Recent results on heavy flavor and quarkonia from ALICE

E. Scomparin - INFN Torino (Italy)
for the ALICE Collaboration

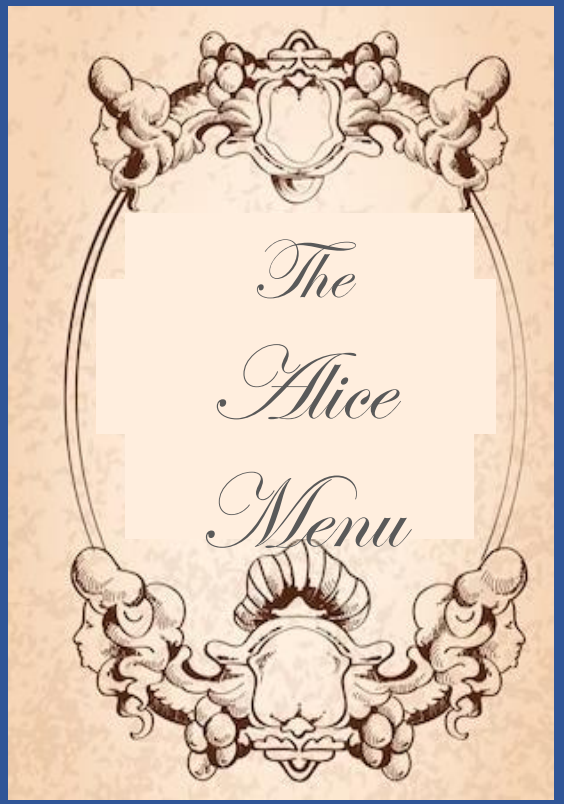
SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

Introduction

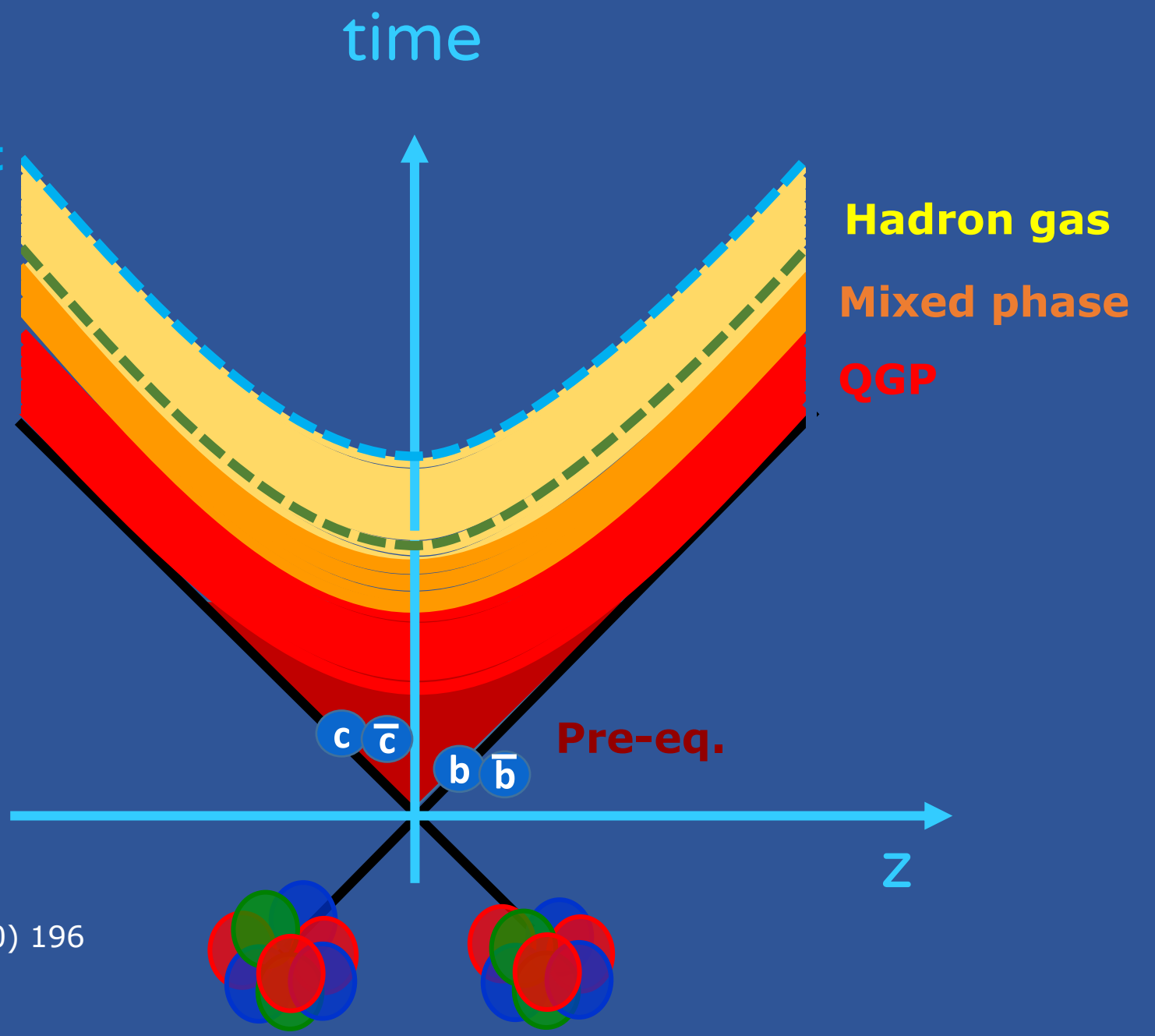
- Heavy quarks, a precise tool to study QGP properties and hadronization mechanisms

- Highlights from our menu today:
  - J/ψ production and polarization, ψ(2S) production in Pb-Pb
  - Charm spatial diffusion coefficient from R_{AA} and v_2 measurements
  - Beauty vs charm energy loss from (non) prompt D
  - Hadronization studies via charm baryon production in pp, p-Pb, Pb-Pb

    … and much more!



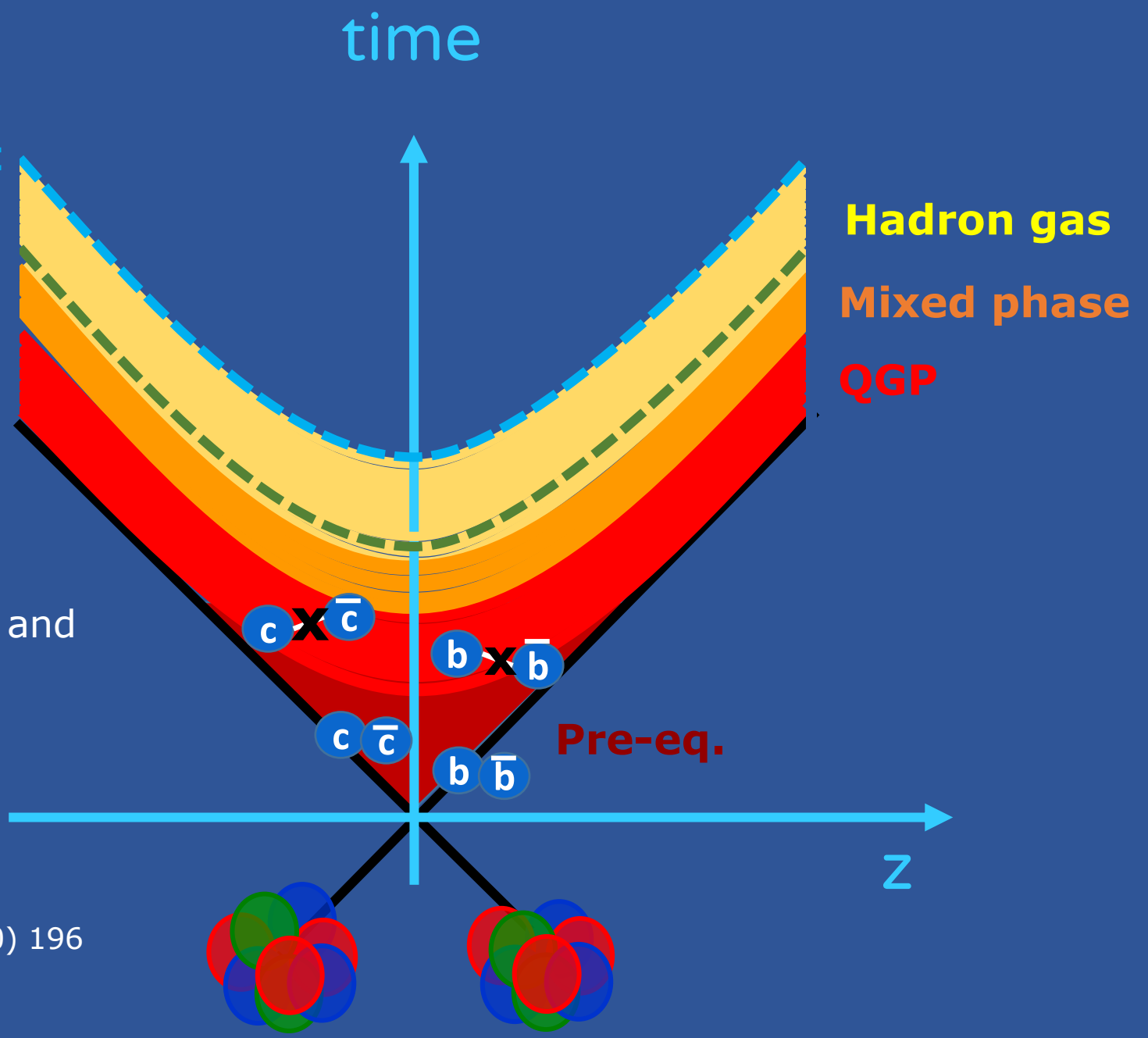
- Some specific features of the ALICE measurements
  - Detection of inclusive charmonium and bottomonium states down to zero p_T
  - Open heavy flavor: extended studies of meson AND baryon states over a wide p_T range



Quarkonium

- Early production (and binding) of heavy quark pairs

T. Matsui and H. Satz, PLB 178(1986) 416
P. Braun-Munzinger and J. Stachel, PLB490(2000) 196
R. Thews et al., PRC63 (2001) 064905
A. Rothkopf, Phys. Rept. 858 (2020) 1



Quarkonium

- Early production (and binding) of heavy quark pairs
- Modification of spectral properties and possible dissociation in the QGP

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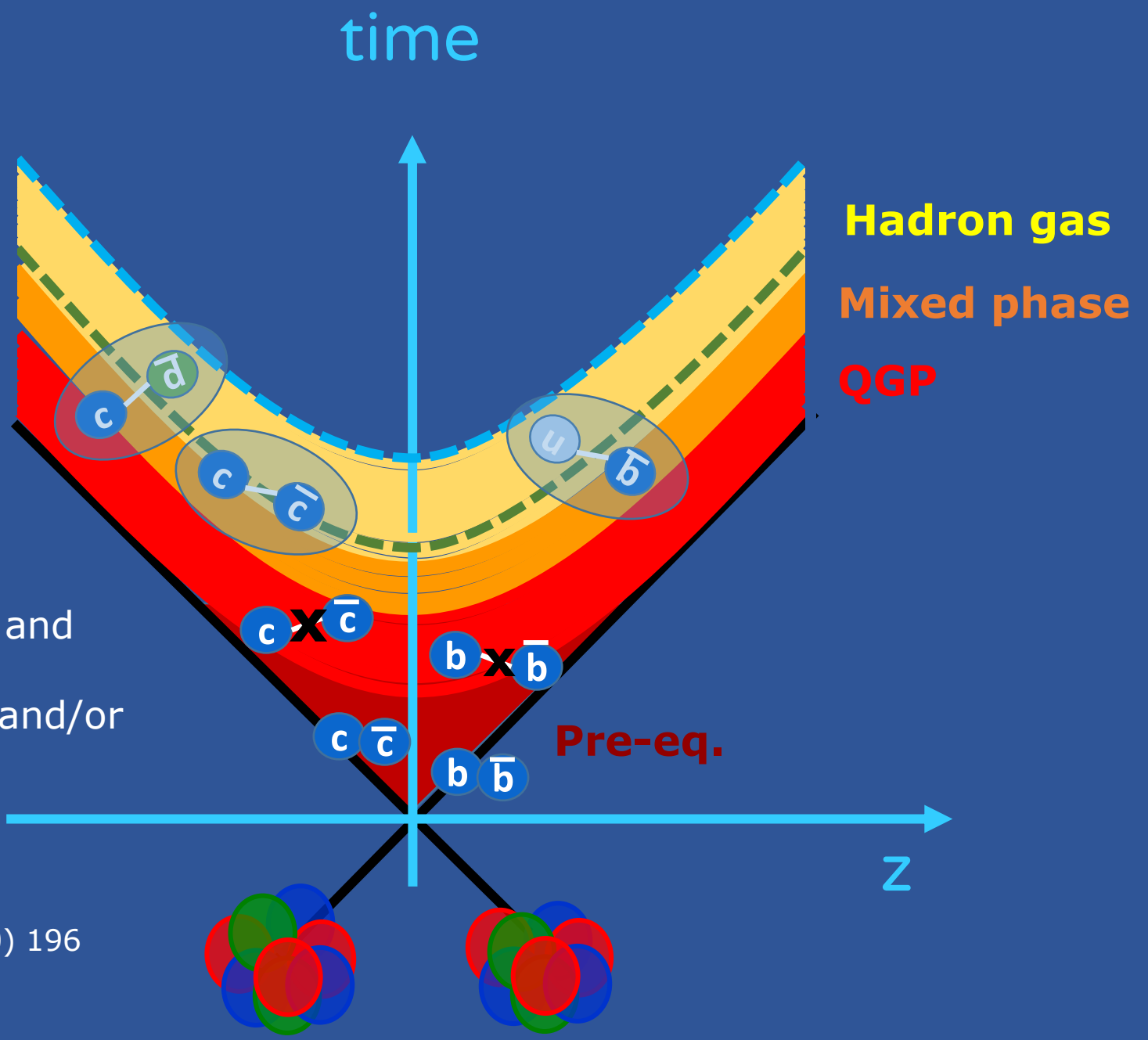

Quarkonium

- Early production (and binding) of heavy quark pairs
- Modification of spectral properties and possible dissociation in the QGP
- Recombination effects in the QGP and/or at phase boundary

T. Matsui and H. Satz, PLB 178(1986) 416
P. Braun-Munzinger and J. Stachel, PLB490(2000) 196
R. Thews et al., PRC63 (2001) 064905
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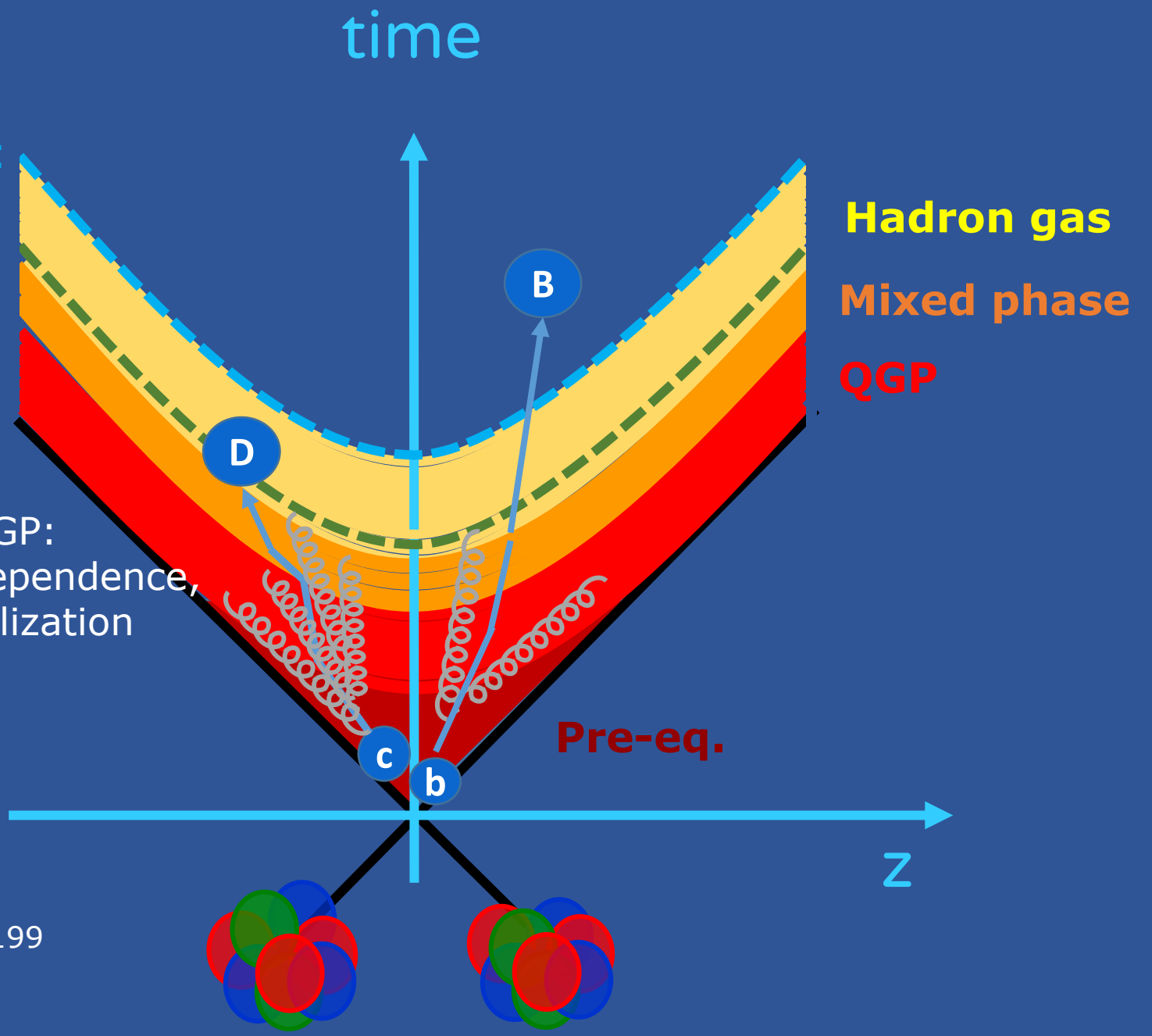
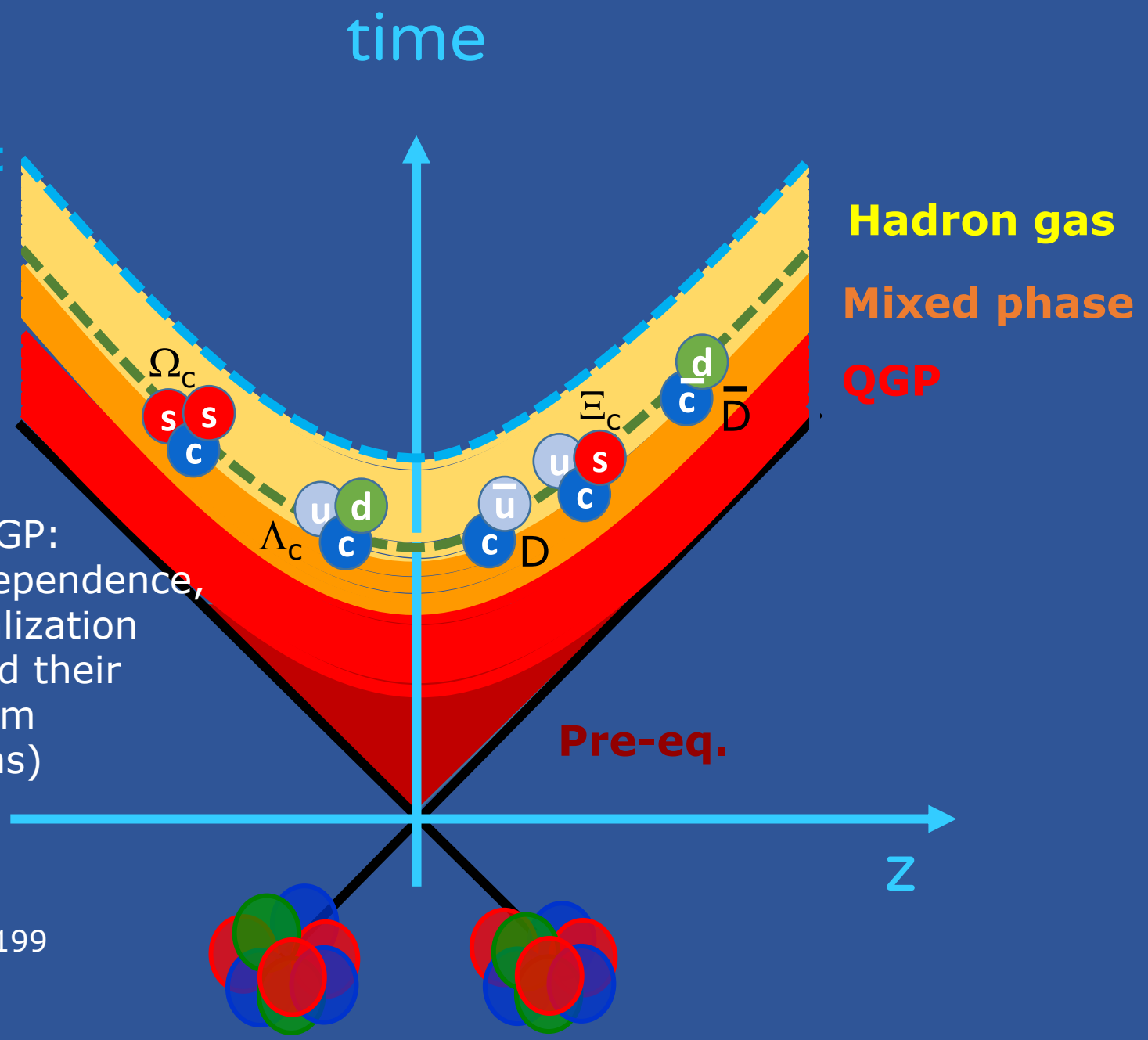


Open heavy flavours

- Heavy quark interactions in the QGP: energy loss and its quark mass dependence, heavy quark diffusion and thermalization

Y. Dokshitzer and D. Kharzeev, PLB 519 (2001) 199
D.Moore and H. Teaney, PRC71 (2005) 064904
F. Prino and R.Rapp J.Phys.G 43 (2016) 9



Open heavy flavours

- Heavy quark interactions in the QGP: energy loss and its quark mass dependence, heavy quark diffusion and thermalization
- Hadron formation mechanisms and their dependence on the collision system (results from pp to Pb-Pb collisions)

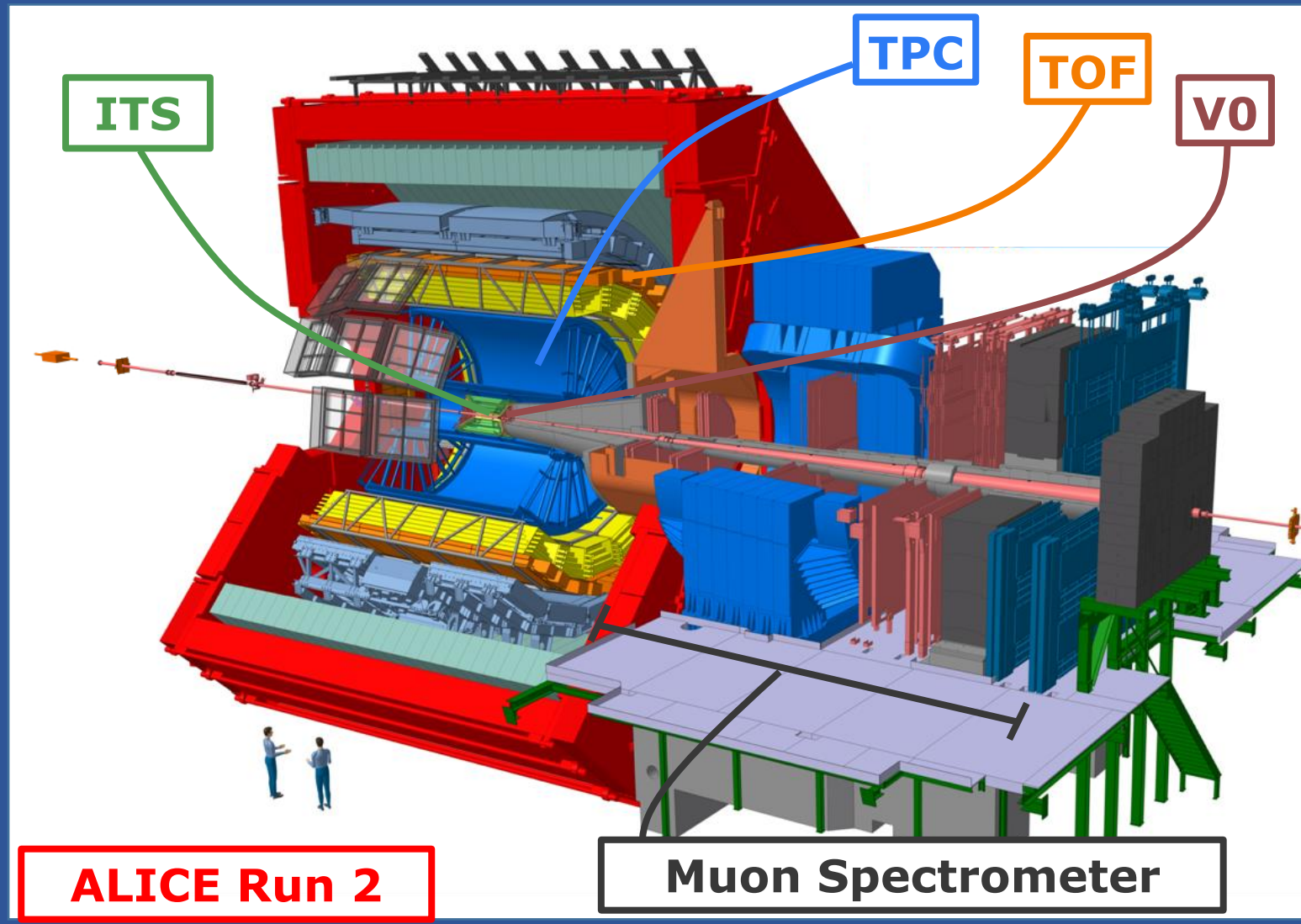
Y. Dokshitzer and D. Kharzeev, PLB 519 (2001) 199
D.Moore and H. Teaney, PRC71 (2005) 064904
F. Prino and R.Rapp J.Phys.G 43 (2016) 9

A Large Ion Collider Experiment

- Quarkonium measurements
  - Central barrel (ee, |y|<0.9)
  - Muon spectrometer ($\mu\mu$, 2.5<y<4)
  - Coverage down to zero p_T
- Open heavy flavours
  - Hadronic measurements (|y|<0.5)

$$D^0 \longrightarrow K^- \pi^+ \quad D^+ \longrightarrow K^- \pi^+\pi^+$$
$$D_s^+ \longrightarrow \phi \pi^+ \longrightarrow K^+ K^- \pi^+$$
$$D^{*+} \longrightarrow D^0\pi^+ \longrightarrow K^- \pi^+ \pi^+$$
$$\Lambda_c^+ \longrightarrow K_S^0 \; p \longrightarrow \pi^+ \pi^- \; p$$
$$\Lambda_c^+ \rightarrow pK^-\pi^+$$
$$\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$$
$$\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e, \Xi^-\pi^+$$
$$\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$$
$$\boldsymbol{\Omega_c^0} \rightarrow \Omega^-\pi^+$$

  - Leptonic measurements (c,b$\rightarrow \ell$ X) at forward and central y



Quarkonia

More details in

PA – OTH session

J/ψ photoproduction and the production of dileptons via photon-photon interactions in hadronic Pb–Pb collisions measured with ALICE
L. Massacrier, Tue 2.40 PM

PA – BLK session

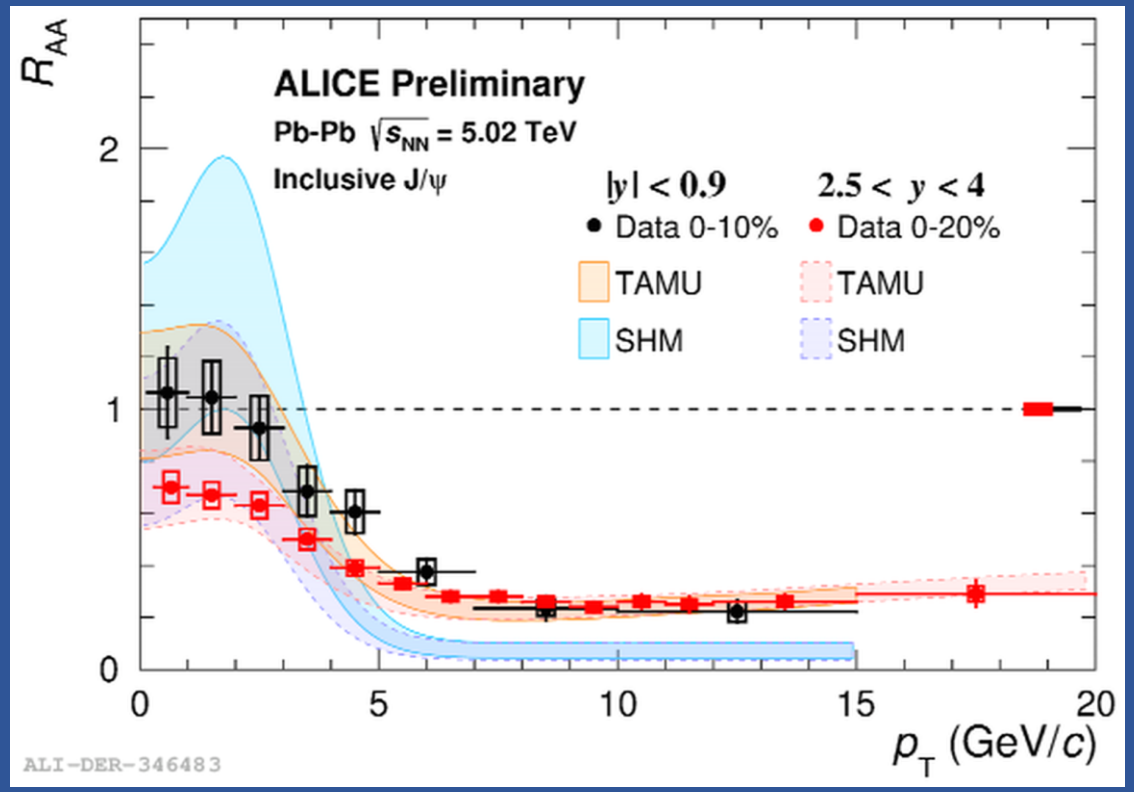
Quarkonia production and elliptic flow in small systems measured with ALICE
R. Sadek, Tue 10 AM

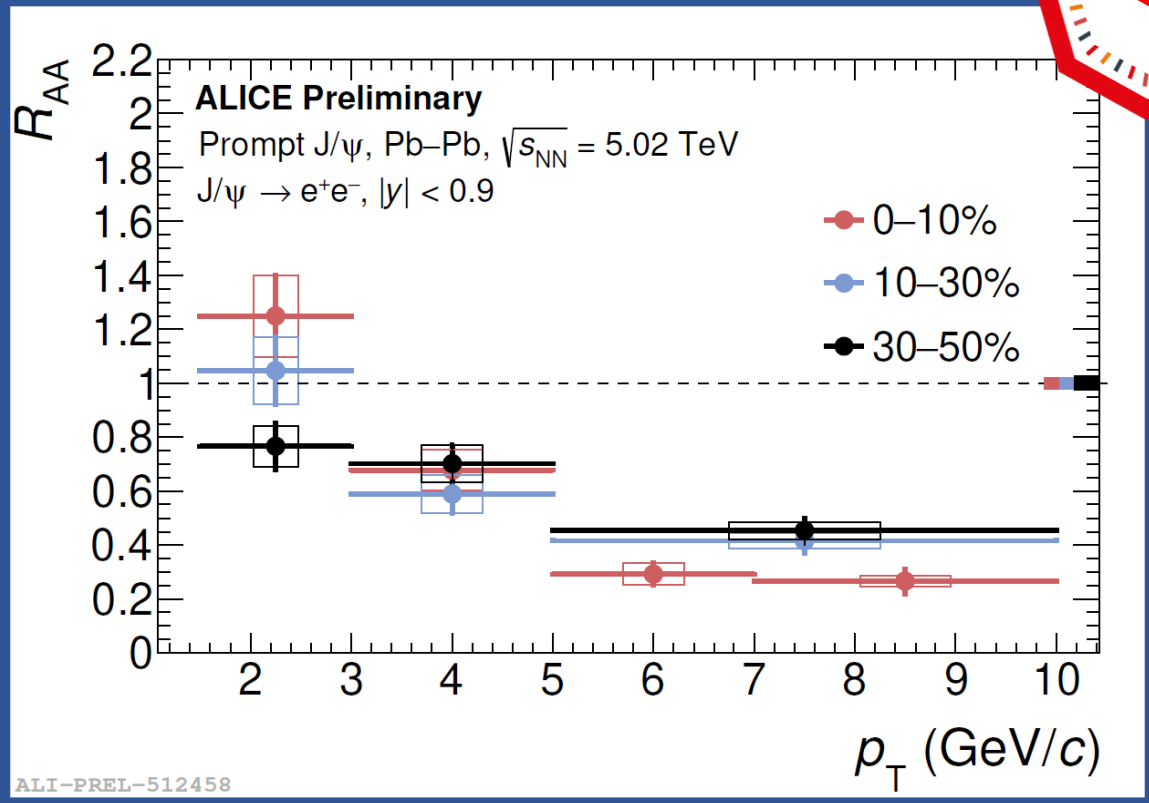
PA – HF session

Measurement of quarkonium production and polarization in pp and Pb-Pb collisions with ALICE
X. Bai, Tue 9 AM

ψ(2S) production and nuclear modification factor in nucleus-nucleus collisions with ALICE
H. Hushnud, Tue 10 AM

Inclusive and prompt J/ψ production in Pb-Pb

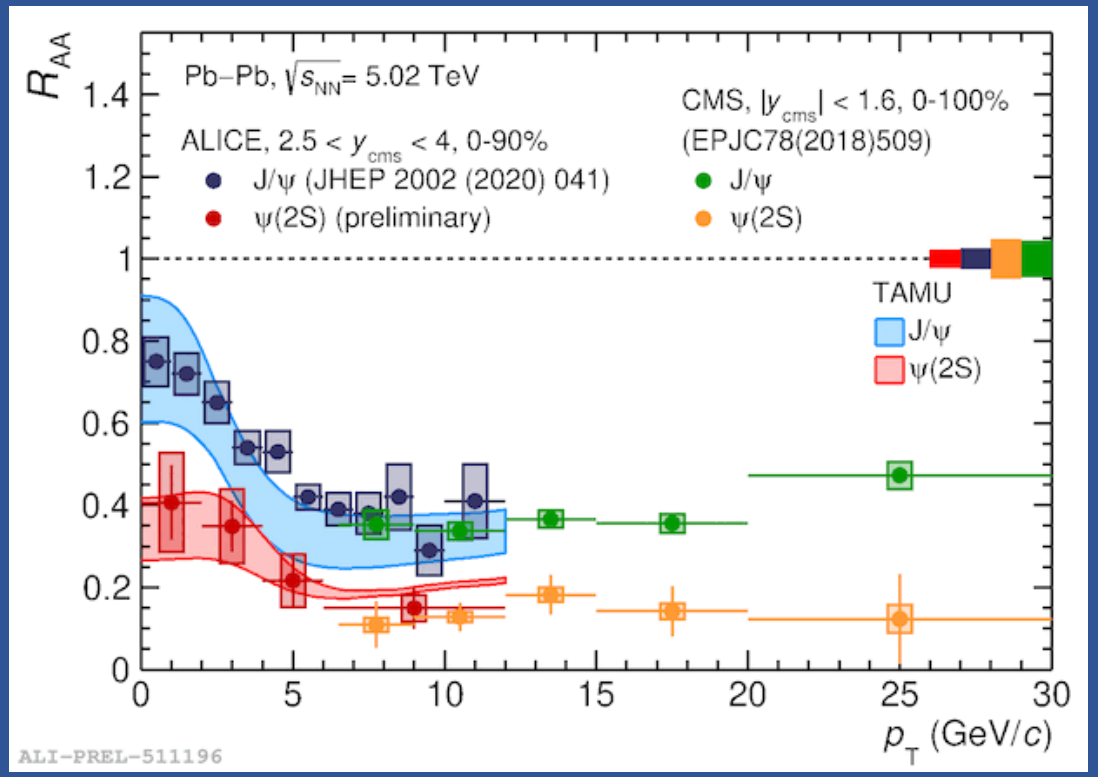




- Rise of inclusive J/ψ R_{AA} at low p_T, stronger effect at y=0 → decisive signature of recombination
- Models include regeneration either at the freeze-out (SHMc) or during the medium evolution (TAMU)
  → Both in agreement with data at low p_T

- Effect confirmed when looking at prompt J/ψ production at midrapidity, clear centrality dependence

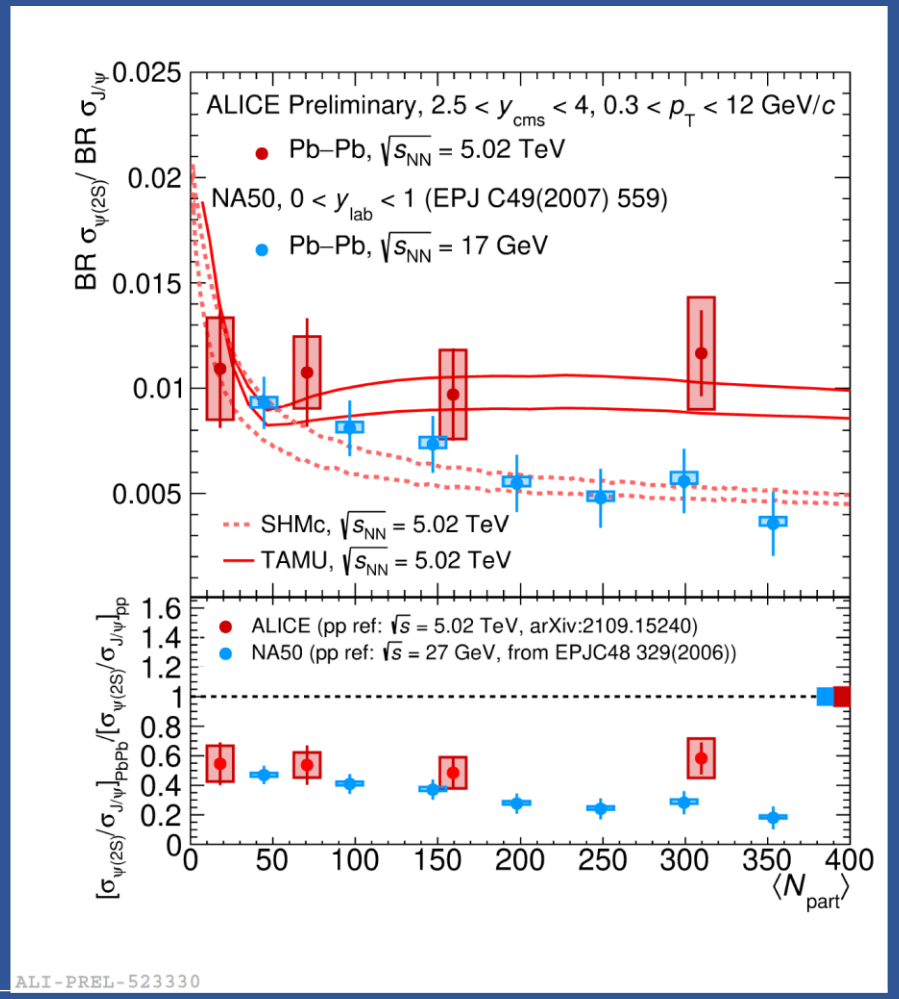
Inclusive ψ(2S) production in Pb-Pb



- Centrality dependence of ψ(2S)/J/ψ described by TAMU and slightly underestimated by SHMc

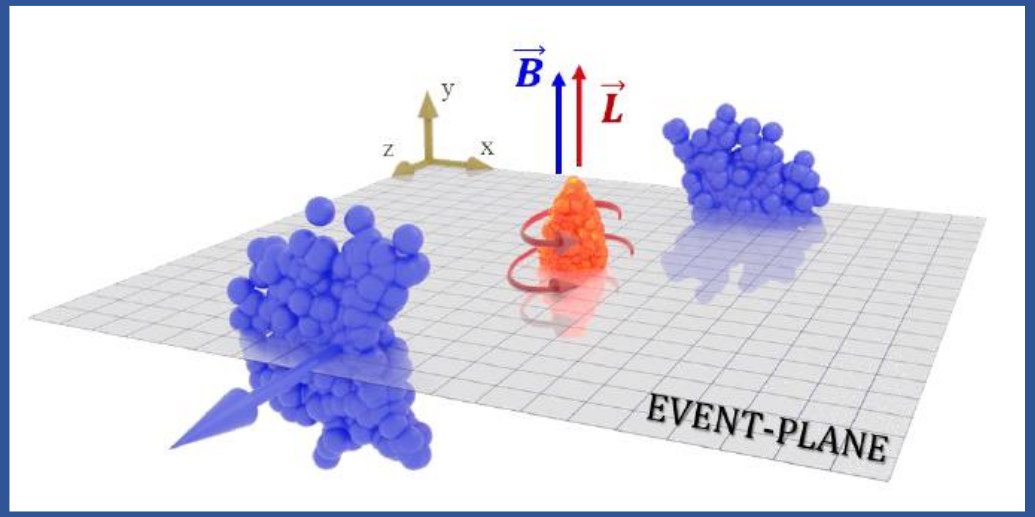
NEW

First LHC measurement down to zero p_T



- Stronger suppression for ψ(2S) compared to J/ψ
  → sequential suppression for charmonia?
- Increasing trend of R_{AA} towards low p_T for ψ(2S)
  → Hint of ψ(2S) production via regeneration
- Compatible with midrapidity CMS results in common p_T range
- p_T dependence of R_{AA} reproduced by TAMU

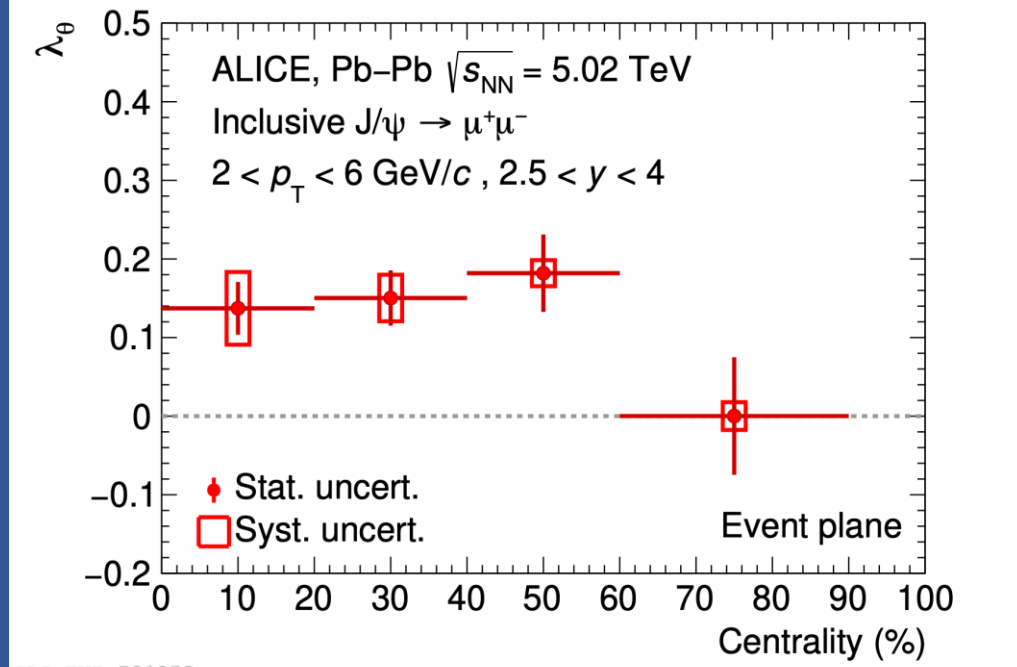
Inclusive J/ψ polarization in Pb-Pb collisions

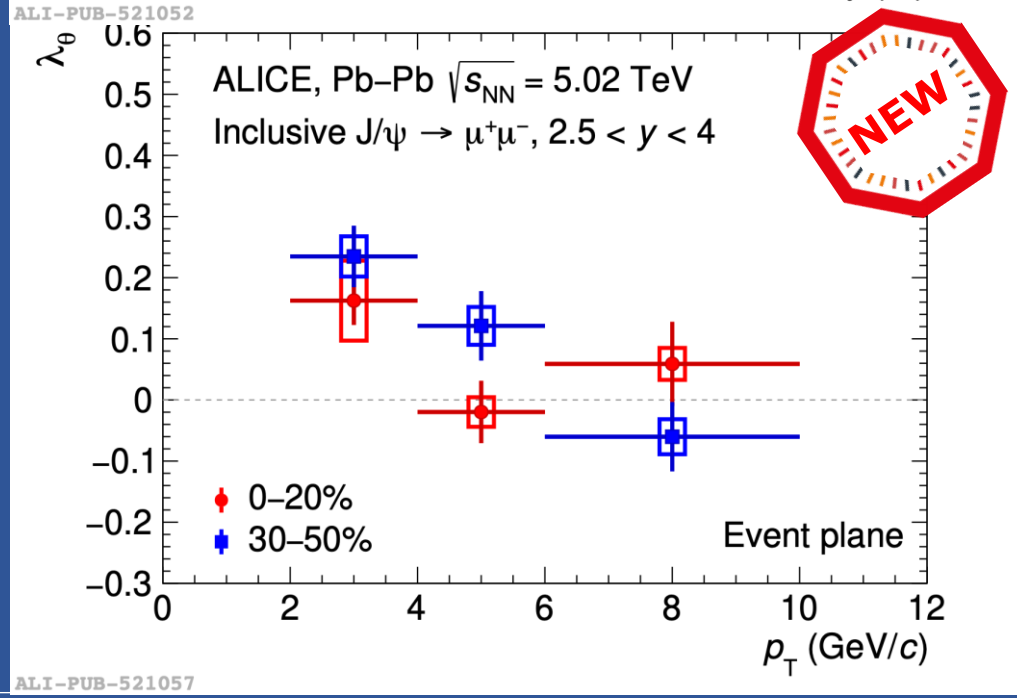


ALICE, arXiv:2204.10171

- Study polarization wrt an axis orthogonal to the event plane, in the collision center of mass frame
  → orthogonal to $\boldsymbol{B}$ and $\boldsymbol{L}$
- Significant spin alignment observed for light vector mesons ($\boldsymbol{K^{*0}}$, $\boldsymbol{\phi}$) (ALICE, PRL 125 (2020) 012301)

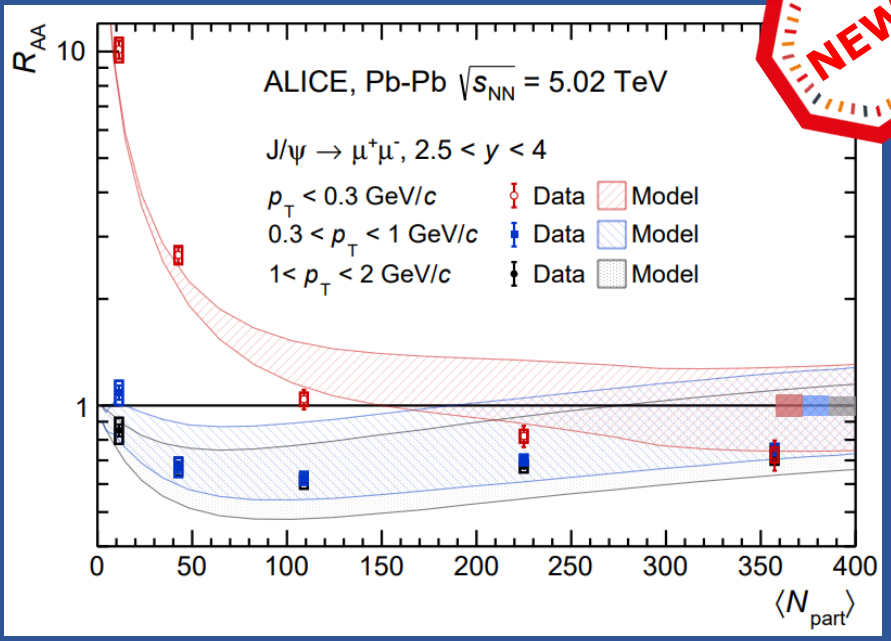
- Centrality dependence → small but significant ($\boldsymbol{3.5\sigma}$) polarization in 40-60% and $2<p_T<6$ GeV/c
- p_T dependence → $\boldsymbol{3.9\sigma}$ effect for $2<p_T<4$ GeV/c, 30-50%



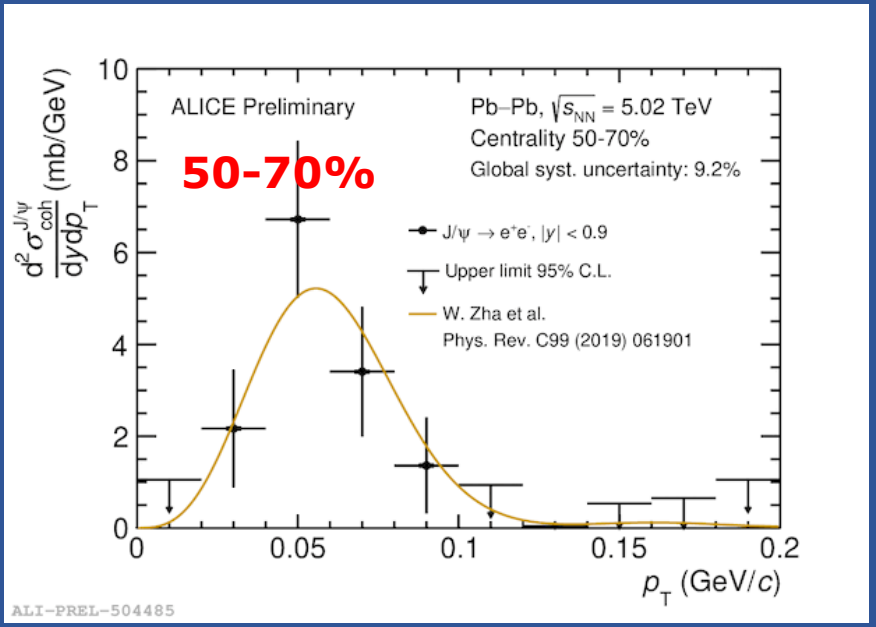


Coherent J/ψ production in (semi)peripheral Pb-Pb

ALICE, arXiv:2204.10684



- Centrality dependence of R_{AA} in p_T intervals
  → evidence for coherent production at low p_T
- p_T shape and cross sections compatible with a model that includes the effect of the overlap between the nuclei
  (W. Zha et al., PRC 99 (2019) 061901)

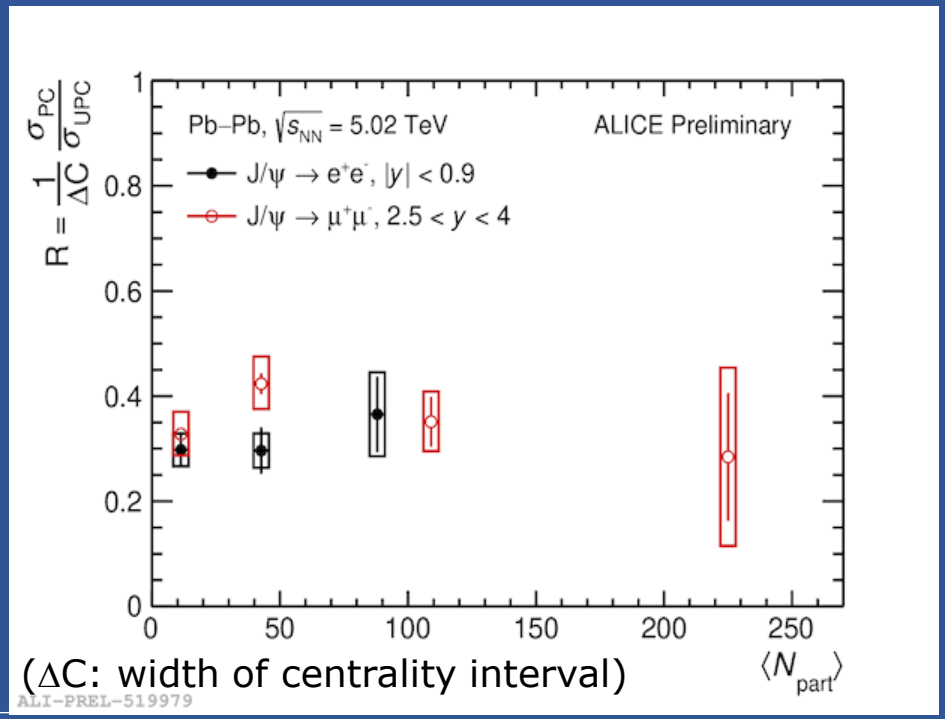


Ratio of coherent cross sections in Pb-Pb collisions with nuclear overlap (PC) over ultraperipheral (UPC) collisions

→

No evidence of modification of σ_{PC} in semicentral collisions with current experimental precision

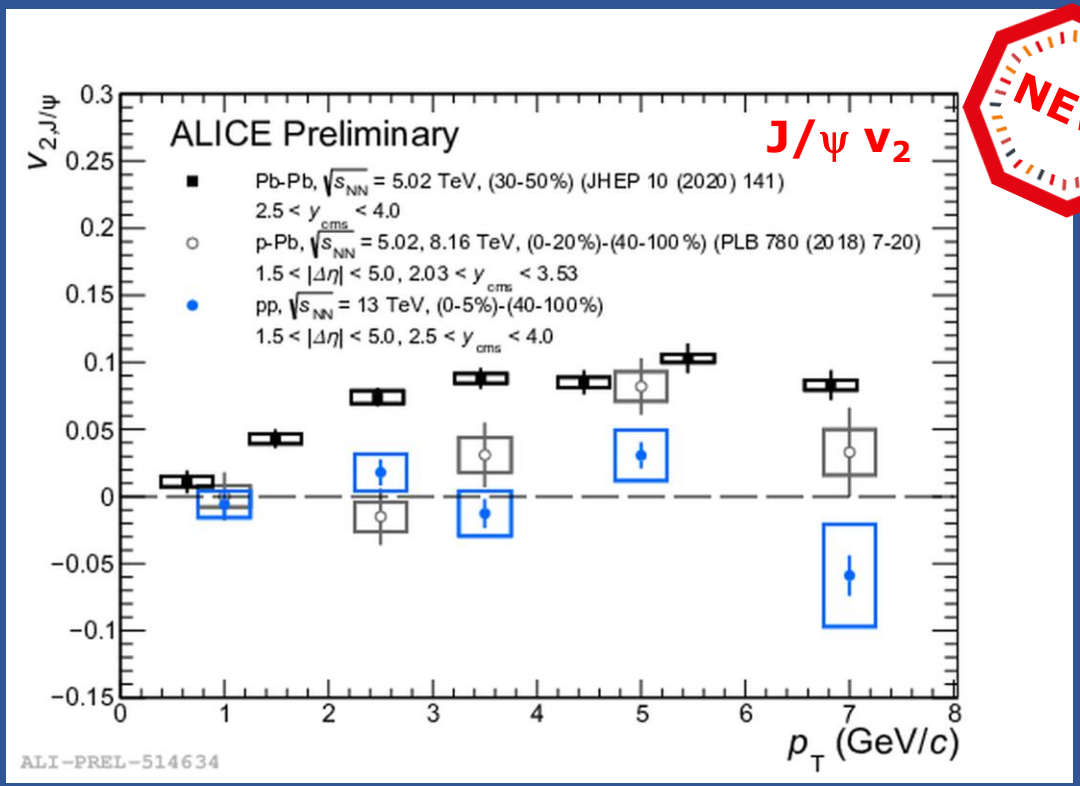
PC: arXiv:2204.10684
UPC: EPJC 81 (2021) 712, PLB 98 (2019) 134926



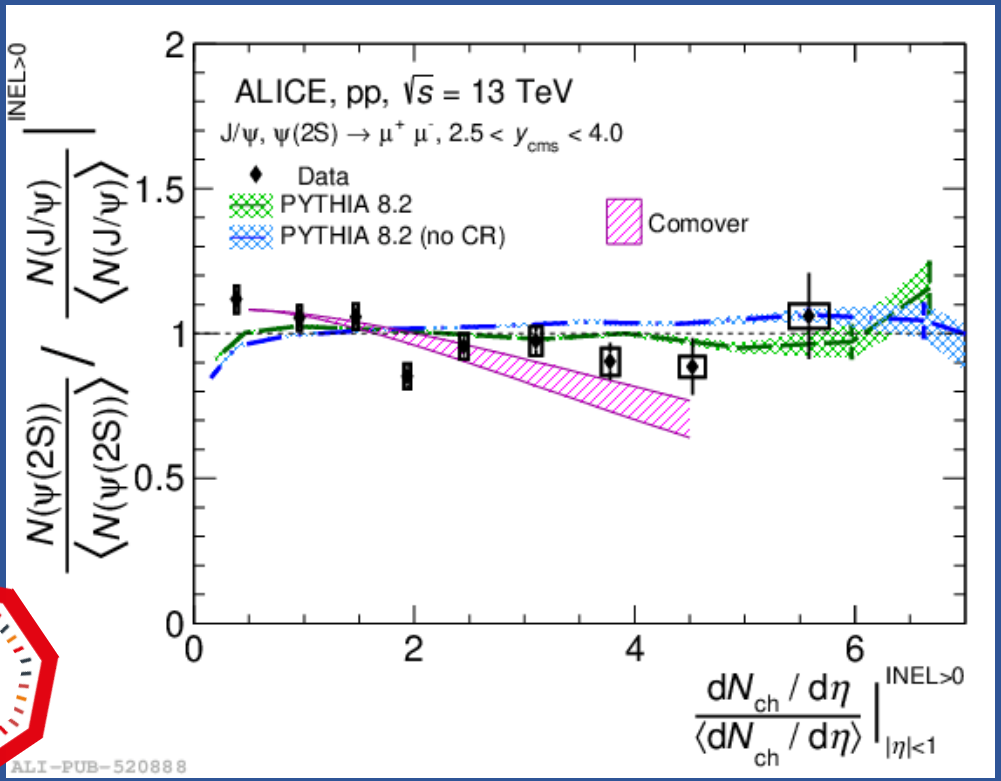
(ΔC: width of centrality interval)

Quarkonium news from pp collisions

ALICE, arXiv:2204.10253



NEW



NEW

- Strong collective effects on J/ψ already assessed in Pb-Pb
- p-Pb: significant flow for p_T>3 GeV/c (not explained by transport models)
- pp: no significant effect, integrated v_2 compatible with zero within 1.5σ

- Self-normalized ratios of ψ(2S) and J/ψ exhibit a similar multiplicity dep. (ratio of ratios is flat)
- Agreement with PYTHIA 8, while comover models predict a suppression effect at large $dN_{ch}/d\eta$, not seen in the data

Open heavy flavours

PA – HF session

More details in

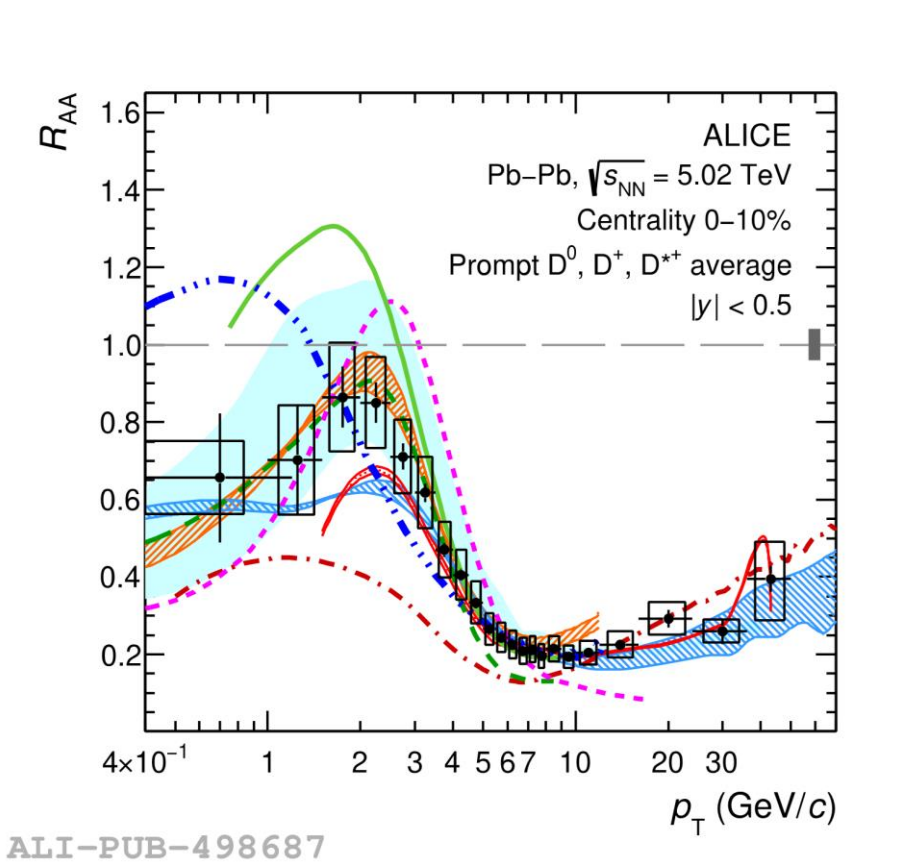
Constraining hadronization processes with charm baryons in pp and p-Pb collisions with ALICE
J. Seo, Tue 12.10 PM

Charm production: constraint to transport models and charm diffusion coefficient with ALICE
M. Völkl, Tue 11.50 AM

Beauty production in heavy-ion collisions with ALICE at the LHC
S. Politanò, Tue 2 PM

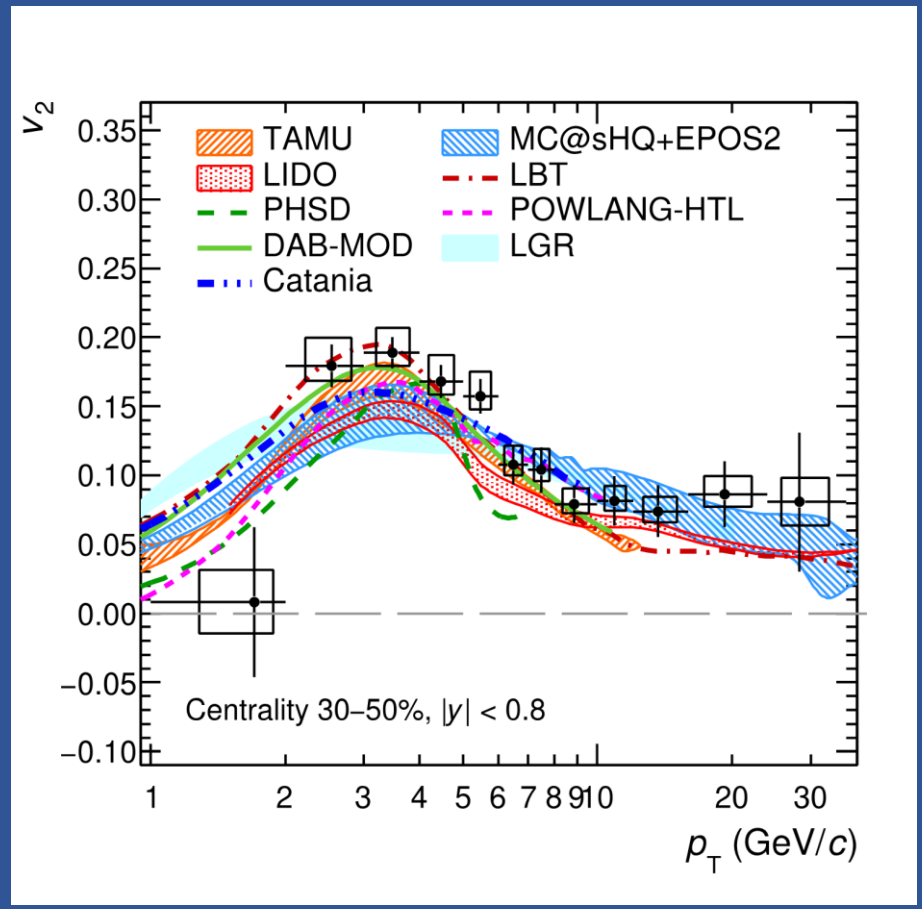
Heavy-flavour jet properties and correlations from small to large systems measured by ALICE
A. Da Silva, Tue 2.20 PM

Charm quark transport and models



ALICE,
JHEP 01 (2022) 174

ALICE,
PLB 813 (2021) 136054

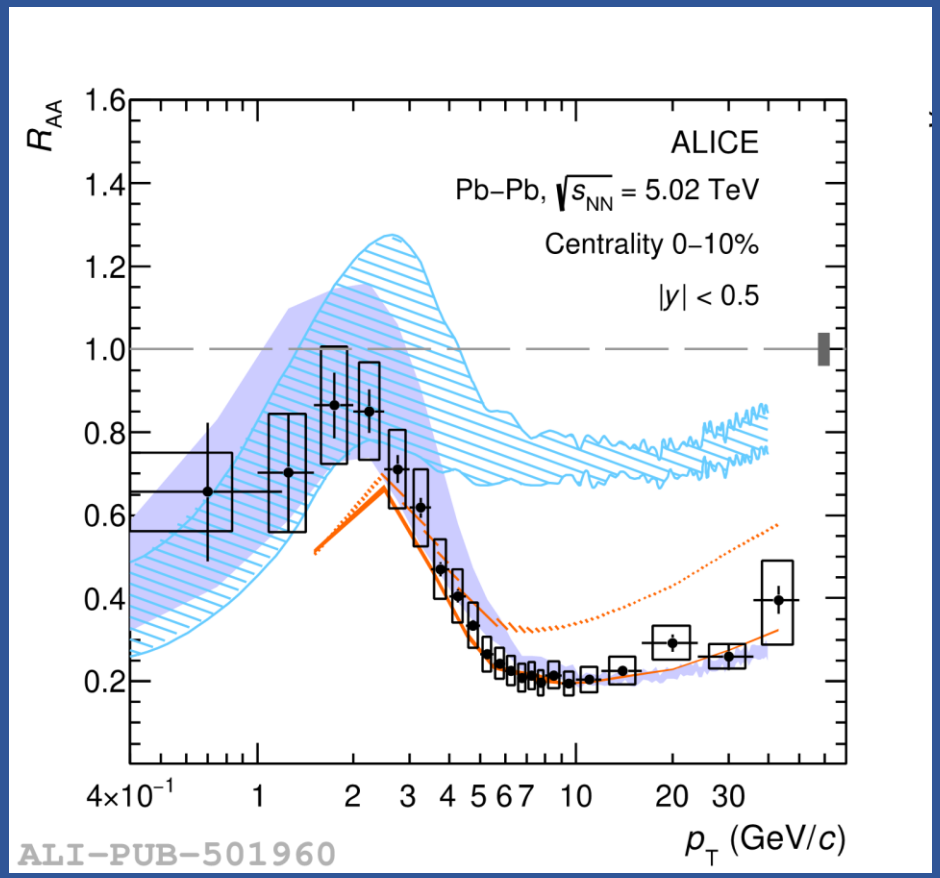


- Most charm-quark transport models able to describe both the R_{AA} and v_2
  - → Use comparison to understand which physics effects are relevant
  - → Use comparison to estimate the spatial diffusion coefficient

TAMU: PRL 124, 042301 (2020), DAB-MOD: PRC 96, 064903 (2017), LBT: PLB 777 (2018) 255-259, LIDO: PRC 98, 064901 (2018), Cat.: PRC 96, 044905 (2017), POWL.: EPJC 75 (2015) 3, 121 PHSD: PRC 93, 034906 (2016), MC@sHQ: PRC 91, 014904 (2015), LGR: EPJC 80 (2020) 7, 671

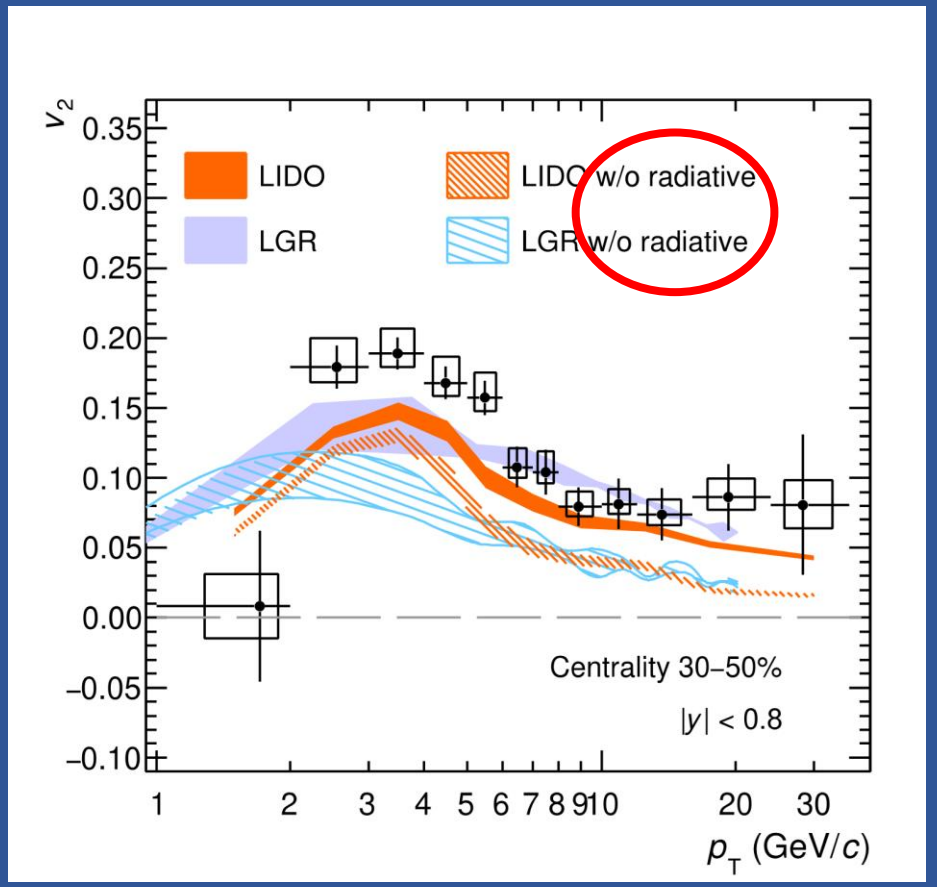
Charm quark energy loss

LIDO: PRC 98, 064901 (2018)
LGR: EPJC 80 (2020) 7, 671



ALICE,
JHEP 01 (2022) 174

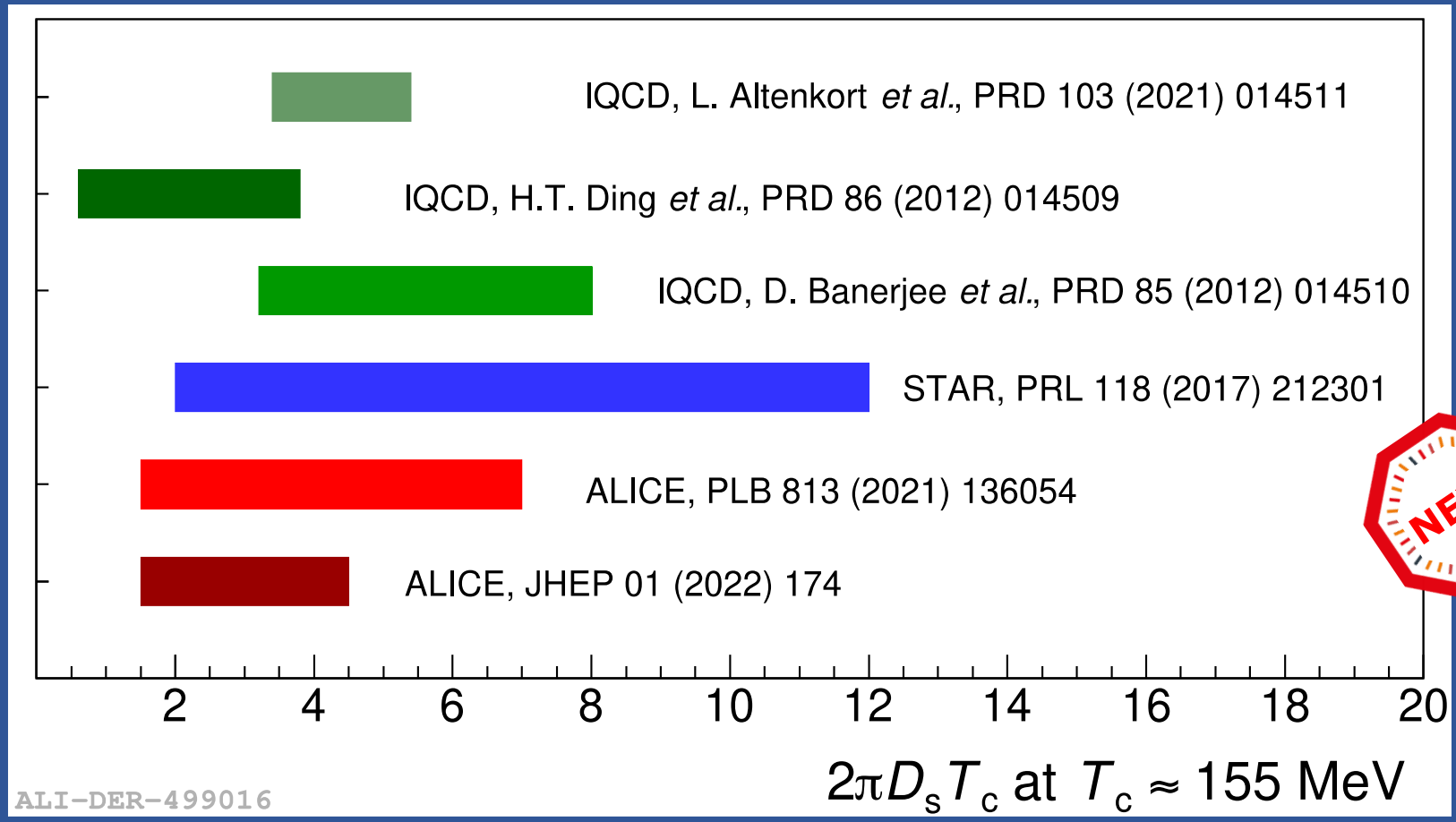
ALICE,
PLB 813 (2021) 136054



Radiative energy loss important to describe intermediate and high p_T
→ Small impact on low p_T region

Estimating the spatial diffusion coefficient

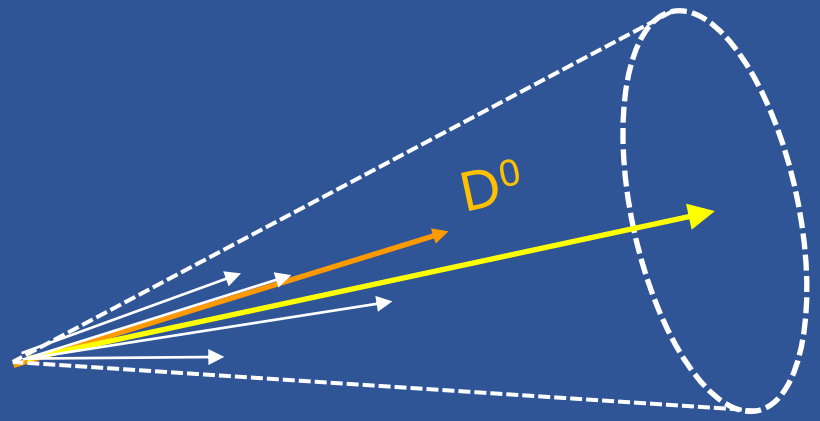
- Constraining the spatial diffusion coefficient via the data-to-model agreement
  → Using R_{AA} (with $\chi^2/\mathrm{ndf} < 5$) and v_2 (with $\chi^2/\mathrm{ndf} < 2$) non-strange D measurements
  → TAMU, MC@sHQ, LIDO, LGR, and Catania "selected"



NEW

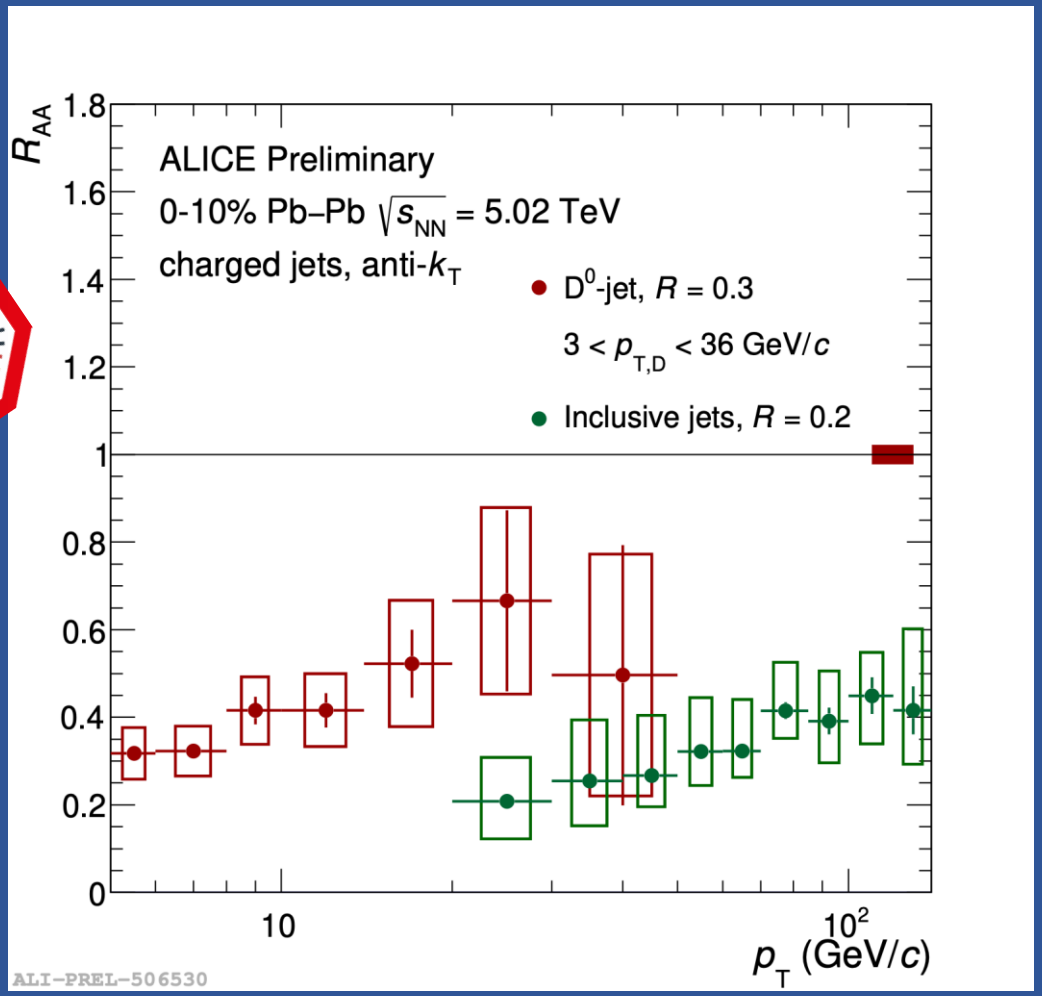
→ $1.5 < 2\pi D_s T_c < 4.5$
→ $\tau_{\mathrm{charm}} \simeq 3 - 8$ fm/c

Charm vs inclusive jets



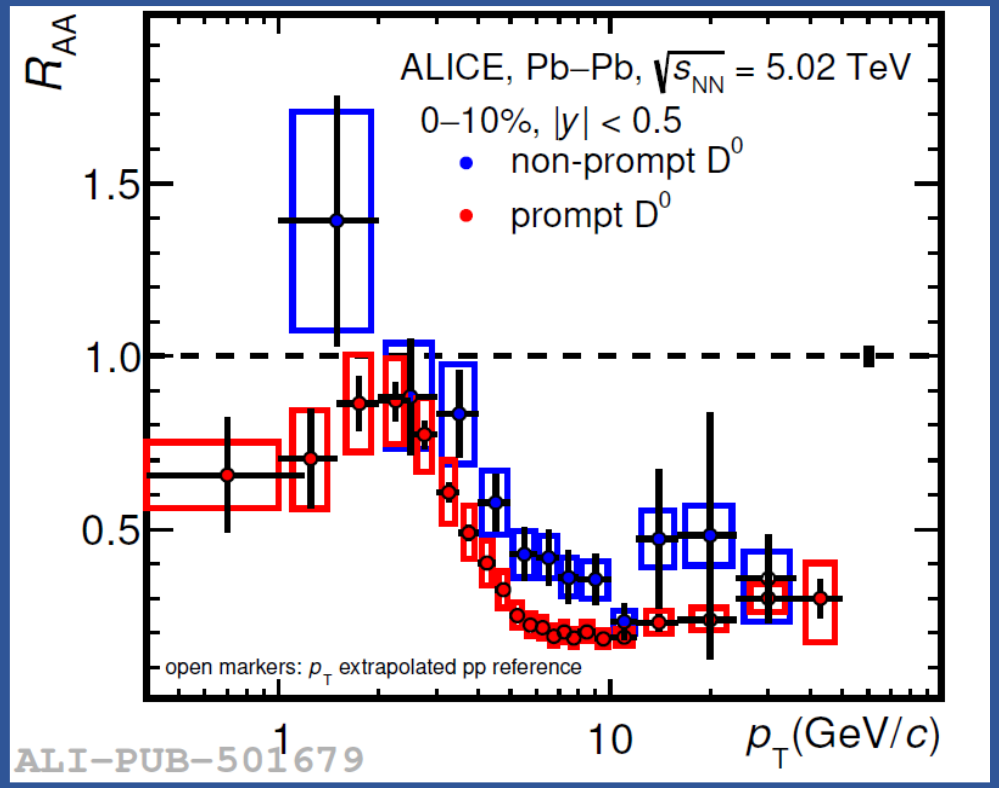
- D^0 meson, $3<p_T<36$ GeV/c
- Charged jets, anti-k_T algorithm with R=0.3
- Jet $5<p_T<50$ GeV/c

NEW

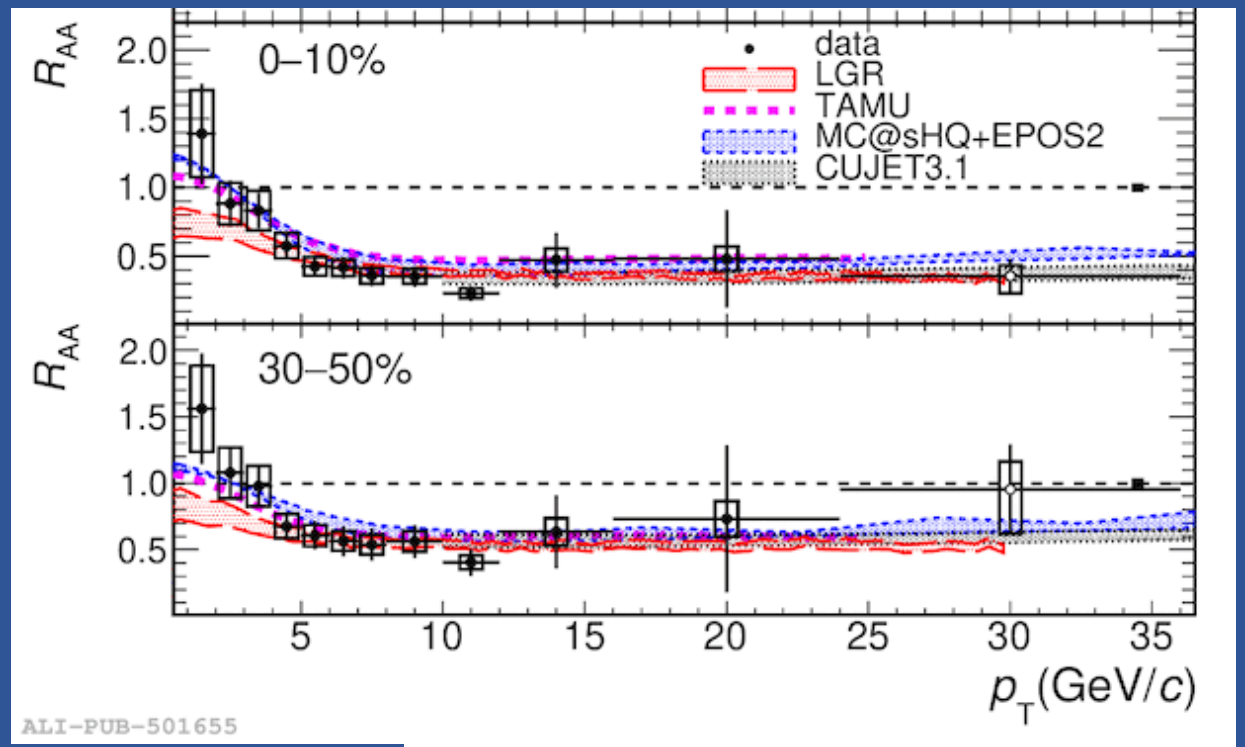


- Hint of a higher R_{AA} of D^0-jets compared to inclusive jets in Pb-Pb
- Comparison sensitive to
  - Difference between quark and gluon energy loss (Casimir colour effect)
  - Mass effects (dead cone)

Beauty vs charm: prompt vs non-prompt D^0 R_{AA}



ALICE,arXiv:2202.00815

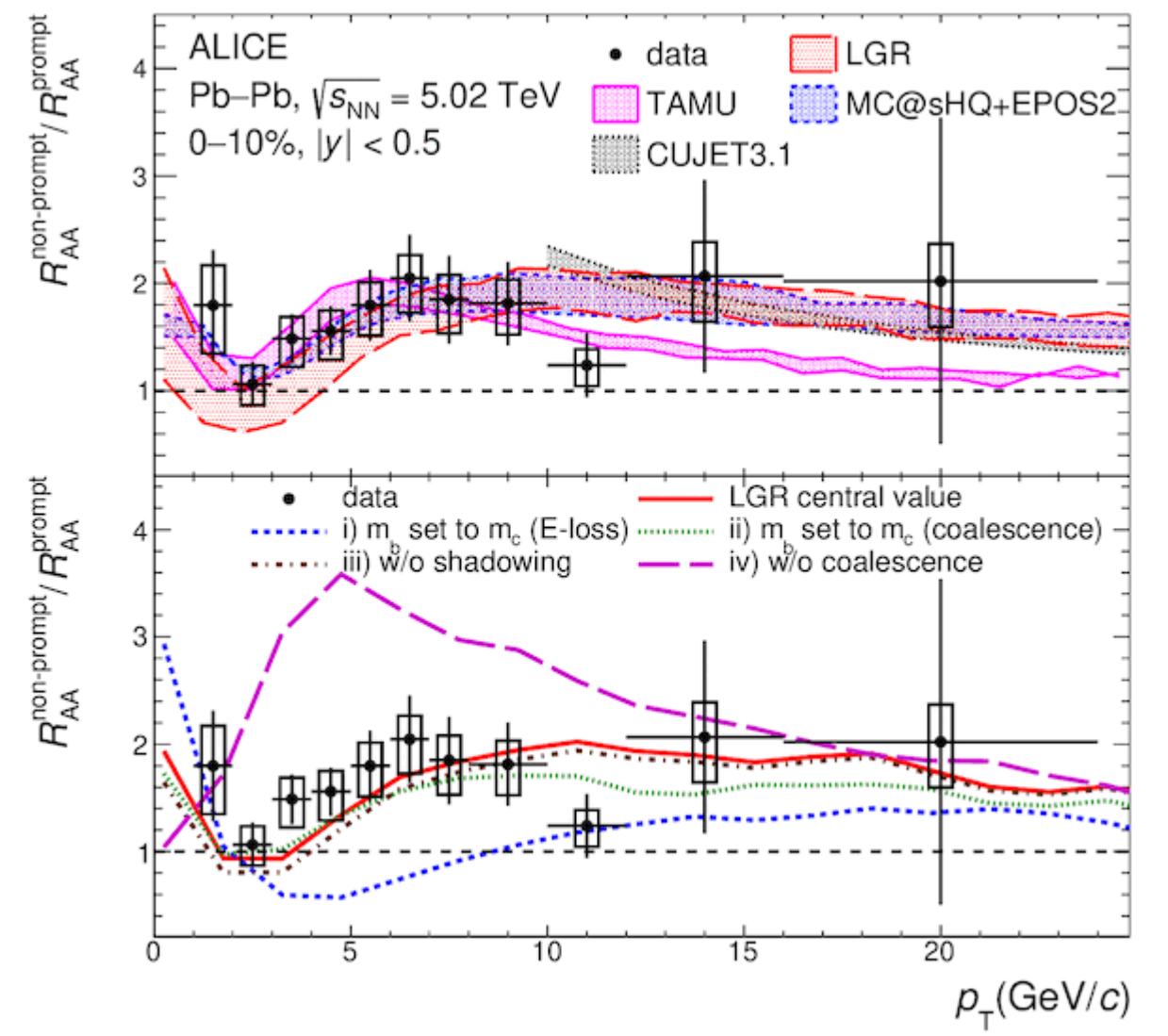


TAMU: PLB 735 (2014) 445
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: EPJC 80, no.7, (2020) 671
EPJC 80 no.12, (2020) 1113
CUJET3: CPC 43, no.4, (2019) 044101

- Suppression of b → D^0 observed
- $R_{AA\ b\to D0} > R_{AA\ c\to D0}$ at intermediate p_T
- R_{AA} (0-10%) < R_{AA} (30-50%)

- Theory models that include collisional and radiative eloss describe the data within uncertainties

Ratio non-prompt/prompt R_{AA} for D mesons

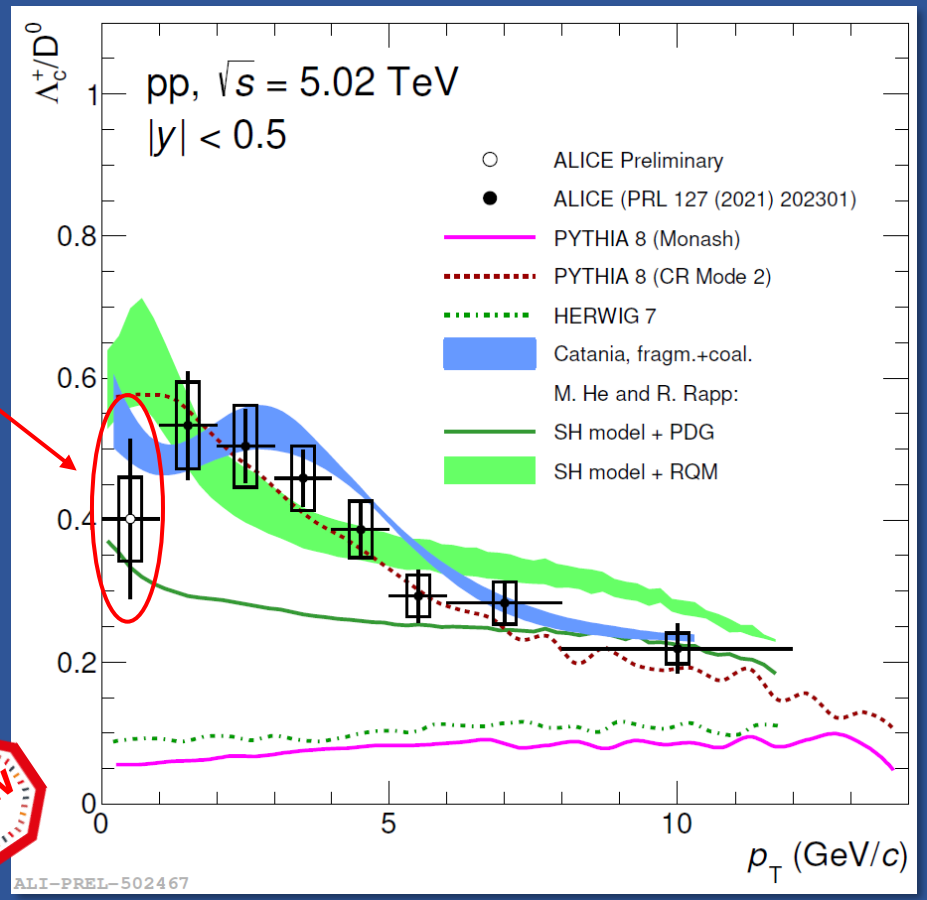


- Sensitive to effects that act differently on charm and beauty quarks
- p_T < 5 GeV/c : difference in shadowing / flow / decay kinematics
- p_T > 5 GeV/c : 3.9 σ above unity
  → beauty quarks undergo less suppression than charm quarks
- Test the double R_{AA} ratio with different LGR configurations
  → The "valley" structure is mainly due to the formation of prompt D-mesons via charm-quark coalescence (iv)
  → The significant enhancement of double ratio at high p_T is related to the mass dependent quark in-medium energy loss (i)

ALICE,arXiv:2202.00815 LGR: EPJC 80 (2020) 671, EPJC 80 (2020) 1113

Λ_c/D^0: pp collisions

Extension down to zero p_T



NEW

→ PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
→ RQM: additional 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c (not yet measured)

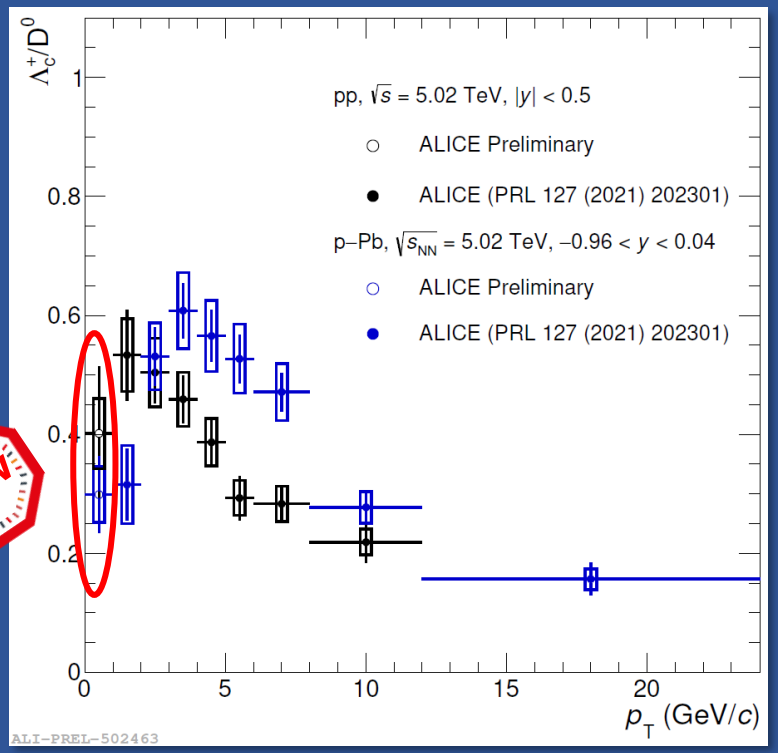
M. He, R. Rapp,
PLB 795 (2019) 117-121

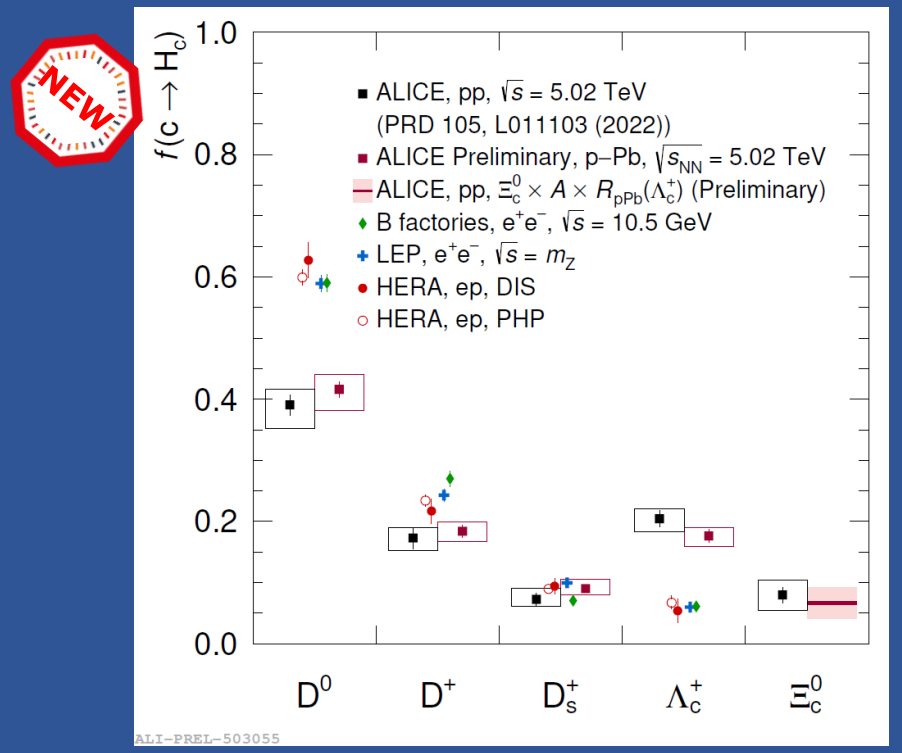
- Ratios underestimated at low p_T by models as PYTHIA 8 Monash, tuned to reproduce e^+e^- results (e^+e^- charm fragmentation functions)

  → non-universal fragmentation of charm to hadrons ?

- PYTHIA 8 with updated Colour Reconnection (CR) modelling J.P. Christiansen, P. Z. Skands: JHEP 1508 (2015) 003
  - CR with SU(3) weights and string length minimization
    → "junction" topology enhances charm baryon production
- Catania model V. Minissale, S. Plumari, V. Greco: arXiv:2012.12001
  - Thermalised system of u,d,s and gluons assumed
  - Mixed hadron formation
    → Fragmentation
    → Coalescence, imposed as only mechanism for $p \to 0$
- Statistical Hadronization Model and Relativistic Quark Model (SHM + RQM)
  - Hadronization driven by statistical weights governed by hadron masses ($n_i \sim m_i^2 T_H K_2(m_i/T_H)$) at a hadronization temperature T_H
  - Strong feed-down from an augmented set of excited charm baryons

From pp to p-Pb: Λ_c/D^0 and charm fragmentation fractions

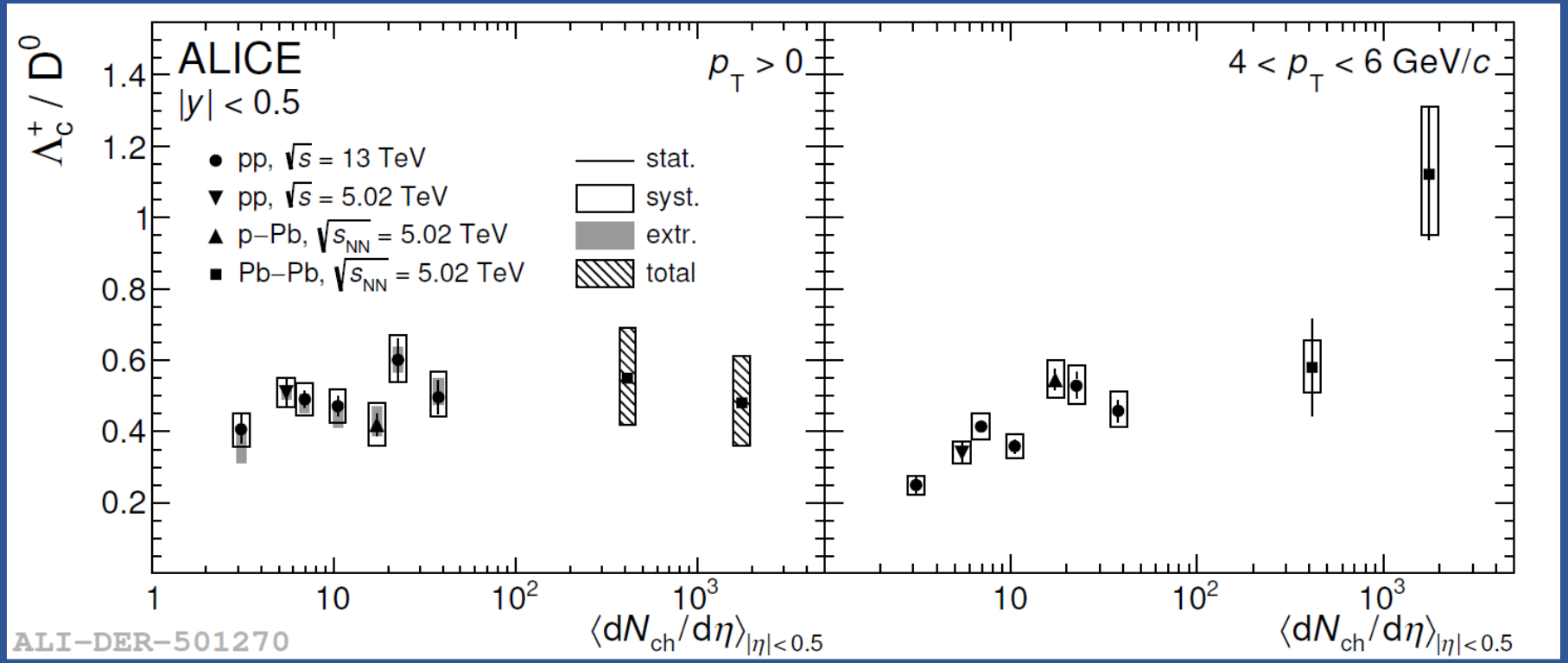




- pp and p-Pb results compatible
- Significant baryon enhancement with respect to e^+e^- and e^-p

- Λ_c^+/D^0 enhancement shifted to larger p_T in p-Pb
- Charm fragmentation fractions measured including several states in pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (ALICE,PRD105(2022)L011103)
- For p-Pb: measured for D^0 and Λ_c , extrapolated to zero p_T with POWHEG+PYTHIA for D^+ and D_s^+ , not measured for Ξ_c but evaluated assuming $R_{pPb}(\Lambda_c^+) = R_{pPb}(\Xi_c^+)$

Λ_c/D^0: moving across systems, pp, p-Pb, Pb-Pb



ALICE, PLB 829 (2022) 137065
ALICE, arXiv:2112.08156

Increase of the ratio from pp to mid-central and central Pb–Pb collisions for $4 < p_T < 8$ GeV/c
→ 2.0σ and 3.7σ significance respectively

- p_T-integrated data do not favour an increase of the yield ratio with multiplicity
  → trend compatible with a constant function.
- Suggests that the increasing trend observed in specific p_T ranges comes from a re-distribution of p_T that acts differently for baryons and mesons

Conclusions

- ALICE Run 1 + 2: several highlights and still investigating exciting topics. Among those:

PRESENT

- Quarkonium
  - Study of recombination in the charmonium sector, now extended to $\psi(2S)$
  - First results on J/ψ polarization with respect to event plane, small but significant effect
  - Large J/ψ v_2 in Pb-Pb, significant signal in p-Pb but no evidence in pp
- Open heavy flavours
  - Studies on thermalization and energy loss, estimate of crucial QGP parameters (D_s)
  - Energy loss hierarchy, via charm-jet studies and non-prompt/prompt D^0 production
  - Detailed studies of charm baryon production, to shed light on anomalous enhancements seen in pp collisions

FUTURE

- LHC Run 3 starting
- Continuous readout at 50 kHz interaction rate for Pb–Pb collisions
  - Target Pb-Pb integrated luminosity (run 3 + 4) → $L_{int} \sim 13\ nb^{-1}$
- Improved tracking precision by a factor 3–6 (new Inner Tracker)
- Longer-term plan: ALICE 3
  → Systematic measurements of (multi-)heavy-flavour hadrons

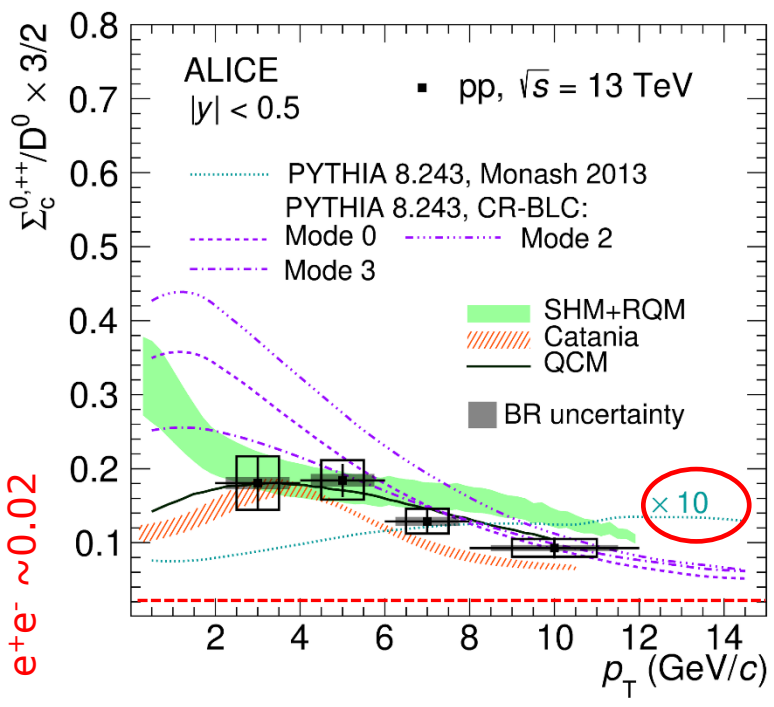
Heavy-ion physics at the LHC with detector upgrades for Runs 3 and 4
S.Porteboeuf, Thu 12.40 PM

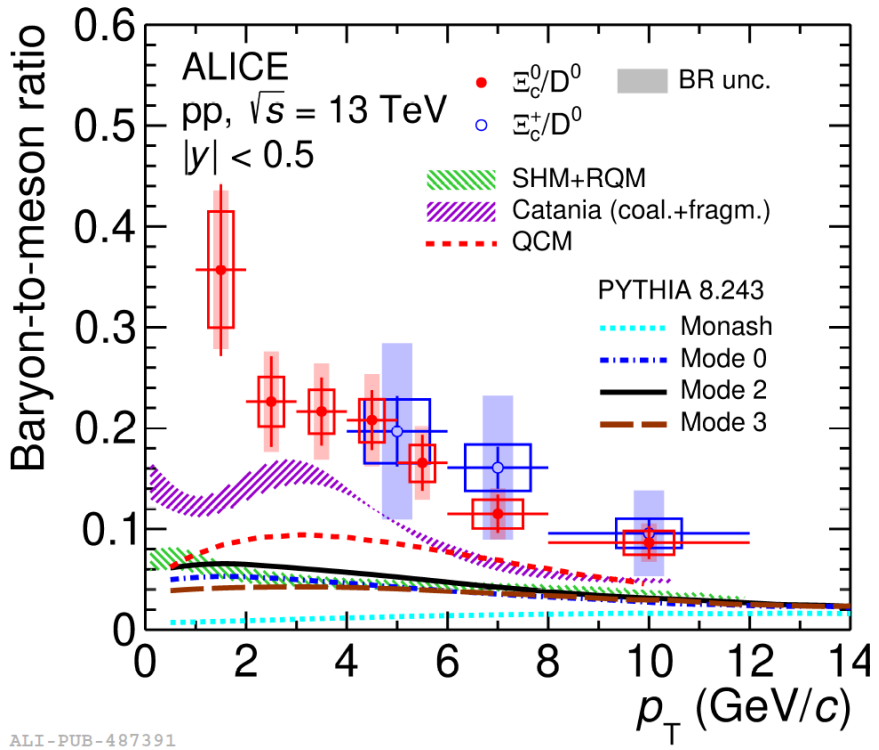
Physics program of the ALICE 3 experiment for the LHC Runs 5 and 6
R.Bailhache, Thu 12.05 PM

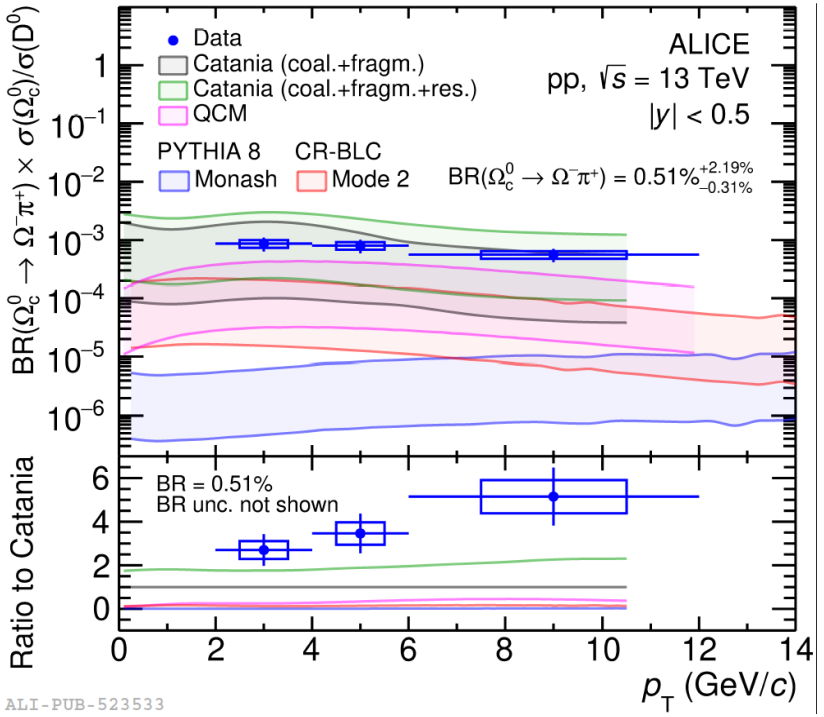
Backup

$\Sigma_c^{0,+,++}$, $\Xi_c^{0,+}$, Ω_c^0 baryons in pp collisions

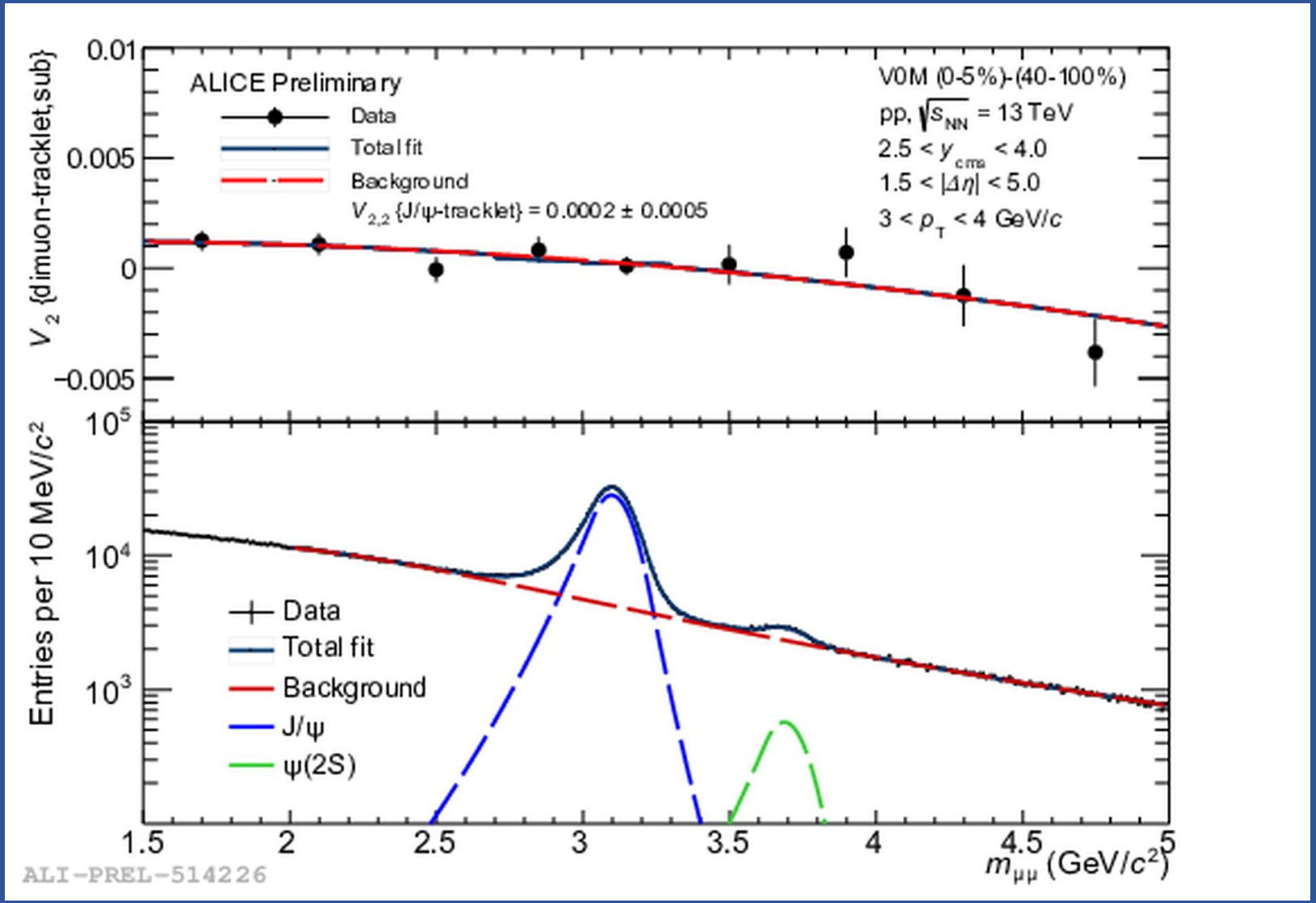
ALICE, PRL 128, 012001
ALICE, PRL 127, 272001
ALICE, JHEP 10 (2021) 159
ALICE:arXiv:2205.13993







- Σ_c/D^0 well described by SHM+RQM, Catania and QCM, its enhancement partially accounts for large Λ_c^+/D^0
- Ξ_c/D^0 significantly underestimated by models, while Ξ_c/Σ_c (not shown) in agreement with Monash
  (N.B. $D_s^+/(D^0 + D^+)$ is compatible with expectations from e^+e^-, effects above not directly related to s-quark content?)
- Ω_c/D^0 , better agreement with coalescence models, PYTHIA 8 underestimates even with CR-BLC effects
  (N.B. $BR(\Omega_c^0 \to \Omega^-\pi^+) = (0.51 \pm 0.07)\%$ not measured → value from Y. Hsiao et al. EPJC 80, 1066 (2020) used to scale model predictions)

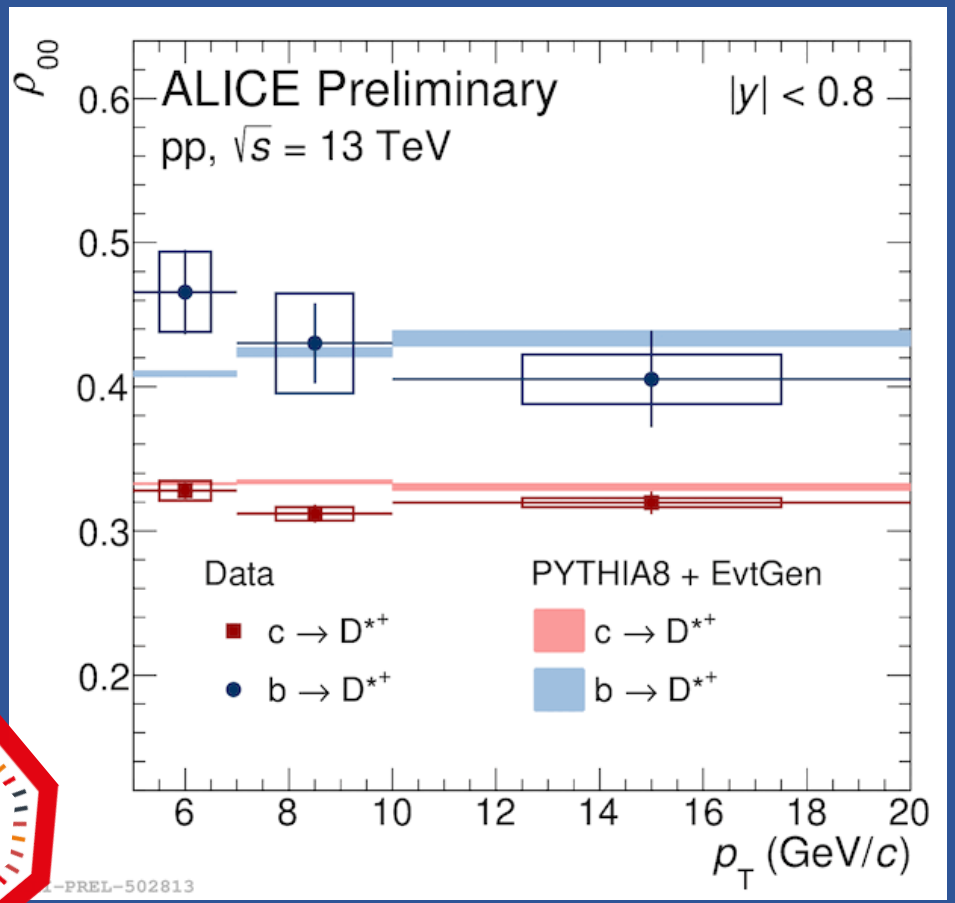

ALICE Preliminary
Data
Total fit
Background
$V_{2,2}$ {J/ψ-tracklet} = 0.0002 ± 0.0005
V0M (0-5%)-(40-100%)
pp, $\sqrt{s_{NN}}$ = 13 TeV
2.5 < y_{cms} < 4.0
1.5 < |Δη| < 5.0
3 < p_T < 4 GeV/c
V_2 {dimuon-tracklet,sub}
Entries per 10 MeV/c^2
Data
Total fit
Background
J/ψ
ψ(2S)
$m_{\mu\mu}$ (GeV/c^2)
ALI-PREL-514226

Reconstructed charm-baryon decays

- $\Lambda_c^+(\mathrm{udc}) \rightarrow \mathrm{pK}^-\pi^+, \mathrm{pK}_S^0$
- $\Sigma_c^{0,++}(\mathrm{ddc}, \mathrm{uuc}) \rightarrow \Lambda_c^+\pi^{-,+}$
- $\Xi_c^0(\mathrm{dsc}) \rightarrow \Xi^-\mathrm{e}^+\nu_e, \Xi^-\pi^+$
- $\Xi_c^+(\mathrm{usc}) \rightarrow \Xi^-\pi^+\pi^+$
- $\Omega_c^0(\mathrm{ssc}) \rightarrow \Omega^-\pi^+$

A brief detour

- Polarization studies can be extended to other particles containing charm quarks
- First step recently carried out by studying D^{*+} polarization in pp collisions



NEW

- Measure spin density matrix ρ_{00}

$$\frac{dN}{dcos\theta^*} = N_0 \times [(1-\rho_{00}) + (3\rho_{00}-1)cos^2\theta^*]$$

- Deviations from ρ_{00} =1/3 signal a net spin alignment
- Separation of prompt and non-prompt component
- Prompt component unpolarized, while non-prompt component from b-hadron decays exhibit a clear polarization

→ Effect seen and in agreement with PYTHIA 8 + EVTGEN

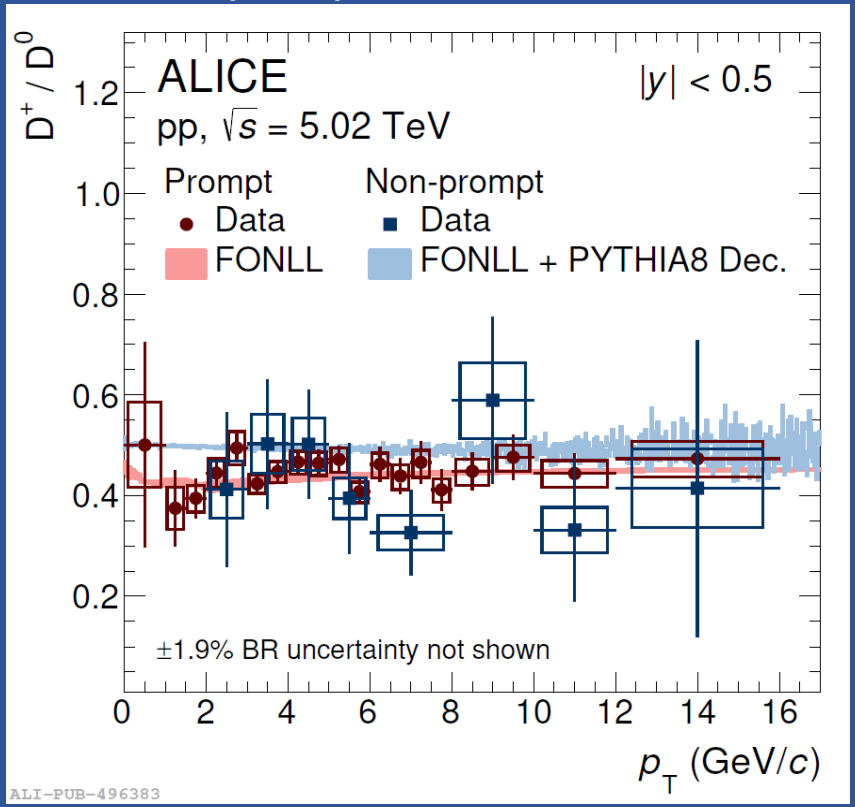
- Next step: measurements in Pb-Pb collisions, to search for effects related to B and/or L

Charm hadronization in pp: baryons vs mesons

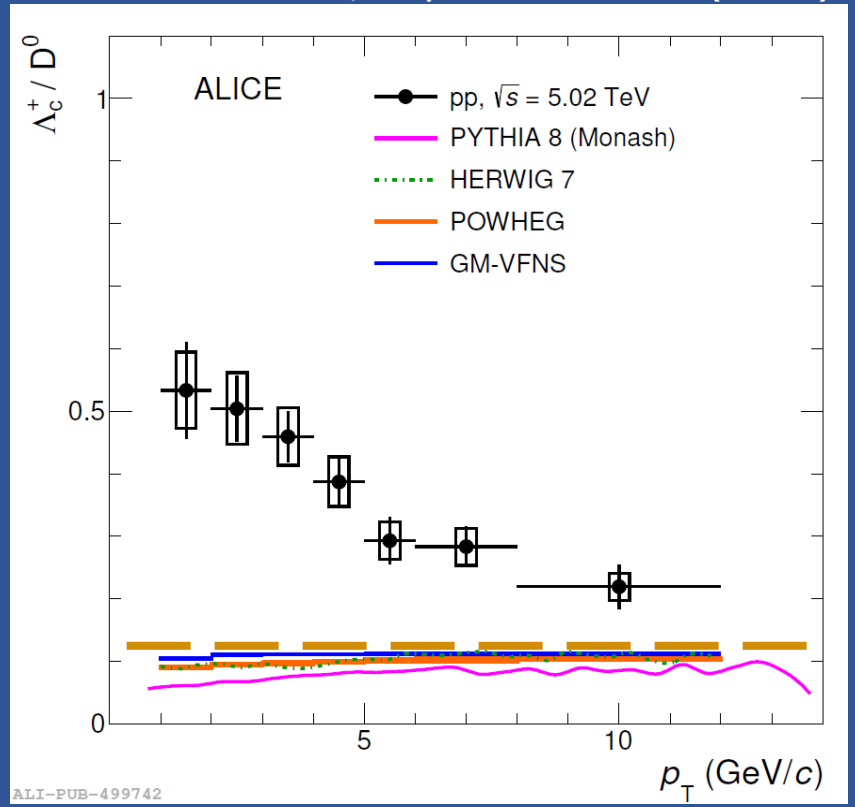
ALICE, JHEP 05(2021) 220

ALICE, Phys. Rev. C 104 (2021) 054905

$\frac{D^+}{D^0}$



$\frac{\Lambda_c^+}{D^0}$



LEP average

$0.113 \pm 0.013 \pm 0.006$

(EPJC75 (2015)19)

- Baryon-to-meson ratios underestimated at low p_T by models as PYTHIA 8 Monash, tuned to reproduce e^+e^- results (e^+e^- charm fragmentation functions)
- Enhancement with respect to PYTHIA 8 at low p_T also observed in the beauty sector by LHCb
- Points towards further hadronization mechanisms → non-universal fragmentation functions
  → Campaign of measurements of various baryon resonances in pp