Charm production: constraint to transport models and charm diffusion coefficient with ALICE

41st International Conference on High Energy Physics

Fabio Catalano on behalf of the ALICE Collaboration

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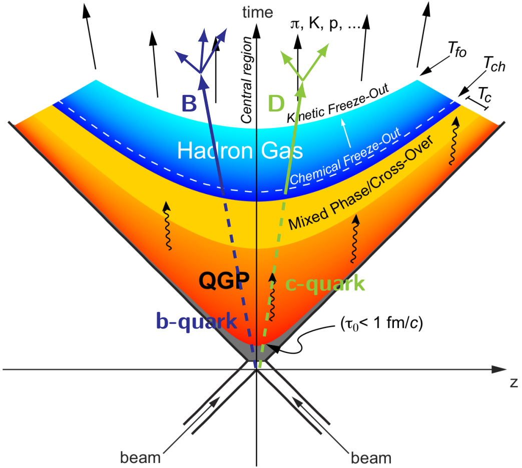
Università and INFN Torino, Italy

fabio.catalano@cern.ch

Heavy flavours in ultrarelativistic heavy-ion collisions

- Heavy flavours (c and b quarks) are produced in hard-scattering processes before the QGP formation
  - $\tau_{prod} \leq \hbar/m_{c,b} \sim 0.1\ (0.04)\ \mathrm{fm}/c$
  - $\tau_{QGP} \sim 0.3\ \mathrm{fm}/c$ (LHC)
- They experience the full QGP evolution
- Negligible in-medium production/annihilation

Excellent QGP probes!



Heavy flavours propagate through the QGP and interact with the medium constituents

- **Energy loss via elastic scatterings and gluon radiation**, depending on
  - colour charge
  - quark mass
  - path length in the medium

- **Participation in the fireball collective motion**
  - Brownian motion of heavy quarks in the QGP
  - possible thermalisation in the medium

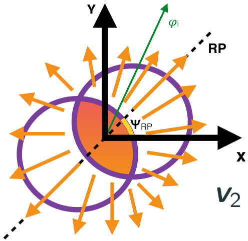
- **Modification of the hadronisation mechanism**
  - recombination with quarks from the medium

Nuclear modification factor (R_{AA})

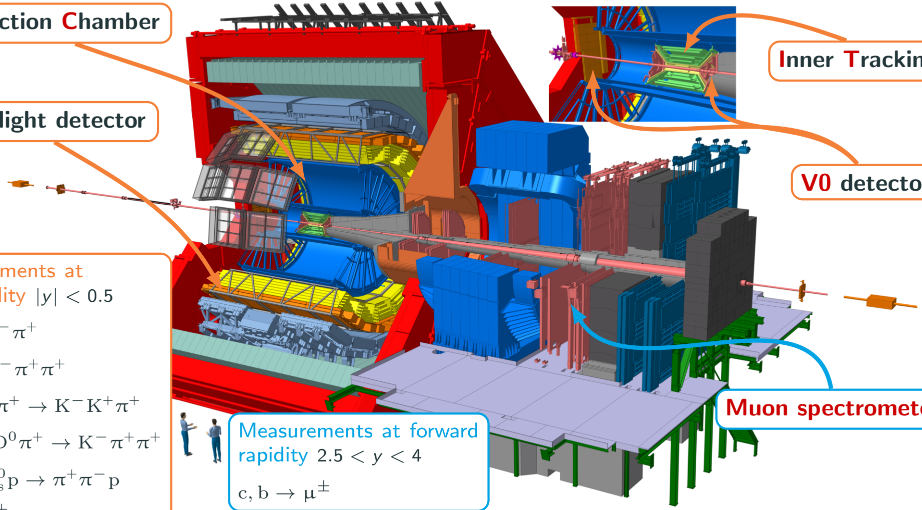
$$R_{\mathrm{AA}}\left(p_{\mathrm{T}}\right) = \frac{1}{\langle N_{coll}^{\mathrm{AA}}\rangle}\frac{\mathrm{d}N_{\mathrm{AA}}/p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/p_{\mathrm{T}}}$$

Flow coefficients (v_n)

$$v_n = \langle \cos[n(\varphi - \Psi_n)]\rangle$$



A Large Ion Collider Experiment



Measurements at midrapidity $|y| < 0.5$

$\mathrm{D}^0 \rightarrow \mathrm{K}^-\pi^+$

$\mathrm{D}^+ \rightarrow \mathrm{K}^-\pi^+\pi^+$

$\mathrm{D}_\mathrm{s}^+ \rightarrow \phi\pi^+ \rightarrow \mathrm{K}^-\mathrm{K}^+\pi^+$

$\mathrm{D}^{*+} \rightarrow \mathrm{D}^0\pi^+ \rightarrow \mathrm{K}^-\pi^+\pi^+$

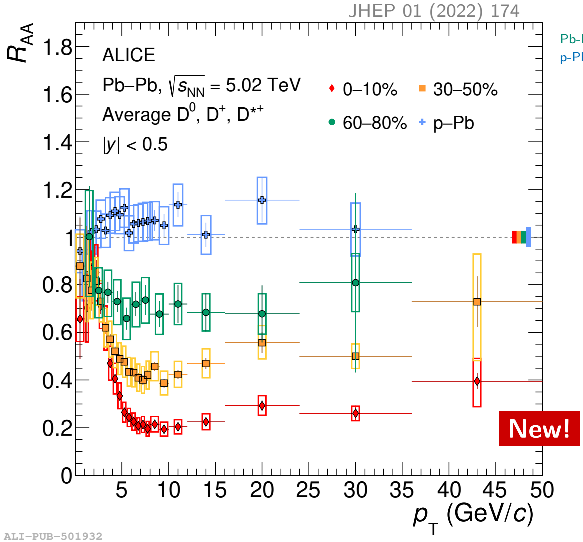
$\Lambda_\mathrm{c}^+ \rightarrow \mathrm{K}_\mathrm{s}^0\mathrm{p} \rightarrow \pi^+\pi^-\mathrm{p}$

$\mathrm{c, b} \rightarrow \mathrm{e}^\pm$

Measurements at forward rapidity $2.5 < y < 4$

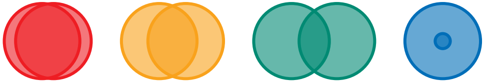
$\mathrm{c, b} \rightarrow \mu^\pm$

Nuclear modification factor — Non-strange D mesons



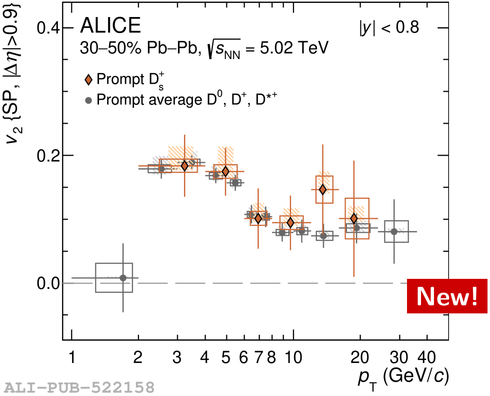
Pb-Pb 60-80%: JHEP 10 (2018) 174
p-Pb: JHEP 12 (2019) 092

- Suppression increasing with collision centrality due to increasing density, size, and lifetime of the medium

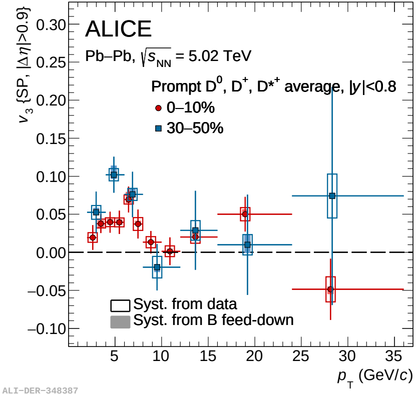


Azimuthal anisotropies — D mesons

PLB 827 (2022) 136986



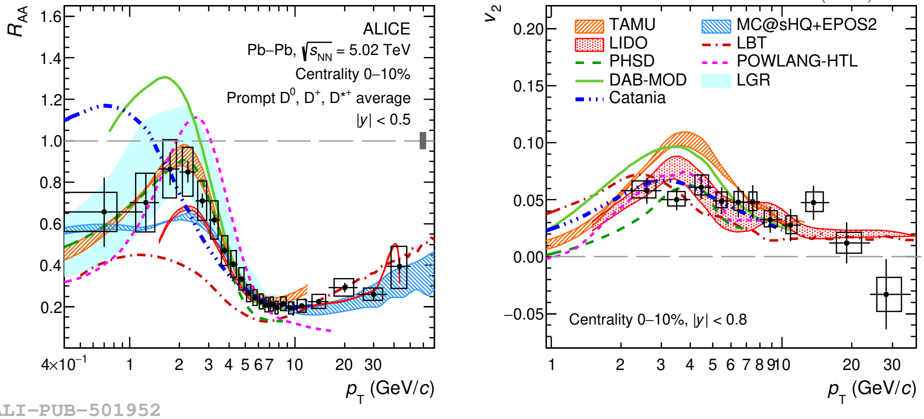
Non-strange D: PLB 813 (2021) 136054



- Positive D-meson v_2 and v_3 → charm-quark participation in QGP collective expansion
- Positive $\mathrm{D_s^+}$ elliptic flow observed in $2 < p_{\mathrm{T}} < 8\ \mathrm{GeV}/c$ with a significance of 6.4σ
  - in agreement with non-strange D-meson v_2 given current uncertainties

Comparison with charm-quark transport models

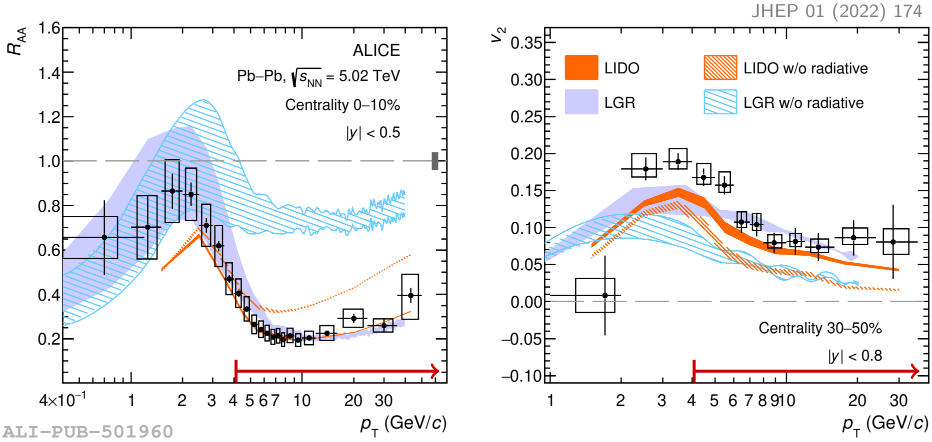
JHEP 01 (2022) 174



TAMU: PRL 124 042301 (2020)
LIDO: PRC 98 064901 (2018)
PHSD: PRC 93 034906 (2016)
DAB-MOD: PRC 96 064903 (2017)
Catania: PRC 96 044905 (2017)
MC@sHQ: PRC 91 014904 (2015)
LBT: PLB 777 255-259 (2018)
POWLANG: EPJC 75 3 121 (2015)
LGR: EPJC 807 671 (2020)

- Simultaneous description of R_{AA} and v_2 challenging for charm-quark transport models
- Model-to-data comparison to:
  - understand relevant physics effects
  - estimate the charm-quark spatial diffusion coefficient D_s

Charm-quark transport models — Radiative energy loss



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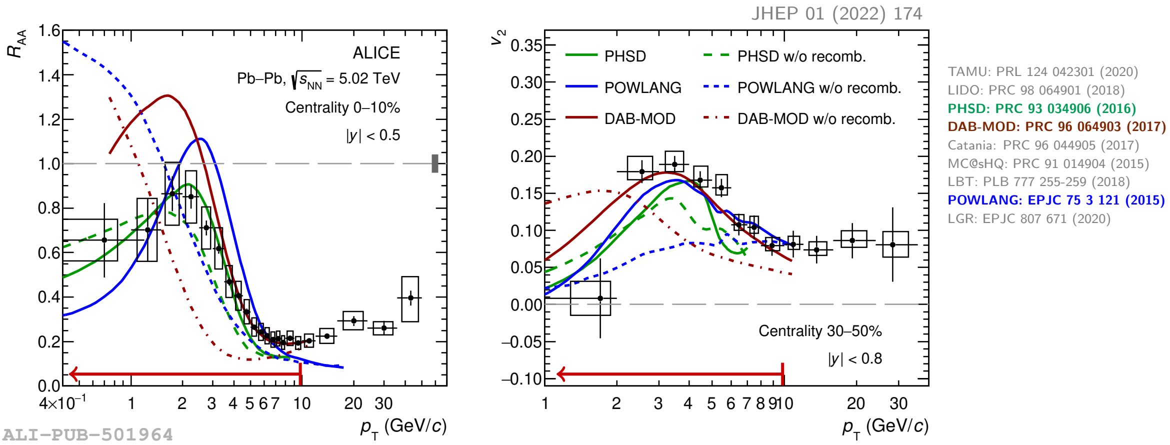
- Radiative energy loss important to describe intermediate and high p_T
  - small impact on low-p_T region

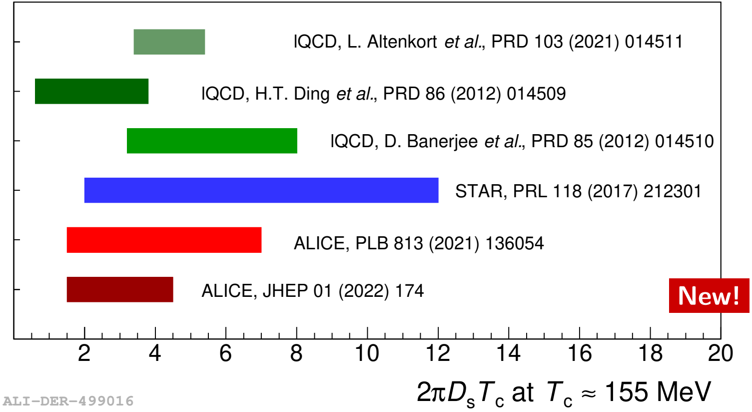
Charm-quark transport models — Hadronisation via recombination



- Charm-quark hadronisation via recombination crucial to describe low and intermediate p_T
  - D mesons acquire additional flow recombining with light quarks

Charm-quark spatial diffusion coefficient

- Spatial diffusion coefficient constrained from model-to-data comparison
  - using R_{AA} ($\chi^2/\mathrm{ndf} < 5$ required), v_2 and v_3 ($\chi^2/\mathrm{ndf} < 2$ required) of non-strange D mesons

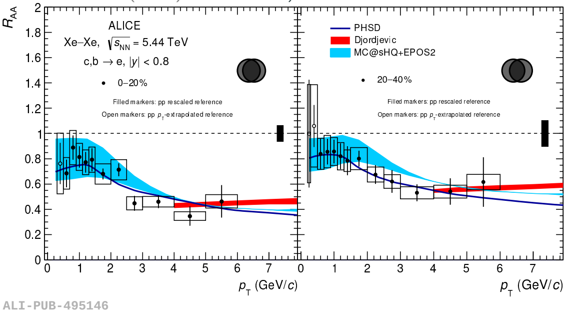


- TAMU, MC@sHQ, LIDO, LGR, and Catania provide a reasonable description
- They have $1.5 < 2\pi D_s T_c < 4.5$ corresponding to a relaxation time $\tau_{\mathrm{charm}} \simeq 3$–$8$ fm$/c$

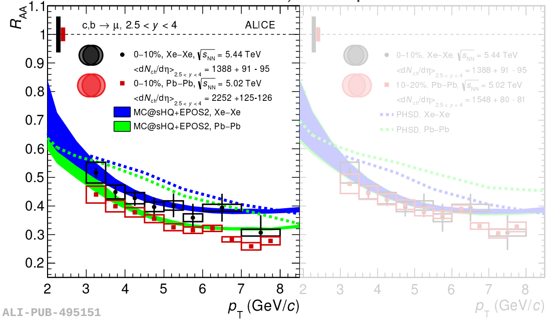
Leptons from heavy-flavour decays in Xe–Xe

PHSD: PRC 93 034906 (2016) Djordjevic: PRC 92 024918 (2015) MC@sHQ+EPOS2: PRC 89 014905 (2014)

PLB 819 (2021) 136637 $c, b \rightarrow e^{\pm}$



$c, b \rightarrow \mu^{\pm}$

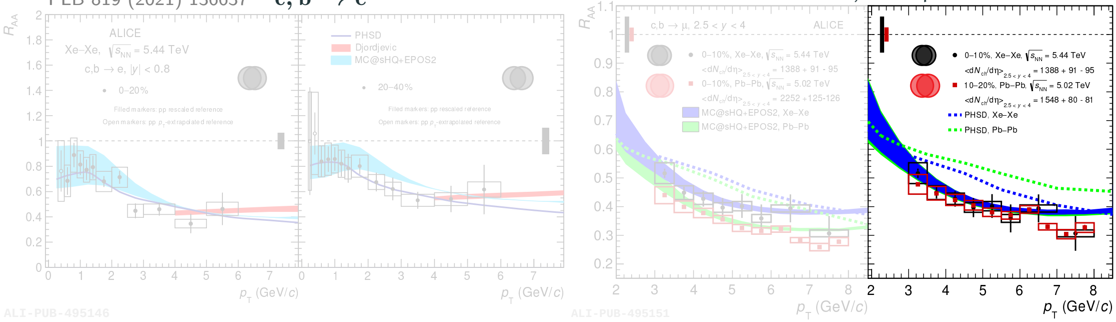


- R_{AA} of $\mu^{\pm}$ and $e^{\pm}$ from heavy-flavour decays reasonably well described by transport models
  - some tension between PHSD (no radiative energy loss) and forward-muon measurement

Leptons from heavy-flavour decays in Xe–Xe — Comparison with Pb–Pb

PHSD: PRC 93 034906 (2016) Djordjevic: PRC 92 024918 (2015) MC@sHQ+EPOS2: PRC 89 014905 (2014)

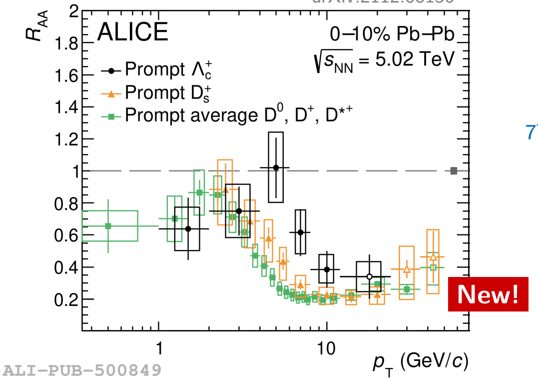
PLB 819 (2021) 136637 $\mathbf{c, b \rightarrow e^{\pm}}$ $\mathbf{c, b \rightarrow \mu^{\pm}}$



- $R_{\rm AA}$ of $\mu^{\pm}$ and $e^{\pm}$ from heavy-flavour decays reasonably well described by transport models
  - some tension between PHSD (no radiative energy loss) and forward-muon measurement
- Similar $R_{\rm AA}$ of $\mu^{\pm}$ in Pb–Pb and Xe–Xe collisions at similar $\langle {\rm d}N_{\rm ch}/{\rm d}\eta \rangle$
  - possibility to further constrain model calculations

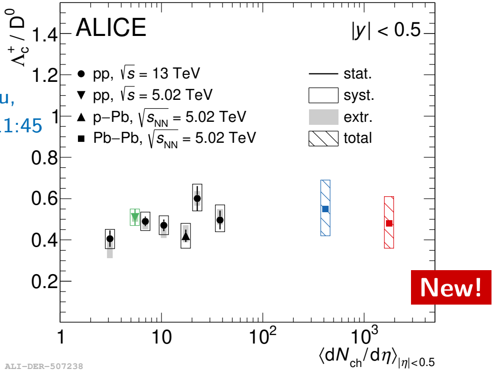
D_s^+ and Λ_c^+ nuclear modification factors

arXiv:2112.08156



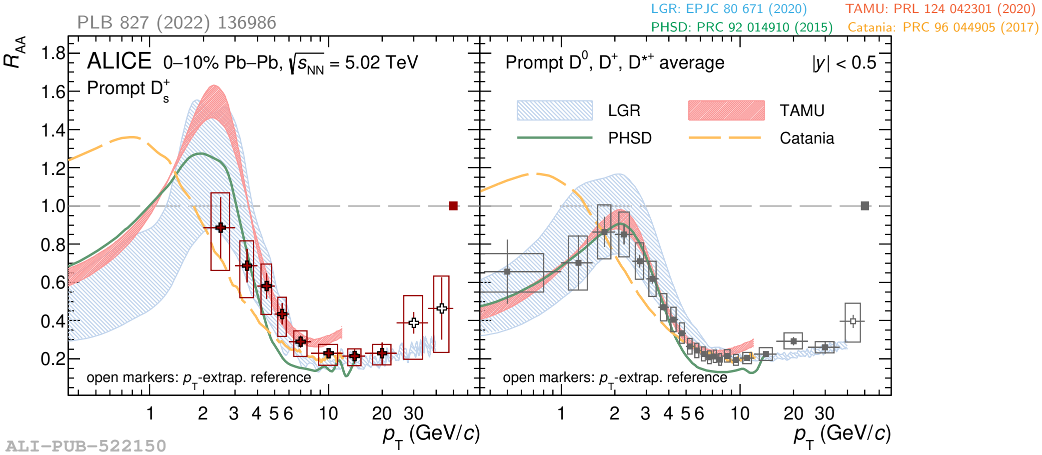
J. Zhu, 7th Jul 11:45

pp at 13 TeV: arXiv:2111.11948



- Hint of hadron-mass ordering $R_{AA}(\Lambda_c^+) > R_{AA}(D_s^+) > R_{AA}(D)$ for $p_T > 4$ GeV/c
- Indication of flat p_T-integrated Λ_c^+/D^0 ratio with multiplicity
  - $R_{AA}(\Lambda_c^+) > R_{AA}(D)$ from interplay between recombination and radial flow? → different p_T redistribution between baryons and mesons?

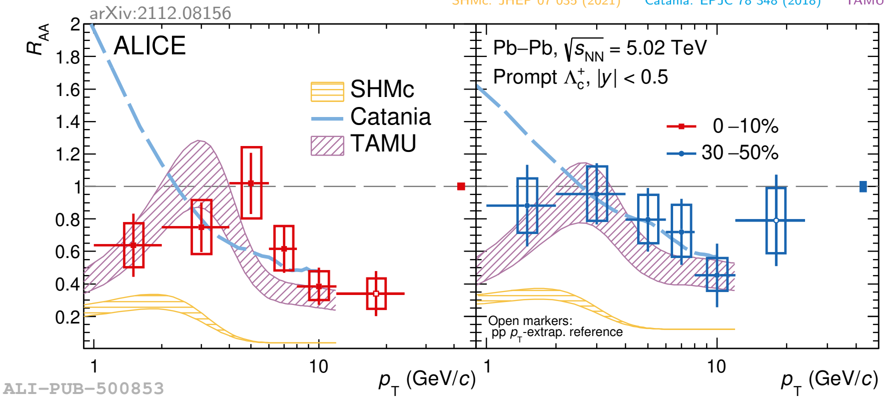
D_s^+-meson R_{AA} — Comparison with models



- Charm-quark transport models describe the D_s^+ R_{AA} and the hierarchy $R_{AA}(D_s^+) > R_{AA}(D)$
  - include hadronisation via recombination and enhanced QGP strange-quark content

Λ_c^+-baryon R_{AA} — Comparison with models

SHMc: JHEP 07 035 (2021) Catania: EPJC 78 348 (2018) TAMU: PRL 124 042301 (2020)



- Transport models fairly catch the measured Λ_c^+-baryon nuclear modification factor
  - Catania (assuming QGP also in pp) off at low p_T
- SHMc (statistical hadronisation + core-corona approach) underestimates the measurements

Conclusions

- Precise charm-hadron measurements down to low p_{T} by ALICE with Run 2 Pb–Pb data
  - beauty sector investigated via non-prompt D mesons and $\mathrm{e}^{\pm}$ from beauty-hadron decays

B. Zhang, 7th Jul 15:20
K. Demmich, 8th Jul 17:45

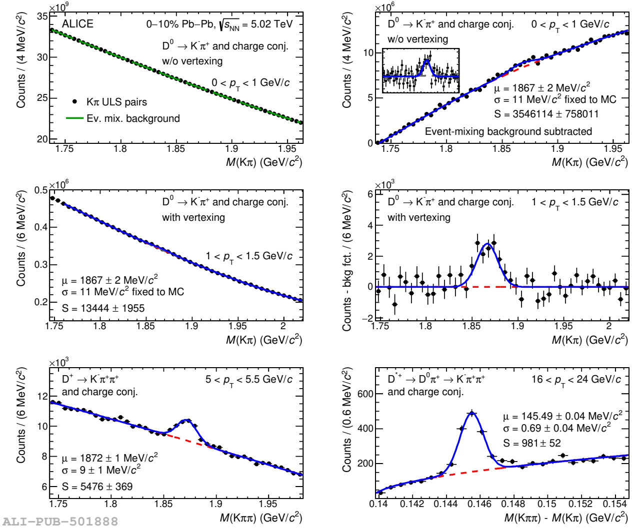
- What did we learn? Charm quarks:
  - interact with the medium via collisional and radiative processes
  - participate in the collective motion of the system
  - hadronise also via recombination in addition to fragmentation

- Just an appetizer for ALICE measurements of Run 3
  - continuous readout of Pb–Pb collisions at 50 kHz → more than 50x larger data samples
  - upgraded ITS → tracking precision improved by a factor 3–4 at $p_{\mathrm{T}} = 200~\mathrm{MeV}/c$

R. Münzer, 8th Jul 9:00
A. Landou, 8th Jul 9:18
I. Cruceru, 8th Jul 11:15

Backup

Charm-hadron yield extraction



D-meson elliptic flow in Pb-Pb collisions

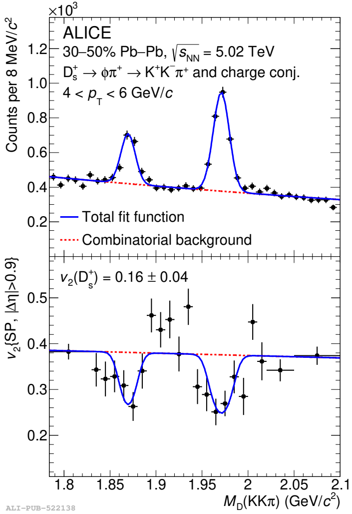
D-meson v_2 measured with the scalar-product (SP) method

$$v_2\{SP\} = \frac{\langle\langle \boldsymbol{u}_2 \cdot \boldsymbol{Q}_2^{\mathrm{A}*}/M^{\mathrm{A}}\rangle\rangle}{\sqrt{\frac{\langle \boldsymbol{Q}_2^{\mathrm{A}}/M^{\mathrm{A}} \cdot \boldsymbol{Q}_2^{\mathrm{B}*}/M^{\mathrm{B}}\rangle \langle \boldsymbol{Q}_2^{\mathrm{A}}/M^{\mathrm{A}} \cdot \boldsymbol{Q}_2^{\mathrm{C}*}/M^{\mathrm{C}}\rangle}{\langle \boldsymbol{Q}_2^{\mathrm{B}}/M^{\mathrm{B}} \cdot \boldsymbol{Q}_2^{\mathrm{C}*}/M^{\mathrm{C}}\rangle}}}$$

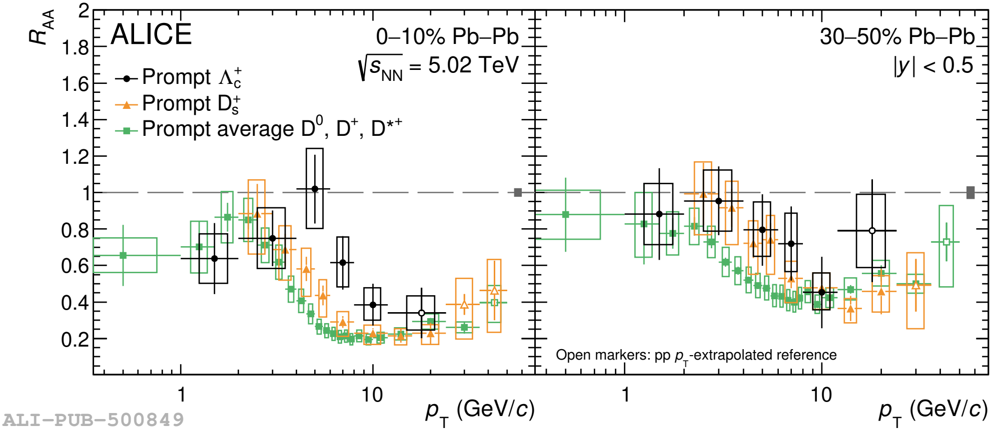
where $\boldsymbol{u}_2 = e^{i2\varphi_D}$ and $\boldsymbol{Q}_2 = \sum_{j=1}^{M} w_j e^{i2\varphi_j}$

- Subevents with different pseudorapidity corverage to suppress non-flow contributions
  - A → V0C ($-3.7 < \eta < -1.7$)
  - B → V0A ($2.8 < \eta < 5.1$)
  - C → TPC ($|\eta| < 0.8$)
- Signal v_2 extracted from a simultaneous fit to invariant-mass and v_2 vs mass distributions

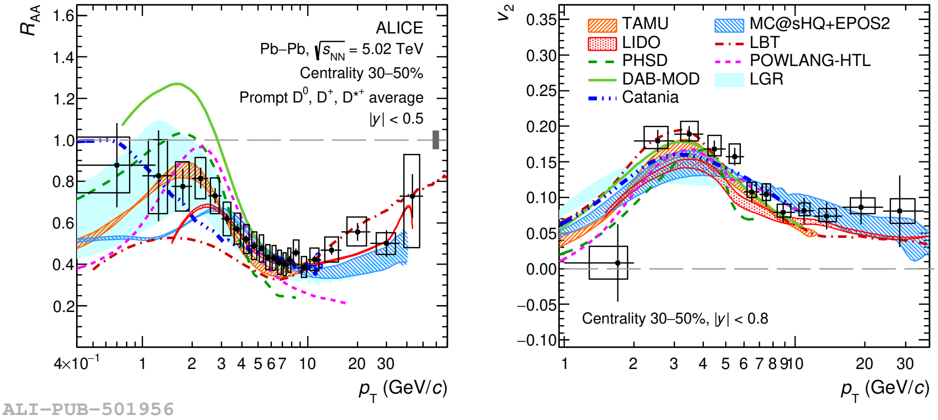
$$v_2^{\mathrm{tot}}(M) = \frac{N^{\mathrm{sig}}(M)v_2^{\mathrm{sig}} + N^{\mathrm{bkg}}(M)v_2^{\mathrm{bkg}}(M) + N^{\mathrm{D}^+}(M)v_2^{\mathrm{D}^+}}{N^{\mathrm{sig}}(M) + N^{\mathrm{bkg}}(M) + N^{\mathrm{D}^+}(M)}$$



D_s^+-meson and Λ_c^+-baryon nuclear modification factor



Comparison with charm-quark transport models

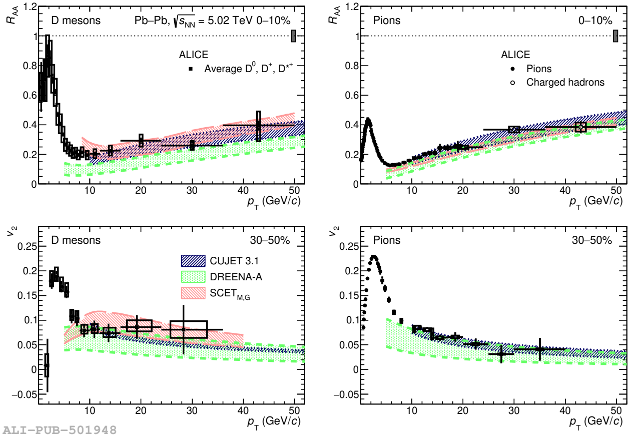


Charm-quark transport models — Ingredients

	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
TAMU	✅	❌	✅	✅	✅
LIDO	✅	✅	✅	✅	✅
PHSD	✅	❌	✅	✅	✅
DAB-MOD	✅	✅	✅	✅	❌
Catania	✅	❌	✅	✅	✅
MC@sHQ+EPOS	✅	✅	✅	✅	✅
LBT	✅	✅	✅	✅	✅
POWLANG+HTL	✅	❌	✅	✅	✅
LGR	✅	✅	✅	✅	✅

But more importantly: different **implementations** and **input parameters**.

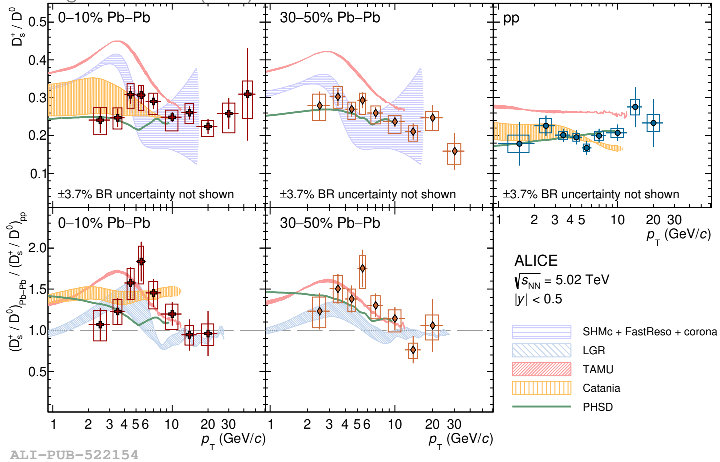
Comparison with models — High-p_T region



	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
CUJET 3.1	✅	✅	❌	✅	✅
DREENA-A	✅	✅	❌	✅	❌
SCET$_{M,G}$	✅	✅	❌	❌	✅

Results — D_s^+-meson abundance

Non-strange D: JHEP 01 (2022) 174



SHMc: JHEP 07 035 (2021)
LGR: EPJC 80, 671 (2020)
PHSD: PRC 92, 014910 (2015)
TAMU: PRL 124, 042301 (2020)
Catania: EPJC 78, 348 (2018)

- Indication of a higher D_s^+/D^0 ratio in Pb-Pb collisions than in pp at $p_T < 8$ GeV/c

- D_s^+ enhancement qualitatively described by transport models including charm-quark recombination in a strangeness-rich medium and by the SHM for charm quark

Statistical hadronisation of charm quarks

- Statistical hadronisation model for charm quarks (SHMc)
  - charm quarks distributed into hadrons at phase boundary according to thermal weights

- Measured yield of mesons in agreement with SHMc predictions

- Measured Λ_c^+-baryon yield underestimated
  - agreement assuming additional charm-baryon resonances