The role of strangeness in heavy-quark hadronisation from small to large collision systems with ALICE

12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

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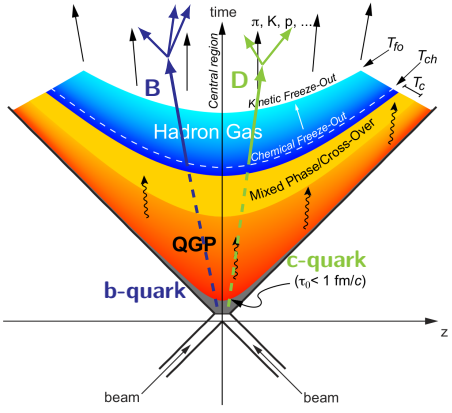
Heavy quarks across collision systems

- Large masses of charm and beauty quarks → produced in hadronic collisions from hard parton-scattering processes

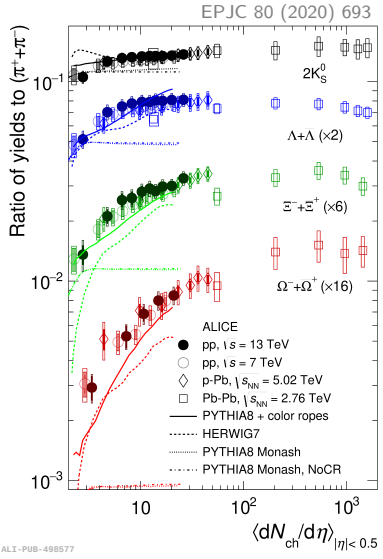
- **proton-proton collisions**
  - test of perturbative-QCD calculations
  - insights on heavy-quark hadronisation

- **p–Pb collisions**
  - test modification of parton distribution functions in bound nucleons

- **Pb–Pb collisions**
  - produced before quark-gluon plasma (QGP)
  - experience the full system evolution
  - sensible to parton energy loss, collective motion, and hadronisation modifications

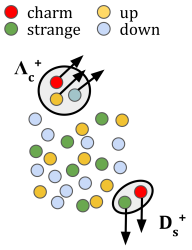


Strange heavy-quark hadron production vs multiplicity



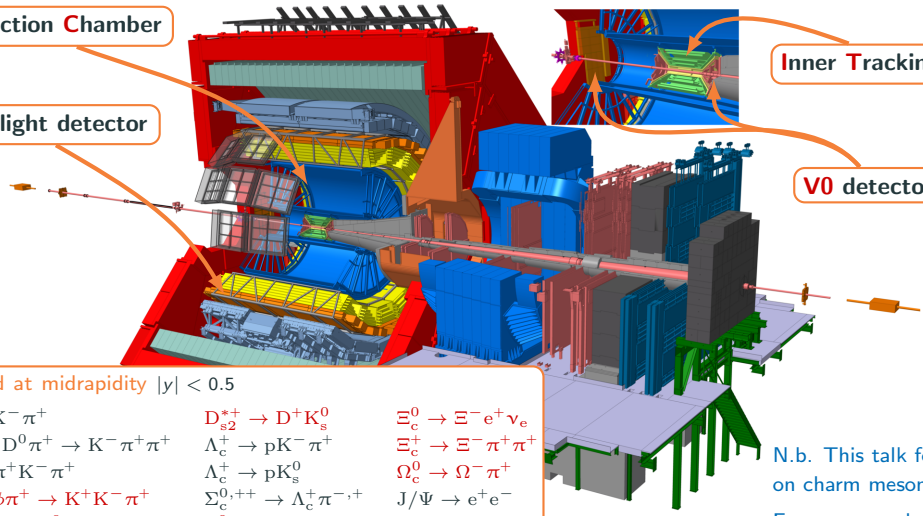
- Strange hadrons over pion yield ratio larger in heavy-ion than minimum-bias pp collisions ➔ strangeness enhancement
  - smooth increase with event multiplicity
  - no clear collision-system dependence

- What about strange charm hadrons?
  - do their production evolve with event multiplicity?
  - are they sensitive to QGP-induced effects (e.g. strangeness enhancement, coalescence, flow, ...)?



Credits: M. Faggin

A Large Ion Collider Experiment (LHC Run 2)



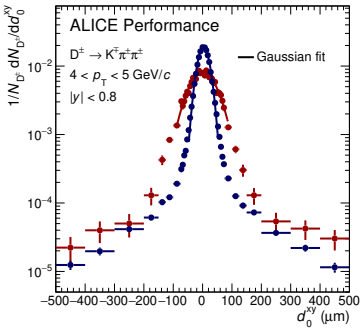
Measured at midrapidity $|y| < 0.5$

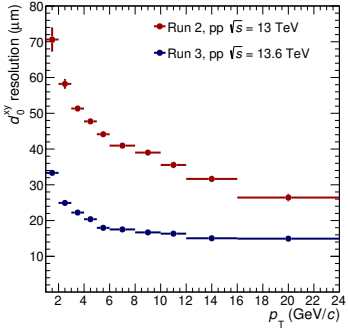
$D^0 \to K^- \pi^+$	$D_{s2}^{*+} \to D^+ K_s^0$	$\Xi_c^0 \to \Xi^- e^+ \nu_e$
$D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi^+$	$\Lambda_c^+ \to p K^- \pi^+$	$\Xi_c^+ \to \Xi^- \pi^+ \pi^+$
$D^+ \to \pi^+ K^- \pi^+$	$\Lambda_c^+ \to p K_s^0$	$\Omega_c^0 \to \Omega^- \pi^+$
$D_s^+ \to \phi \pi^+ \to K^+ K^- \pi^+$	$\Sigma_c^{0,++} \to \Lambda_c^+ \pi^{-,+}$	$J/\Psi \to e^+ e^-$
$D_{s1}^+ \to D^{*+} K_s^0$	$\Xi_c^0 \to \Xi^- \pi^+$	

N.b. This talk focus mainly on charm mesons!

For more on charm baryons: F. Zanone, 23rd Sep 17:50

- ALICE performed several upgrades in view of the LHC Run 3
  - data acquisition in continuous readout mode → higher rates: 500 kHz in pp and 50 kHz in Pb–Pb
  - updated TPC readout. New Fast Interaction Trigger and Muon Forward Tracker detectors
  - upgraded ITS2 detector (finer granularity since fully pixels, first layer closer to beam pipe, lower X_0)





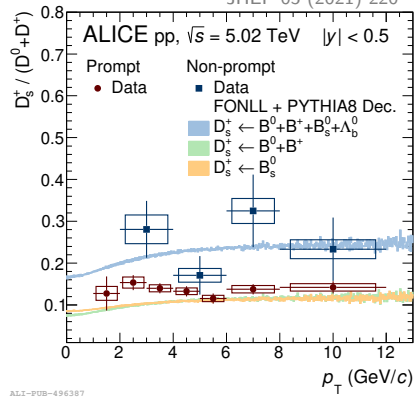
ALI-PERF-577966

- Improved impact-parameter resolution for charm hadrons thanks to ITS2 detector
- Better separation between primary vertex and heavy-quark hadron decay points

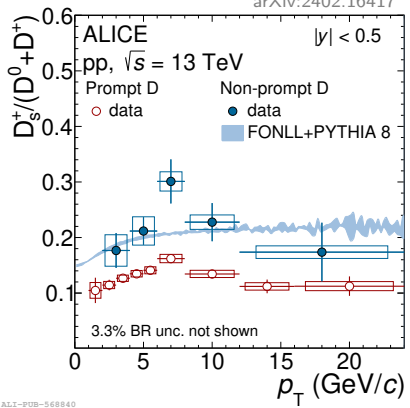
Strange over non-strange D-meson ratio

FONLL: JHEP 1210 (2012) 137 PYTHIA 8: EPJC 74 (2014) 3024

JHEP 05 (2021) 220



arXiv:2402.16417



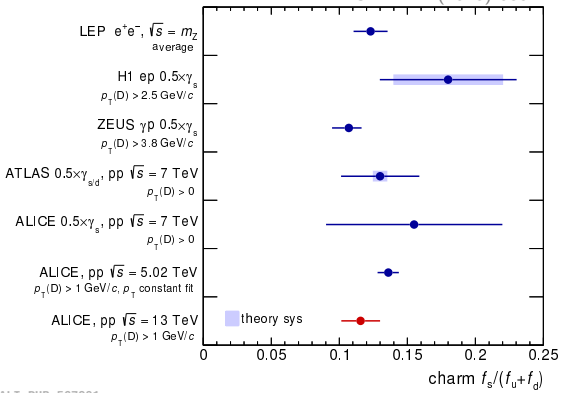
- Prompt and non-prompt $\mathrm{D_s^+}/(\mathrm{D^0}+\mathrm{D^+})$ ratios in pp collisions do not depend significantly on p_T and collision energy

Prompt → from charm-quark hadronisation or excited charm-hadron decays. Non-prompt → from beauty-hadron decays

Charm and beauty strange-to-non-strange fragmentation fractions

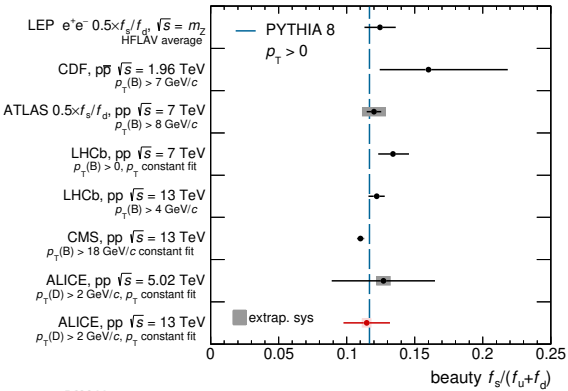
PYTHIA 8: EPJC 74 (2014) 3024

JHEP 12 (2023) 086



ALI-PUB-567901

arXiv:2402.16417

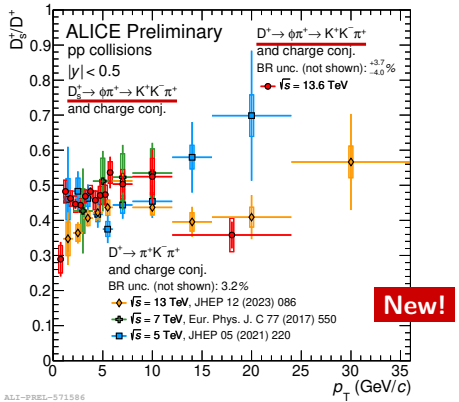


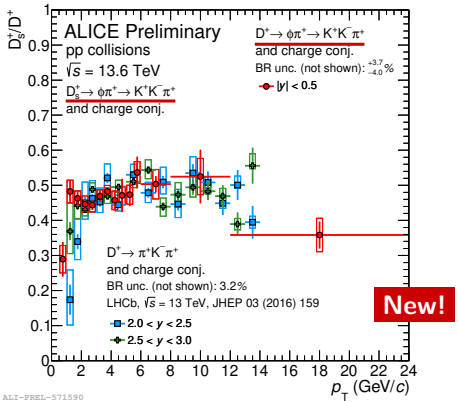
ALI-PUB-568844

- Charm- and beauty-quark $f_{\rm s}/(f_{\rm u}+f_{\rm d})$ compatible between different collision systems and energies
- Beauty $f_{\rm s}/(f_{\rm u}+f_{\rm d})$ $\simeq$ charm $f_{\rm s}/(f_{\rm u}+f_{\rm d})$

More on beauty sector:
A. Tavira Garcia, 23rd Sep 14:40

Prompt $\mathrm{D_s^+/D^+}$ ratio in Run 3 pp collisions

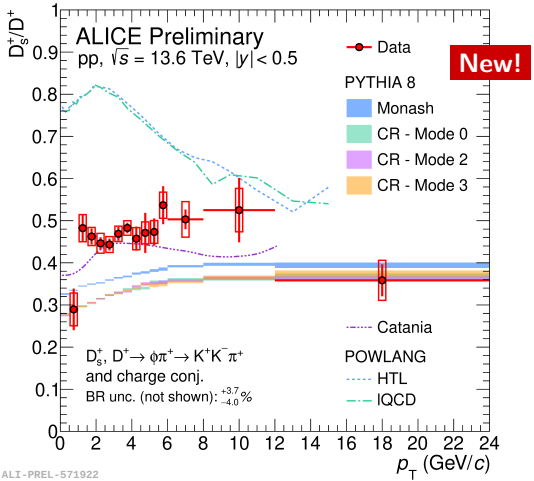




- First measurement of prompt $\mathrm{D_s^+/D^+}$ ratio in pp collisions at $\sqrt{s} = 13.6$ TeV
  - improved measurement granularity and p_{T} reach w.r.t. ALICE Run 2 results
- No significant energy and rapidity dependence observed

Prompt D_s^+/D^+ ratio in Run 3 pp collisions

PYTHIA 8: JHEP 08 (2015) 003 Catania: PLB 821 (2021) 136622 POWLANG: arXiv:2306.02152



- PYTHIA 8
  - Monash ➔ colour reconnection among multiparton interactions only with leading-colour topology
  - CR Modes ➔ string formation beyond leading-colour approximation, resulting in baryon enhancement
- Catania and POWLANG
  - hadronisation via coalescence and fragmentation processes in a thermalised QGP-like system
- Catania qualitatively describes the D_s^+/D^+ ratio
  - PYTHIA 8 and POWLANG underestimate or overestimate the measurement

Strange charm hadrons vs multiplicity

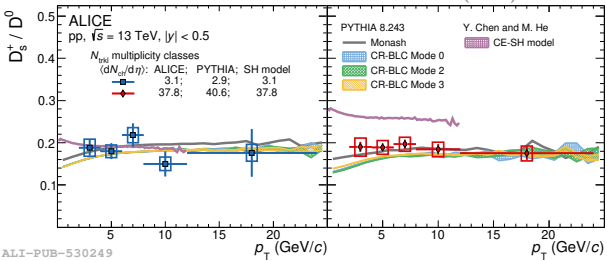
PYTHIA 8: JHEP 08 (2015) 003 CE-SH: PLB 815 (2021) 136144

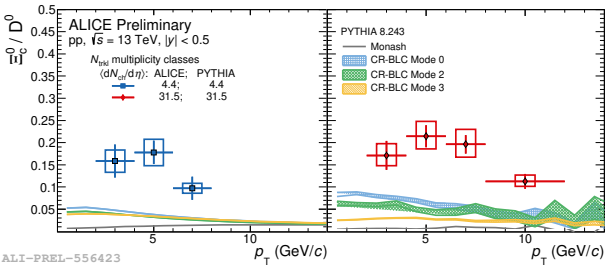
PLB 829 (2022) 137065

- $\mathrm{D_s^+/D^0}$ ratio in pp at midrapidity not dependent on event multiplicity
  - agreement with PYTHIA 8 predictions
  - described by canonical-ensemble statistical hadronization model (CE-SH) at low multiplicity

- Hint of p_T dependence for $\Xi_\mathrm{c}^0/\mathrm{D}^0$ ratio
  - no multiplicity dependence observed given current uncertainties
  - significantly underestimated by PYTHIA 8 calculations

More on charm baryons: F. Zanone, 23rd Sep 17:50

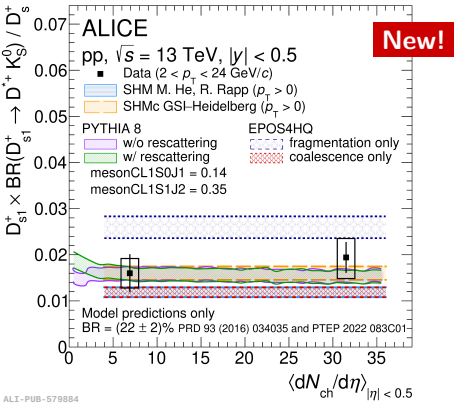


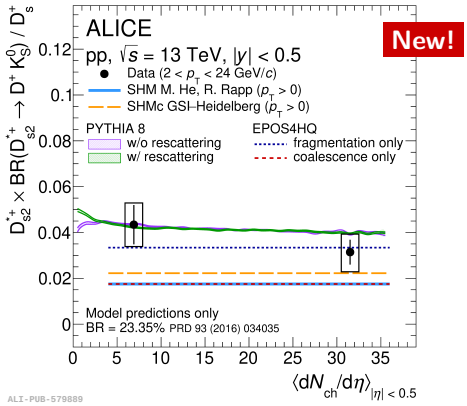


Strange D-meson resonances production

SHM: PLB 795 (2019) 117-121 SHMc: JHEP 07 (2021) 035 PYTHIA 8: EPJC 74 (2014) 3024 EPOS4HQ: PRD 109 (2024) 054011

arXiv:2409.11938



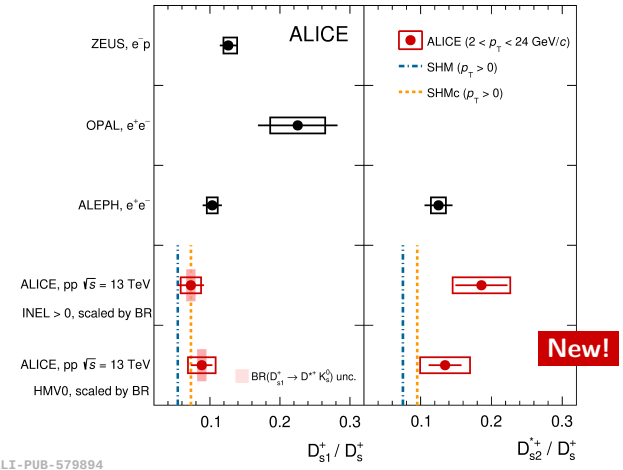


- First measurement of prompt D_s^+-resonance production in pp collisions
  - D_{s1}^+/D_s^+ and D_{s2}^{*+}/D_s^+ ratios flat vs. charged-particle multiplicity, as ground-state D-meson ratios
  - multiplicity trend described by SHM, SHMc, EPOS4HQ models and by PYTHIA 8 calculations

Strange D-meson resonances production

SHM: PLB 795 (2019) 117-121 SHMc: JHEP 07 (2021) 035

arXiv:2409.11938



ALI-PUB-579894

ZEUS: EPJC 60 (2009) 25-45
OPAL: ZPC 76 (1997) 425-440
ALEPH: PLB 526 (2002) 34-49

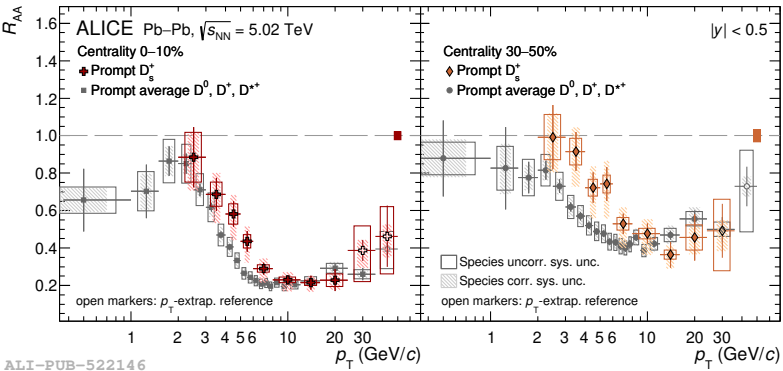
- $\mathrm{D_{s1}^{+}/D_s^{+}}$ and $\mathrm{D_{s2}^{*+}/D_s^{+}}$ ratios in pp collisions in agreement with those measured in $\mathrm{e^+e^-}$ and $\mathrm{e^-p}$ collisions within 2.1σ
- Production ratios fairly described by statistical hadronisation models SHM and SHMc

Strange and non-strange D-meson R_{AA}

PLB 827 (2022) 136986

Nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



- Hint of reduced suppression ($\sim 1\sigma$) for D_s^+ w.r.t. non-strange D mesons for $p_T < 8$ GeV/c
  - expected for hadronisation via coalescence + strangeness enhancement in the QGP

    I. Kuznetsova et al. EPJC 51 (2007) 113

More on heavy flavours in Pb–Pb:
B. Zhang, 23rd Sep 16:50

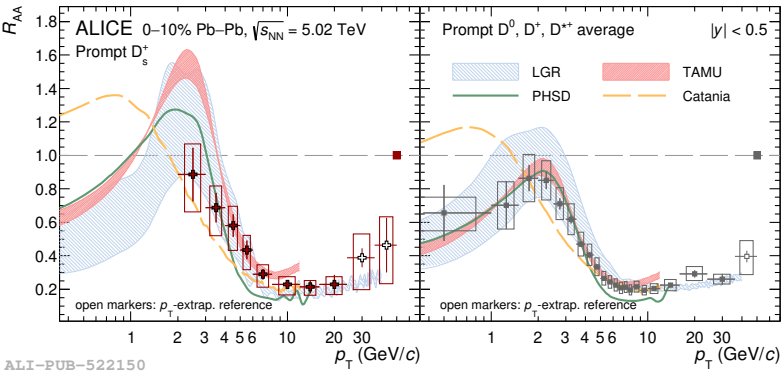
Strange and non-strange D-meson R_{AA}

PLB 827 (2022) 136986

LGR: EPJC 80 (2020) 671 PHSD: PRC 92 (2015) 014910
TAMU: PRL 124 (2020) 042301 Catania: PRC 96 (2017) 044905

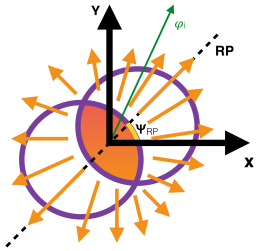
Nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



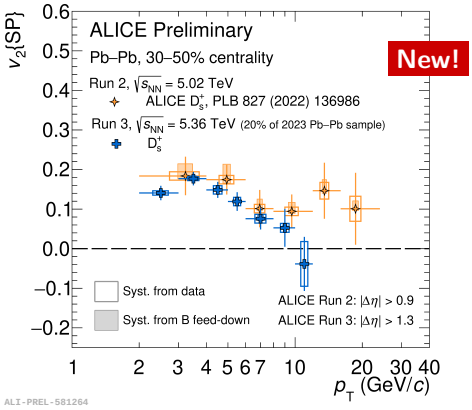
- Hint of reduced suppression ($\sim 1\sigma$) for D_s^+ w.r.t. non-strange D mesons for $p_T < 8$ GeV/c
  - expected for hadronisation via coalescence + strangeness enhancement in the QGP
    I. Kuznetsova et al. EPJC 51 (2007) 113
- Charm-quark transport models including coalescence catch the hierarchy $R_{AA}(D_s^+) > R_{AA}(D)$

Strange D-meson elliptic flow in Run 3



Elliptic flow

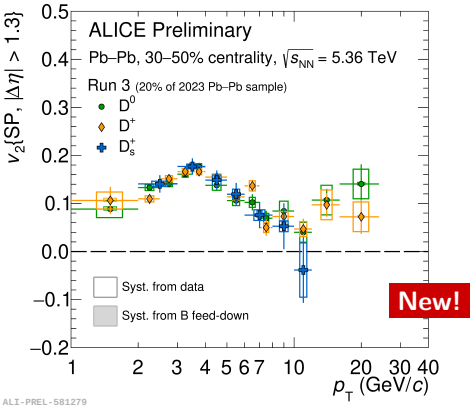
$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$

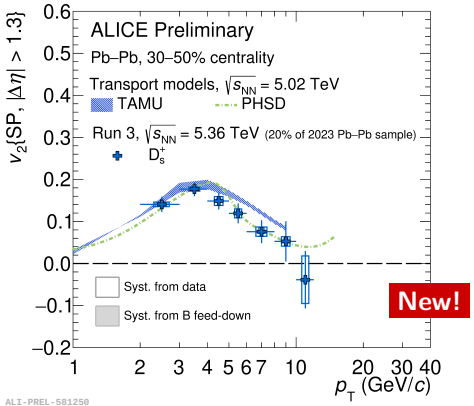


- Prompt D_s^+-meson v_2 measured for semicentral collisions using Run 3 Pb–Pb data sample
  - current (partial) sample about 4x larger than Run 2 one
  - measurement precision significantly improved w.r.t. Run 2 results

Strange D-meson elliptic flow in Run 3

TAMU: PRL 124 (2020) 042301 PHSD: PRC 92 (2015) 014910





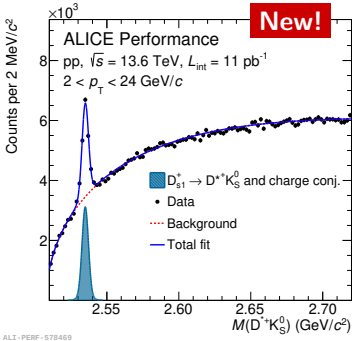
- Prompt D_s^+-meson v_2 measured for semicentral collisions using Run 3 Pb–Pb data sample
- No significant difference between strange and non-strange D mesons
  - strange D-meson elliptic flow reproduced by TAMU and PHSD models

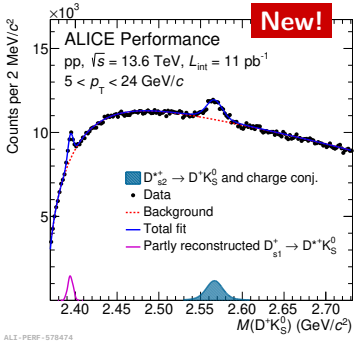
Summary and outlook

- Prompt and non-prompt strange charm-hadron production measurements
  - probe the charm- and beauty-quark fragmentation in pp collisions
  - in Pb–Pb, support heavy-quark hadronisation via coalescence and charm thermalisation in the QGP

- Measurement precision significantly improves in Run 3
  - larger data samples. In pp collisions also thanks to software triggers
  - better detector performance

Stay tuned for further upcoming ALICE Run 3 measurements!

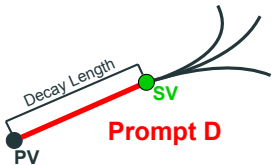


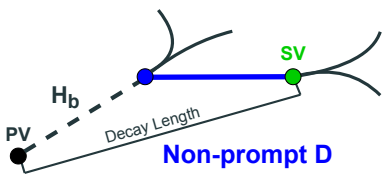


Backup

Prompt and non-prompt $\mathrm{D_s^+}$ mesons

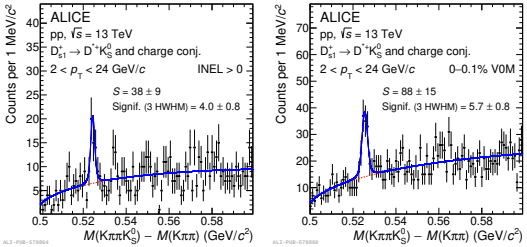
- $\mathrm{D_s^+}$ mesons
  - Prompt, from charm-quark hadronisation or excited charm-hadron decays
  - Non-prompt, from beauty-hadron decays





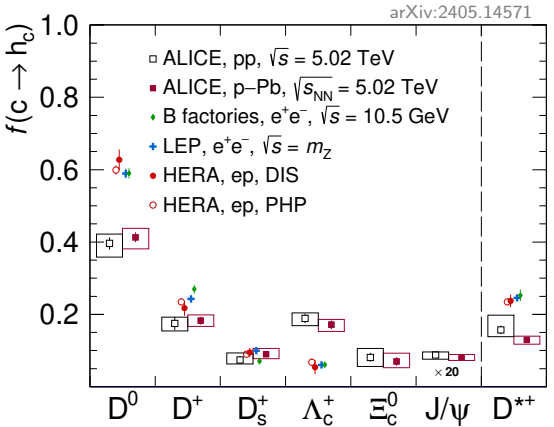
- Non-prompt $\mathrm{D_s^+}$ mesons → $\mathrm{B_s^0}$-meson production
  - $\sim$ 50% from $\mathrm{B_s^0}$ decays and $\sim$ 50% from non-strange B
- Possible to disentangle prompt and non-prompt $\mathrm{D_s^+}$
  - beauty hadrons have $c\tau \simeq 500\ \mu\mathrm{m}$
  - non-prompt $\mathrm{D_s^+}$ on average more displaced from the interaction vertex
  - different topology and kinematic features
- ML to separate prompt $\mathrm{D_s^+}$ mesons, non-prompt $\mathrm{D_s^+}$ mesons and combinatorial background

Raw yields of strange D-meson resonances in Run 2



arXiv:2409.11938

Charm-quark fragmentation fractions



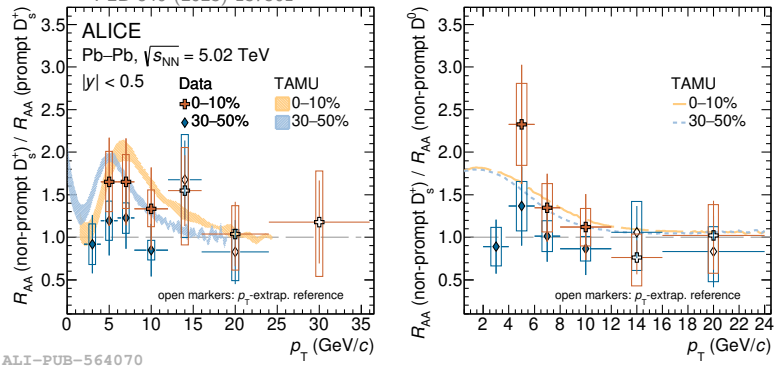
- Charm-quark fragmentation fractions obtained from measurements of charm-hadron production cross sections
- Results in pp and p–Pb collisions are in good agreement
- Significant modifications w.r.t. e^+e^- and $e^\pm p$ collisions → enhanced baryon production
  - Λ_c^+ baryon higher by factor ~ 3.3
  - non-strange D mesons lower by factor ~ 1.5

Non-prompt $\mathrm{D_s^+}$-meson R_{AA}

TAMU: PLB 735 (2014) 445-450, PRL 124 (2020) 042301

- Hint of enhancement of non-prompt $R_{\mathrm{AA}}(\mathrm{D_s^+})/R_{\mathrm{AA}}(\mathrm{D^0})$ ratio for $4 < p_{\mathrm{T}} < 12$ GeV/c in central collisions
  - hadronisation via coalescence + strangeness enhancement in the QGP

PLB 846 (2023) 137561

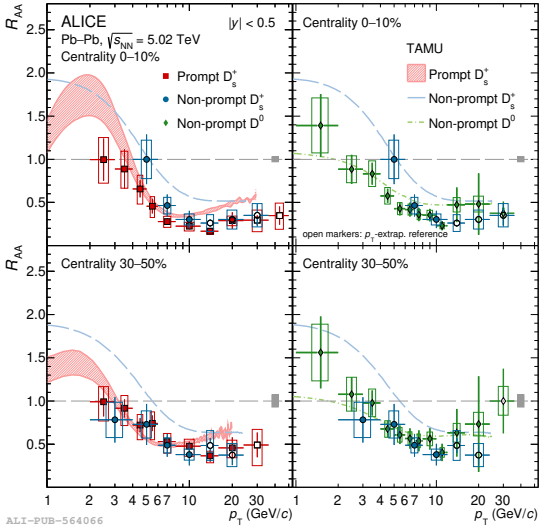


- Hint of non-prompt $R_{\mathrm{AA}}(\mathrm{D_s^+}) >$ prompt $R_{\mathrm{AA}}(\mathrm{D_s^+})$ in central collisions
  - mass-dependent parton energy loss
- Results qualitatively described by TAMU

Non-prompt D_s^+-meson R_{AA}

PLB 846 (2023) 137561

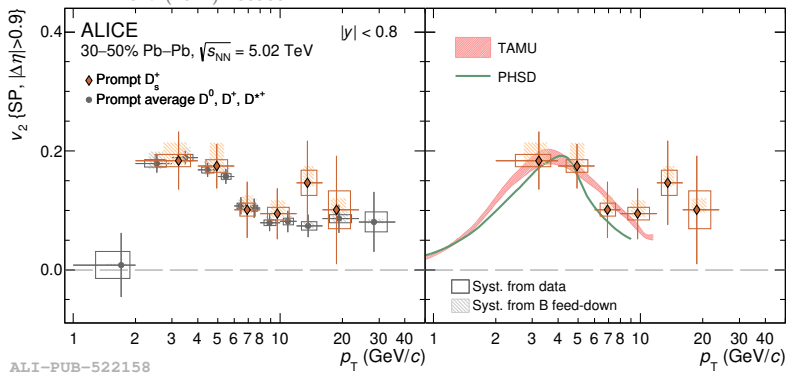
TAMU: PLB 735 (2014) 445-450, PRL 124 (2020) 042301



Strange and non-strange D-meson elliptic flow

PLB 827 (2022) 136986

TAMU: PRL 124 (2020) 042301 PHSD: PRC 92 (2015) 014910



- Positive v_2 of prompt D mesons → charm quarks participate in the QGP collective motion
  - no significant difference between strange and non-strange D mesons
- Strange D-meson elliptic flow reproduced by TAMU and PHSD models