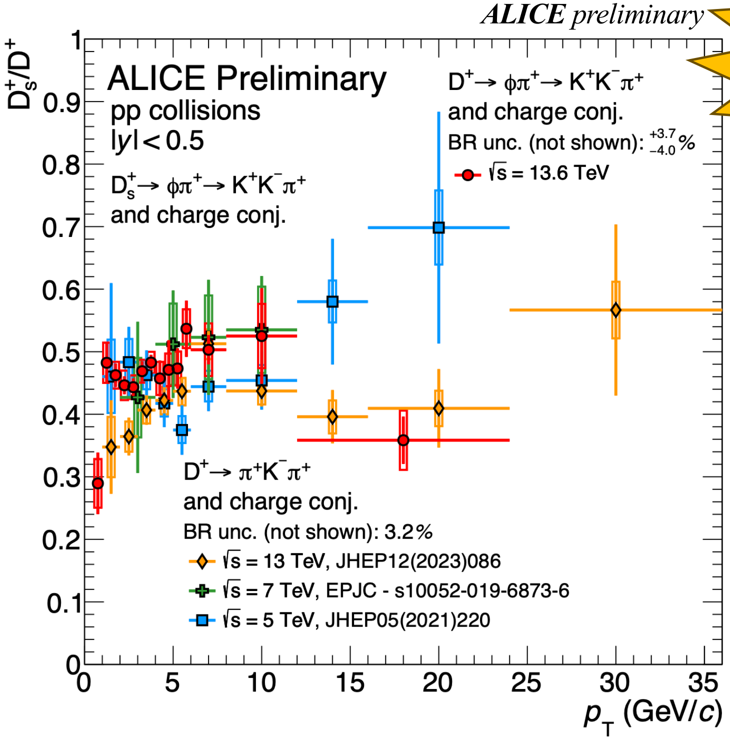
D-meson production in pp collisions

- **New results at $\sqrt{s} = 13.6$ TeV**
- No dependence with energy collision is observed
- Results are compatible with LHCb results



Run 3 Result

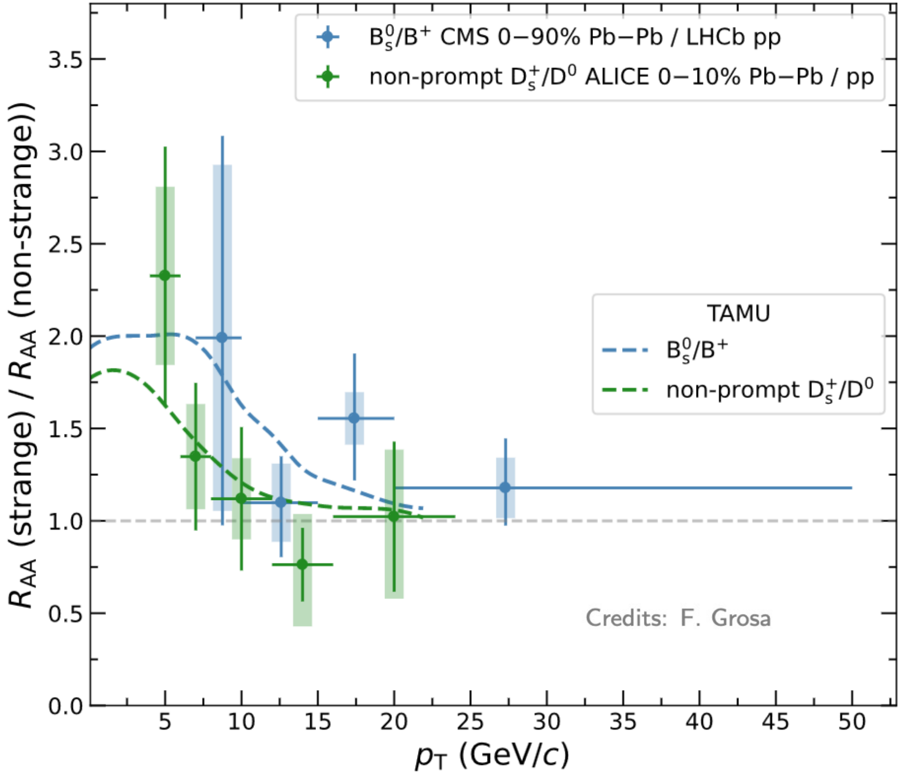




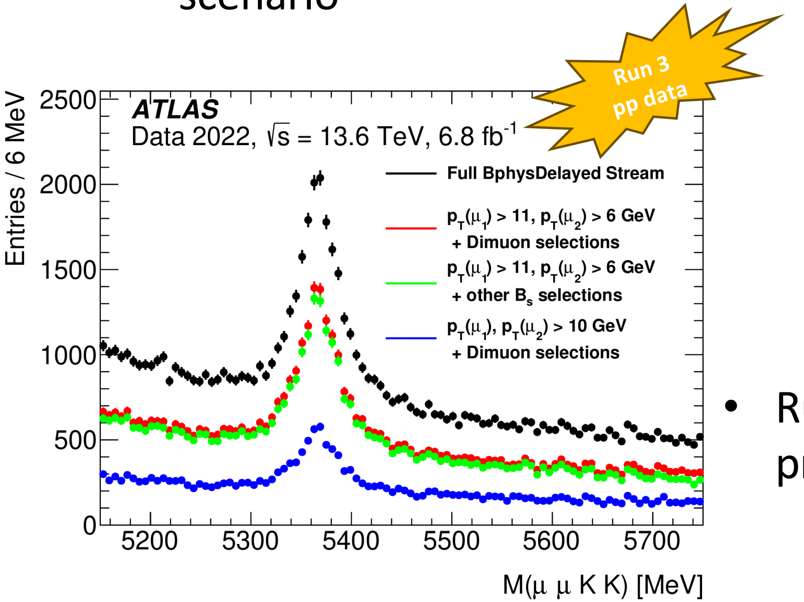
D-meson production in Pb–Pb collisions

- Prompt strange-to-non-strange meson ratio in Pb–Pb collisions shows hint of a strangeness enhancement
- Model implementing strangeness enhancement and hadronisation via recombination compatible with data
- Measurements also compatible with no enhancement scenario

CMS, Phys. Lett. B 829 (2022) 137062
ALICE, Phys. Lett. B 846 (2023) 137561



TAMU, Phys. Lett. B 735 (2014) 445

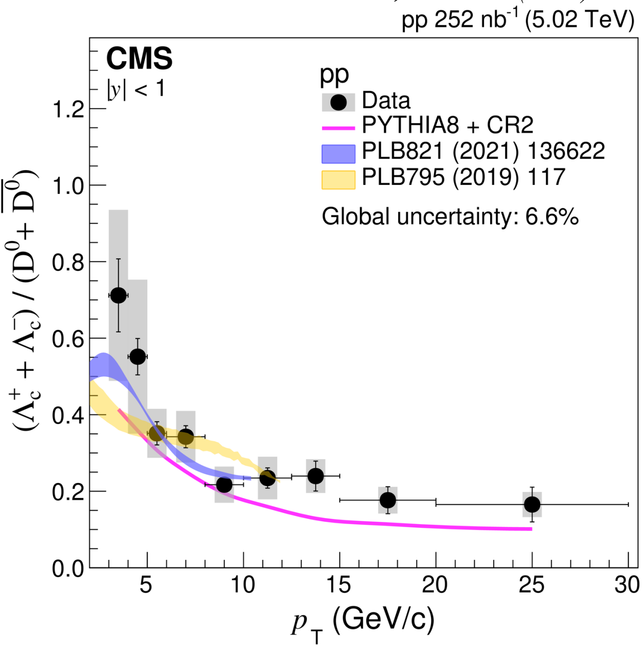


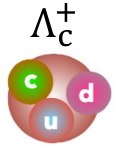
- Run 3 data will allow more precise measurements

Λ_c^+ measurement in pp collisions

- The Λ_c^+/D^0 production in pp collisions shows a **decreasing trend with increasing p_T**
- The Λ_c^+/D^0 production in pp collisions in ALICE shows a similar **decreasing trend with increasing p_T**
- PYTHIA 8 predictions shows good agreement with data for p_T < 10 GeV/c, understimates data for p_T > 10 GeV/c

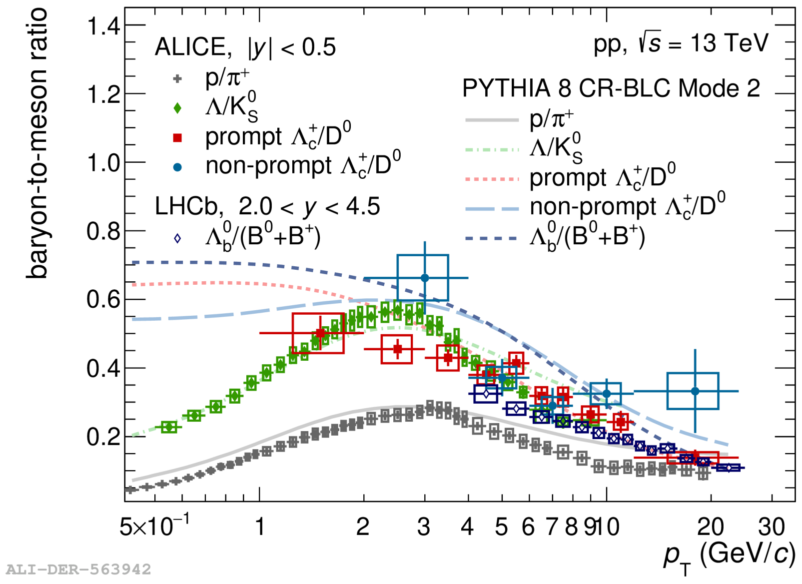
CMS, *JHEP 01 (2024) 128*





PYTHIA 8, *JHEP 08 (2015) 003*
Catania, *Phys. Lett. B 821 (2021) 136622*
SHM, *Phys. Lett. B 795 (2019) 117*

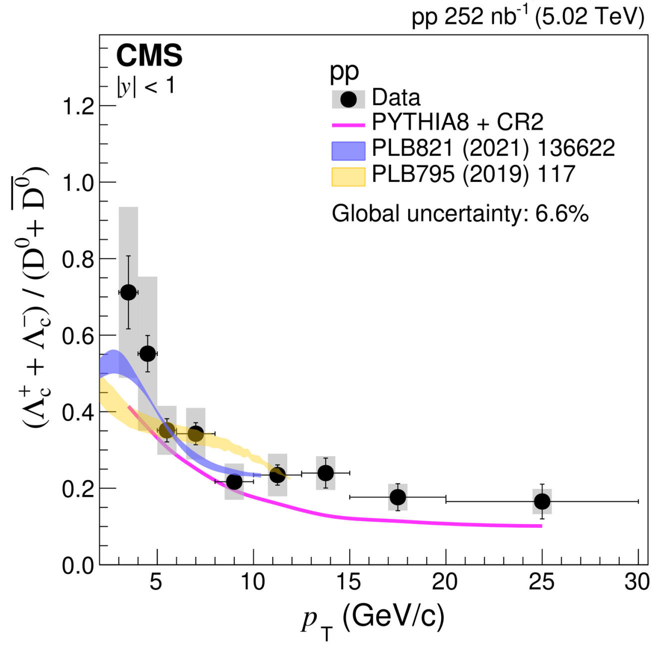
ALICE, *Phys. Rev. D (2023)108, 112003*
LHCb, *Phys. Rev. D (2019)100, 031102*

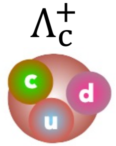


Λ_c^+ measurement in pp collisions

- Model with coalescence & fragmentation processes (PLB821(2021)136622) shows good agreement in the available p_T range and reproduces the trend
- Statistical hadronization model (PLB795(2019)117) shows also good agreement with data in the available range

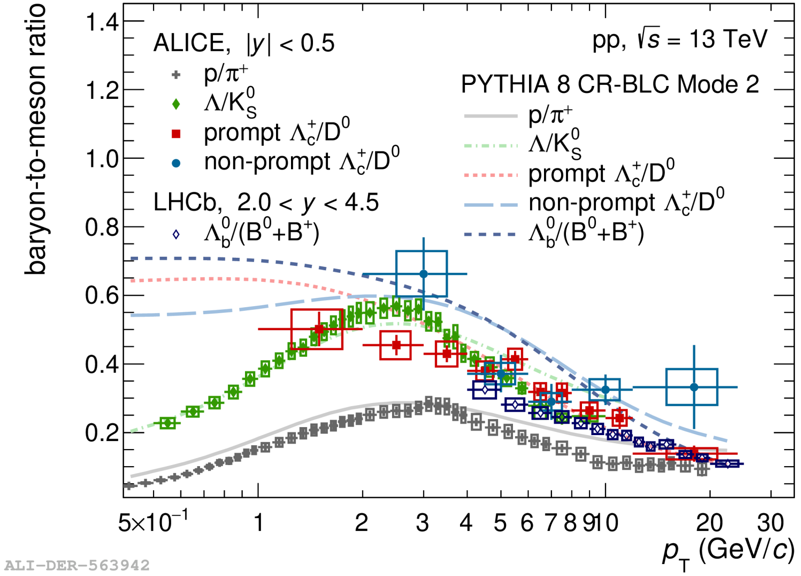
***CMS,** JHEP 01 (2024) 128*





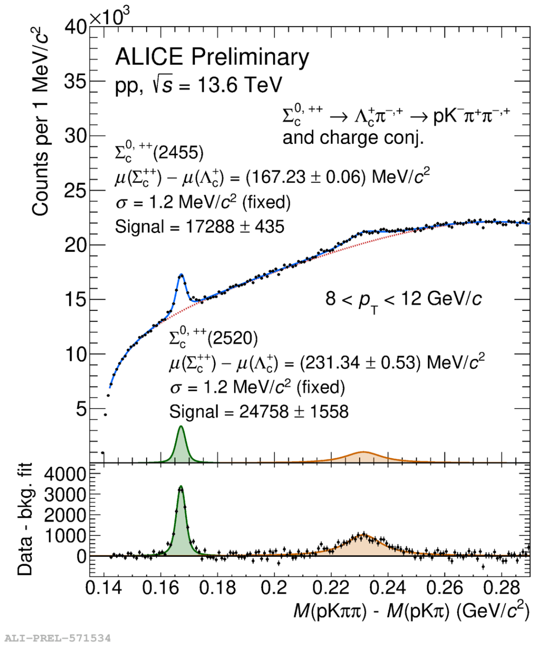
***PYTHIA 8,** JHEP 08 (2015) 003*
***Catania,** Phys. Lett. B 821 (2021) 136622*
***SHM,** Phys. Lett. B 795 (2019) 117*

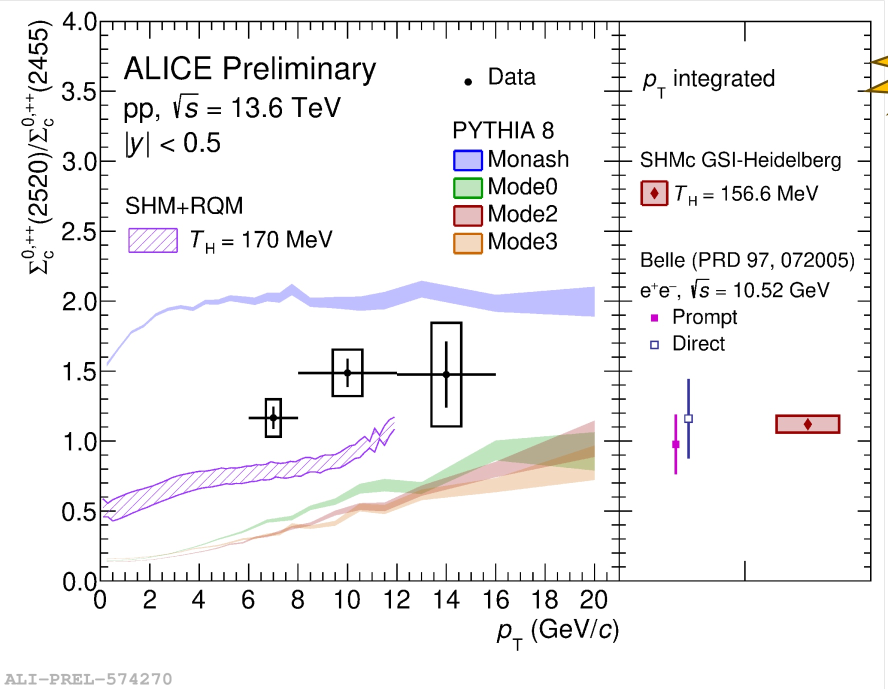
***ALICE,** Phys. Rev. D (2023)108, 112003*
***LHCb,** Phys. Rev. D (2019)100, 031102*



Run 3 measurement in pp collisions

- Run 3 data is being analyzed and new results in pp at $\sqrt{s} = 13.6$ TeV are starting to be published





Run 3 Result

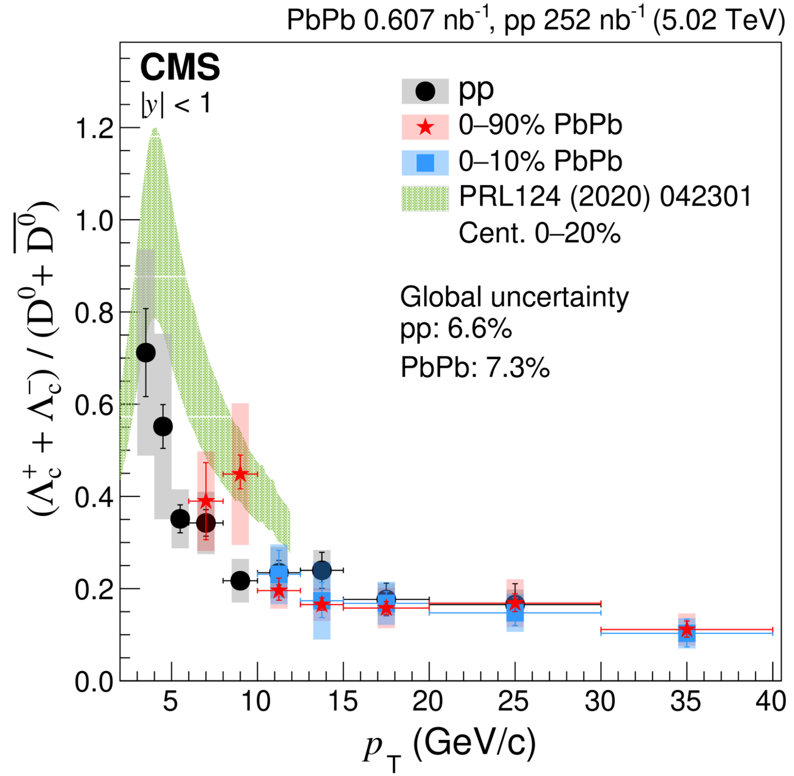
Pythia 8 (Monash), Eur. Phys. J. C 74 (2014)
Pythia 8 (Mode 0/2/3), JHEP 08 (2015) 003
SHM+RQM, Phys. Lett. B 795 (2019) 117-121
SHMc, Phys. Lett. B 797 (2019) 134836
Belle, Phys. Rev. D 97, 072005 (2018)

→ first measurement of $\Sigma_c^{0,++}(2520)$ in ALICE

Λ_c^+ measurement in pp & Pb–Pb collisions

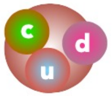
- The Λ_c^+/D^0 production in Pb–Pb collisions is compatible with the pp result
- Model prediction shows good agreement with the data in the overlapping p_T range ($10 < p_T < 12.5$ GeV/c)
- Both pp and Pb–Pb results tend toward the value found for e^+e^- collisions in this high p_T region
  → No significant contribution from coalescence at high p_T in Pb–Pb

CMS, *JHEP 01 (2024) 128*



M. He & R. Rapp, *Phys. Rev. Lett. 124 (2020) 042301*

Λ_c^+



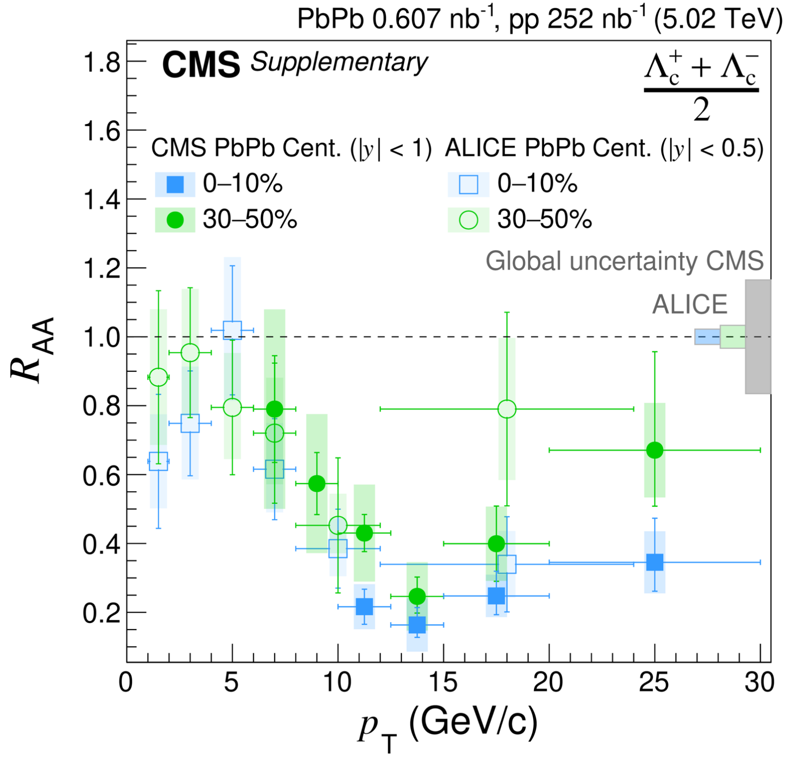
Λ_c^+ measurement in Pb–Pb collisions

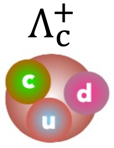
CMS, JHEP 01 (2024) 128
ALICE, Phys. Lett. B 839 (2023) 137796

- The R_{AA} shows a suppression for central collisions, with a maximal suppression around $p_T \approx 14$ GeV/c

- Comparison with ALICE values show a good agreement in the overlapping p_T range

- ALICE and CMS combined results show that the **suppression is larger at intermediate p_T values**, similar to what was observed for D^0 mesons

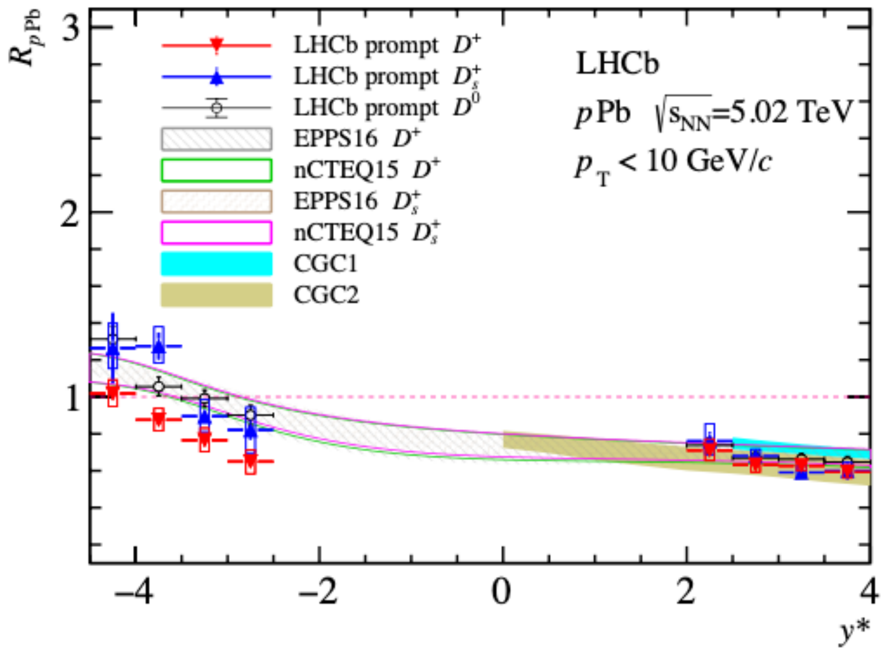


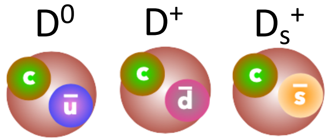


D meson in p–Pb collisions

- The R_{pPb} of D^+ and D_s^+ mesons has been measured at $\sqrt{s_{\text{NN}}} = 5.02$ TeV
- At forward rapidity, good agreeement between D^0 and D^+
- At backward rapidity, the D^+ R_{pPb} is lower than D^0 and D_s^+ one
- Calculations with 2 different set of nPDFs agree with data at forward rapidity, overestimate D^+ data at backward rapidity
- CGC model prediction (which include saturation of partons at small Bjorken-x) agree with the data at forward rapidity

LHCb, JHEP 01 (2024) 070
LHCb, JHEP 10 (2017) 090





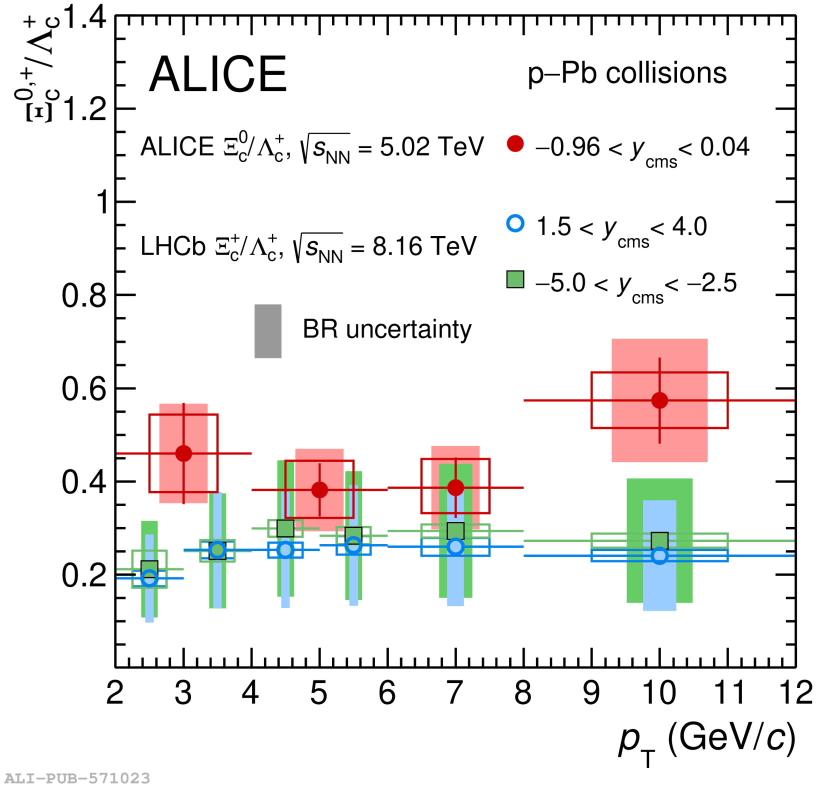
EPPS16: Eur.Phys.J.C 77 (2017) 3, 163
nCTEQ: Phys.Rev.D 93 (2016) 8, 085037
CGC: Phys. Rev. D91 (2015) 114005

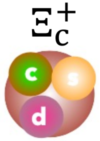
Ξ_c^+ production in p–Pb collisions

- The Ξ_c^+/Λ_c^+ ratio show no significant p_T dependence for both p–Pb and Pb–p directions.
  → strong indication that the same processes govern hadronization in p–Pb and Pb–p collisions

- ALICE and LHCb points are compatible within uncertainties

***LHCb**, Phys. Rev. C (2024) 109, 044901*
***ALICE**, arXiv:2405.14538*

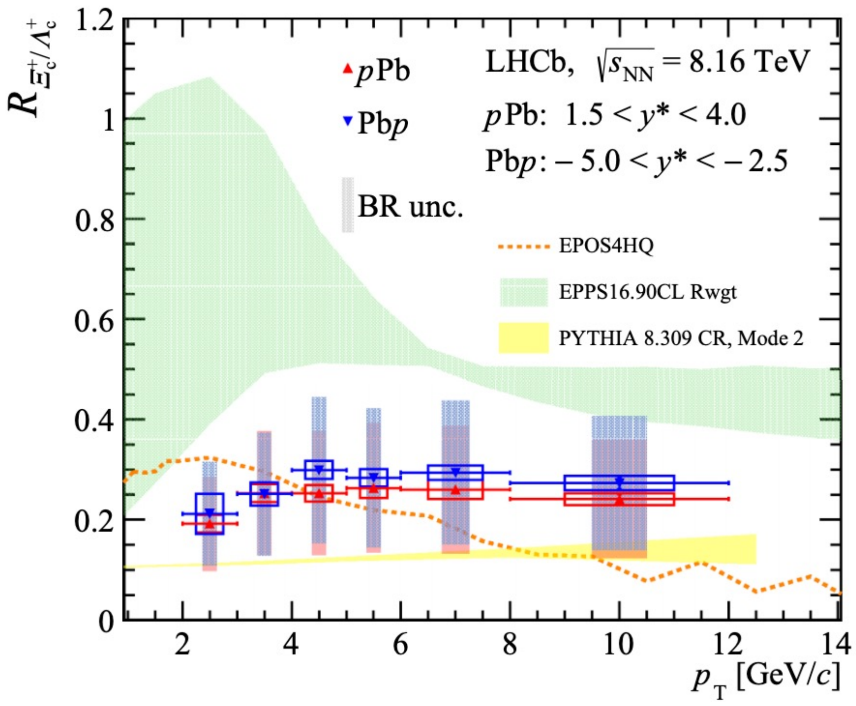




Ξ_c^+ production in p–Pb collisions

- The Ξ_c^+/Λ_c^+ ratio show no significant p_T dependence for both p–Pb and Pb–p directions.
  → strong indication that the same processes govern hadronization in p–Pb and Pb–p collisions
- ALICE and LHCb points are compatible within uncertainties
- The EPPS16 model significantly overestimates LHCb data but shows similar trend
- PYTHIA 8.3 calculations describe data within uncertainties
- EPOS4HQ calculations describe data within uncertainties but show different trend

***LHCb**, Phys. Rev. C (2024) 109, 044901*

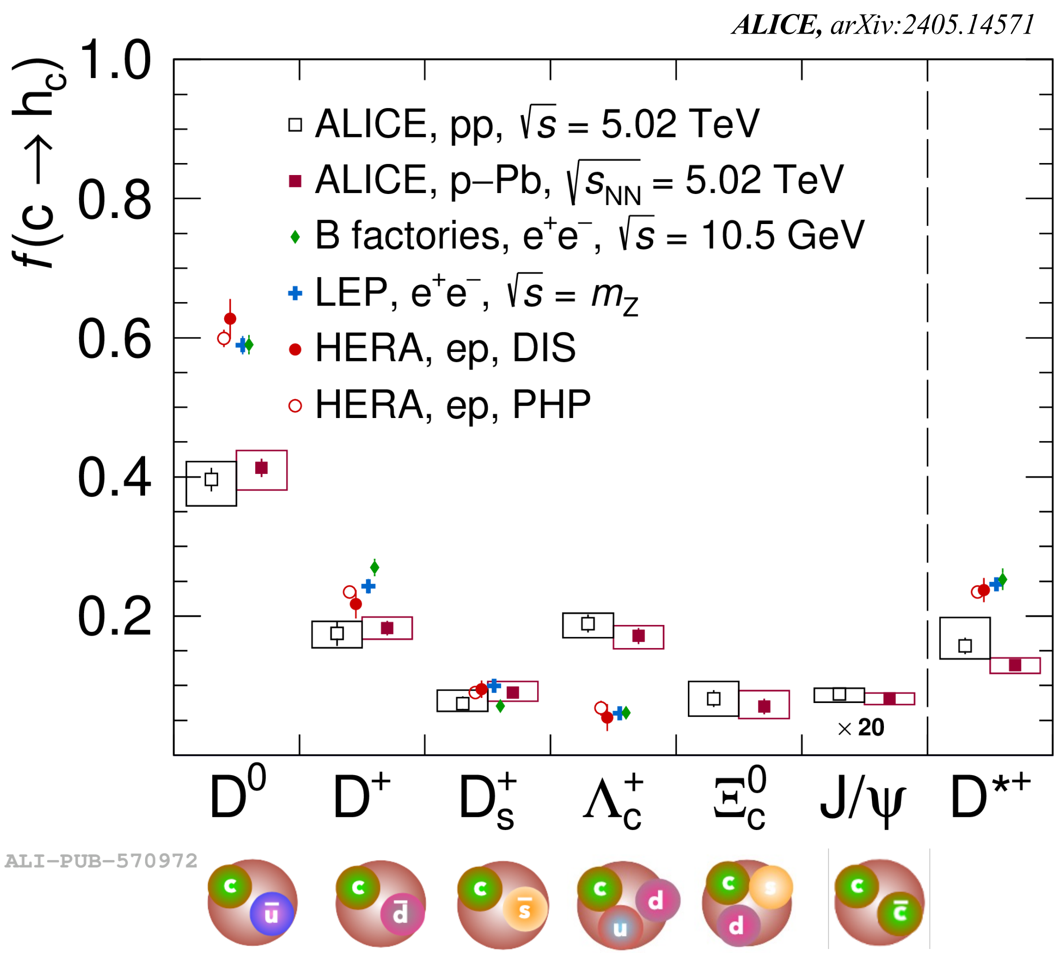


***EPPS16**, Eur. Phys. J. C 77 (2017) 163*
***PYTHIA8.3**, J. High Energy Phys. 08 (2015) 003.*
***EPOS4HQ**, Phys. Rev. C (2023) 108, 034904*

Charm fragmentention functions

- Heavy-flavor charm mesons and baryons are used to evaluate the charm fragmentation fractions
- The values are consistent between pp and p–Pb collisions
- A difference is observed in pp and p–Pb collisions with respect to e$^+$e$^-$ and ep collisions
- Increase in Λ_c^+ production accompanied by a concomitant decrease in D^0

  → evidence that universality (i.e. collision-system independence) of parton-to-hadron fragmentation is not valid



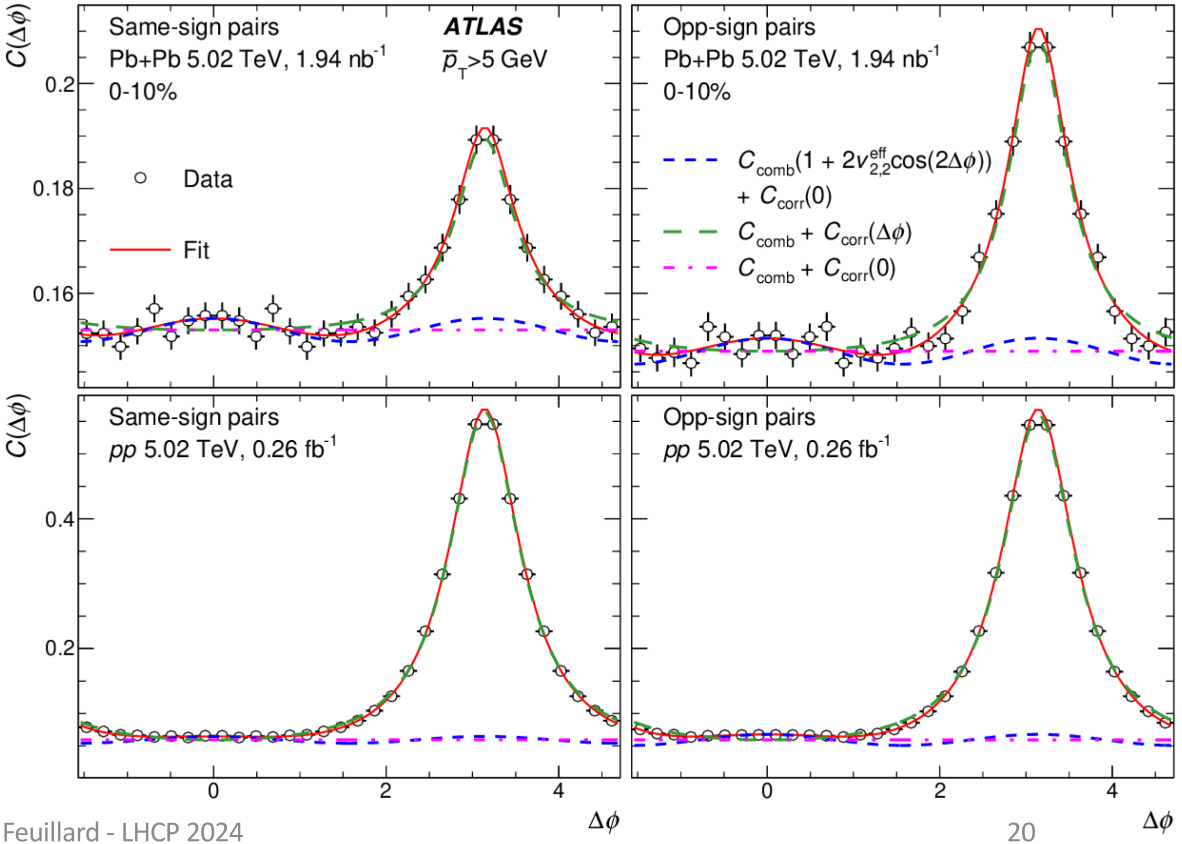
Muons produced via heavy-flavor decays in pp & Pb–Pb collisions

- Two-muon correlation functions were constructed and studied as a function of azimuthal angle difference $\Delta\phi$

- A strong enhancement is observed in the correlation functions at $\Delta\phi \sim \pi$
  ➜ consistent with semileptonic decays of heavy-quark pair

- The peaks are characterized :
  - half-width at half-maximum Γ
  - the standard deviation σ

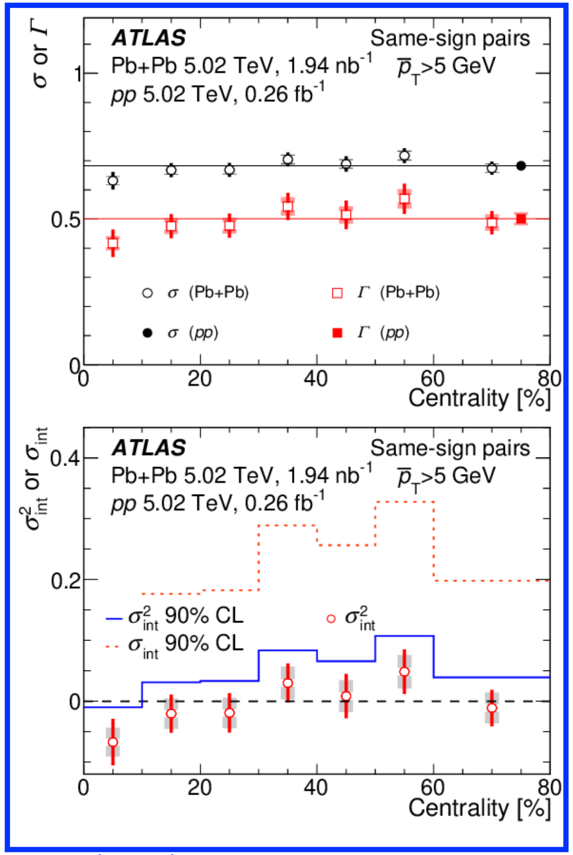
ATLAS, Phys. Rev. Lett. 132 (2024) 202301



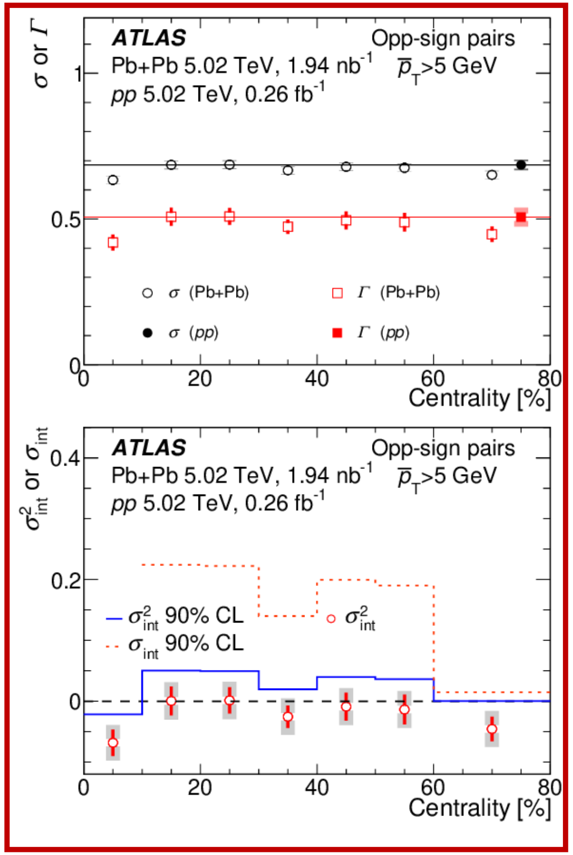
Muons produced via heavy-flavor decays in pp & Pb–Pb collisions

ATLAS, Phys. Rev. Lett. 132 (2024) 202301

- Γ and σ show no significant difference between pp collisions Pb–Pb collisions
- Γ and σ show no significant variation with centrality except in the 0–10% most central collisions, where a significant decrease in the Pb–Pb widths is observed
- The results are consistent between same-sign pairs (negligible charm contribution) and opposite-sign pairs (~90% of the yield in pp collisions from $b\bar{b}$)
- **Results can provide constraints on models** for the additional angular deflection introduced by the QGP



same-sign pairs



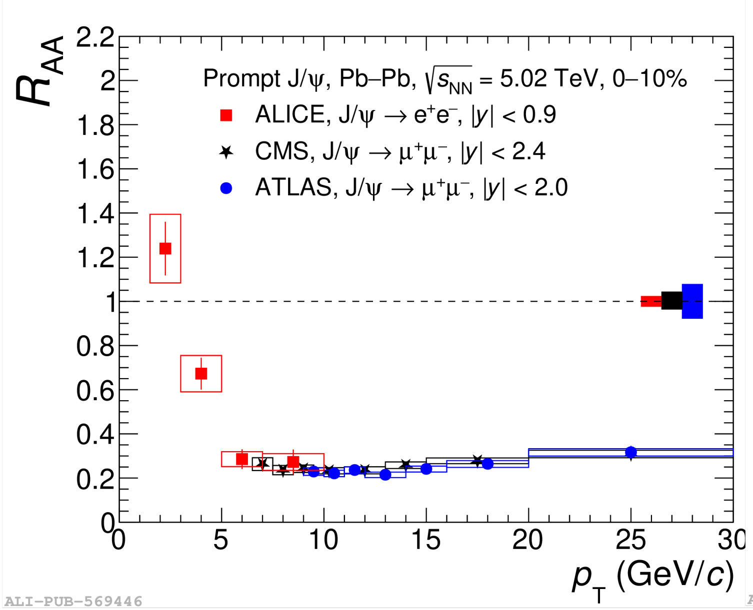
opposite-sign pairs

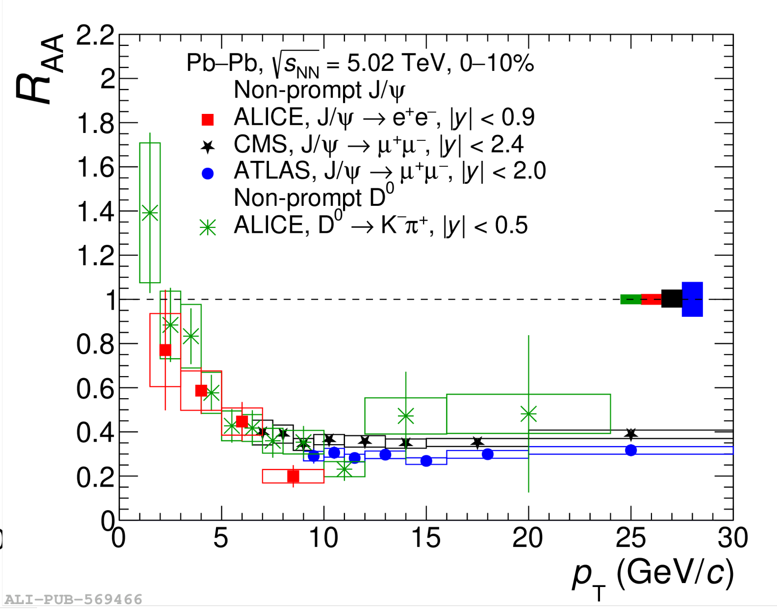
Charmonium production

- The prompt J/ψ R_{AA} increases towards low p_T, and even exceeds unity in the lowest p_T bin
  ➜ likely due to cold nuclear matter effects
- The non-prompt J/ψ R_{AA} increases towards low p_T, but remains <1
  ➜ small cold nuclear matter effects

ALICE, JHEP 02 (2024) 066
ATLAS, Eur. Phys. J. C 78 (2018) 762
CMS, Eur. Phys. J. C 78 (2018) 509

- Results are compatible between ALICE, ATLAS and CMS in the overlapping p_T region
- Results are compatible with non-prompt D^0 measurements

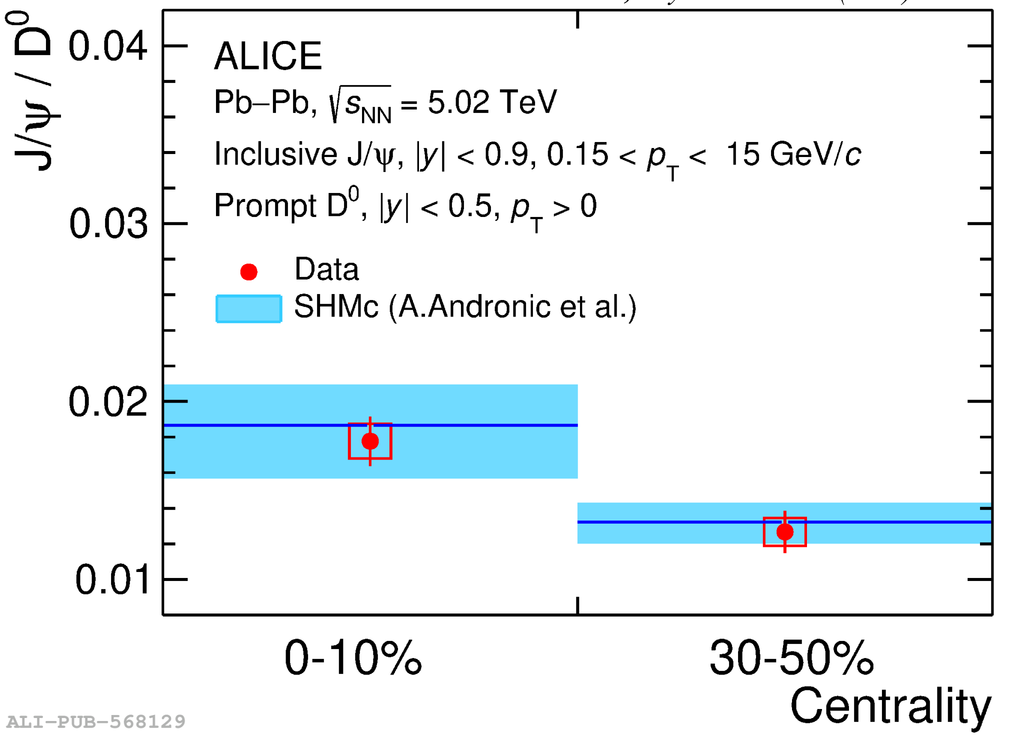




Charmonium production

- The J/ψ/D^0 provides tight constraint to models because uncertainties related to the $c\bar{c}$ cross section cancel out
  → parameter-free prediction relying only on deconfined and thermalized charm quarks
- The ratio is sensitive to the hadronisation mechanisms of the different charm hadron
- The ratio is higher in most central collisions
- SHMc model predictions describe the data well
  → hints that both J/ψ and D^0 are produced via the coalescence of charm quarks

ALICE, Phys. Lett. B 849 (2024) 138451



SHMc, Phys. Lett. B 797 (2019) 134836

Conclusion

- The measurement of many heavy flavor species offers a solid ground to test the pQCD models and the factorization approach
  ➜ breaking of universal hadronisation for all systems

- The ability to measure several observables (R_{AA}, production ratios…) provides many avenues for model comparison and improves our understanding of heavy quark interaction with the medium
  ➜ Charmed hadrons produced through colaescence at low p_T, no significant contribution from coalescence at high p_T in Pb–Pb

- Run 3 data allows more precise measurements with smaller uncertainties, and the first results are being shown this year

Other Talks

- **Hadronic and semi-leptonic decays of charm baryons**, Chong Kim

  → Tuesday June 5th at 11:54 (link)

- **HF production, propagation and hadronization in QGP**, Stefano Politano

  → Tuesday June 5th at 14:36 (link)

- **Heavy-flavour polarization measurements**, Xiaozhi Bai

  →Tuesday June 5th at 14:36 (link)

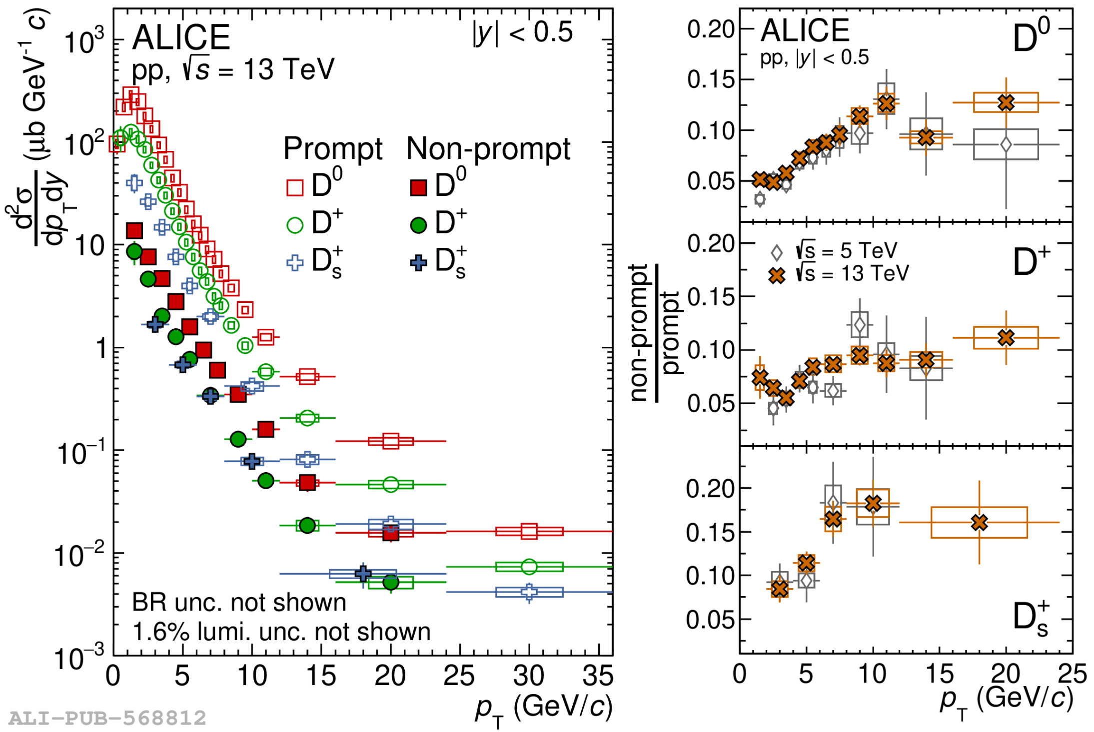
THANK YOU FOR YOUR ATTENTION!

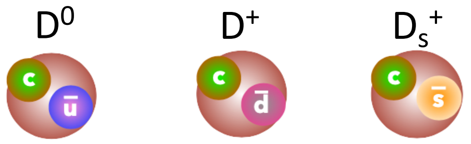
BACK-UPS

D mesons cross sections in pp collisions

ALICE, JHEP 12 (2023) 086
ALICE, arxiv:2402.16417

- Measurement of p_T-differential cross-sections of D mesons
- The production of prompt D mesons is larger than the one of non-prompt D at low p_T.
  → expected since $m_c < m_b$
- The ratios exhibit an increasing trend as a function of p_T up to ~12 GeV/c
  → Indicates a harder p_T spectrum of beauty hadrons w.r.t prompt charm mesons





D mesons cross sections in pp collisions

ALICE, JHEP 12 (2023) 086
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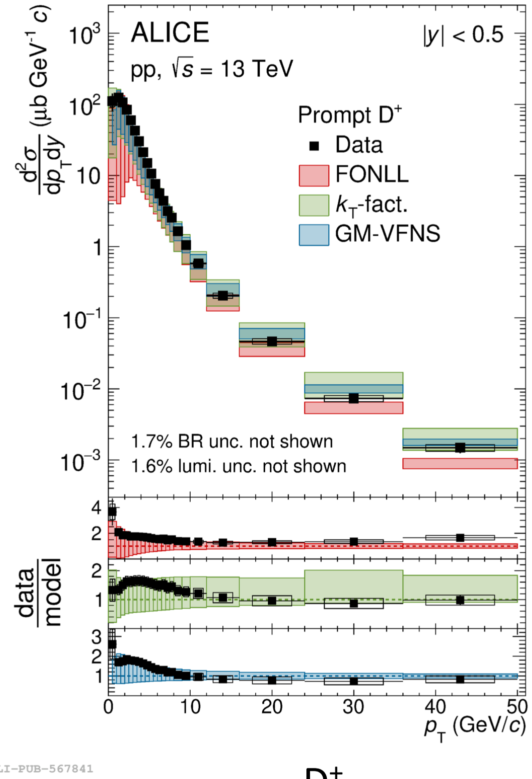
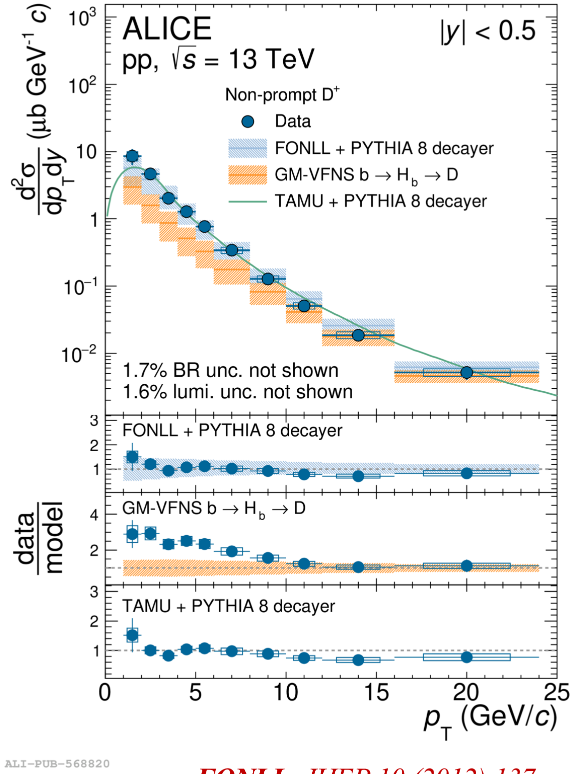
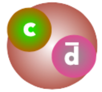
- Comparison with pQCD calculations implementing the factorisation approach
- For FONLL calculations :
  - slightly underestimate the prompt data
  - good agreement for the non-prompt
- For GM-VFNS:
  - slightly underestimate the prompt data at low p_T and overestimate at high p_T
  - Understimate the non-prompt data at low p_T but good agreement at high p_T
- For k_T-factorization : overestimate the prompt measurement at high p_T
- For TAMU : good agreement with the non-prompt measurement





D^+



FONLL, JHEP 10 (2012) 137
kT-fact., Phys. Rev. D 104 (2021) 094038
GM-VFNS, Nucl. Phys. B 925 (2017) 415–430
TAMU, Phys. Rev. Lett. 131 (Jul, 2023) 012301

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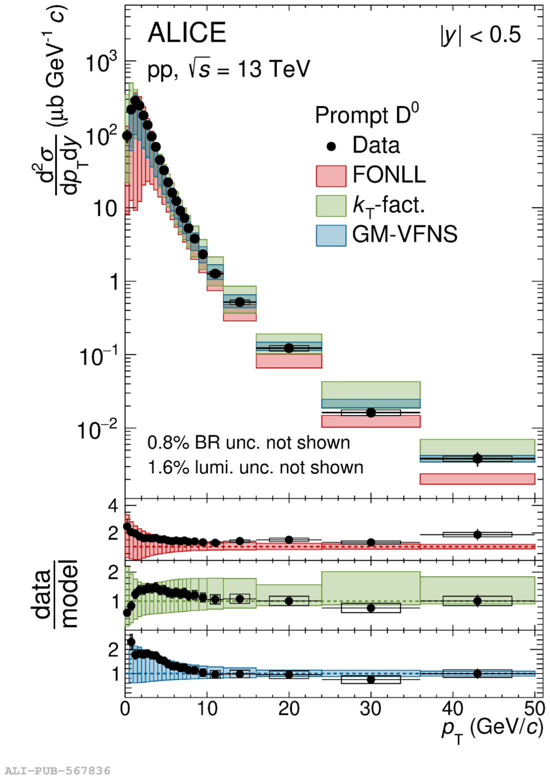

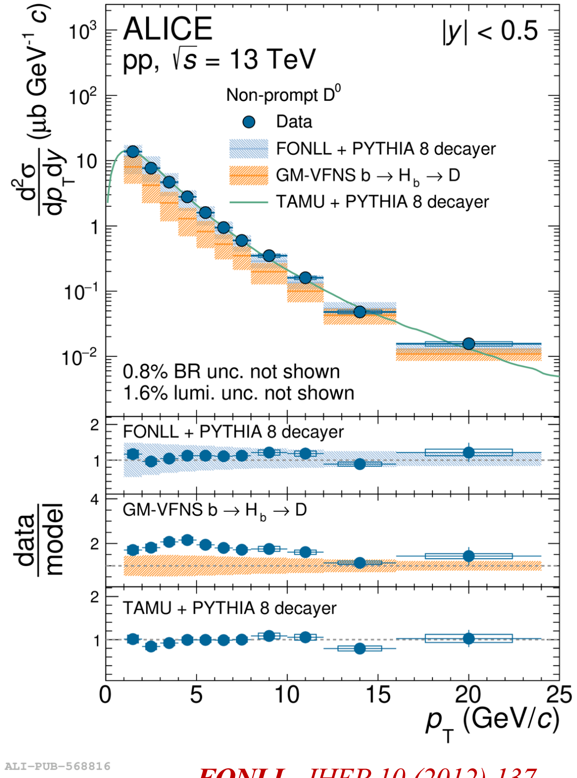

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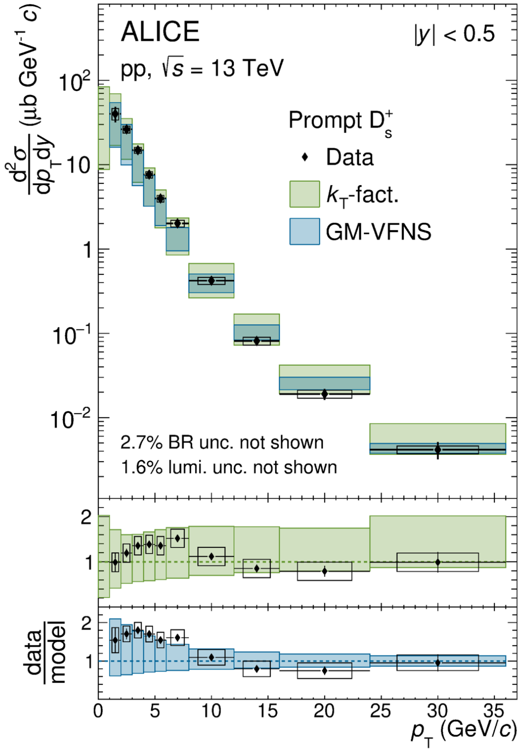
- For TAMU : overestimates the data

***ALICE**, JHEP 12 (2023) 086*
***ALICE**, arxiv:2402.16417*



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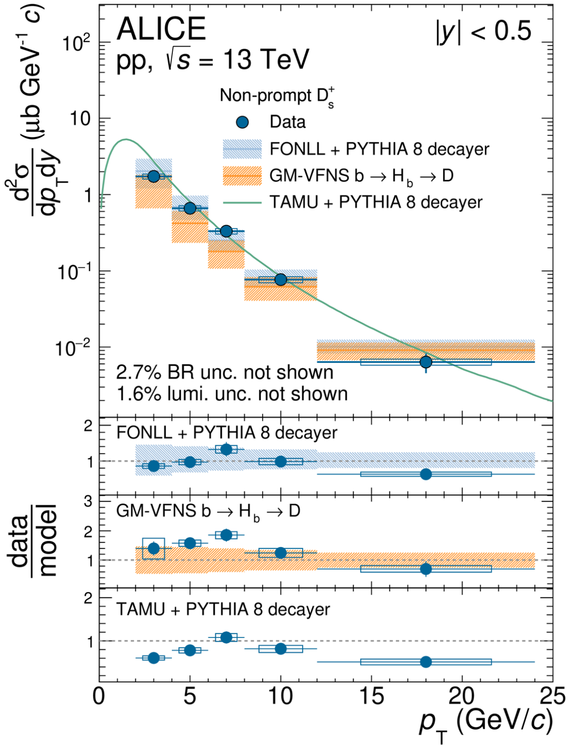


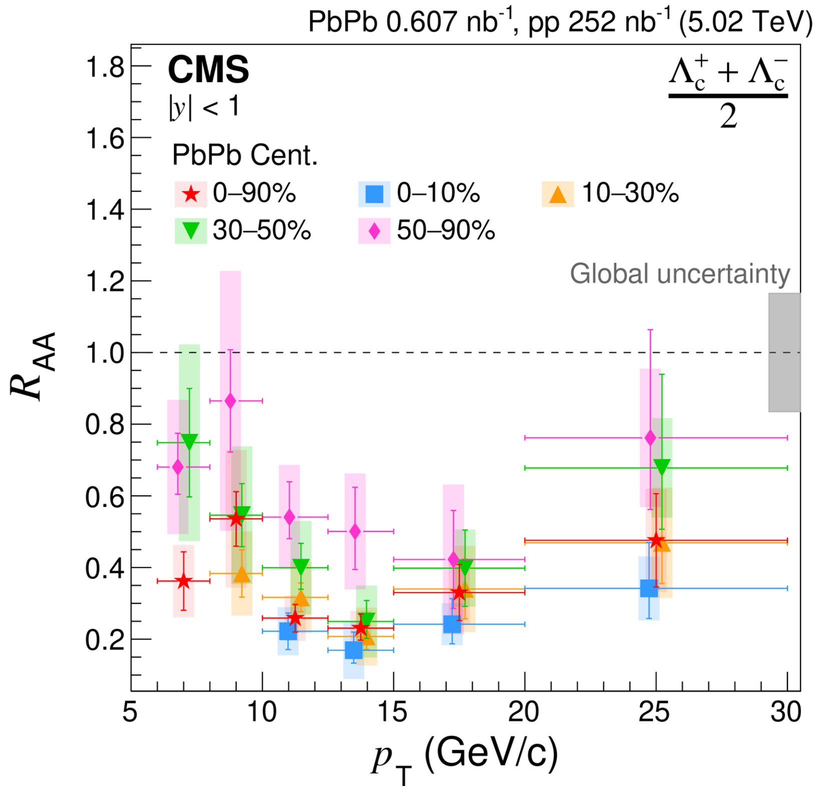
ALI-PUB-568824

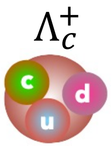
***FONLL**, JHEP 10 (2012) 137*
***kT-fact.**, Phys. Rev. D 104 (2021) 094038*
***GM-VFNS**, Nucl. Phys. B 925 (2017) 415–430*
TAMU, Phys. Rev. Lett. 131 (Jul, 2023) 012301

Lambdac+ measurement

CMS, JHEP 01 (2024) 128

- The R_{AA} shows a suppression for central collisions, with a maximal suppression around $p_T \approx 14$ GeV/c
- Suppression is stronger for more central collisions

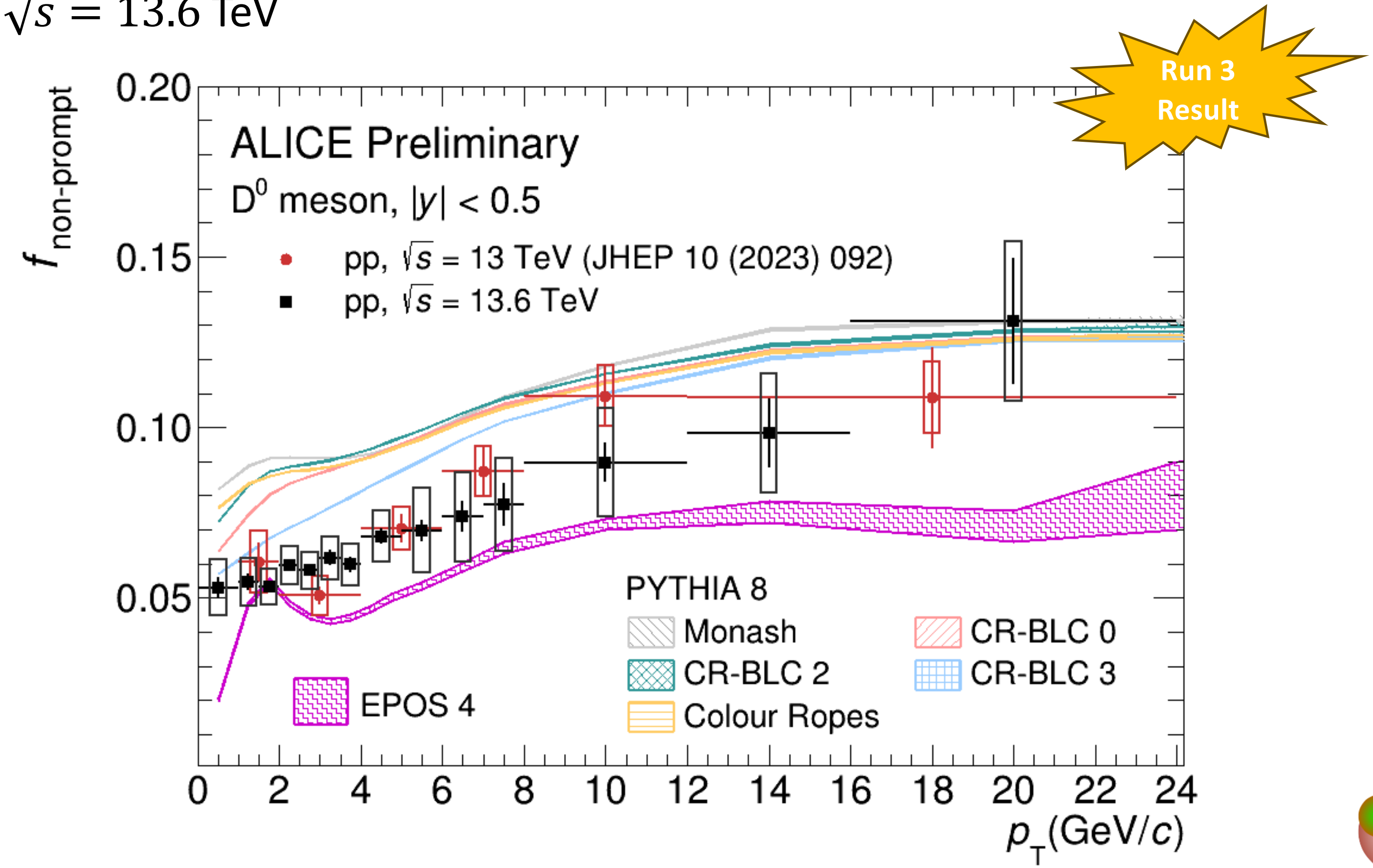


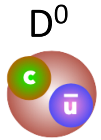


D mesons cross sections in pp collisions

ALICE preliminary

- New result at $\sqrt{s} = 13.6$ TeV





$B_s^0 \to \mu\mu$ lifetime

ATLAS, JHEP 09 (2023) 199
CMS, Phys. Lett. B 842 (2023) 137955

- Measurement of the B_s^0 lifetime can be a test to find Beyond Standard Model effects
- ATLAS and CMS measured the lifetime with unprecedented precision
- Measured values :
  - CMS : $\tau_{\mu\mu} = 1.83^{+0.23}_{-0.20}(stat.)^{+0.04}_{-0.04}(syst.)$
  - ATLAS : $\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}(stat.)^{+0.17}_{-0.17}(syst.)$
- Compatible within uncertainties with PDG value