Recent heavy flavour measurements from ALICE

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for the ALICE Collaboration

XXXI International Workshop on Deep Inelastic Scattering

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ALICE

筑波大学

University of Tsukuba

Introduction

- Heavy-ion collisions at the LHC → explore the state of matter in which quarks and gluons are deconfined,
  ➔ quark-gluon plasma, QGP

- Heavy quarks (charm and beauty) are effective probes of the QGP;
  - ✓ predominantly produced in the initial hard scattering processes
  - ✓ experience the full evolution of medium created by heavy-ion collisions, and subsequently interact with the medium constituents
  - ✓ lose energy while traversing the medium via radiative and collisional processes, and participate in the collective expansion of the medium

- Production cross section in pp collisions can be calculated using a **factorisation approach**

$$\frac{d\sigma^H}{dp_T} = PDF(x_1)PDF(x_2) \times \frac{d\sigma^q}{dp_T^q} \times D_{q \to H}(z = p_H/p_q)$$

$PDF(x_1)PDF(x_2)$:
- non-perturbative
- initial condition from data

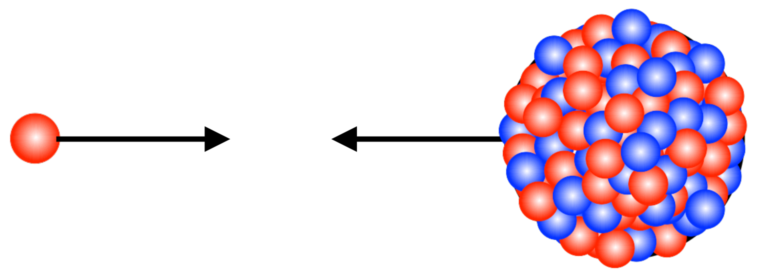
$\frac{d\sigma^q}{dp_T^q}$:
- perturbative (pQCD)

$D_{q \to H}(z = p_H/p_q)$:
- non-perturbative
- fit to data (e^-p, e^+e^-)

pp collisions

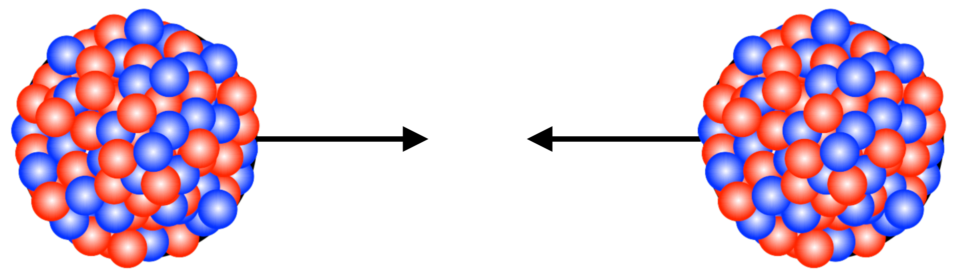
- Test and constraint pQCD calculations
- Reference for p–A and A–A collisions

p–A collisions



- Study cold nuclear matter (CNM) effects

A–A collisions



- Study transport properties of the QGP
- Hadronisation in the presence of QGP

ALICE detector in Run 2

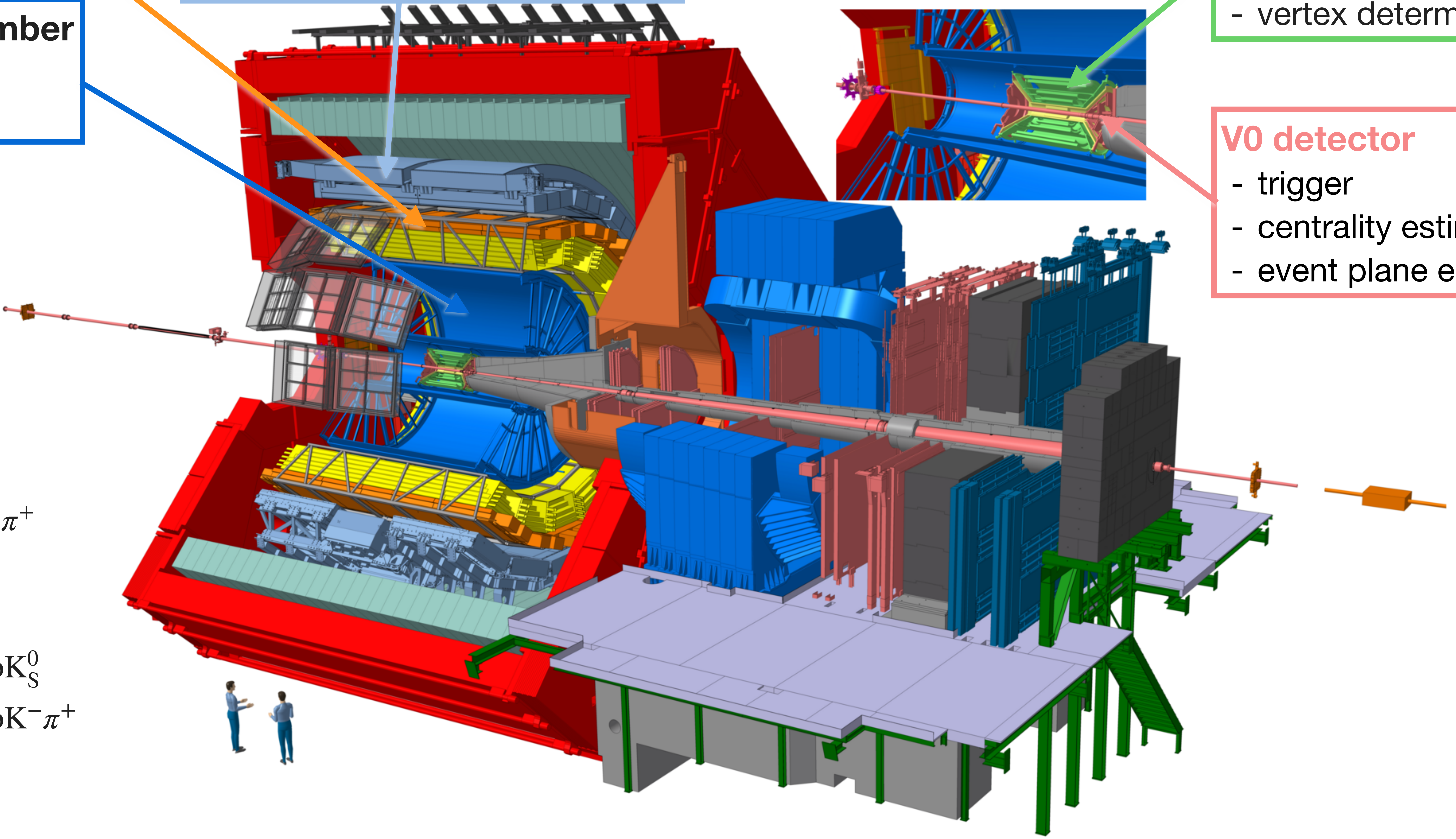
Time-Of-Flight detector
- particle identification

Time Projection Chamber
- track reconstruction
- particle identification

ElectroMagnetic Calorimeter
- trigger
- particle identification

Inner Tracking System
- track reconstruction
- vertex determination

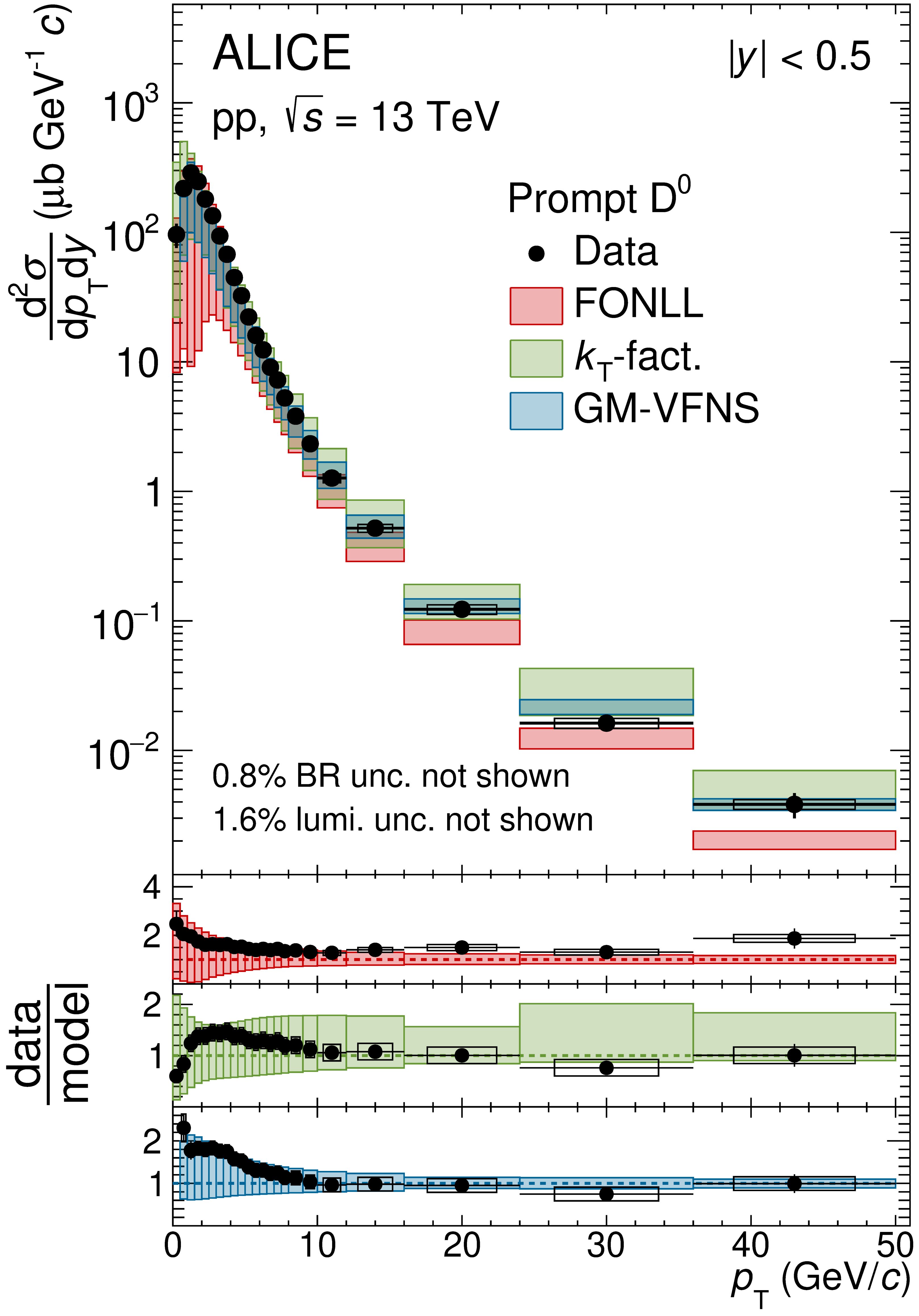
V0 detector
- trigger
- centrality estimation
- event plane estimation



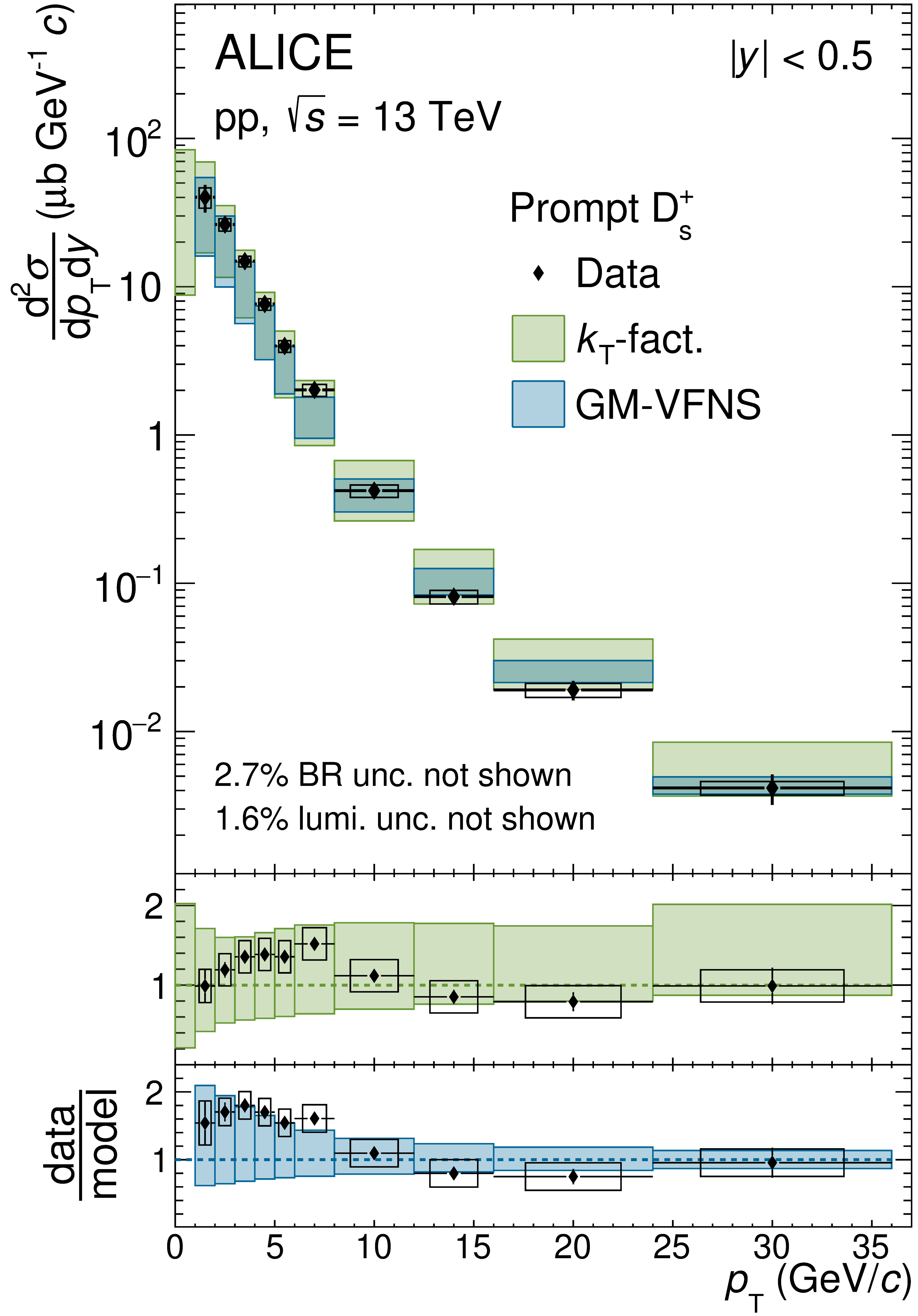
HF hadrons in ALICE

- $D^0 \to K^-\pi^+$
- $D^+ \to K^-\pi^+\pi^+$
- $D_s^+ \to \phi\pi^0 \to K^+K^-\pi^+$
- $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$
- $\Lambda_c^+ \to pK^-\pi^+$
- $\Lambda_c^+ \to pK_S^0 \to p\pi^+\pi^-$
- $\Xi_c^+ \to \Xi^-\pi^+\pi^+ \to \Lambda\pi^-\pi^+\pi^+$
- $\Xi_c^0 \to \pi^+\Xi^- \to \pi^+\pi^-\Lambda$
- $\Omega_c^0 \to \pi^+\Omega^- \to \pi^+K^-\Lambda$
- $\Sigma_c^{0,++} \to \pi^{-,+}\Lambda_c^+ \to \pi^{-,+}pK_S^0$
- $\Sigma_c^{0,++} \to \pi^{-,+}\Lambda_c^+ \to \pi^{-,+}pK^-\pi^+$
- $D_{s1}^+ \to D^{*+}K_S^0$
- $D_{s2}^{*+} \to D^+K_S^0$

Cross section of D mesons in pp collisions



ALI-PUB-567836



ALI-PUB-567851

JHEP 12 (2023) 086

Prompt charm hadron

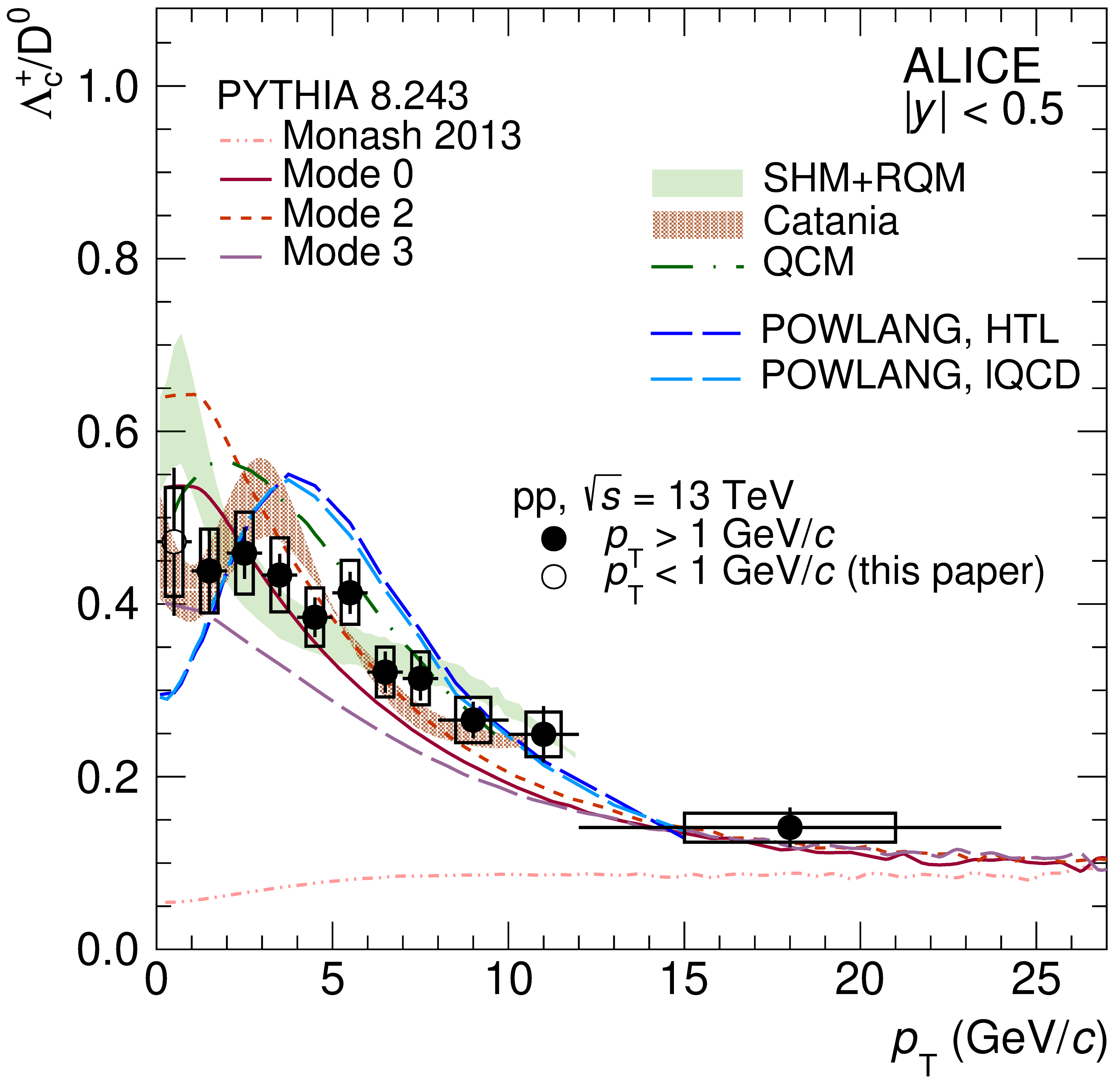
hadrons from c-quark hadronisation or from the decay of excited charm hadrons

p_T-differential cross sections **described by pQCD calculations** (FONLL, k_T-factorization, GM-VFNS)

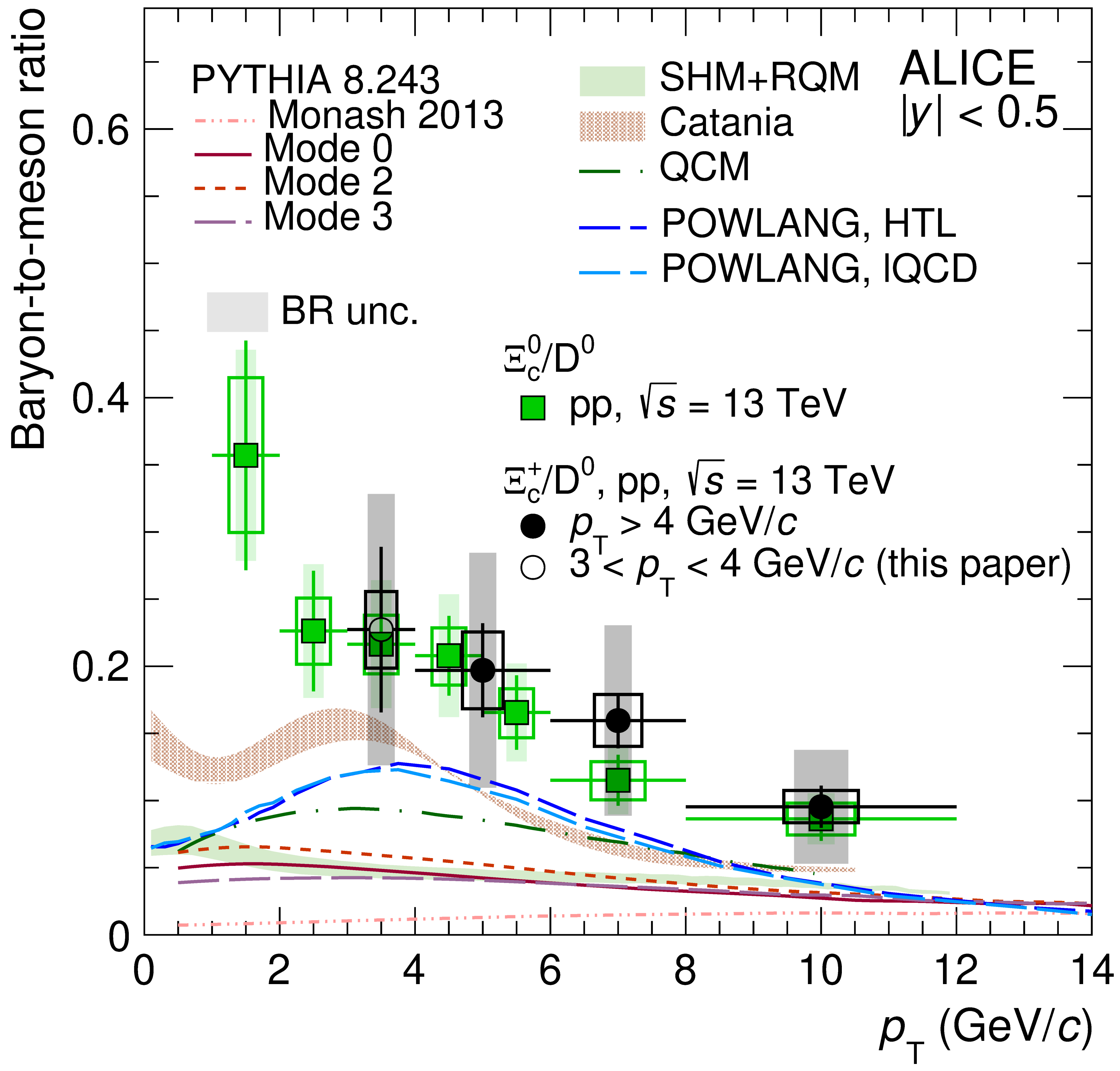
➡ **Good agreement** within uncertainties

FONLL : JHEP 05 (1998) 007, JHEP 10 (2012) 137
k_T-factorization : Phys. Rev. D 104 (2021) 094038
GM-VFNS : JHEP 12 (2017) 021, Nucl. Phys. B 925 (2017) 415–430

Charm baryon-to-meson ratio in pp collisions



ALI-PUB-567876



I-PUB-567881

JHEP 12 (2023) 086

PYTHIA 8

Monash tune : Eur. Phys. J. C 74 (2014) 3024

Mode 0, 2, 3 : JHEP 08 (2015) 003

- Fragmentation tuned on e^+e^-
- Colour reconnection (Mode 0, 2, & 3)

SHM+RQM Phys. Lett. B 795 (2019) 117–121

- Presence of excited charm baryons

Catania Phys. Lett. B 821 (2021) 136622

- Fragmentation + recombination
- Assuming the formation of a small QGP

QCM Eur. Phys. J. C 78 (2018) 344

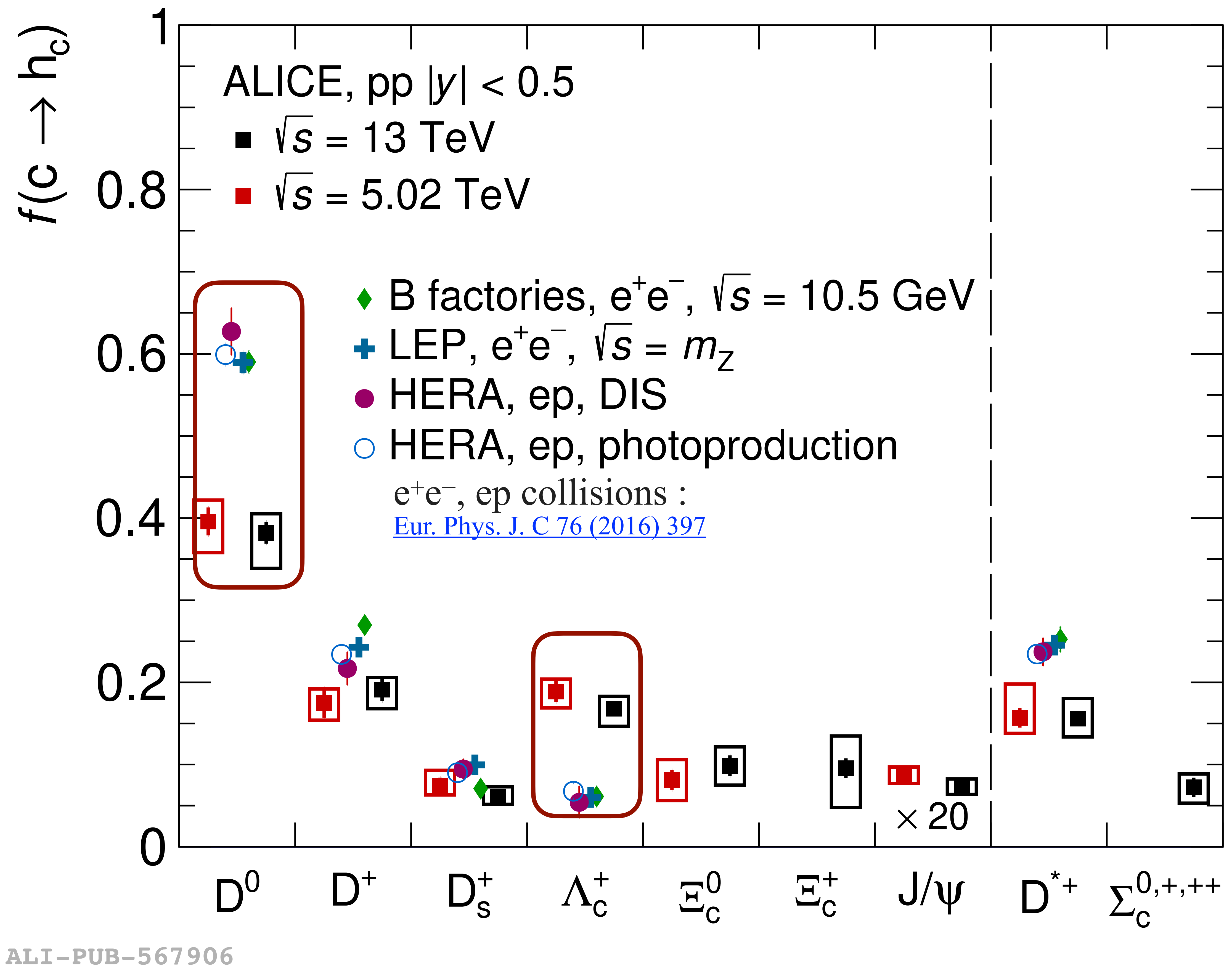
- Recombination with surrounding equal-velocity light quarks

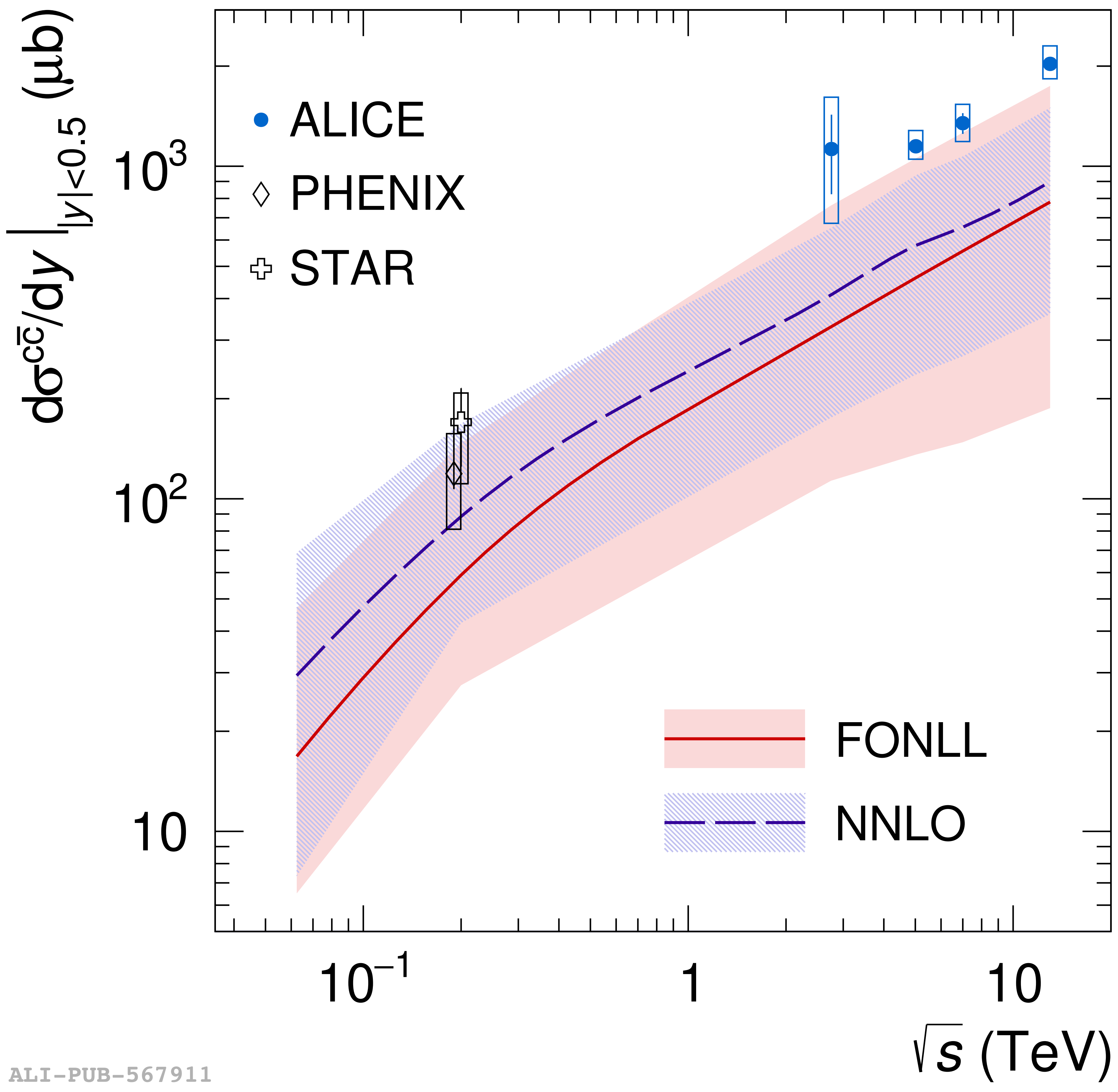
POWLANG arXiv:2306.02152 [hep-ph]

- Fragmentation + recombination
- Assuming the formation of a small QGP

- Charm baryon-to-meson ratios compared to model predictions (PYTHIA 8, Catania, QCM, SHM+RQM, POWLANG)
  - ✓ The Λ_c^+/D^0 is not described by a model based on fragmentation function tuned on e^+e^- collisions
- Models underestimate the measured Ξ_c^+/D^0 ratios, but **coalescence models provide better descriptions**

FF and total charm cross section in pp collisions





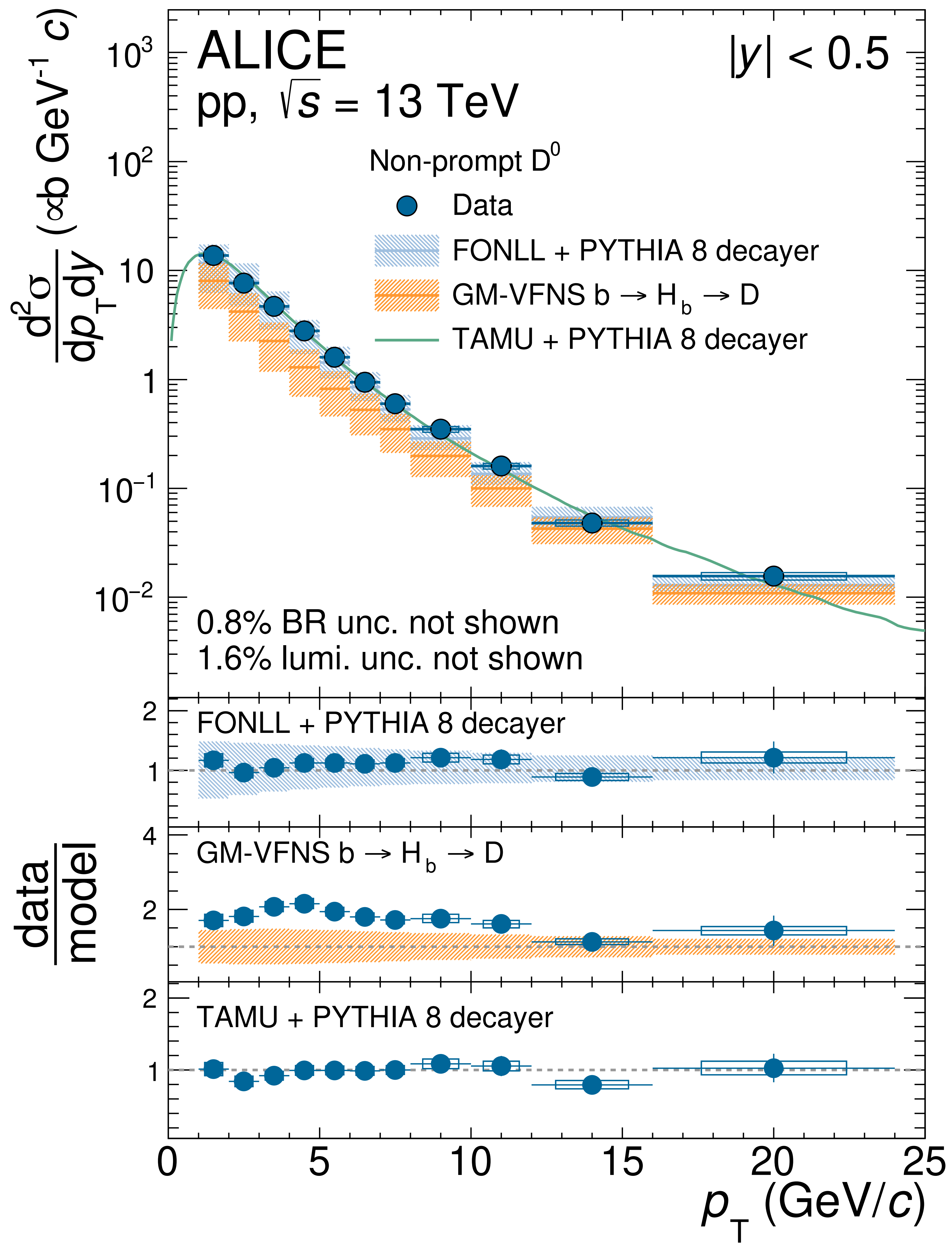
FONLL :
JHEP 05 (1998) 007
JHEP 10 (2012) 137

NNLO :
Phys. Rev. Lett. 118 (2017) 122001
Eur. Phys. J. C 78 (2018) 359
Phys. Rev. Lett. 110 (2013) 252004

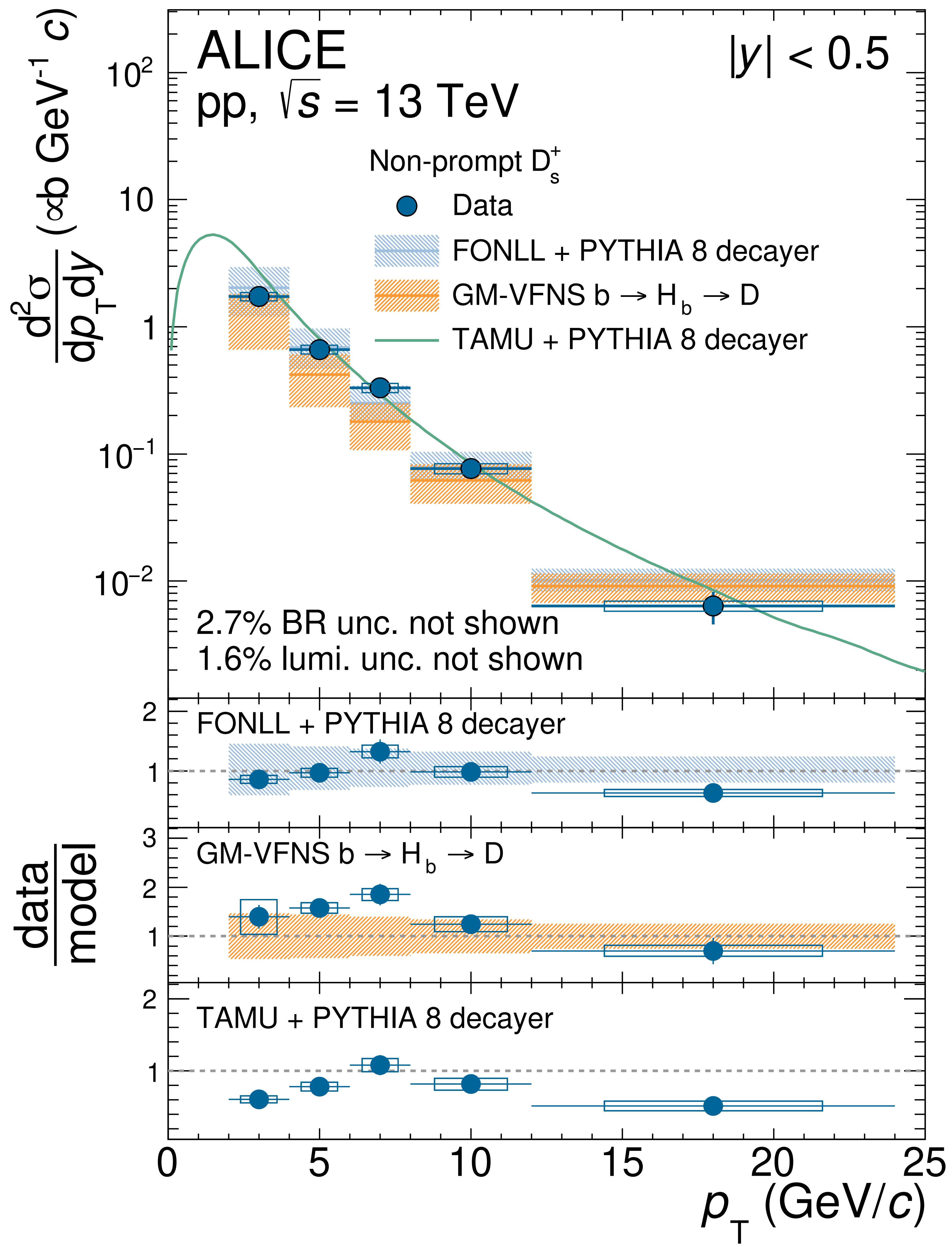
JHEP 12 (2023) 086

- Charm-quark fragmentation fractions $f(c \to h_c)$
  - ✓ **No significant energy dependence** at the LHC
  - ✓ **Enhancement of baryons → overall reduction of the D-meson abundance relative to e^+e^- and e^-p collisions**
- Total $c\bar{c}$ cross section from the sum of the production cross sections of D^0, D^+, D_s^+, J/ψ, Λ_c^+, Ξ_c^0, and Ξ_c^+
  - ✓ Lie on the upper edge of FONLL and NNLO predictions

Cross section of non-prompt D mesons in pp collisions



ALI-PUB-568816



ALI-PUB-568824

arXiv:2402.16417

Non-prompt charm hadron

- Charm hadrons from beauty-hadron decays

PYTHIA 8

Comput. Phys. Commun. 191 (2015) 159–177
Eur. Phys. J. C 74 (2014) 3024

FONLL

JHEP 05 (1998) 007
JHEP 10 (2012) 137

- Consistent with data within uncertainties

TAMU

Phys. Rev. Lett. 131 (2023) 012301

- Good agreement for D^0
- Tend to overestimate the non-prompt D_s^+

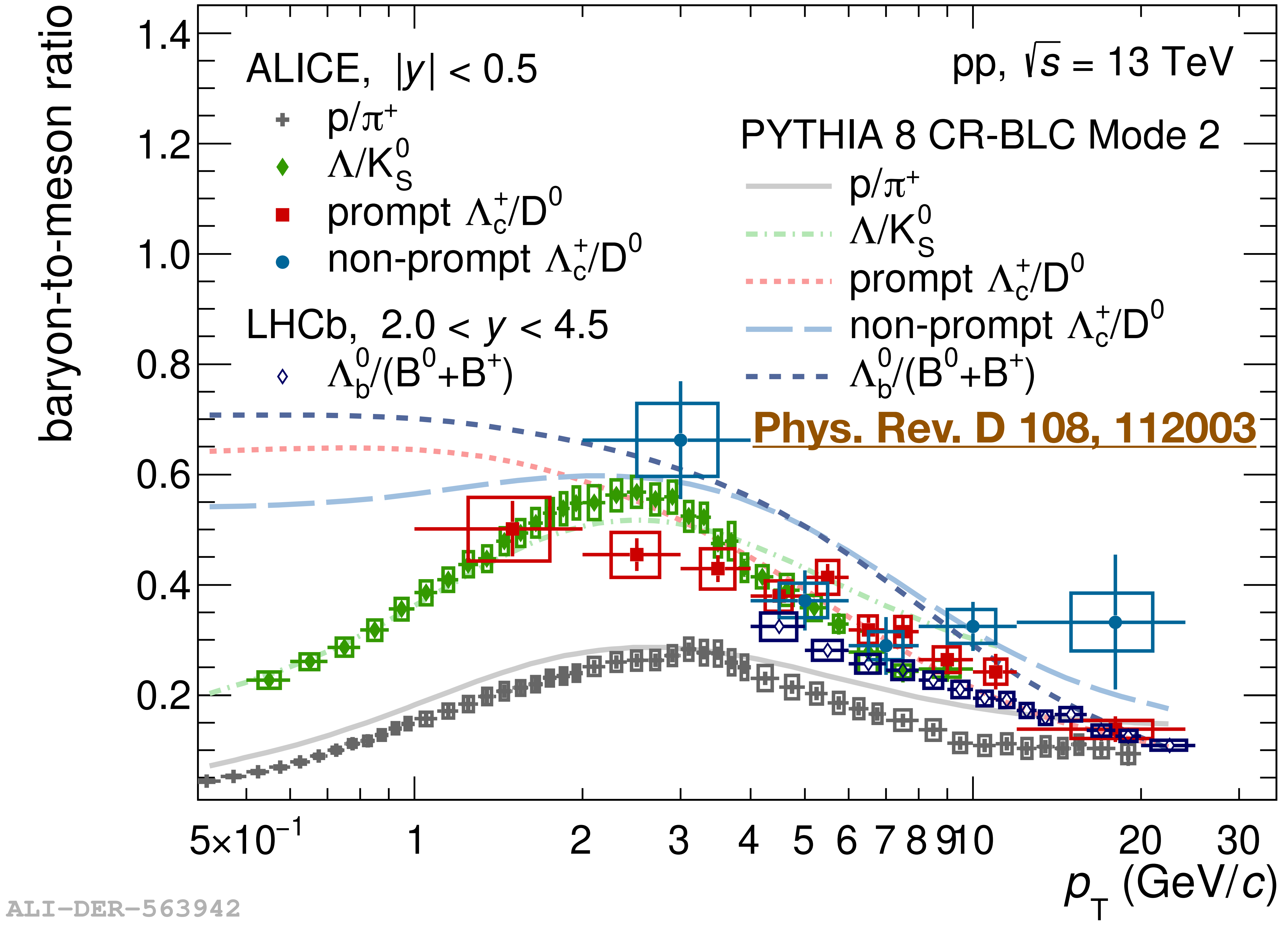
GM-VFNS

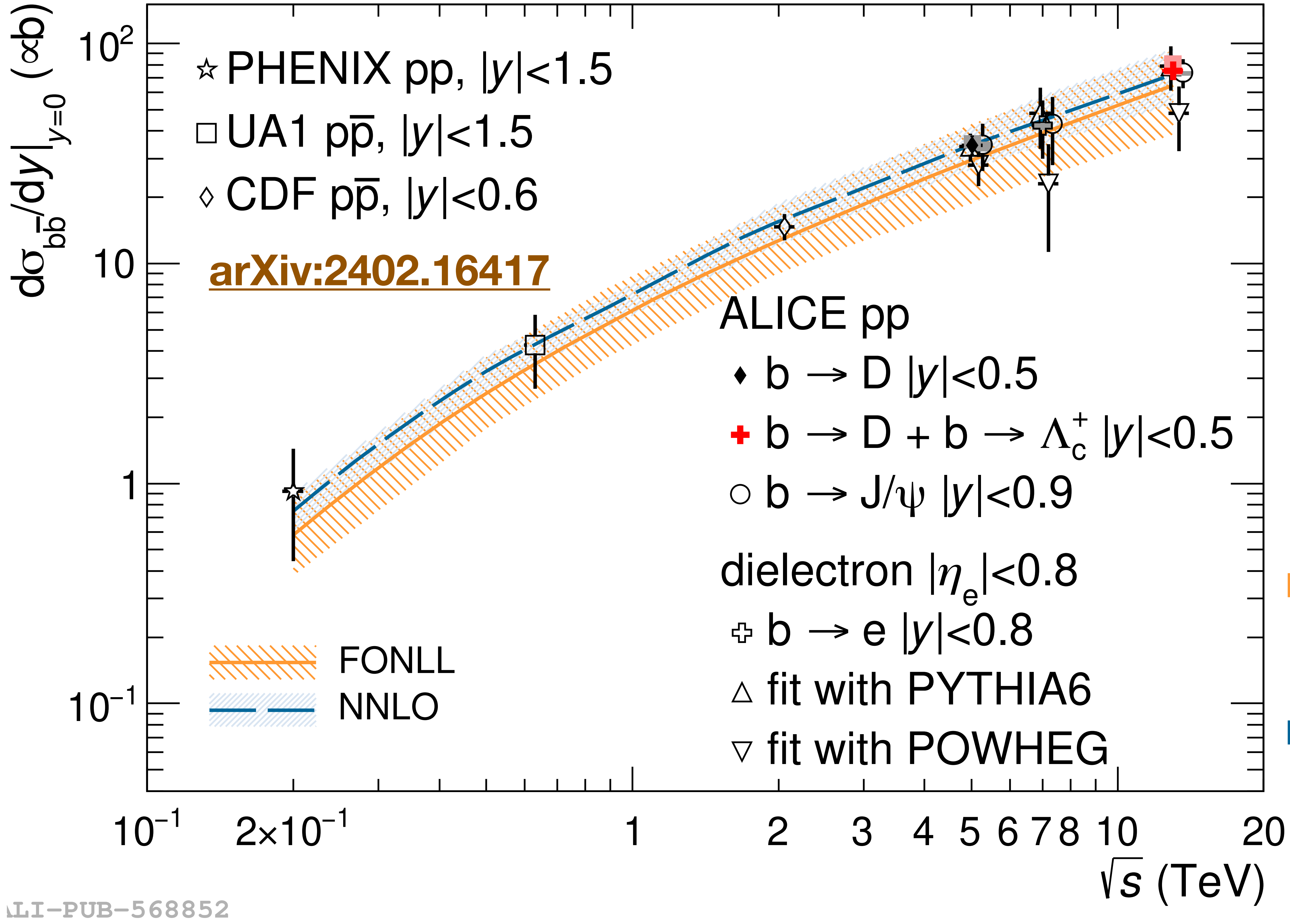
JHEP 12 (2017) 021
Nucl. Phys. B 925 (2017) 415–430
J. Phys. G 41 (2014) 075006

- Underestimate the data at low p_T, whereas a better description at high p_T

Non-prompt Λ_c/D^0 ratio and total cross section in pp collisions

- Ratio of p_T-differential production cross section of non-prompt Λ_c^+ and D^0
  - ✓ Ratio, $\Lambda_b^0/(B^0+B^+)$ is a bit lower than non-prompt Λ_c^+/D^0
  - ✓ Beauty, charm, and strange hadrons have a similar trend and are compatible within uncertainties
  - ✓ PYTHIA with CR-BLC tune describes the data for $p_T > 2$ GeV/c and significantly higher at low p_T for heavy-flavour hadrons
- Total $b\bar{b}$ cross section as a function of $\sqrt{s}$ → described by pQCD calculations (FONLL and NNLO) within uncertainties → NNLO is closer to data due to higher perturbative accuracy



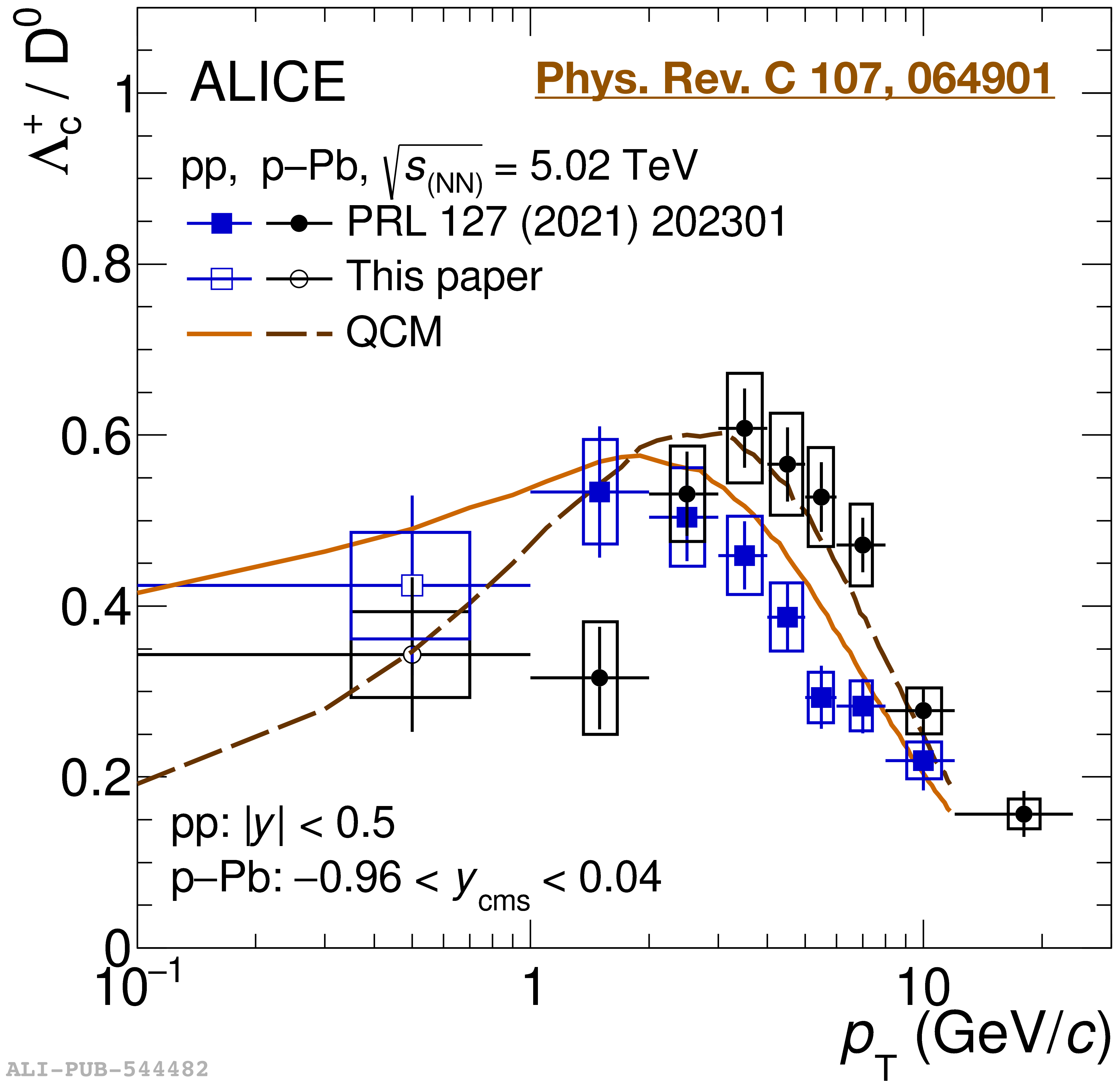


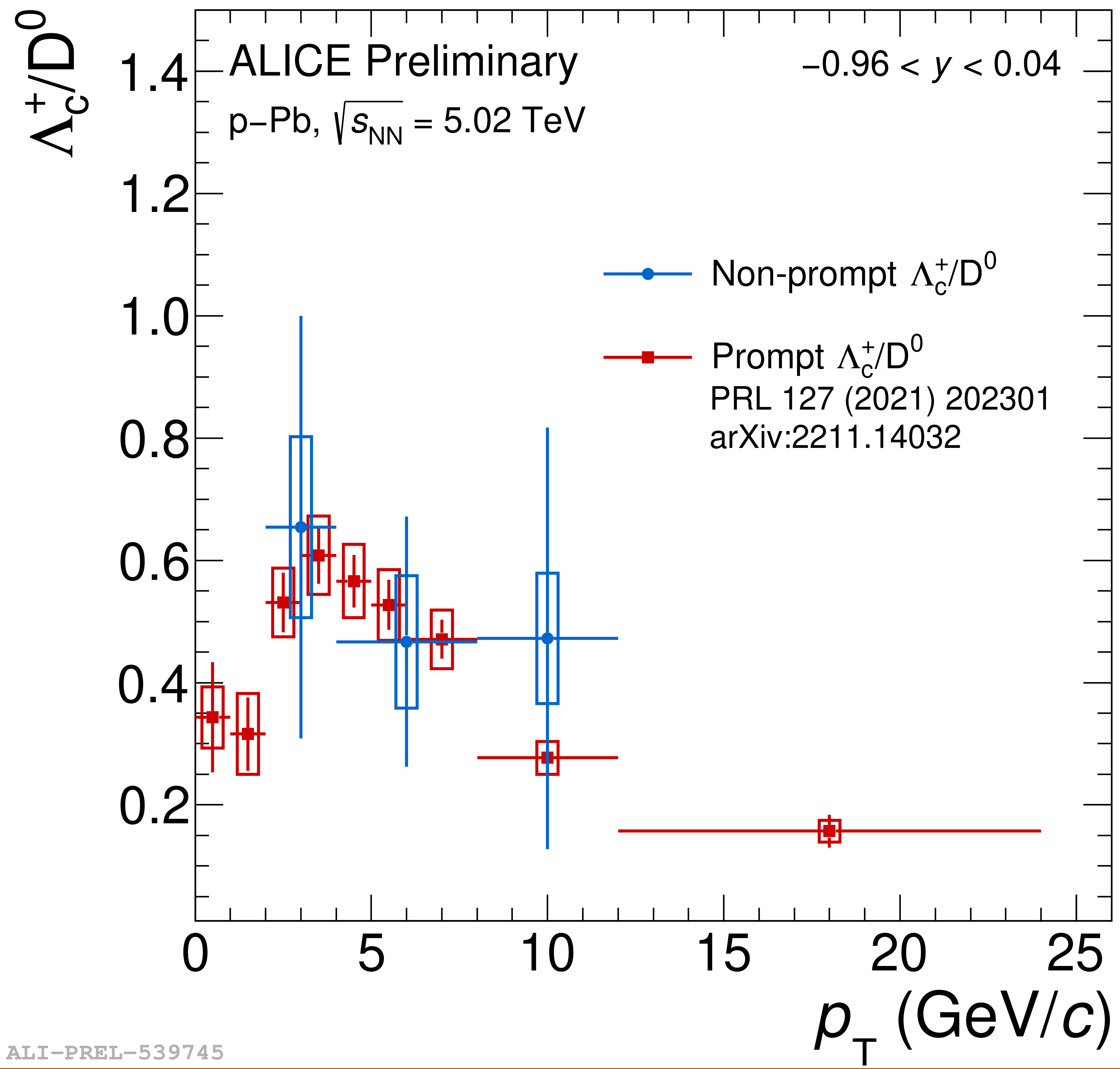
FONLL
JHEP 05 (1998) 007
JHEP 10 (2012) 137
JHEP 03 (2001) 006

NNLO
JHEP 03 (2021) 029

Prompt and non-prompt Λ_c/D^0 ratio in p–Pb collisions

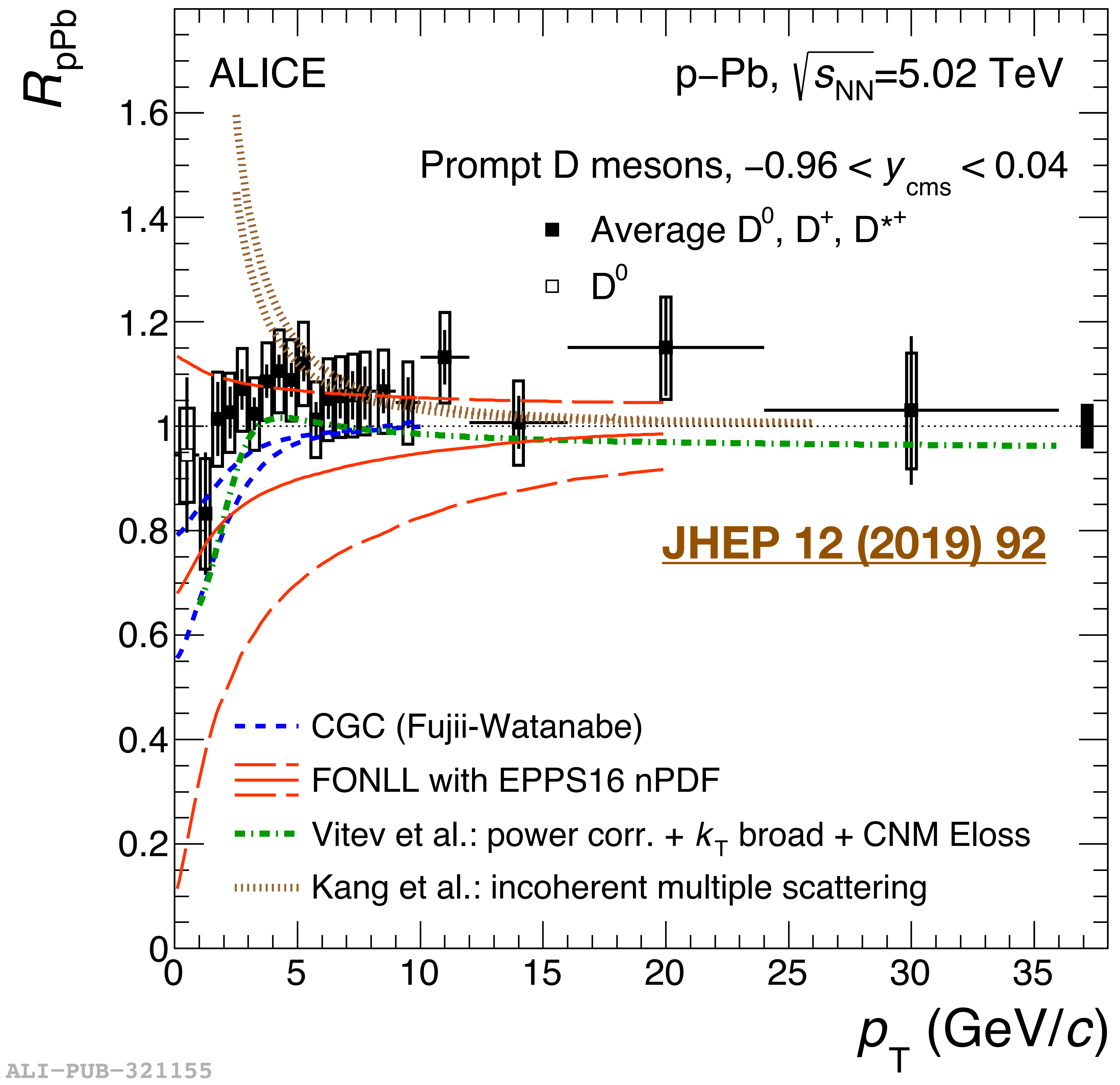
- Similar trend of Λ_c^+/D^0 in both pp and p–Pb collisions
  - ✓ **Shift towards higher p_T in p–Pb collisions attributed to radial flow** (described by QCM prediction)
- Decreasing trend of non-prompt Λ_c^+/D^0 at midrapidity with increasing p_T
  - ✓ **Baryon enhancement at low p_T → hadronisation effects apart from in-vacuum fragmentation**

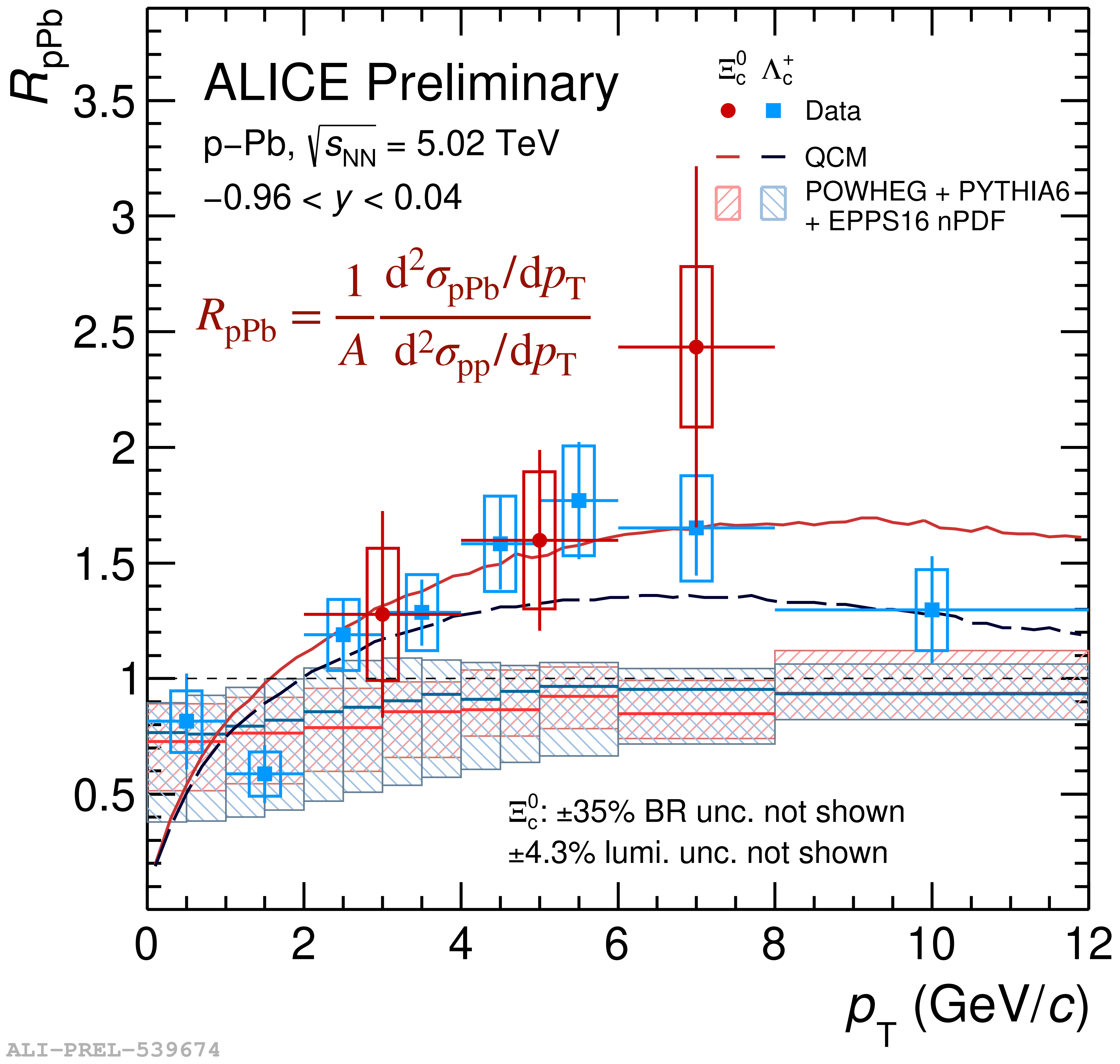




QCM
pp : Chin. Phys. C 45 (2021) 113105
pPb : Phys. Rev. C 97 (2018) 064915

R_{pPb} of prompt charm hadrons in p–Pb collisions





CGC
arXiv:1706.06728

FONLL with EPPS16 nPDF
JHEP 10 (2012) 137
EPJC 77 (2017) 163

Vitev et al.
Phys. Rev. C 80 (2009) 054902

Kang et al.
Phys. Lett. B 740 (2015) 23

POWHEG
JHEP 09 (2007) 126

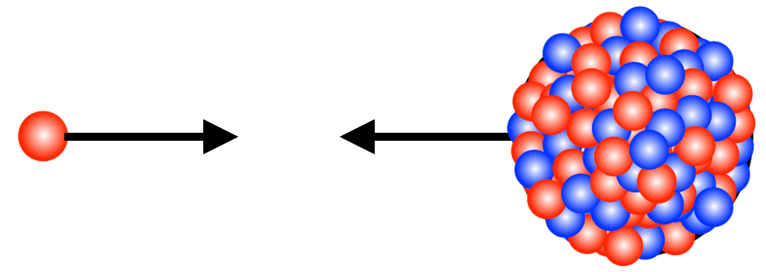
PYTHIA 6
JHEP 05 (2006) 026

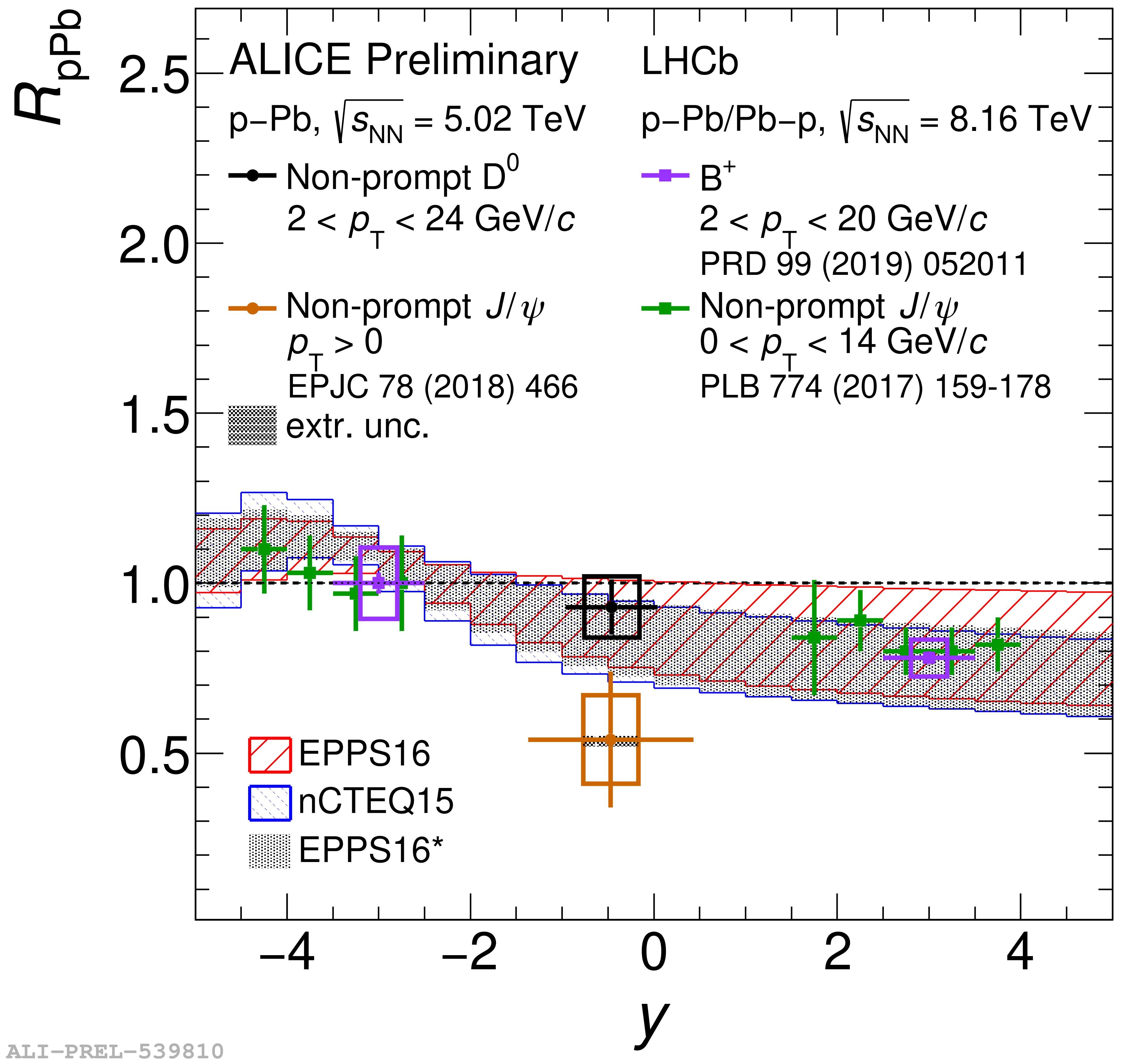
EPPS16 nPDF
EPJC 77 (2017) 163

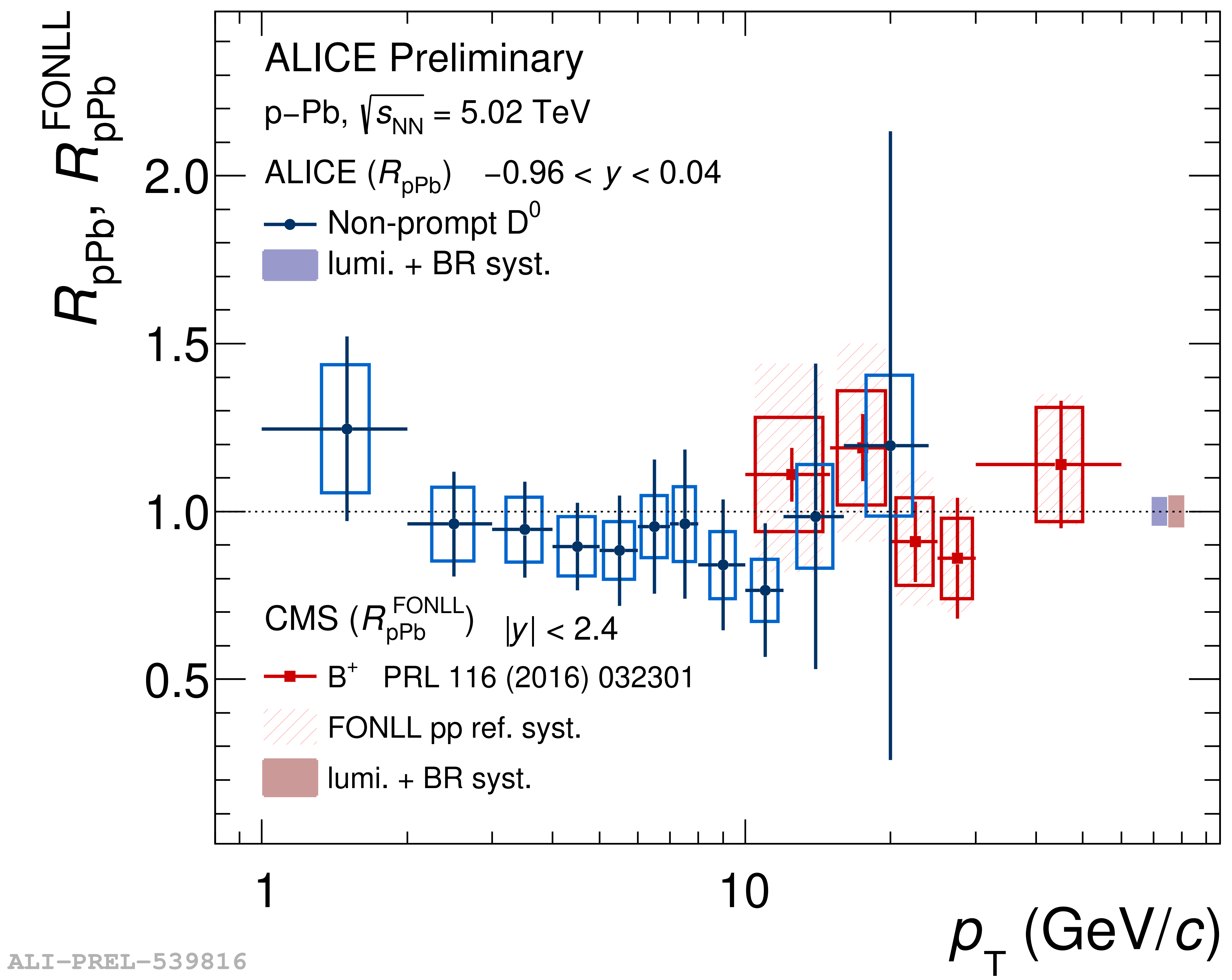
QCM
Phys. Rev. C 97 (2018) 064915

- D-meson R_{pPb} is compatible with unity and compared to model predictions including CNM effects
- Both Λ_c^+ and Ξ_c^0 R_{pPb} are compatible within uncertainties → **similar modification of the production in p–Pb collisions**
  - ✓ R_{pPb} of Ξ_c^0 is larger than unity → no conclusion of increasing trend with p_T due to large uncertainties
  - ✓ Models underestimate the data (only Λ_c^+ R_{pPb} is described below 2 GeV/c)

R_{pPb} of non-prompt charm hadrons in p–Pb collisions





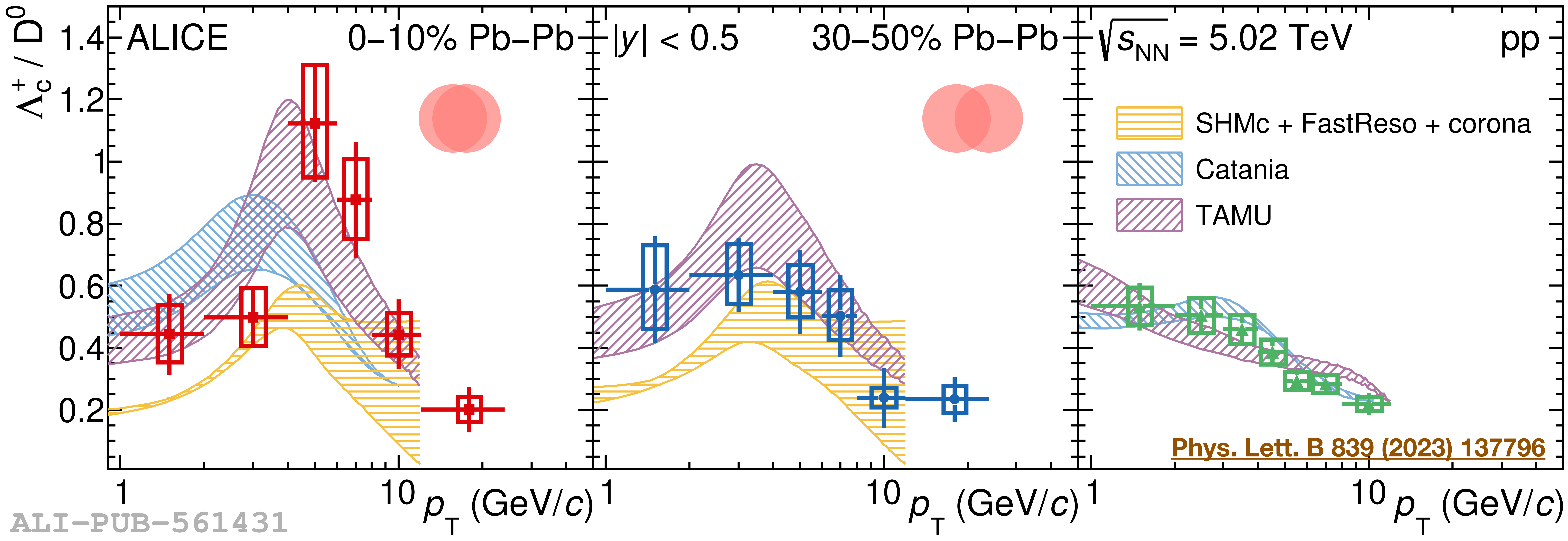


$$R_{pPb} = \frac{1}{A}\frac{d^2\sigma_{pPb}/dp_T}{d^2\sigma_{pp}/dp_T}$$

EPPS16
EPJC 77 (2017) 163
nCTEQ15
Phys. Rev. D 93 (2016) 085037
EPPS*
Phys. Rev. Lett. 121 (2018) 052004

- p_T-integrated R_{pPb} of non-prompt D^0 and J/ψ measured at midrapidity
  - ✓ Observed a **possible suppression for non-prompt J/ψ**
  - ✓ Suppression at forward rapidity whereas compatible with unity at backward rapidity
  - ✓ Good agreement with model predictions within uncertainties
- Consistent with B meson R_{pPb} result from CMS at high p_T

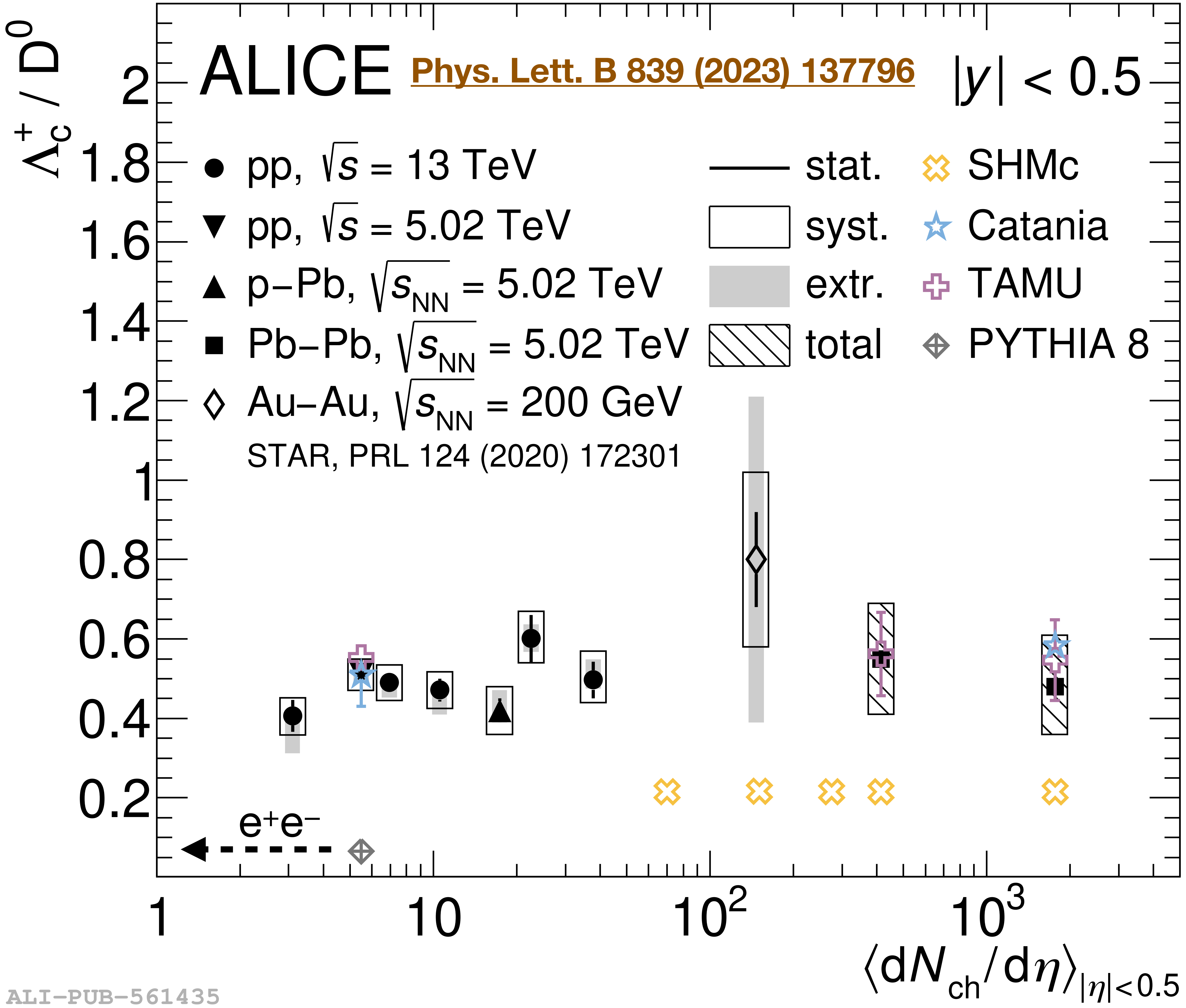
Λ_c/D^0 ratio in Pb–Pb collisions



SHMc : JHEP 07 (2021) 035 **Catania :** Phys. Lett. B 821 (2021) 136622 (pp) EPJC 78 (2018) 348 (Pb–Pb) **TAMU :** Phys. Lett. B 795 (2019) 117–121 (pp) Phys. Rev. Lett. 124 (2020) 042301 (Pb–Pb)

- Ratio of Λ_c^+/D^0 increases from pp to semicentral and central Pb–Pb collisions at the intermediate p_T region
- Compare to different model predictions
  - ✓ SHMc : describe the ratio in semicentral collisions and underestimate the data in $4 < p_T < 8$ GeV/c in central collisions
  - ✓ Catania : underestimate the data in the intermediate p_T region
  - ✓ TAMU : reproduce the magnitude and shape of the data, and better description within uncertainties

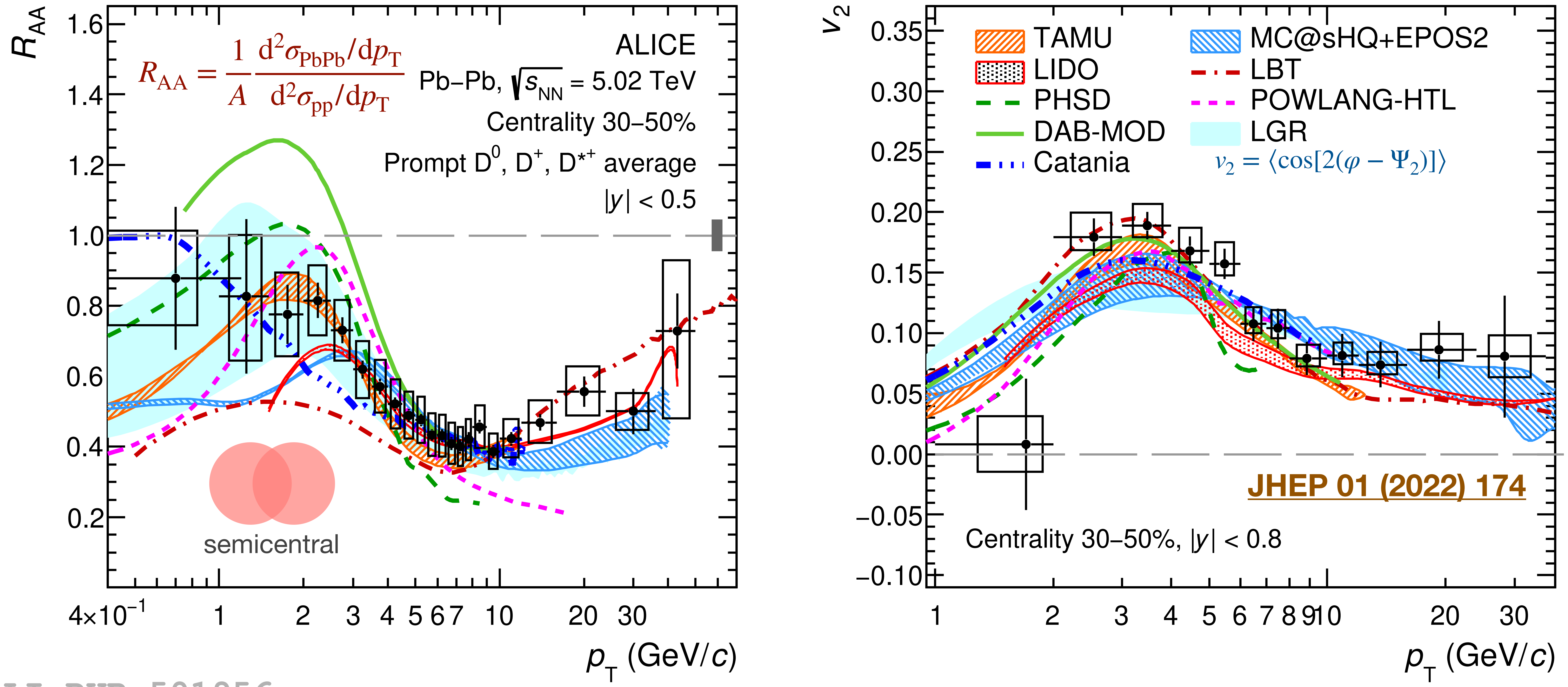
Λ_c/D^0 ratio in Pb–Pb collisions



- p_T-integrated Λ_c^+/D^0 ratio vs multiplicity from pp to Pb–Pb
  - ✓ **No multiplicity dependence observed**
- Suggest a modified mechanism of hadronisation in all hadronic collisions w.r.t e^+e^- and e^-p collisions (PYTHIA 8)
- Catania and TAMU describe the data, while SHMc underestimates the data
  - ✓ unobserved charm-baryon states need to be assumed in normalisation

SHMc : JHEP 07 (2021) 035
Catania : Phys. Lett. B 821 (2021) 136622 (pp) EPJC 78 (2018) 348 (Pb–Pb)
TAMU : Phys. Lett. B 795 (2019) 117–121 (pp) Phys. Rev. Lett. 124 (2020) 042301 (Pb–Pb)
PYTHIA 8 : Comput. Phys. Commun. 191 (2015) 159–177

R_{AA} and v_2 of non-strange D mesons in Pb–Pb collisions



ALI-PUB-501956

TAMU
Phys. Rev. Lett. 124 (2020) 042301

LIDO
Phys. Rev. C 100 (2019) 064911

PHSD
Phys. Rev. C 92 (2015) 014910

DAB-MOD
Phys. Rev. C 102 (2020) 024906

Catania
Phys. Rev. C 96 (2017) 044905
Phys. Lett. B 805 (2020) 135460

MC@sHQ+EPOS2
Phys. Rev. C 89 (2014) 014905

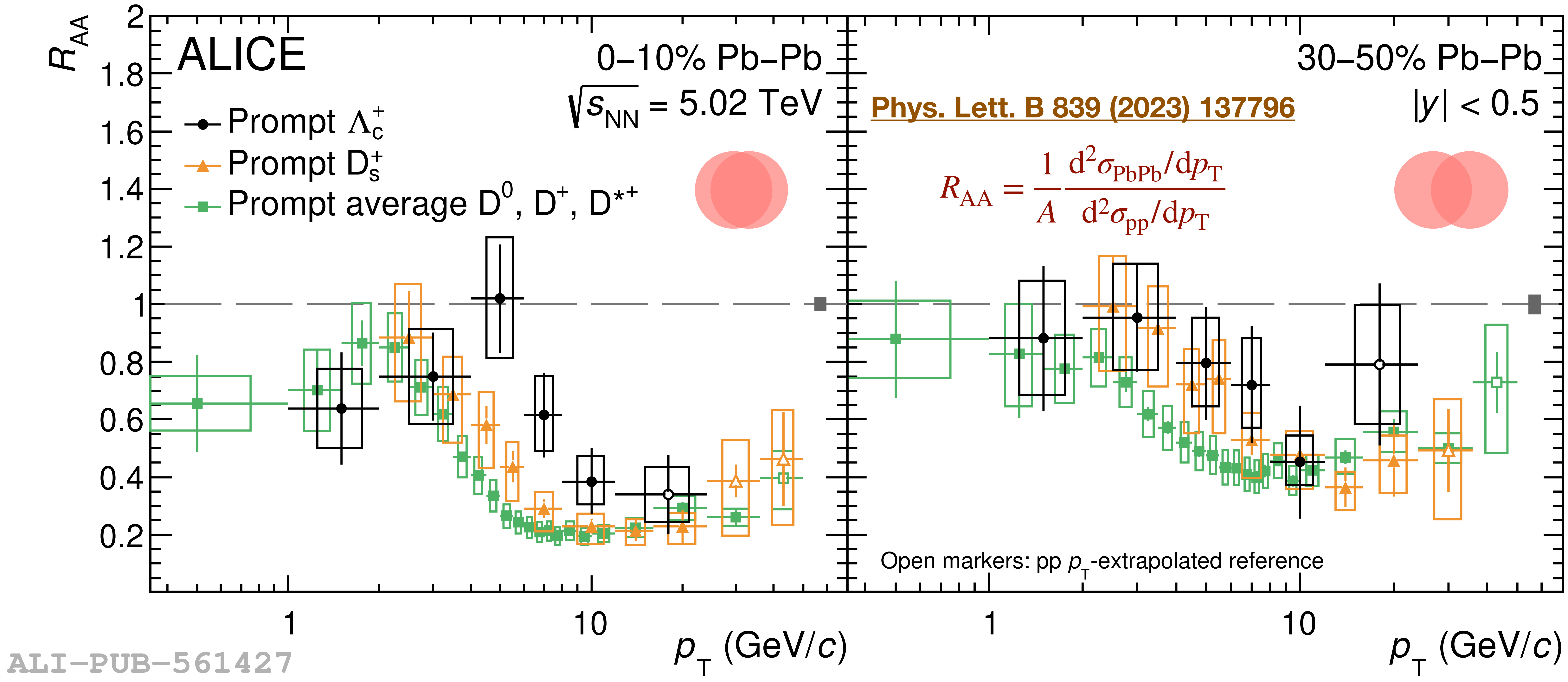
LBT
Phys. Rev. C 94 (2016) 014909
Phys. Lett. B 777 (2018) 255

POWLANG+HLT
EPJC 75 (2015) 121
JHEP 02 (2018) 043

LGR
EPJC 80 (2020) 671

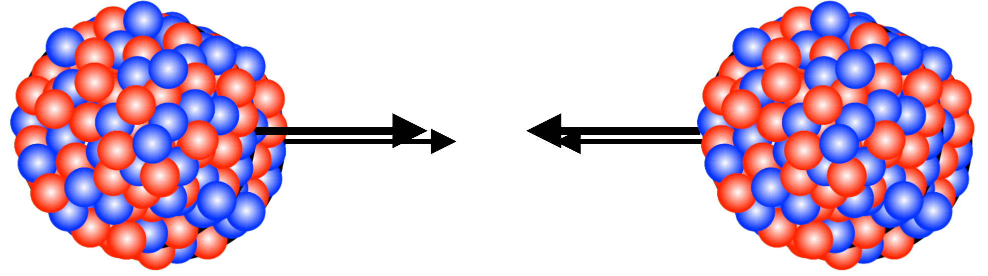
- Understanding the heavy-quark interactions with the medium constitutes by comparing R_{AA} and v_2 with models
  - ✓ Models fairly describe the data, but challenging to describe the R_{AA} and v_2 simultaneously
  - ✓ Realistic QGP evolution, collisional/radiative energy loss, and hadronisation mechanisms (fragmentation/coalescence) are required to describe the data
- Sensitive to quark diffusion, thermalisation with the medium, and hadronisation mechanisms for $2 < p_T < 6$ GeV/c

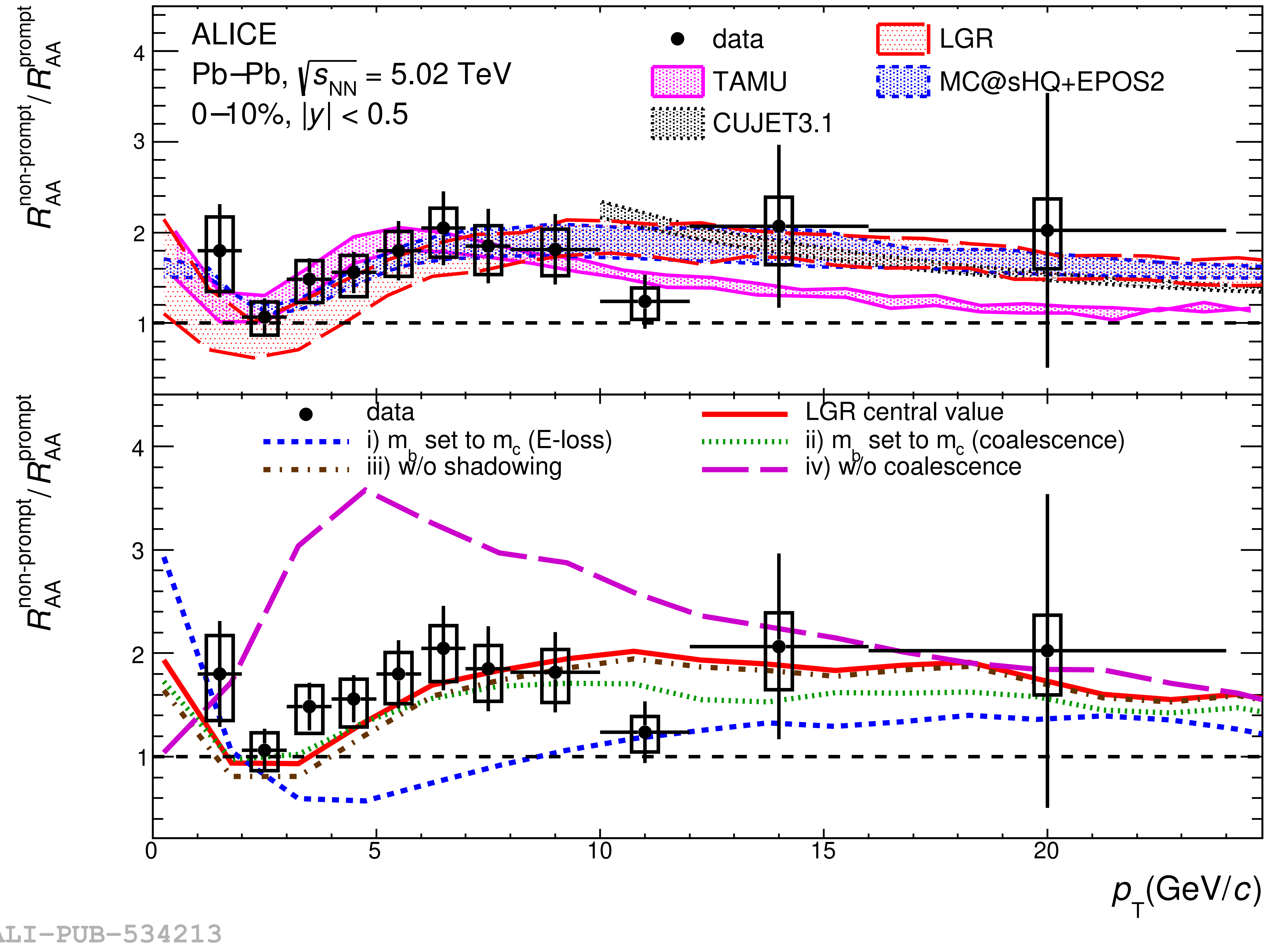
R_{AA} of charm hadrons in Pb–Pb collisions

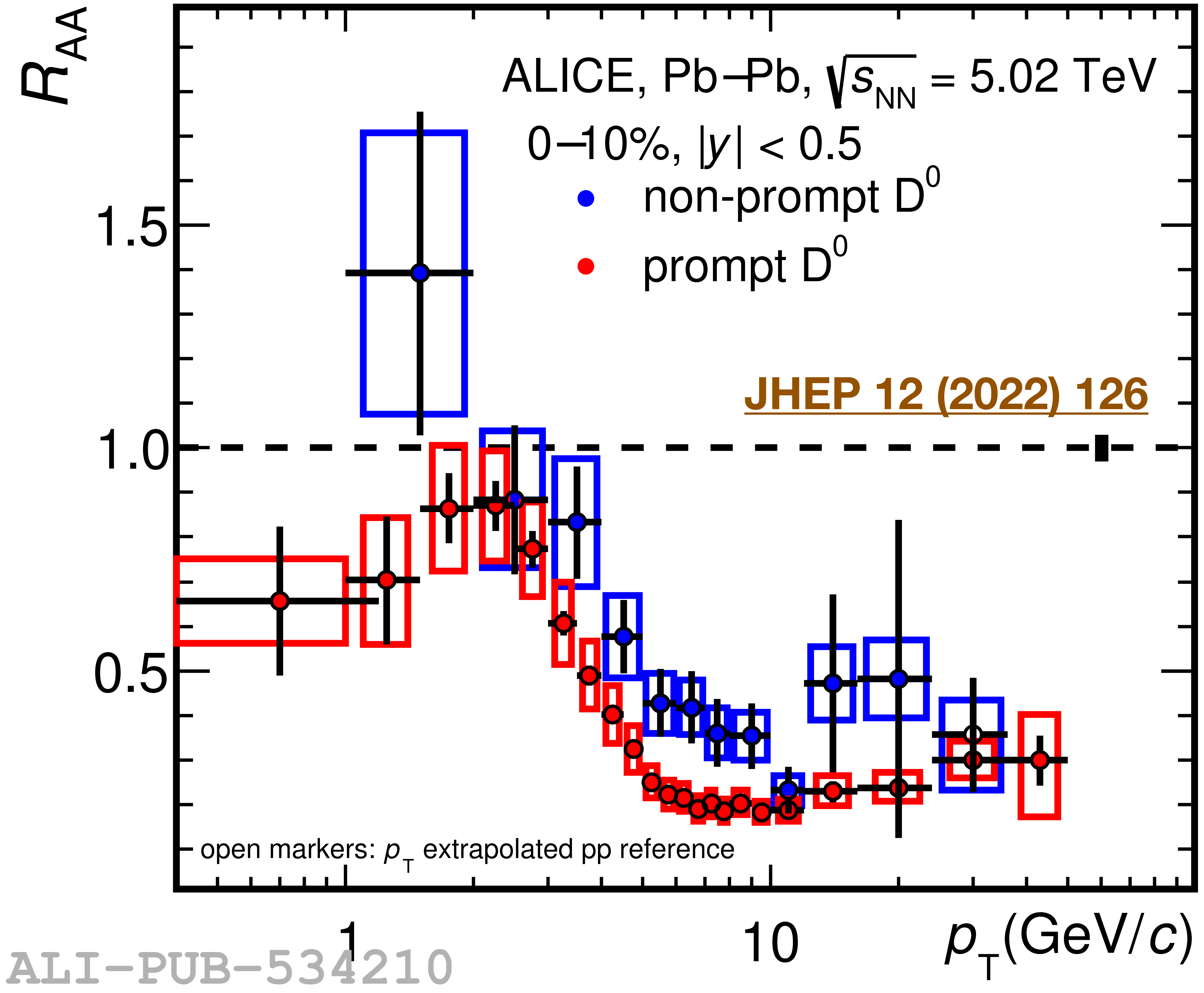


- **Suppression of all charm species** from $p_T > 6$ GeV/c for 0–10% and from $p_T > 4$ GeV/c for 30–50%
  - ✓ Interaction of charm quarks with the medium
- **Hint of a hierarchy $R_{AA}(D^0) < R_{AA}(D_s^+) < R_{AA}(\Lambda_c^+)$** in $4 < p_T < 8$ GeV/c in 0–10%, while less pronounced in 30–50%
- For $p_T > 10$ GeV/c, all R_{AA} are compatible within uncertainties

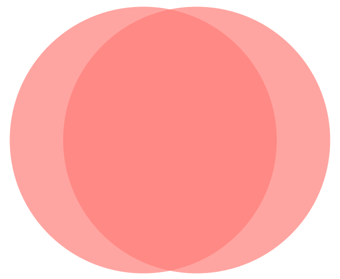
R_{AA} ratio of prompt D⁰ in Pb–Pb collisions







$$R_{AA} = \frac{1}{A}\frac{d^2\sigma_{PbPb}/dp_T}{d^2\sigma_{pp}/dp_T}$$



TAMU
Phys. Lett. B 735 (2014) 445

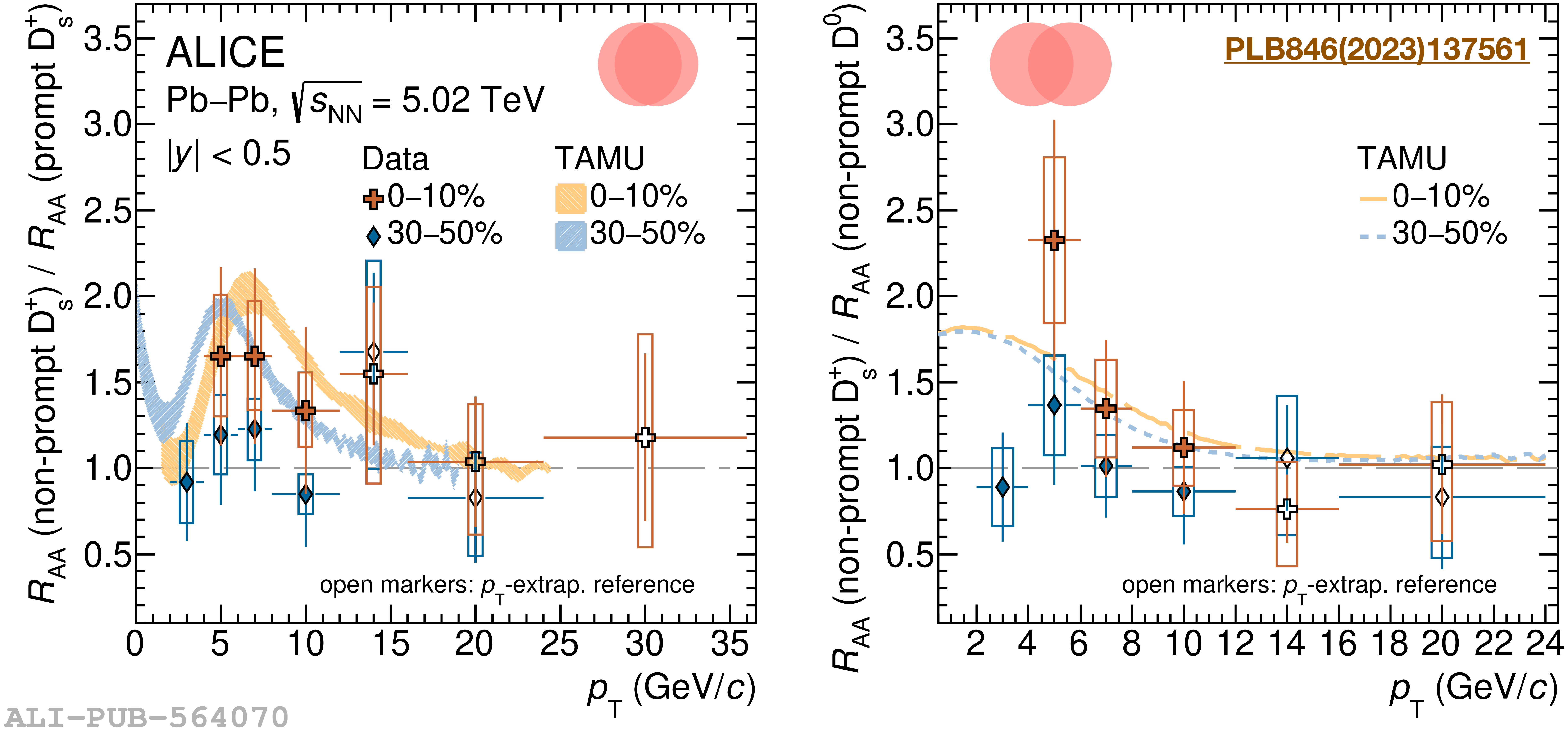
CUJET3.1
Chin. Phys. C 43 (2019) 044101

LGR
EPJC 80 (2020) 671
Phys. J. C 80 (2020) 1113

MC@sHQ+EPOS2
Phys. Rev. C 89 (2014) 014905

- Non-prompt D⁰ R_{AA} is systematically higher than that of prompt D⁰ for $p_T > 5$ GeV/c
  - ✓ **Hint of a mass dependent in-medium energy loss**
- R_{AA} ratio of non-prompt D⁰ to prompt D⁰ as a function of p_T in 0–10% centrality compared to model predictions
  - ✓ At low p_T, formation of D mesons via **coalescence makes a hardening of the prompt D⁰ meson p_T**
  - ✓ At hight p_T, beauty quarks lose less energy than charm quarks via radiative processes

R_{AA} ratio of non-prompt D mesons in Pb–Pb collisions



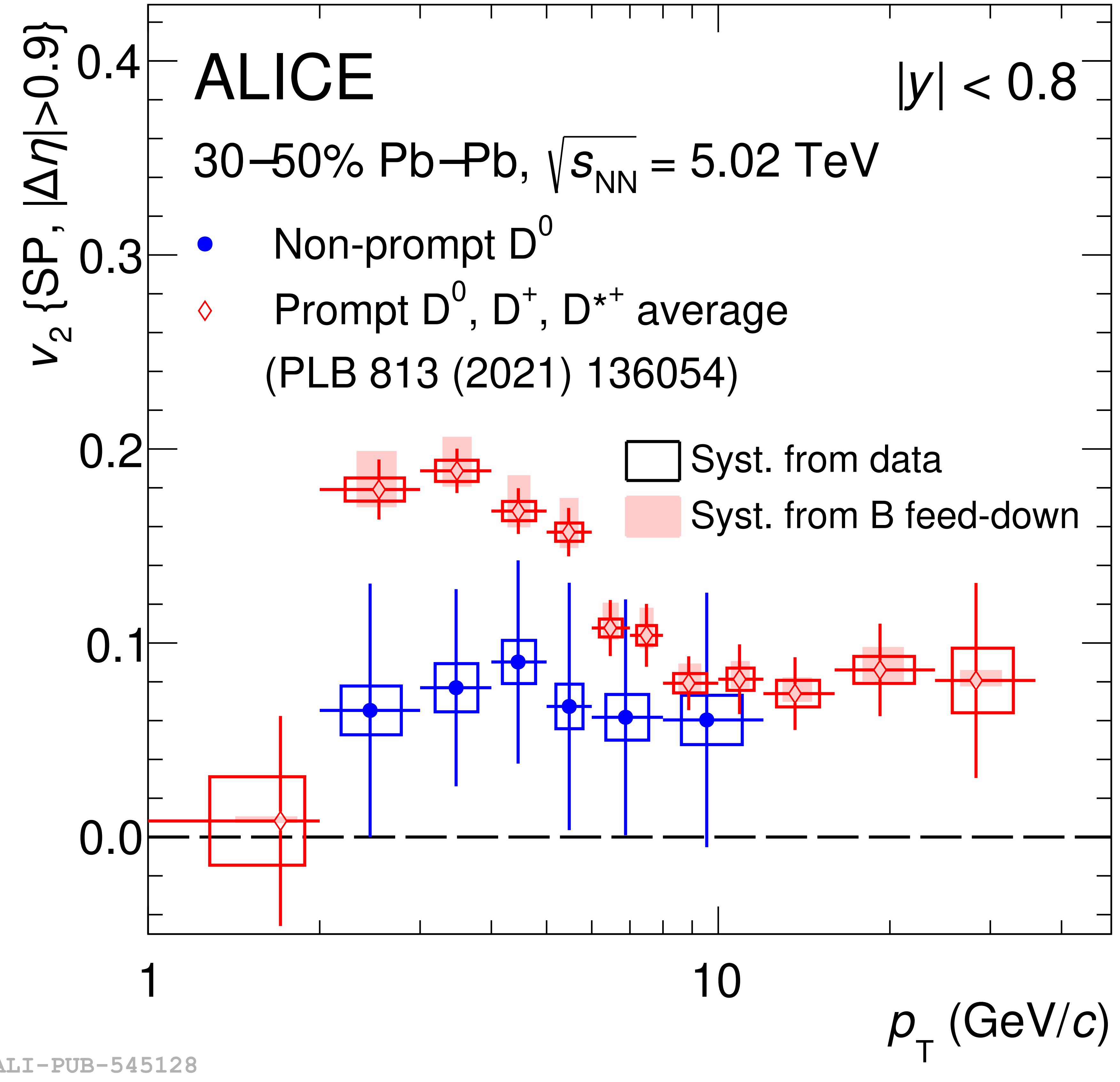
$$R_{AA} = \frac{1}{A}\frac{d^2\sigma_{PbPb}/dp_T}{d^2\sigma_{pp}/dp_T}$$

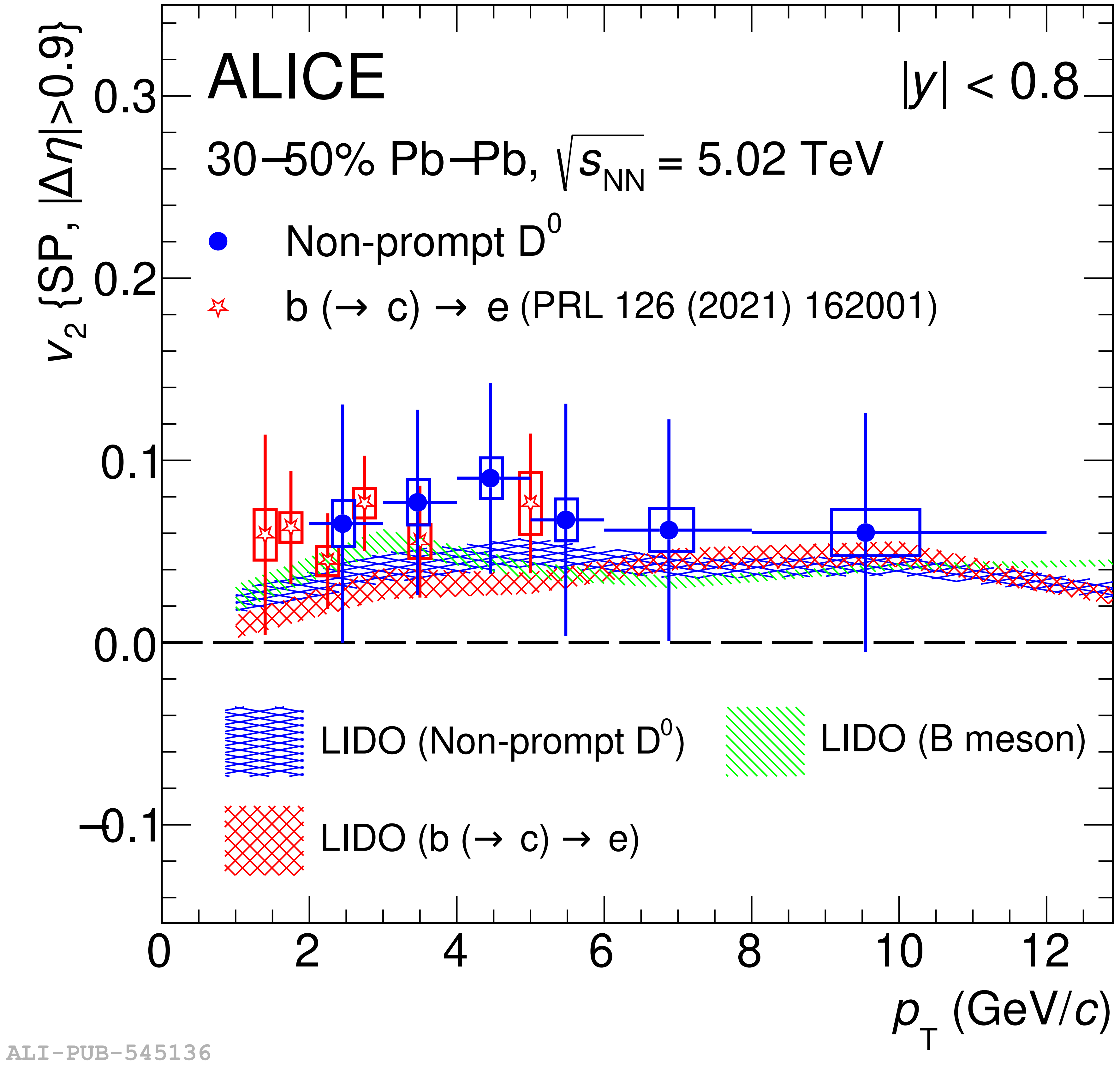
TAMU
Phys. Lett. B 735 (2014) 445

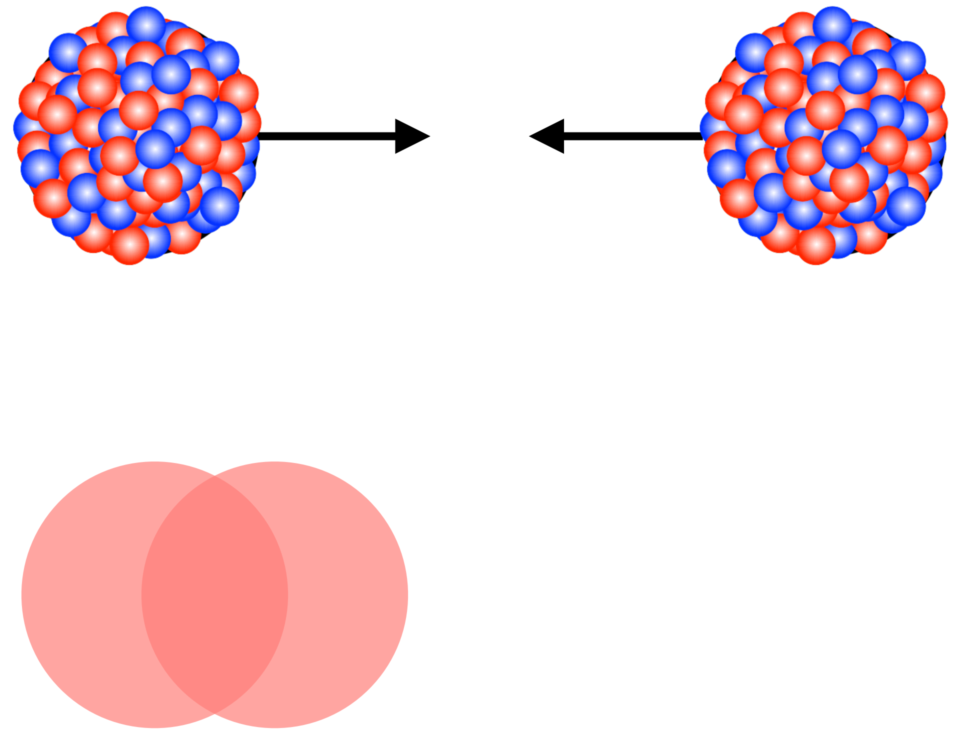
ALI-PUB-564070

- R_{AA} ratio of non-prompt D_s^+ to prompt D_s^+ and non-prompt D^0
  - ✓ Larger energy loss of charm quark with respect to beauty quark in central collisions
  - ✓ Consistent with unity in semicentral collisions
- TAMU model describes the data for central collisions while overestimates for semicentral collisions
  - ✓ Possible enhancement at low p_T → the abundance of strange quarks and the hadronisation via recombination

Elliptic flow of non-prompt D mesons in Pb–Pb collisions







EPJC 83 (2023) 1123

LIDO

Phys. Rev. C 98 (2018) 064901
Phys. Rev. C 100 (2019) 064911

- beauty quark transport
- collisional+radiative
- fragmentation+coalescence

- Non-prompt D^0 v_2 is lower than that of prompt non-strange D meson v_2
  - ✓ **Different degree of participation between charm and beauty quarks in the medium expansion**
- Compatible with the v_2 of beauty-decay electrons within uncertainties
  - ✓ Good agreement with LIDO predictions
  - ✓ **No significant difference of decay kinematics between B meson and non-prompt D^0 meson**

Summary

Heavy flavour (charm & beauty) measurements in pp, p–Pb, and Pb–Pb collisions with ALICE detector

In pp collisions :

- Production cross section described by pQCD calculations
- Fragmentation function universality is violated in pp collisions
  - ✓ Hadronisation via recombination is dominant at low p_T

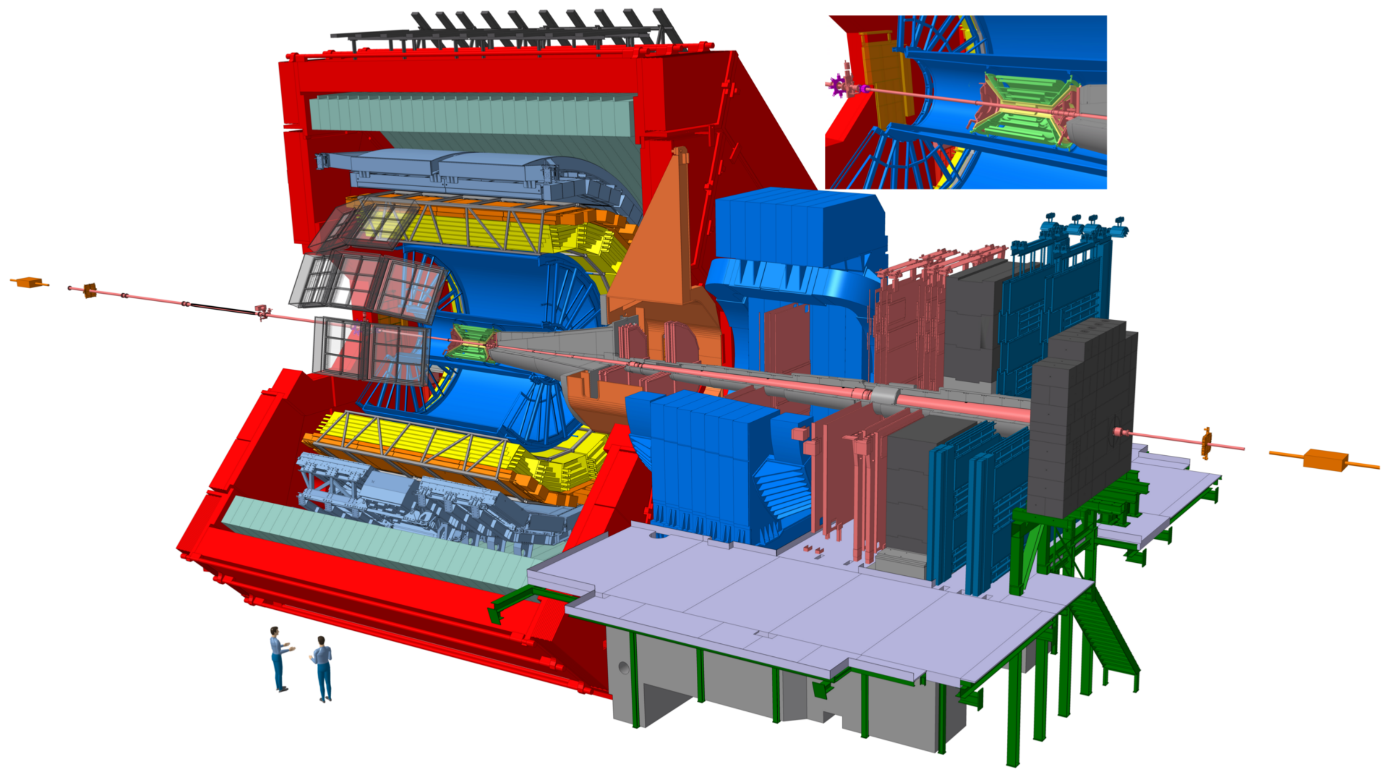
In p–Pb collisions :

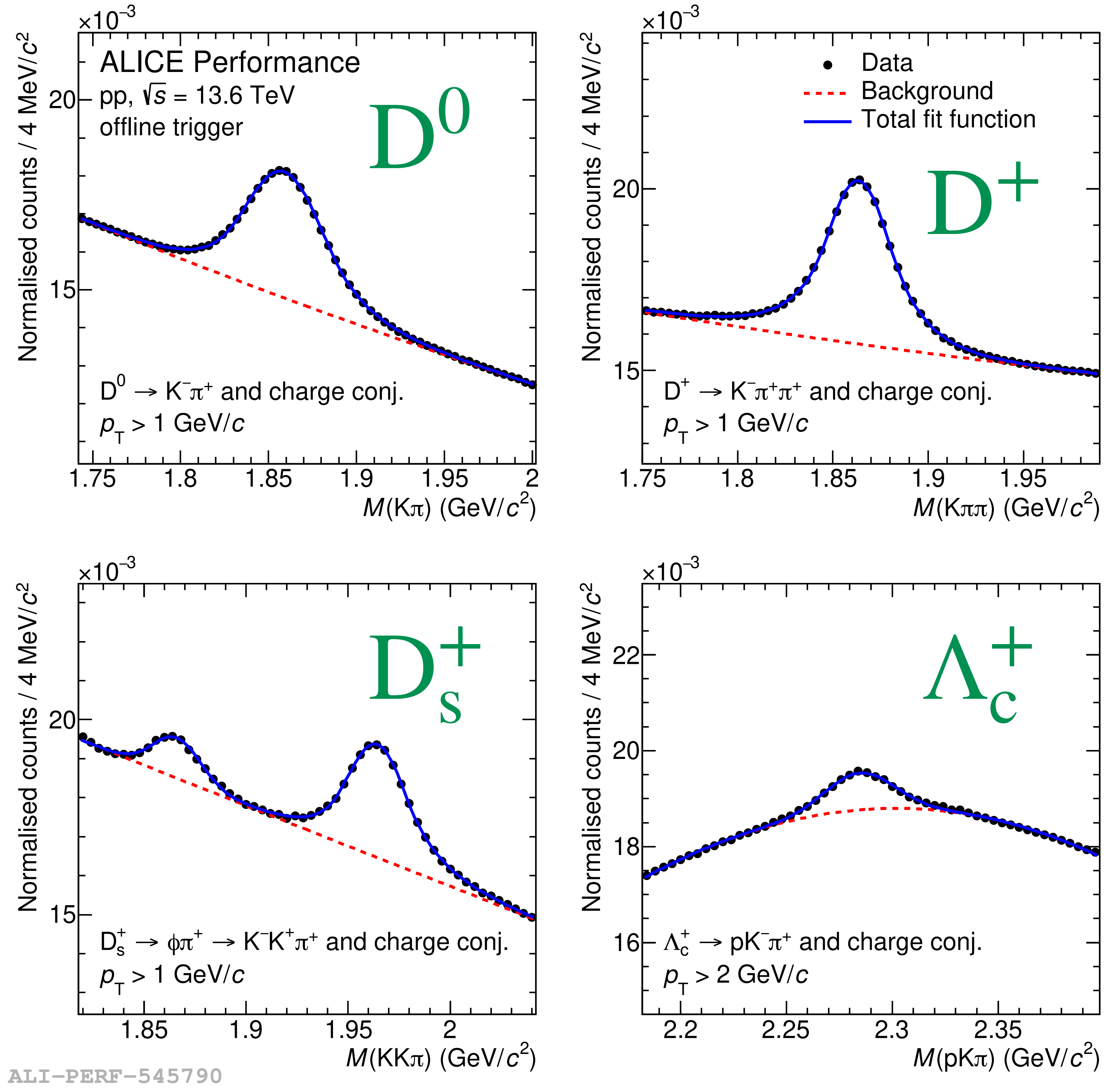
- Heavy-quark production is not significantly affected by CNM effects
- Enhanced baryon production in p–Pb collisions w.r.t pp collisions in the intermediate p_T region

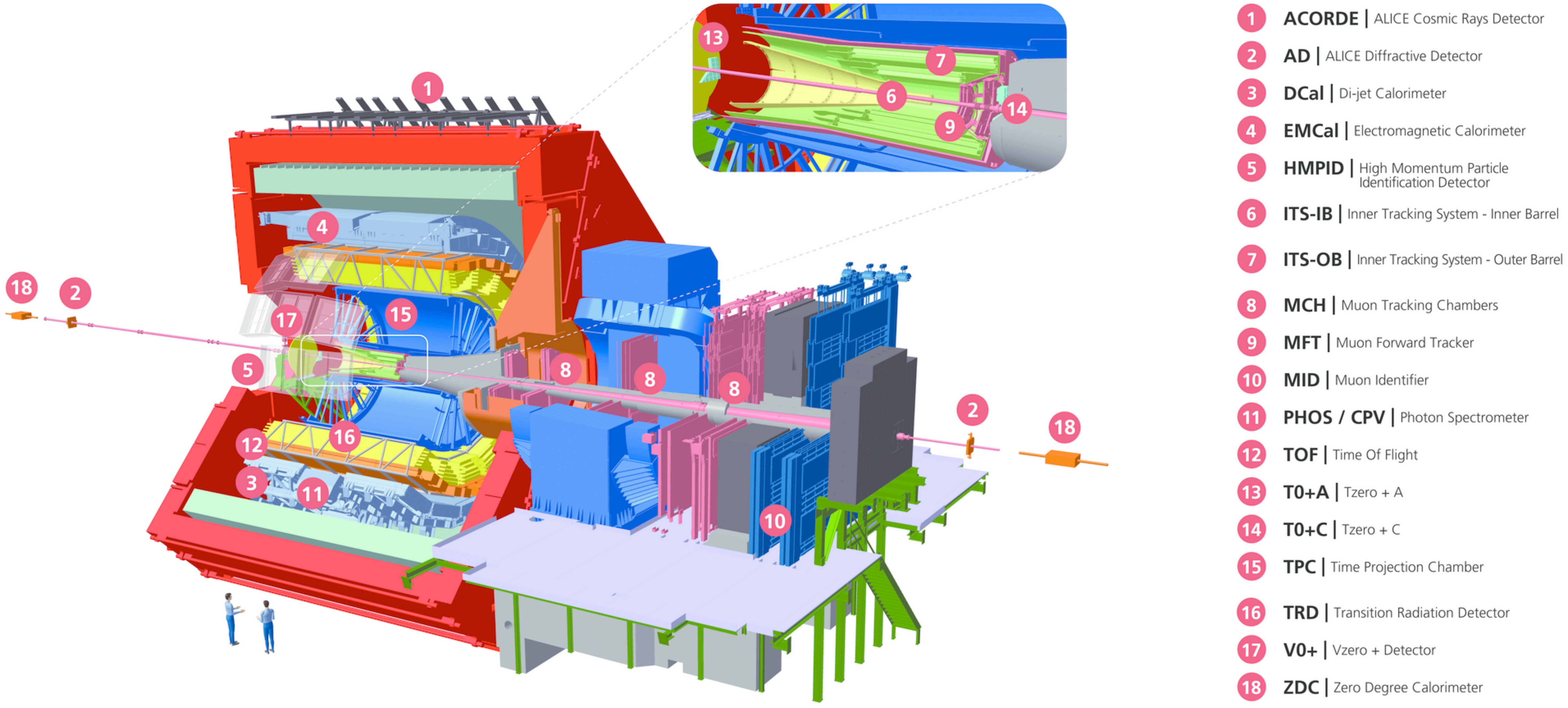
In Pb–Pb collisions :

- Baryon enhancement depends on the event multiplicity, while p_T-integrated baryon-to-meson ratio is consistent across collision systems
- Both charm and beauty quarks lose energy in the medium
  - ✓ Beauty quarks lose less energy than charm quarks
- Heavy quarks participate in a hydrodynamically expanding medium, v_2(HF) > 0
  - ✓ $v_2(c) > v_2(b)$

Outlook in Run 3







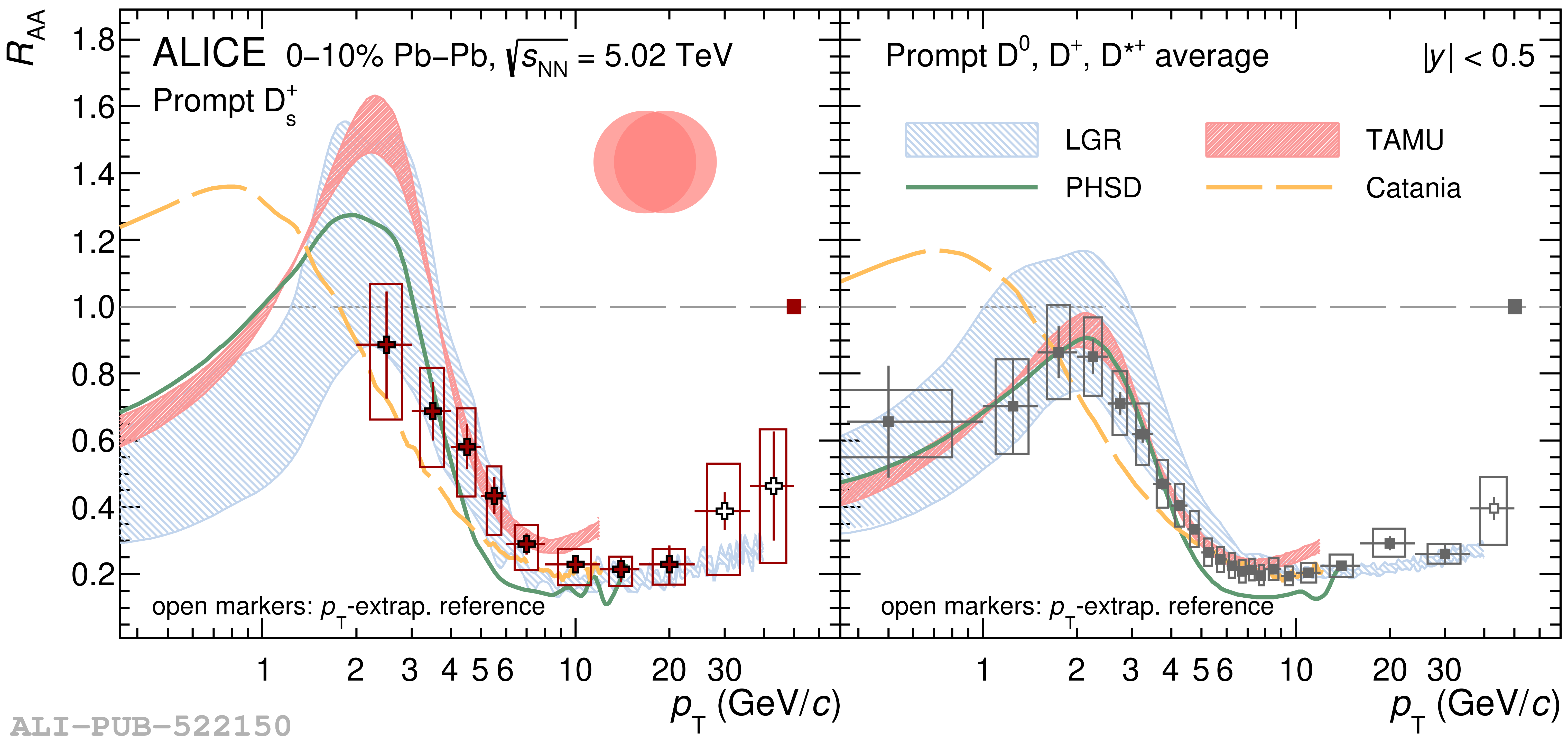
- New Inner Tracking System
  - ✓ 2 pixels + 2 drifts + 2 strips → 7 pixels (3 inners + 4 outers)
  - ✓ Based on MAPS, pixel size + material budget reduction, and fast readout
  - ✓ Improve vertexing and tracking
- New readout for most sub detectors
  - ✓ Higher statistics and performance

New observables in addition to precise measurements on HF sector

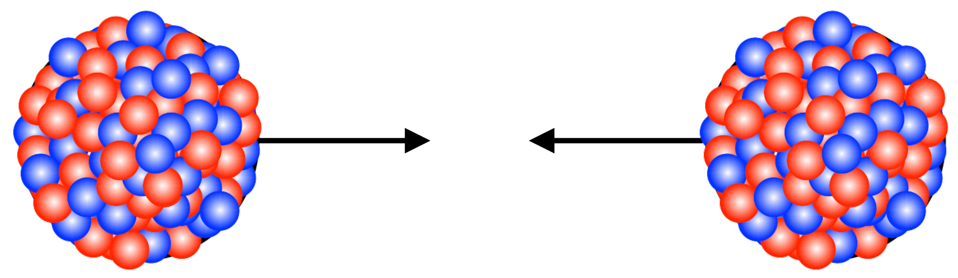
Backup

R_{AA} of D_s mesons in Pb–Pb collisions

Phys. Lett. B 827 (2022) 136986



A–A collisions



$$R_{AA} = \frac{1}{A}\frac{d^2\sigma_{PbPb}/dp_T}{d^2\sigma_{pp}/dp_T}$$

TAMU
Phys. Rev. Lett. 124 (2020) 042301

PHSD
Phys. Rev. C 92 (2015) 014910
Phys. Rev. C 93 (2016) 034906

Catania
Phys. Rev. C 96 (2017) 044905
EPJC 78 (2018) 348

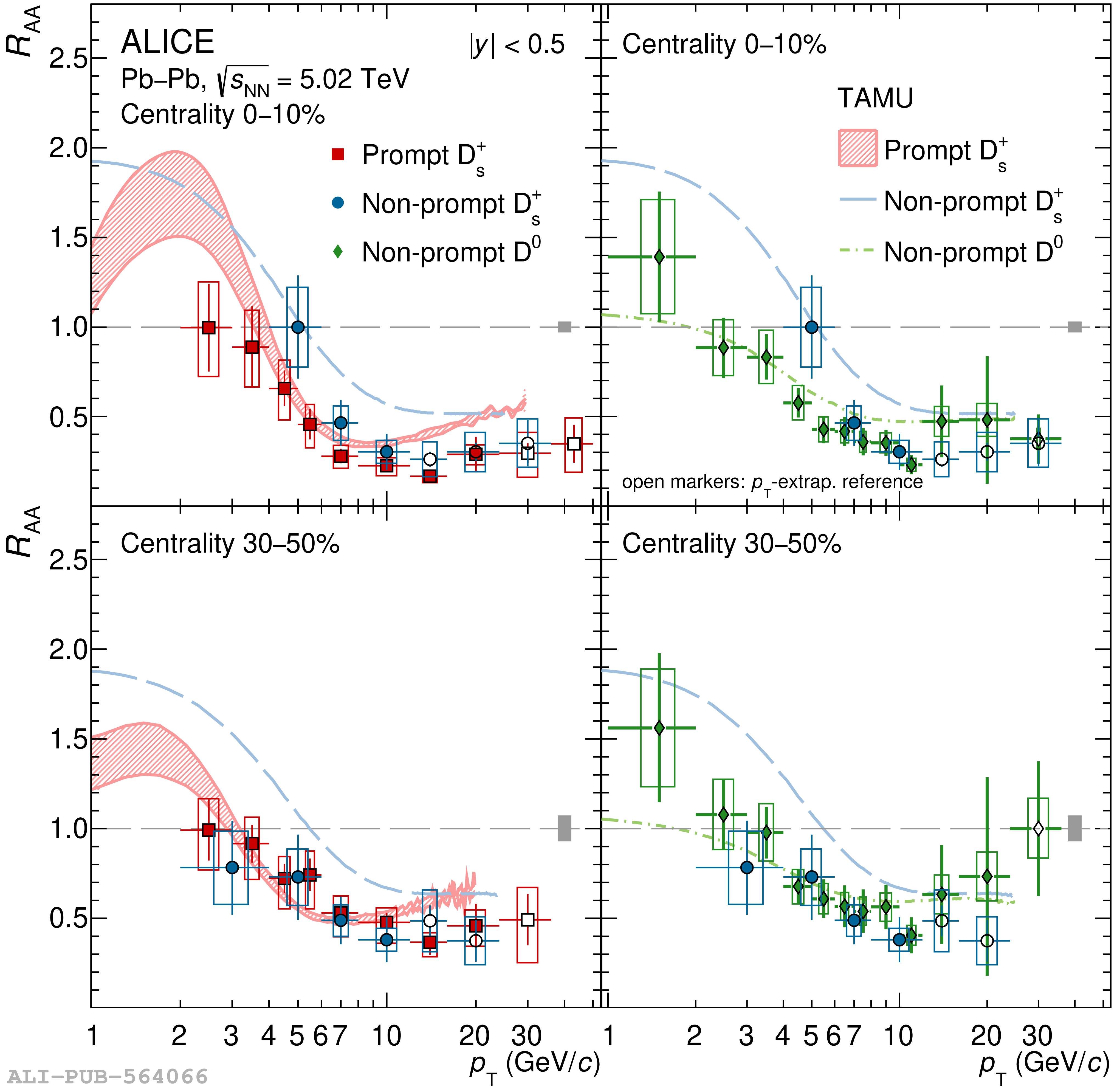
LGR
EPJC 80 (2020) 671

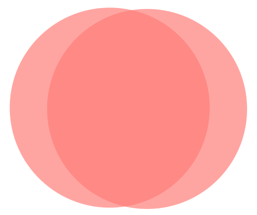
- Compared to model predictions implementing charm quark transport in the medium
  - ✓ Include an enhancement of the strangeness in the medium and the hadronisation either via fragmentation and coalescence
- Models qualitatively reproduce the measured R_{AA}
  - ✓ LGR model including both collisional and radiative interactions, gives a better description of the data up to high p_T

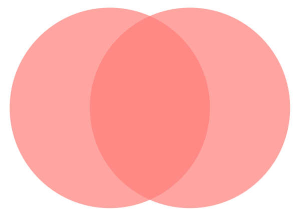
R_{AA} of non-prompt D mesons in Pb–Pb collisions

JHEP 12 (2022) 126

TAMU
Phys. Lett. B 735 (2014) 445

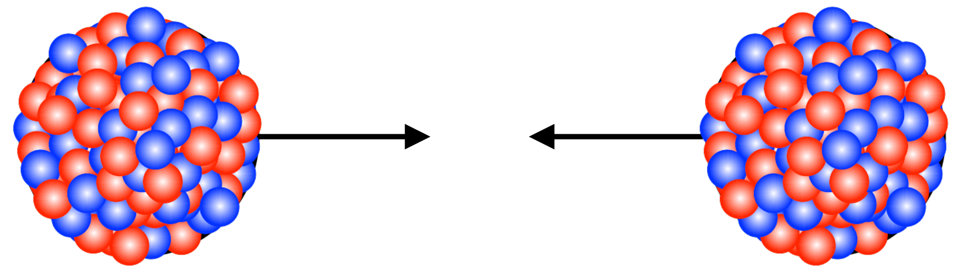






A–A collisions

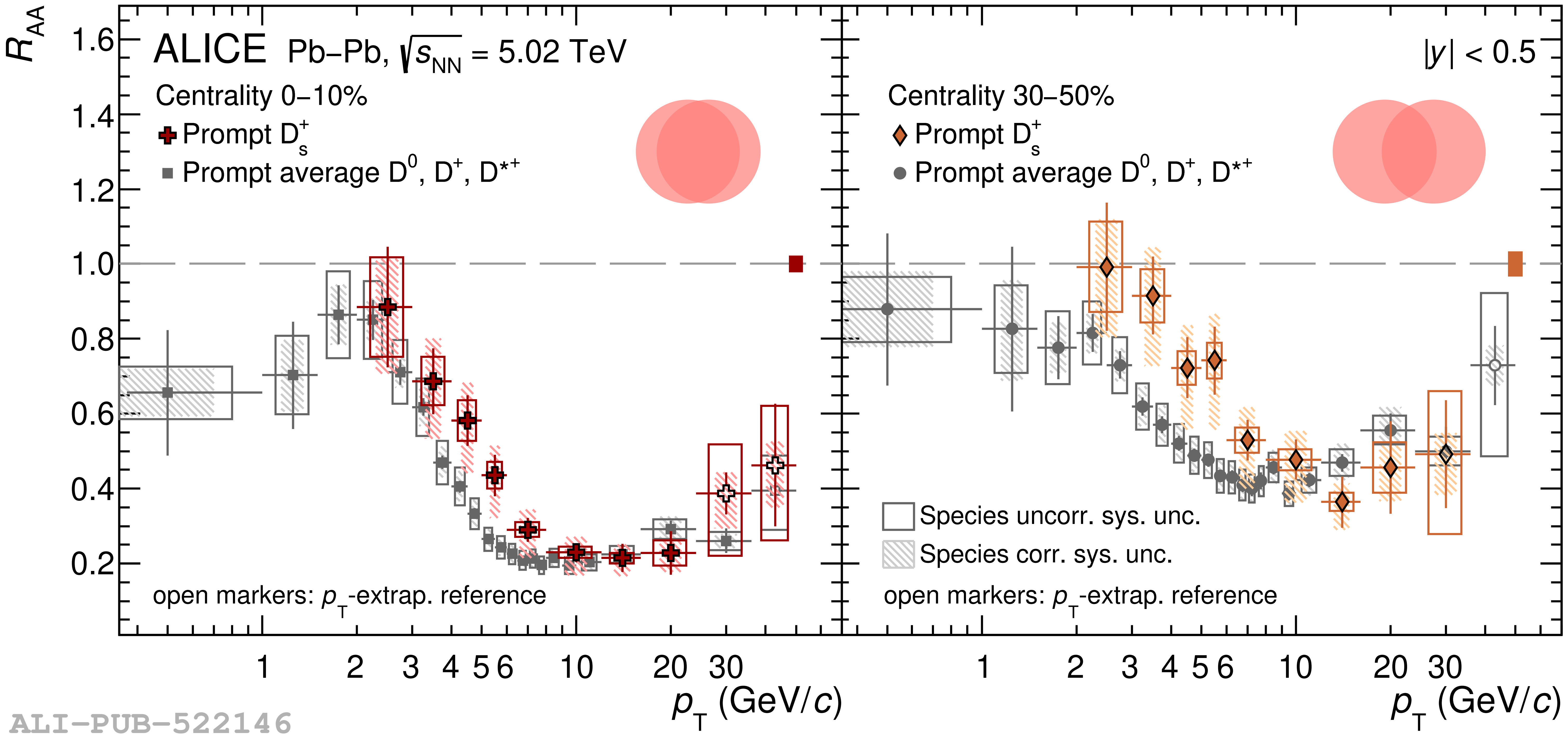
$$R_{AA} = \frac{1}{A}\frac{d^2\sigma_{PbPb}/dp_T}{d^2\sigma_{pp}/dp_T}$$



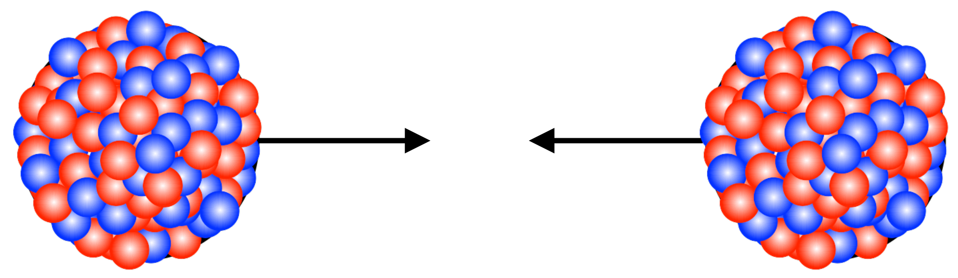
- Comparison of non-prompt D_s^+ R_{AA} to ones of prompt D_s^+ and non-prompt D^0 mesons
  - ✓ Give a hint of the interaction of heavy quarks with medium and of the beauty quark hadronisation mechanism
- Non-prompt D_s^+ R_{AA} vs prompt D_s^+ R_{AA}
  - ✓ Mass dependence of the in-medium energy loss
- Non-prompt D_s^+ R_{AA} vs non-prompt D^0 R_{AA}
  - ✓ Effect of hadronisation via recombination and a strangeness-rich environment
- In semicentral collisions, consistent within uncertainties
- Compare to model prediction and qualitatively describes the p_T trend, although the model overestimates the data

R_{AA} of D_s mesons in Pb–Pb collisions

Phys. Lett. B 827 (2022) 136986



A–A collisions

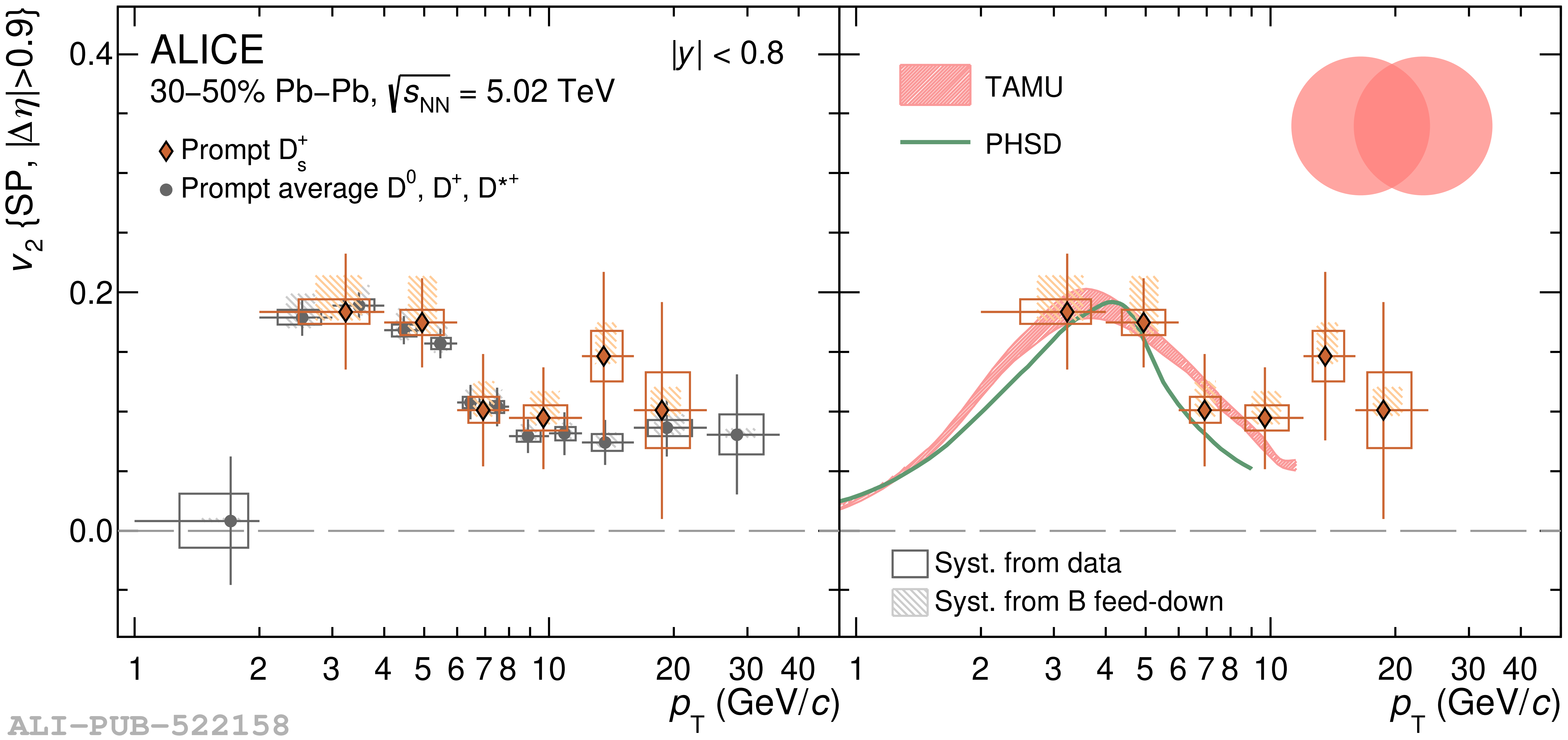


$$R_{AA} = \frac{1}{A}\frac{d^2\sigma_{PbPb}/dp_T}{d^2\sigma_{pp}/dp_T}$$

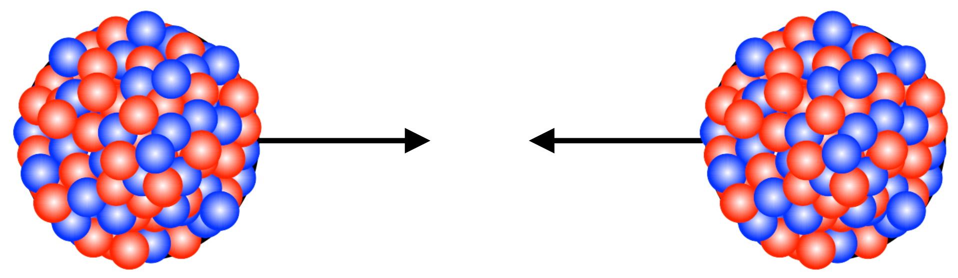
- Both D_s^+ and non-strange D mesons have a minimum value of R_{AA} around 10 GeV/c
- For $p_T < 10$ GeV/c, D_s^+ R_{AA} is systematically higher than that of non-strange D mesons
  - ✓ Hadronisation via recombination with abundantly produced strange quarks in the medium
- For $p_T > 10$ GeV/c, both R_{AA} are compatible within uncertainties
  - ✓ Hadronisation via fragmentation is dominant

Elliptic flow of prompt D mesons in Pb–Pb collisions

Phys. Lett. B 827 (2022) 136986



A–A collisions



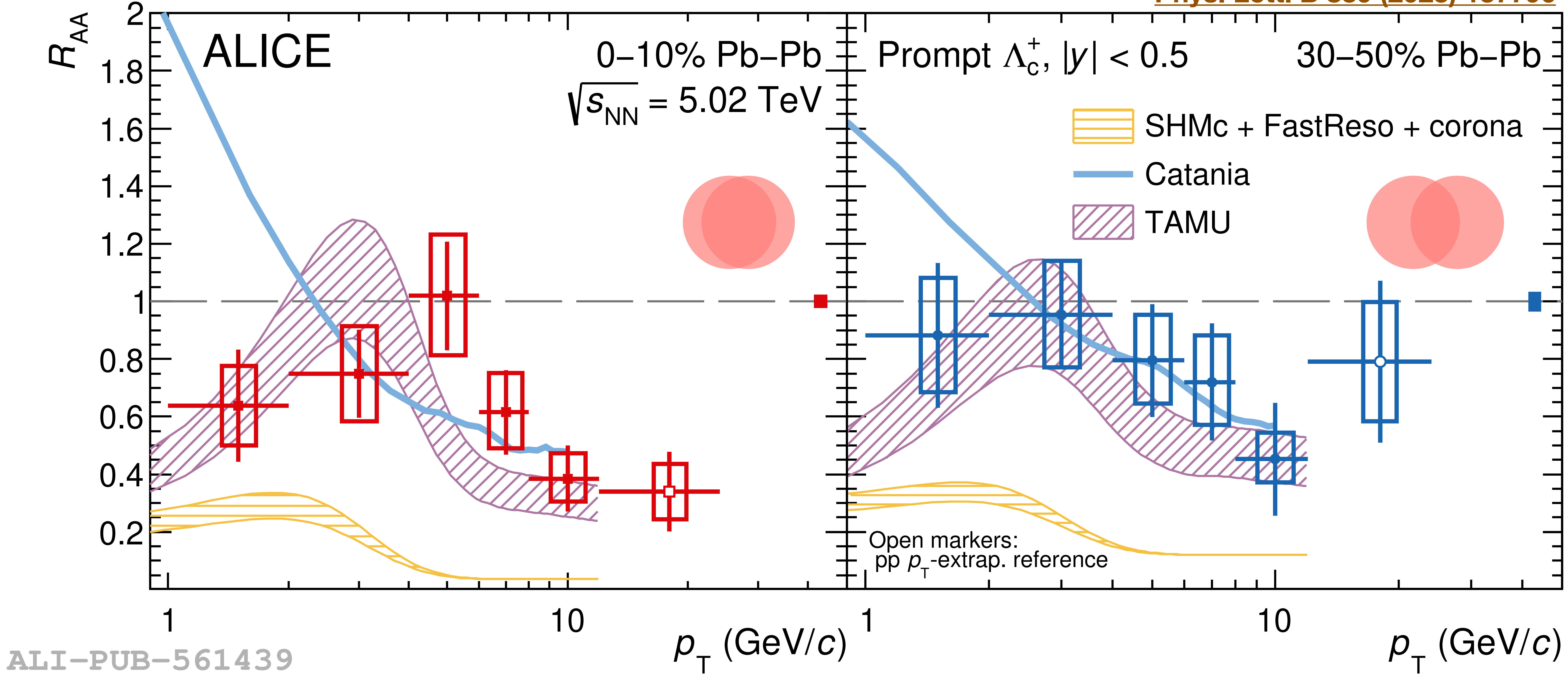
TAMU
Phys. Rev. Lett. 124 (2020) 042301

PHSD
Phys. Rev. C 92 (2015) 014910
Phys. Rev. C 93 (2016) 034906

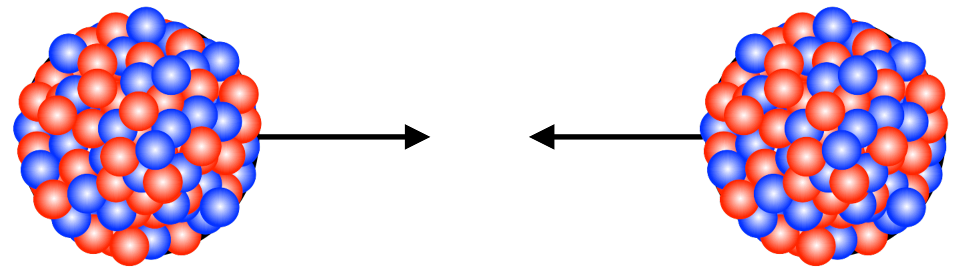
- Comparison of v_2 between strange and non-strange D mesons
  - ✓ No differences within uncertainties
  - ✓ Different mass, hadronisation via recombination with strange vs light quarks, possible differences in hadronic phase
- Models, including charm quark coalescence with strange quarks in the medium, describe the data within uncertainties

R_{AA} of Λ_c in Pb–Pb collisions

Phys. Lett. B 839 (2023) 137796



A–A collisions



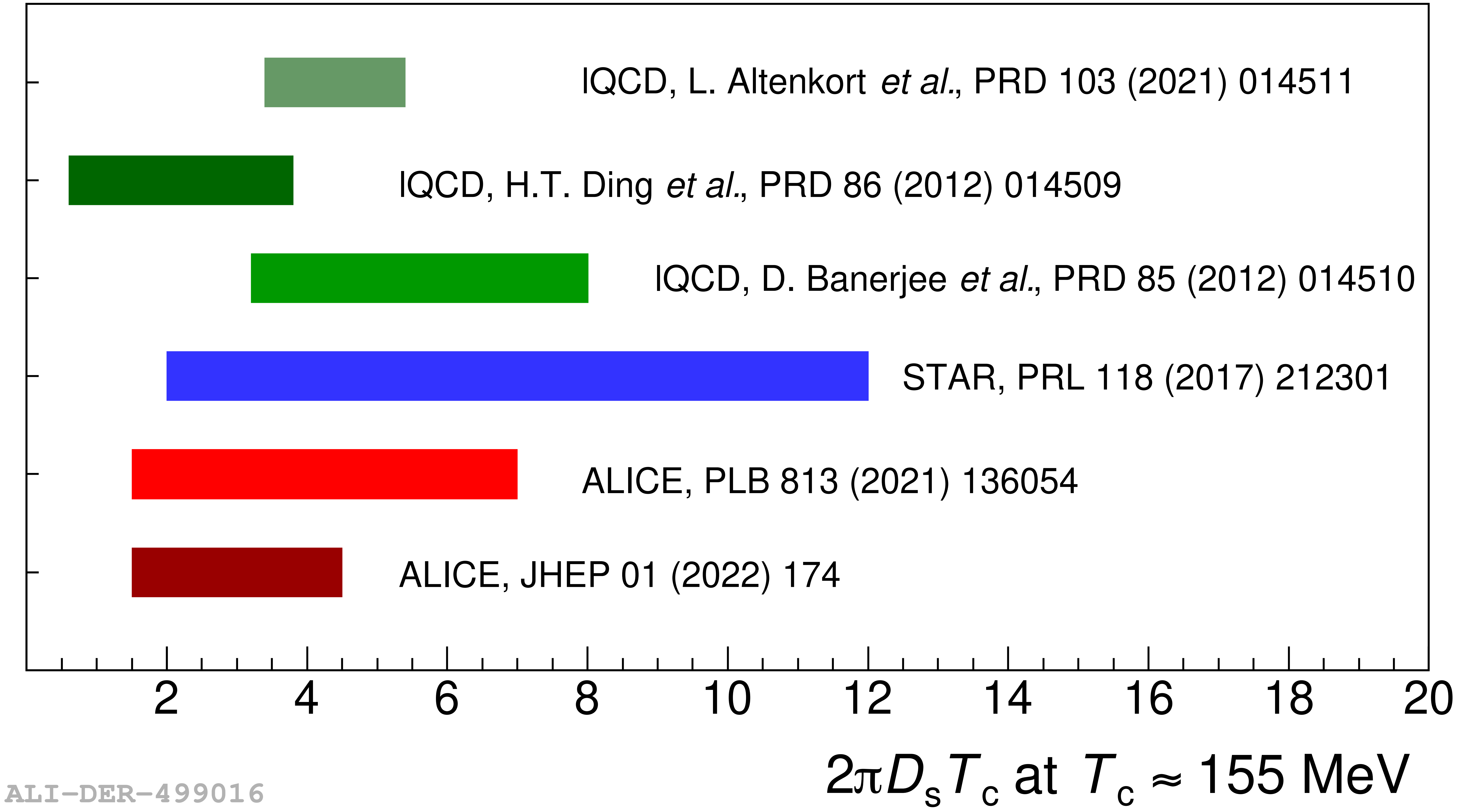
$$R_{AA} = \frac{1}{A}\frac{d^2\sigma_{PbPb}/dp_T}{d^2\sigma_{pp}/dp_T}$$

SHMc
JHEP 07 (2021) 035
Catania
EPJC 78 (2018) 348
TAMU
Phys. Rev. Lett. 124 (2020) 042301

- TAMU model provides a good description over the full p_T range in both 0–10% and 30–50% centralities
- Catania model describe the data for p_T > 2 GeV/c in both centrality classes, and disfavour below 2 GeV/c
- SHMc model significantly underestimates the data over the whole p_T range

Heavy-flavour transport coefficients

- Compute χ^2/ndf between data and models to constrain model parameters
- Heavy-quark spatial diffusion coefficient ($2\pi D_s T_c$) at 155 MeV → $1.5 < 2\pi D_s T_c < 4.5$
  - Imply a charm quark relaxation time : 3–8 fm/c



- Compute $\chi 2$/ndf between data and models to constrain model parameters
- Heavy-qaurk spatial diffusion coefficient ($2\pi D_s T_s$) at 155 MeV → $1.5 < 2\pi D_s T_s < 4.5$
  - ✓ Imply a charm quark relaxation time : 3–8 fm/c
  - ✓ charm quark can be fully thermalized with medium (QGP lifetime ~ 10 fm/c)