SQM 2024

The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

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

Mattia Faggin, CERN
on behalf of the ALICE Collaboration

Strangeness in Quark Matter 2024
Strasbourg, France
4th June 2024

ALICE

CERN

Heavy quarks: a unique probe for high-density QCD

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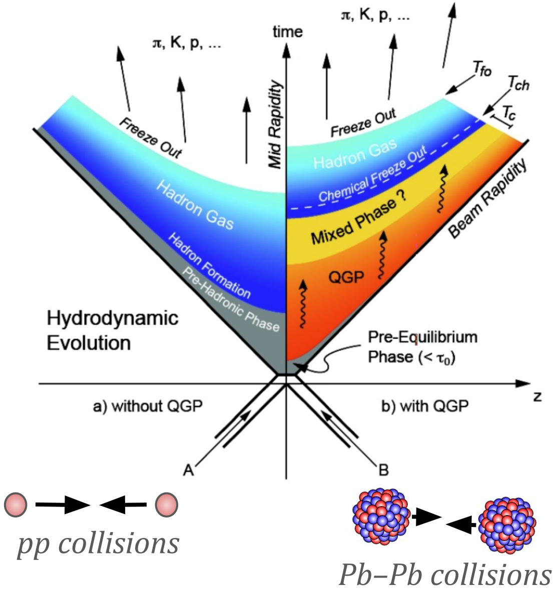
- Charm and beauty quarks: $m_c \sim 1.3\ \mathrm{GeV}/c^2$, $m_b \sim 4.2\ \mathrm{GeV}/c^2$
- Produced in hard scattering processes among partons

- Ultrarelativistic heavy-ion collisions at the LHC: quark-gluon plasma (QGP)
  - state of matter expected in the first ~ 10 μs after the Big Bang
  - heavy quarks experience the full evolution of the system



Charm- and **beauty- quarks dynamic** tested via **measurements** of **charm-** and **beauty- hadron production**

pp collisions

- **Test of pQCD calculations**
  - heavy-quark production
  - hadronization
  - parton distribution functions (PDFs)
- Reference for Pb–Pb collisions

p–Pb collisions

Cold nuclear matter effects

- Modification in PDFs in bound nucleons

Pb–Pb collisions

Hot nuclear matter effects

- Energy loss in the QGP
- Collective motion
- Modification of hadronization

Strange heavy-flavour hadron production vs. multiplicity

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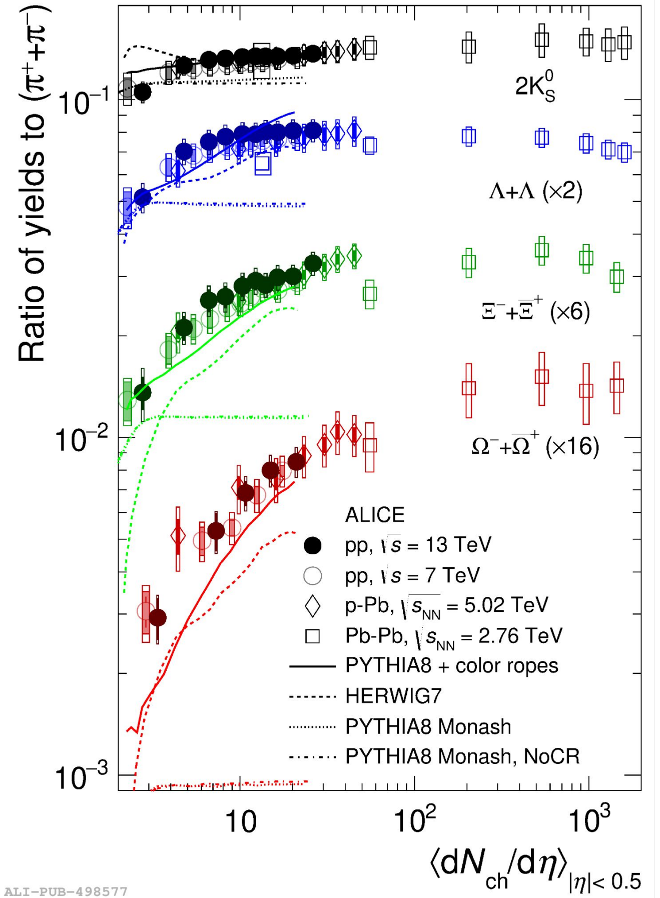
- **Strangeness enhancement** (SE): yield-ratio between (multi)strange hadrons and $\pi^{\pm}$ larger **in heavy-ion collisions** than minimum-bias pp collisions
- **Smooth increase vs.** event **multiplicity**, **without** a clear **collision-system dependence**
- Baryon production in Pb–Pb collisions at intermediate p_{T} enhanced by hadronization via **coalescence**

"Measuring the system size dependence of the strangeness production with ALICE"
R. Nepeivoda, 04/06/2024

Do not miss!

Eur. Phys. J. C 80 (2020) 693



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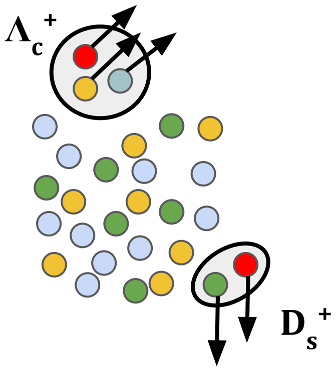
charm
strange
up
down



- What do **strange D-meson** production measurements teach us about heavy-quark **hadronization** at the LHC?
- Do their production **evolve vs.** event **multiplicity**?
- Are they **sensitive** to **QGP**-induced **effects** (e.g. strangeness enhancement, coalescence, *E*-loss, flow, …)?

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ALICE

The ALICE experiment in Run 1 and Run 2

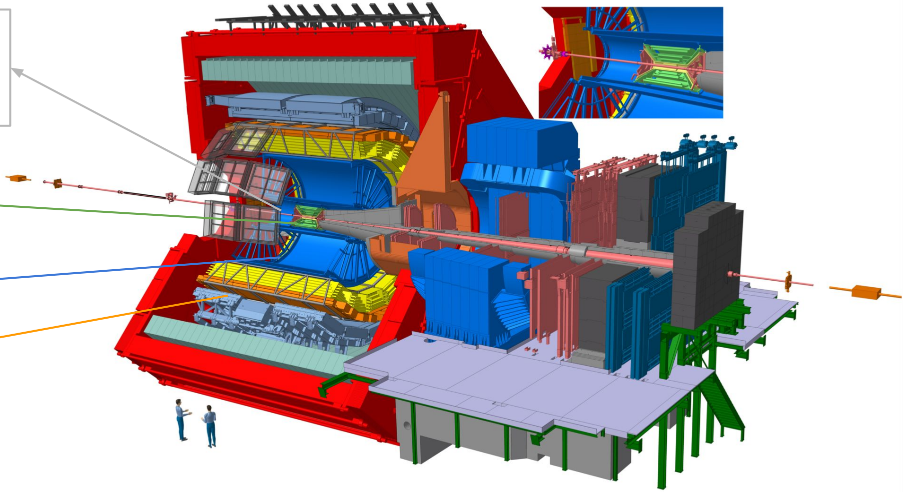
Central barrel: $|\eta| < 0.9$
Muon spectrometer: $-4 < \eta < -2.5$

V0
Trigger, centrality

Inner Tracking System (ITS)
Tracking, vertexing (primary, secondary HF)

Time Projection Chamber (TPC)
Tracking, PID via dE/dx

Time-Of-Flight (TOF)
PID via time of flight



Charm-hadron decay channels

$D^0 \to K^-\pi^+$
$D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$
$D^+ \to K^-\pi^+\pi^+$
$D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$
$D_{s1}^+ \to D^{*+}K_s^0$
$D_{s2}^{*+} \to D^+K_s^0$

$\Lambda_c^+ \to pK^-\pi^+, pK_s^0$
$\Xi_c^0 \to \Xi^- e^+\nu_e$
$\Xi_c^0 \to \Xi^-\pi^+$
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$
$\Sigma_c^{0,++} \to \Lambda_c^+\pi^{-,+}$
$\Omega_c^0 \to \Omega^-\pi^+$

"Investigation of charm-quark hadronisation into baryons in hadronic collisions with ALICE"
J. Cho, 04/06/2024

Do not miss!

Datasets

pp $\sqrt{s}$ = 5.02 TeV → $\mathcal{L}_{int}$ ~ 19 nb^{-1} (MB)
pp $\sqrt{s}$ = 7 TeV → $\mathcal{L}_{int}$ ~ 5.9 nb^{-1} (MB)
pp $\sqrt{s}$ = 13 TeV → $\mathcal{L}_{int}$ ~ 32 nb^{-1} (MB)

p–Pb $\sqrt{s_{NN}}$ = 5.02 TeV → $\mathcal{L}_{int}$ ~ 287 μb^{-1} (MB)
Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV → $\mathcal{L}_{int}$ ~ 130 μb^{-1} (0-10%)
→ $\mathcal{L}_{int}$ ~ 56 μb^{-1} (30-50%)

The ALICE experiment in Run 3

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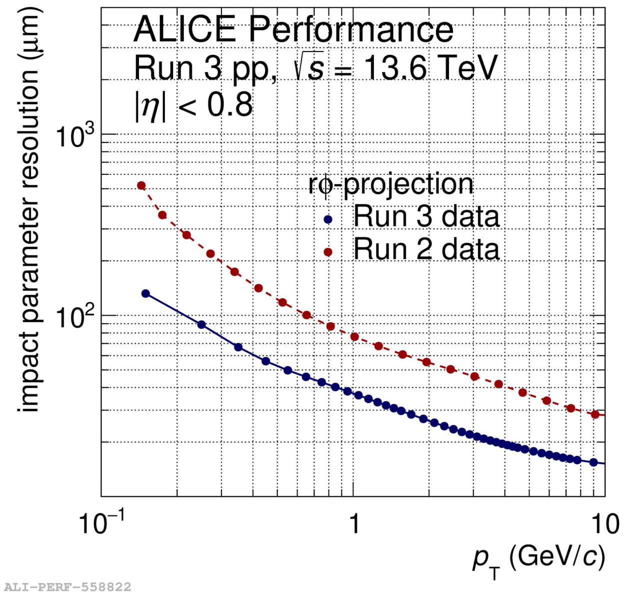
Run 3 upgrades

1. Upgraded ITS detector
2. Gas Electron Multipliers (GEMs) in TPC readout
3. Data acquisition in continuous readout mode
4. New Fast Interaction Trigger (FIT) detector
5. Muon Forward Tracker → $2.5 < \eta < 3.6$

Datasets

pp $\sqrt{s}$ = 13.6 TeV → $\mathcal{L}_{int}$ ~ 1 pb^{-1} (2022 MB)

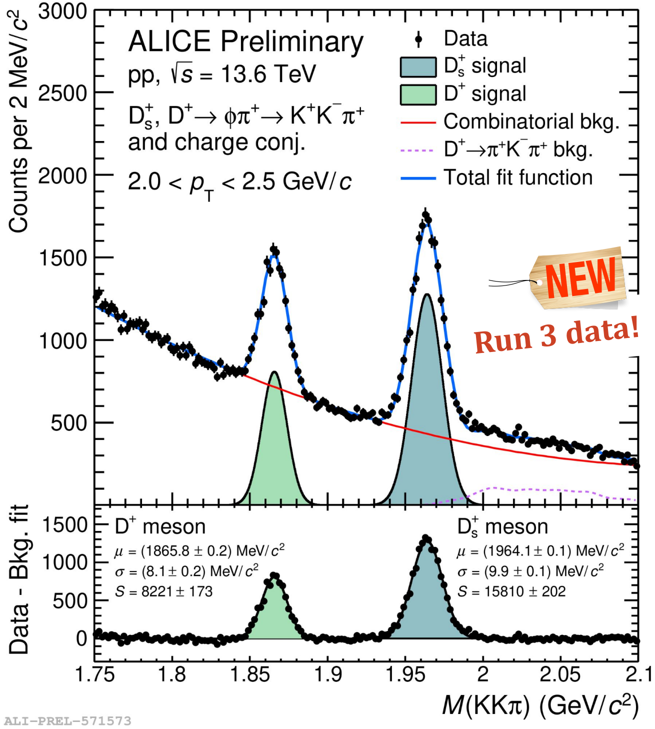


Charm-hadron decay channels

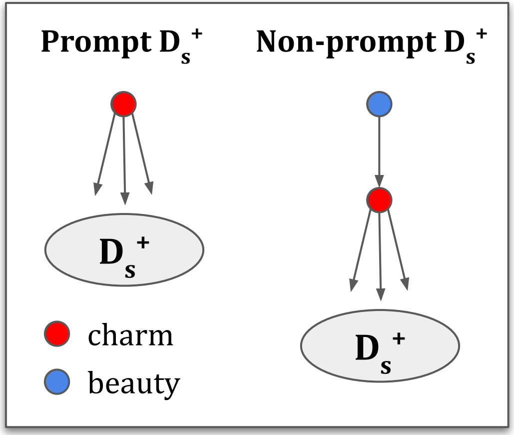
D^+, $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$

→ same decay channel, to reduce the systematic uncertainties on the D_s^+/D^+ ratio

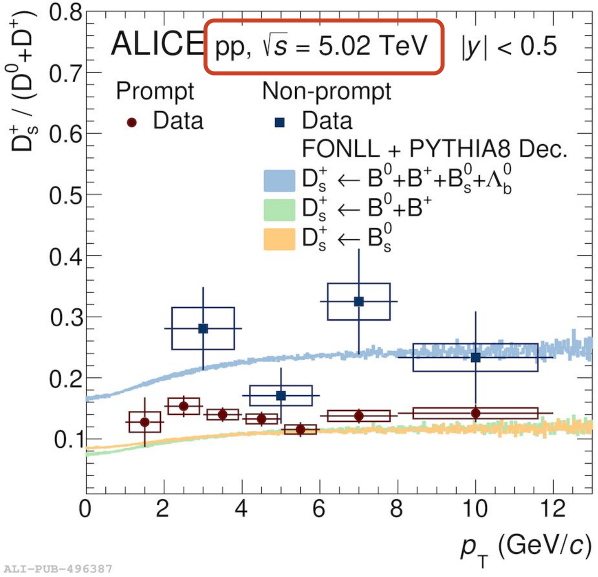
→ better separation between primary vertex and HF decay points to the improved pointing resolution to the primary vertex



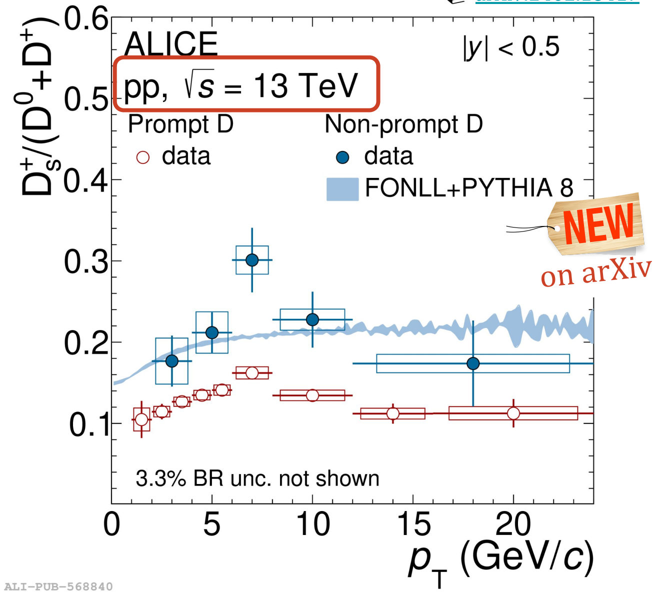
Strange/non-strange D-meson ratio



JHEP 05 (2021) 220



arXiv:2402.16417



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

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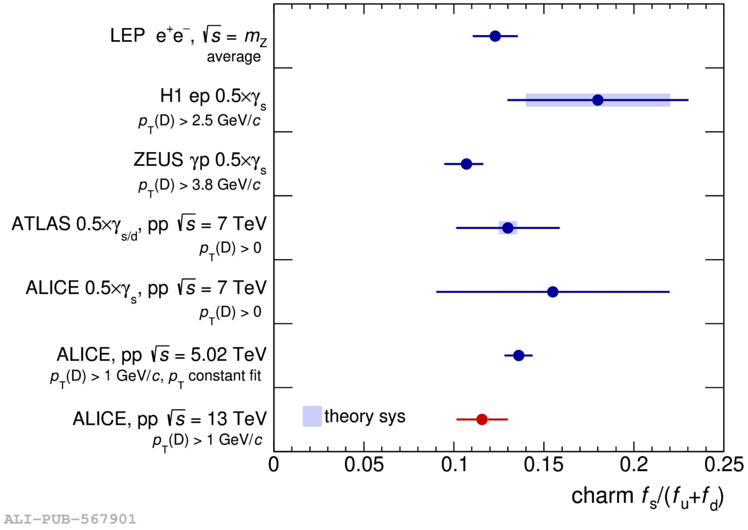
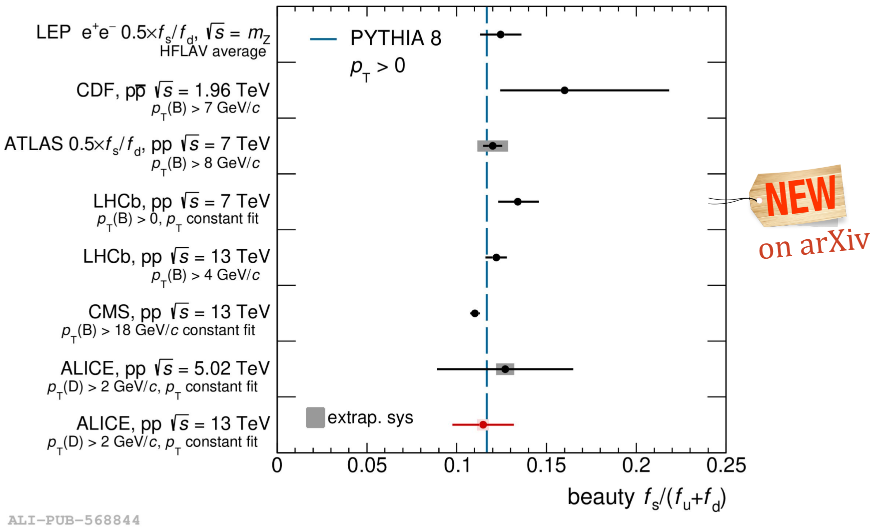
JHEP12 (2023) 086



arXiv:2402.16417



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

- No significant collision system and energy dependence of charm quark fragmentation function ratios into strange and non-strange D mesons

- Charm and beauty $f_s/(f_u + f_d)$ fragmentation-fraction ratio from prompt and non-prompt $D_s^+/(D^0 + D^+)$ ratio, respectively
  - Beauty: FONLL+PYTHIA correction for D_s^+ from non-strange B-meson decays
- Beauty $f_s/(f_u + f_d)$ = charm $f_s/(f_u + f_d)$

Prompt D_s^+/D^+ at different energy and rapidity

pp collisions

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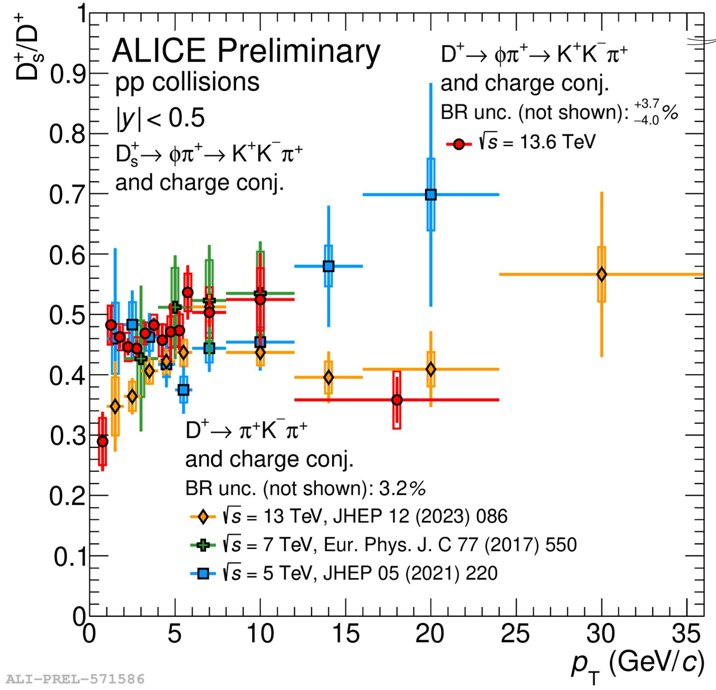
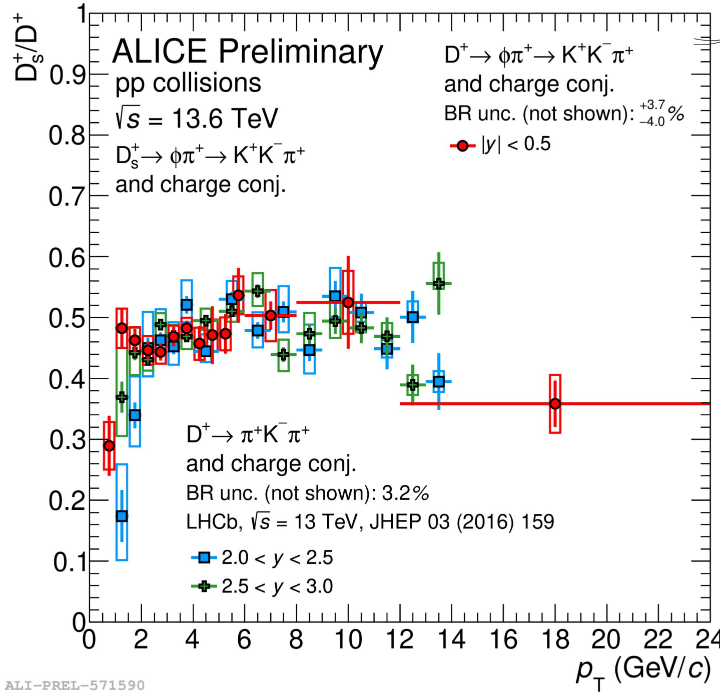
ALICE



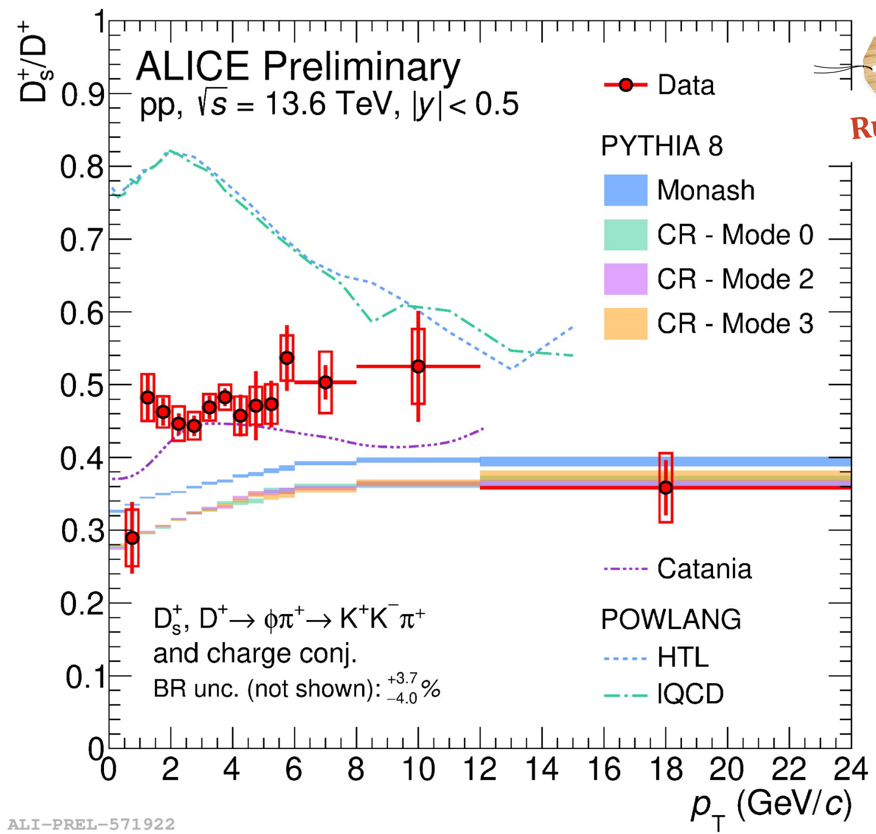
NEW
Run 3 data!



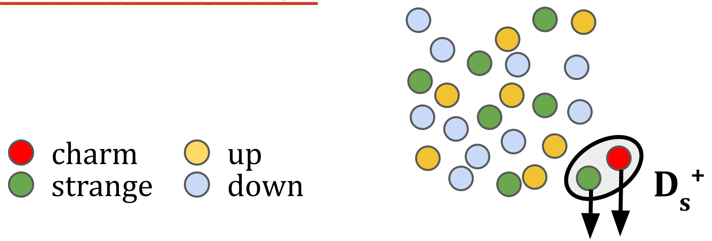
NEW
Run 3 data!

- First measurement of prompt D_s^+/D^+ ratio in pp collisions at $\sqrt{s}$ = 13.6 TeV
  - x2 improvement in granularity for $1 < p_T < 6$ GeV/c
  - down to p_T = 0.5 GeV/c
- No significant energy dependence observed
- No significant rapidity dependence observed

- PYTHIA 8 (J. R. Christiansen, P. Z. Skands): JHEP 08 (2015) 003
- POWLANG (A. Beraudo et. al.): arXiv:2306.02152
- CATANIA (V. Minissale et al.): Phys. Lett. B 821 (2021) 136622



- **PYTHIA 8**
  - Monash: colour reconnection (CR) among different multiparton interactions (MPIs) only with leading-colour topology
  - CR - Mode 0, 2, 3: colour reconnections among MPIs allowed also beyond leading-colour topologies → baryon enhancement
  - Measurement underestimated
    - → D^+-meson production overestimated
- **POWLANG** and **Catania**
  - fireball/thermalised system formation already assumed in pp collisions
  - heavy-quark hadronization also via coalescence
  - Measurement overestimated by POWLANG
  - Catania better describes it

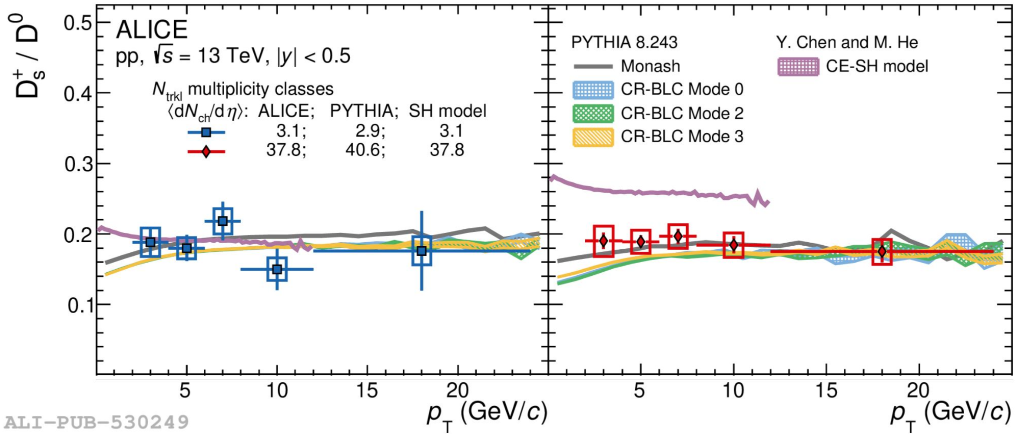


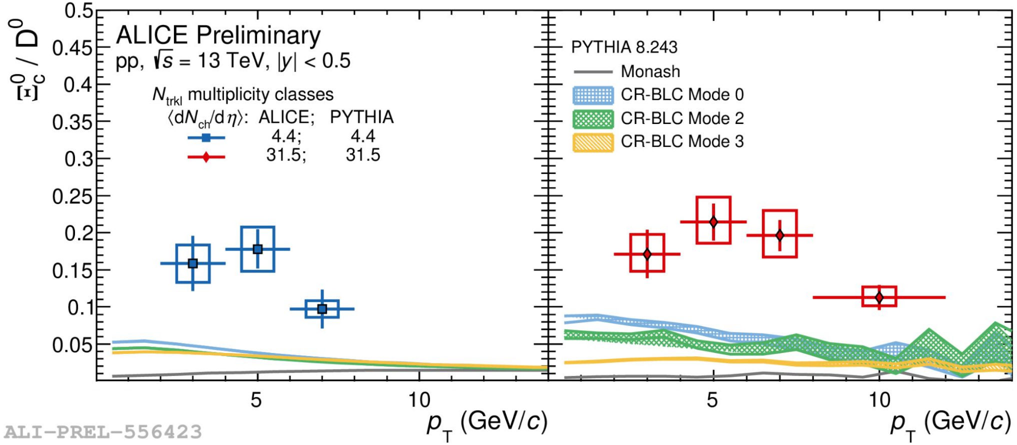
Strange charm hadrons vs. multiplicity

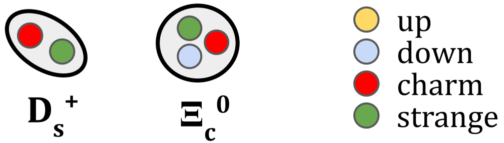
Phys.Lett.B 829 (2022) 137065

PYTHIA 8 (J. R. Christiansen, P. Z. Skands): JHEP 08 (2015) 003

CE-SH (J Y. Chen, M. He): Phys. Lett. B 815 (2021) 136144







- D_s^+/D^0 ratio in pp collisions at midrapidity does not show any significant dependence vs. p_T and event multiplicity

- D_s^+/D^0 ratio described by PYTHIA 8 predictions at both low and high multiplicity
- D_s^+/D^0 ratio not described by canonical-ensemble statistical hadronization model (CE-SH) at high event multiplicity

- Ξ_c^0/D^0 ratio significantly underestimated by PYTHIA 8 predictions

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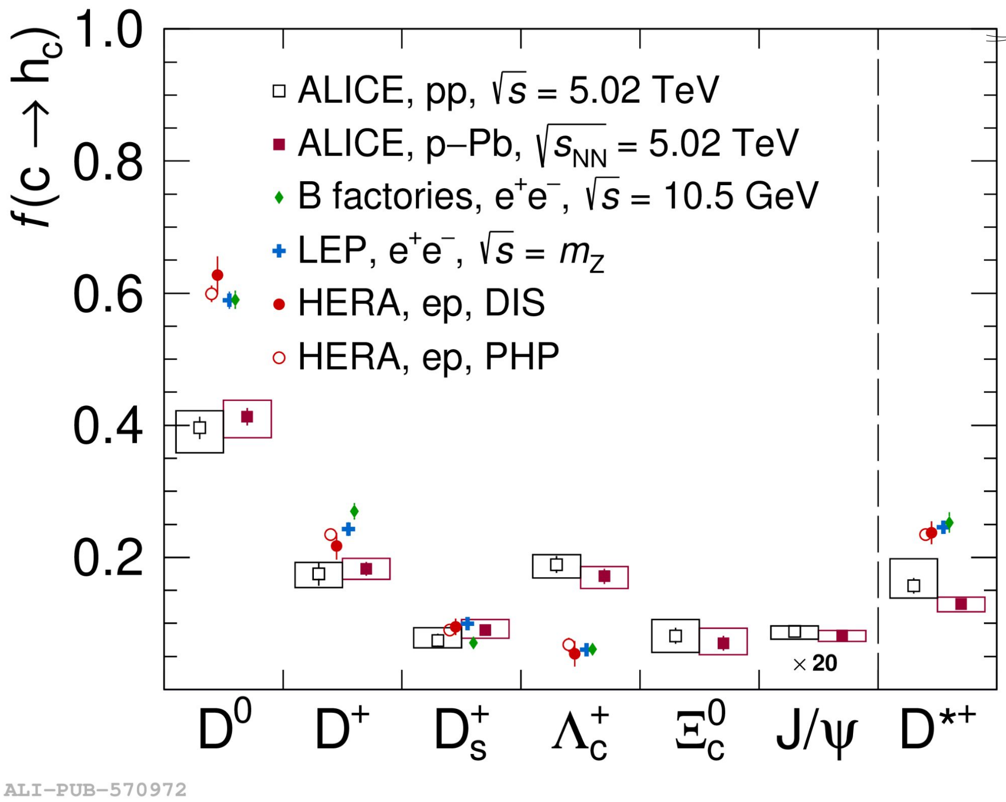
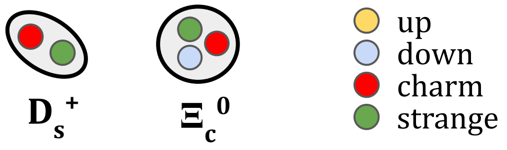
arXiv:2405.14571



NEW on arXiv



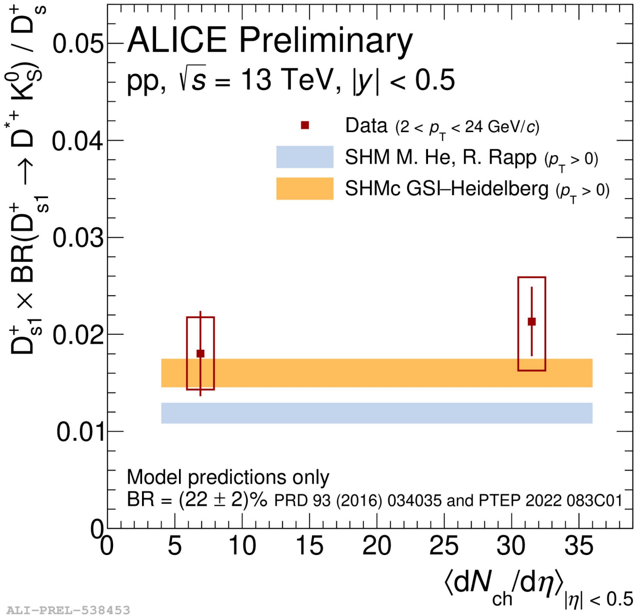
- Enhanced production of baryons at midrapidity relative to that of mesons at the LHC compared to e^+e^- collisions
- No significant differences in the charm fragmentation fractions $f(c \to h_c)$ between pp and p–Pb collisions
- Comparable production of D_s^+ mesons and Ξ_c^0, Ξ_c^+ baryons

"Investigation of charm-quark hadronisation into baryons in hadronic collisions with ALICE"
J. Cho, 04/06/2024

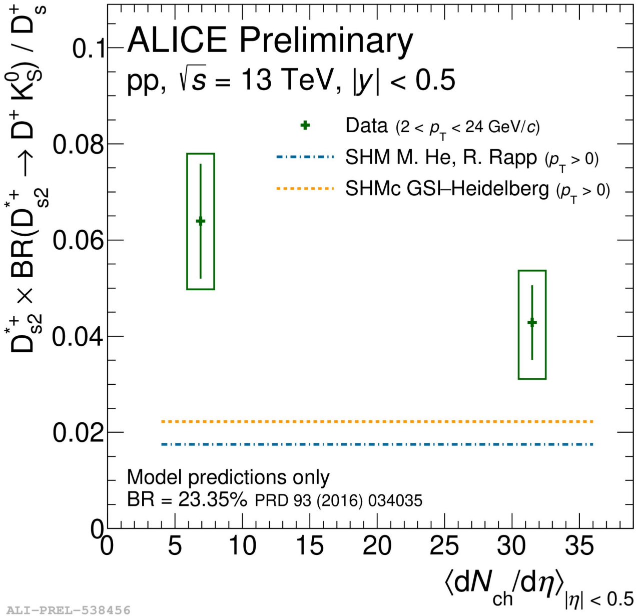
Do not miss!

D_{s1}^{+} and D_{s2}^{*+} production

D_s^+ in pp at 13 TeV: [Phys.Lett.B 829 (2022) 137065]



ALI-PREL-538453



ALI-PREL-538456

[R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update]

$\tau(D_{s1}^{+}(2536)) \sim 214$ fm/c
$\tau(D_{s2}^{*+}(2573)) \sim 12$ fm/c

First measurement of **D_s-resonance** production in **pp collisions**

→ *measurement to be improved with Run 3 data!*

- No multiplicity dependence on D-meson ratios in pp collisions
- No differences compared to e^+e^- collisions

→ What about charm-resonances?

- No multiplicity dependence on D_{s1}^{+}/D_s^{+} ratio
- Hint of tension with SHM predictions for D_{s2}^{*+}/D_s^{+} ratio
  - SHM predictions p_T integrated, measurement for $p_T > 2$ GeV/c
  - BR not measured

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

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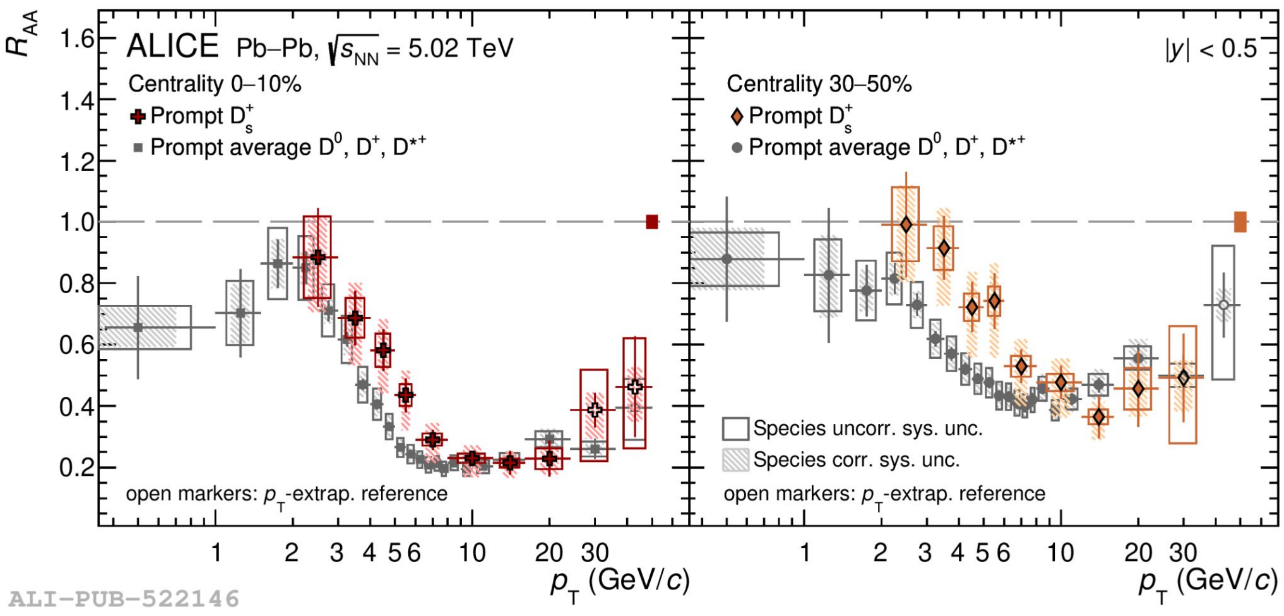
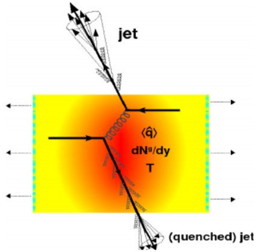
Pb–Pb collisions

Phys. Lett. B 827 (2022) 136986



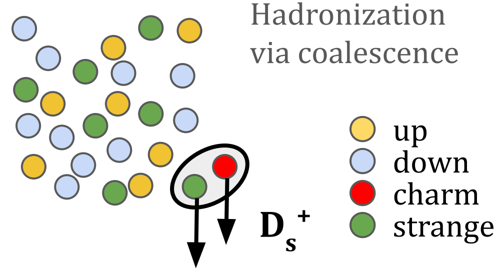
1

High p_T
In-medium *E*-loss
(jet quenching)



2

Intermediate p_T
Hadronization
via coalescence



$$R_{AA}(p_T, y) = \frac{1}{\langle T_{AA} \rangle} \frac{d^2N_{AA}/dp_T dy}{d^2\sigma_{pp}/dp_T dy}$$

Nuclear modification factor sensitive to QGP-induced effects on (heavy) quark dynamics

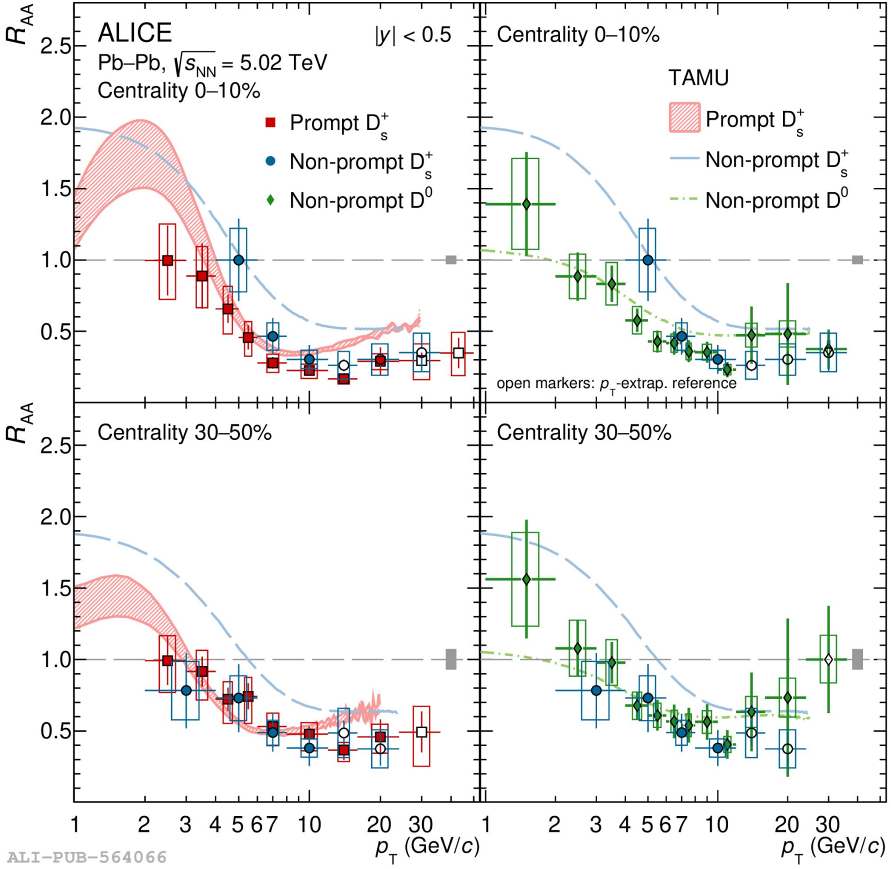
1. R_{AA} of strange and non-strange D-mesons significantly lower than 1 at high p_T
   - in-medium parton energy loss
2. Hint of $R_{AA}(D_s^+)$ > R_{AA}(non-strange D mesons) for p_T < 6 GeV/*c*
   - hadronization via coalescence + strangeness enhancement in the QGP

Prompt and non-prompt D_s^+-meson R_{AA}

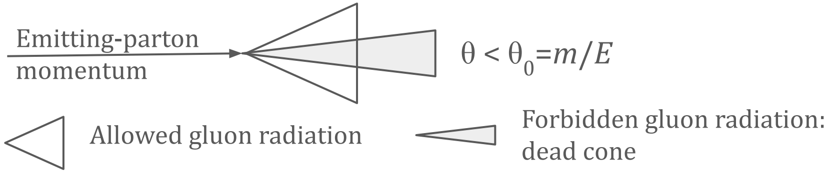
Pb–Pb collisions

TAMU: (M. He et. al.) Phys. Lett. B 735 (2014) 445–450
(M. He, R. Rapp) Phys. Rev. Lett. 124 (2020) 042301

Phys. Lett. B 846 (2023) 137561



- Hint of R_{AA}(non-prompt D_s^+) > R_{AA}(non-prompt D^0) for $p_T < 6$ GeV/c
  - hadronization via coalescence + strangeness enhancement in the QGP
- Hint of R_{AA}(non-prompt D_s^+) > R_{AA}(prompt D_s^+) for $p_T < 6$ GeV/c
  - sensitivity to different in-medium diffusion (collisional E-loss) for charm and beauty quarks ($D_s \sim 1/m_Q$)
  - At higher p_T: $m_b > m_c$ and dead-cone effect
    → uncertainties still too large

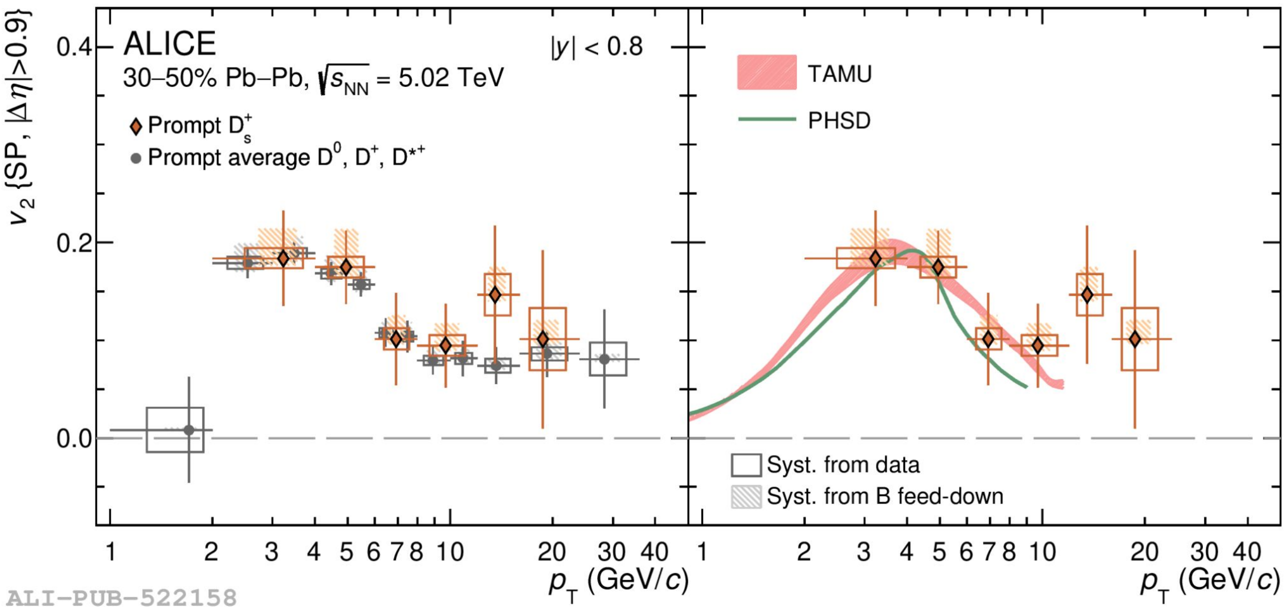


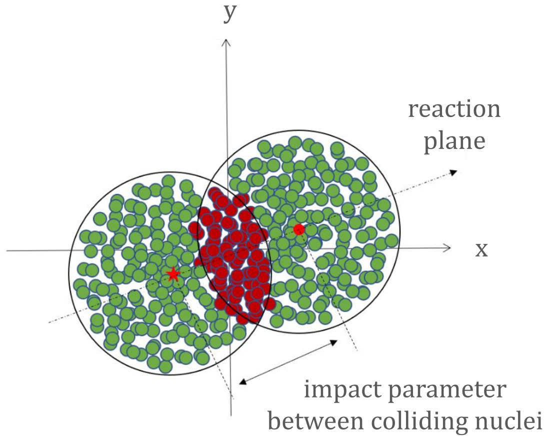
- TAMU: transport model with
  - hadronization via fragmentation and coalescence
  - E-loss only via elastic collisional processes only
    → measurement overestimated at high p_T

Phys. Lett. B 827 (2022) 136986

TAMU: (M. He, R. Rapp) Phys. Rev. Lett. 124 (2020) 042301

PHSD: (T. Song et. al.) Phys. Rev. C 92, 014910





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

Elliptic flow v_2 sensitive to charm-quark thermalization and hadronization in the QGP

- $v_2(D_s^+) > 0$ by ~6.4 σ
  - charm-quark participation to collective motion
- No significant difference between $v_2(D_s^+)$ and v_2(non-strange D mesons)
- $v_2(D_s^+)$ in p_T < 10 GeV/c described by models implementing charm-quark hadronization via coalescence and strange-quark v_2

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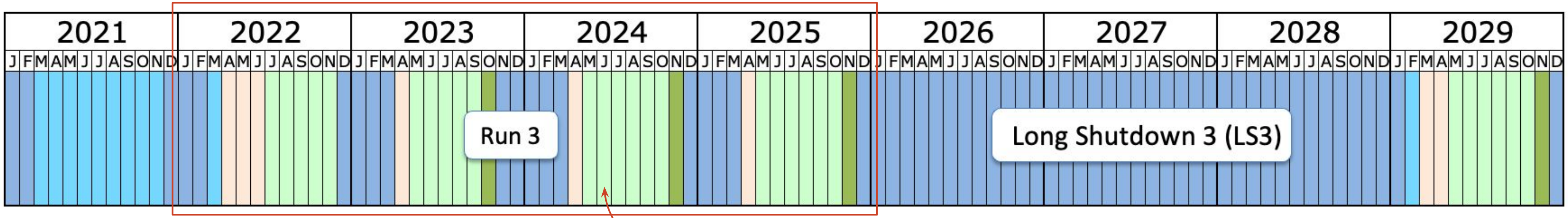
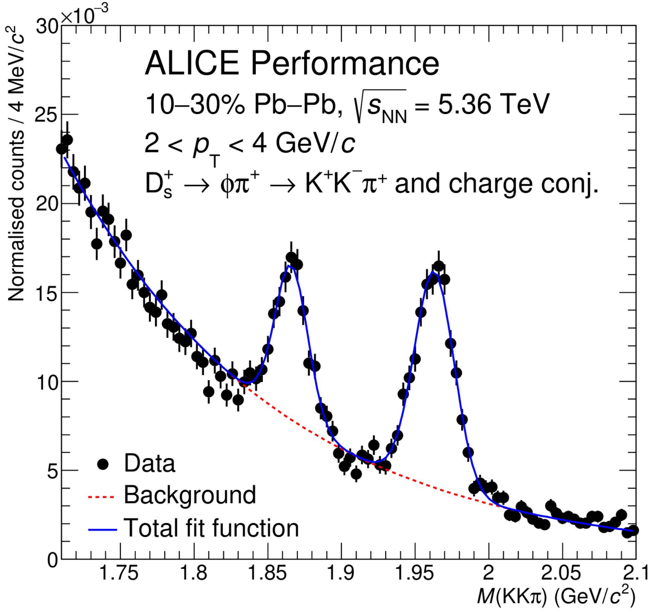


we are here!



ALI-PERF-568632

- Prompt and non-prompt strange D-meson production measurements in pp collisions useful to probe the charm- and beauty-quark fragmentation
- Prompt and non-prompt strange D-meson production measurements in Pb–Pb support scenarios with charm- and beauty-quark hadronization via coalescence and charm-quark thermalization in the QGP

More results from LHC Run 3 soon!

"Study of charm fragmentation with charm meson and baryon angular correlation measurements with ALICE"
A. Palasciano, 04/06/2024

Do not miss!

Thank you very much for the attention

Backup

Heavy-flavour hadron production at large Q^2 in pp collisions

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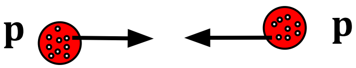


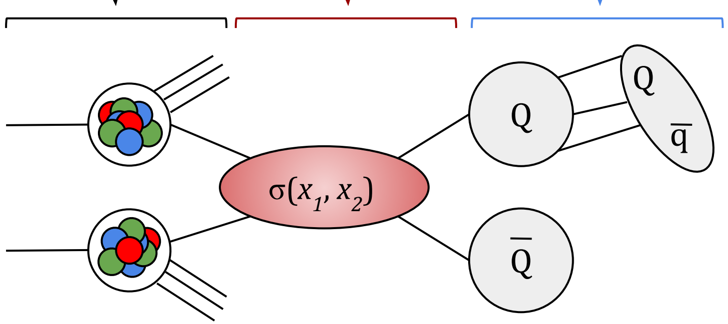
Factorization approach

$$\frac{d\sigma^{H_c}}{dp_T^{H_c}}(p_T;\mu_F,\mu_R) = \mathrm{PDF}(x_1,\mu_F)\cdot\mathrm{PDF}(x_2,\mu_F)\otimes\frac{d\sigma^{c}}{dp_T^{c}}(x_1,x_2,\mu_F,\mu_R)\otimes D_{c\rightarrow H_c}(z=p_{H_c}/p_c,\mu_F)$$

Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronization)



- No first-principle description of hadronization
  - Non-perturbative problem, pQCD calculations not applicable
  - Necessary to resort to models and make use of phenomenological parameters

- Charm-hadron production typically described by models via a factorisation approach

Independent fragmentation

- Fragmentation functions assumed universal across collision systems and constrained from e^+e^- and e^-p measurements

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ALICE

Run 3 upgrades

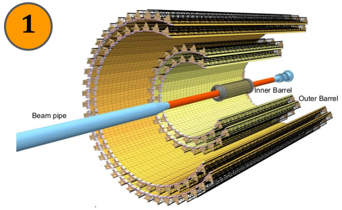
1. Upgraded ITS detector
   - up to ~100x higher readout rate than Run 2
   - ~3x lower material budget than Run 2 (1^{st} layer)

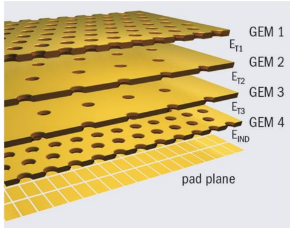
2. Gas Electron Multipliers (GEMs) in TPC readout
3. Data acquisition in continuous readout mode

4. New Fast Interaction Trigger (FIT) detector
   - excellent time resolution ($\sigma \leq 18$ ps)

5. Muon Forward Tracker → $2.5 < \eta < 3.6$
   - Secondary vertex reconstruction at forward-y

1





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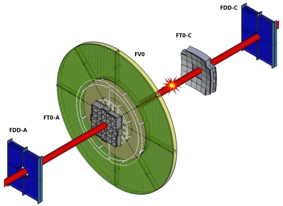
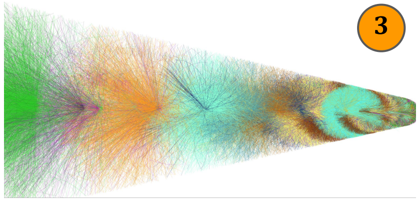
4





3

Charm-hadron decay channels

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

Datasets

pp $\sqrt{s}$ = 5.02 TeV	→ $\mathcal{L}_{int}$ ~ 19 nb^{-1} (MB)
pp $\sqrt{s}$ = 7 TeV	→ $\mathcal{L}_{int}$ ~ 5.9 nb^{-1} (MB)
pp $\sqrt{s}$ = 13 TeV	→ $\mathcal{L}_{int}$ ~ 32 nb^{-1} (MB)
pp $\sqrt{s}$ = 13.6 TeV	**→ $\mathcal{L}_{int}$ ~ 1 pb^{-1} (2022 MB)**
p–Pb $\sqrt{s_{NN}}$ = 5.02 TeV	→ $\mathcal{L}_{int}$ ~ 287 μb^{-1} (MB)
Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV	→ $\mathcal{L}_{int}$ ~ 130 μb^{-1} (0-10%)
	→ $\mathcal{L}_{int}$ ~ 56 μb^{-1} (30-50%)

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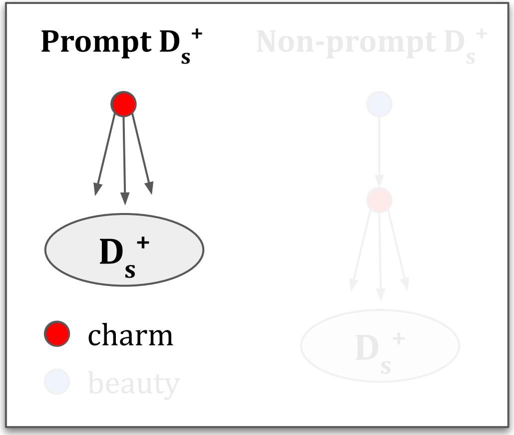

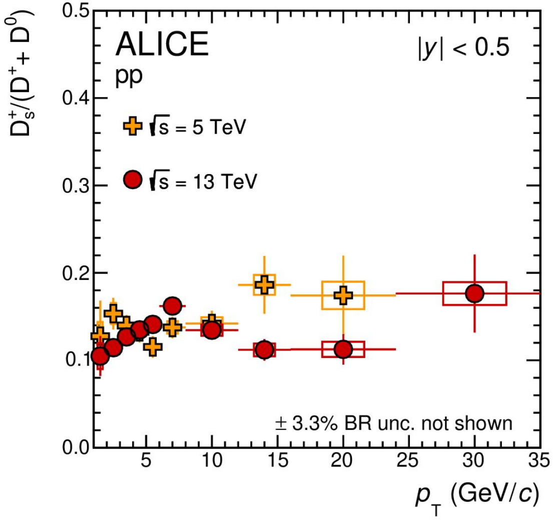

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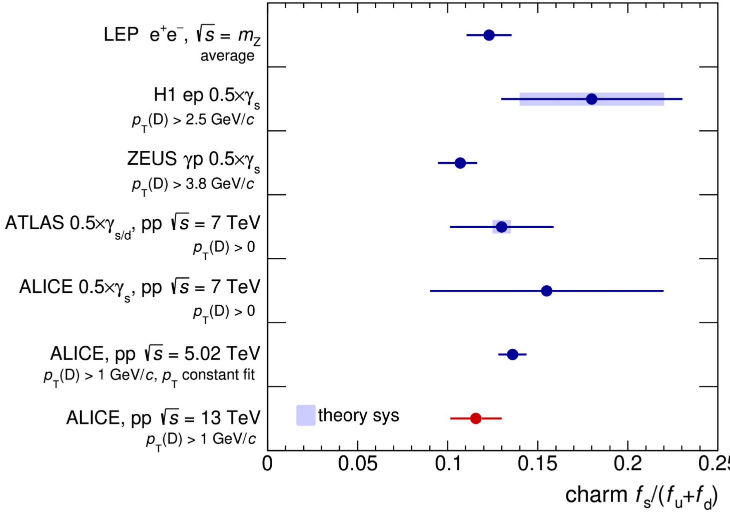

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- No strong p_T dependence for strange/non-strange D-meson ratios
- The measured yield ratios do not depend significantly neither on collision system nor collision energy

from factorization …

$$\frac{\dfrac{d\sigma^{H_c^1}}{dp_T^{H_c^1}}(p_T;\mu_F,\mu_R)}{\dfrac{d\sigma^{H_c^2}}{dp_T^{H_c^2}}(p_T;\mu_F,\mu_R)} \sim \frac{D_{c\to H_c^1}(z=p_{H_c^1}/p_c,\mu_F)}{D_{c\to H_c^2}(z=p_{H_c^2}/p_c,\mu_F)}$$

No significant collision system and energy dependence of charm quark **fragmentation function ratios** into strange and non-strange D mesons

Non-prompt strange/non-strange D-meson ratio

pp collisions

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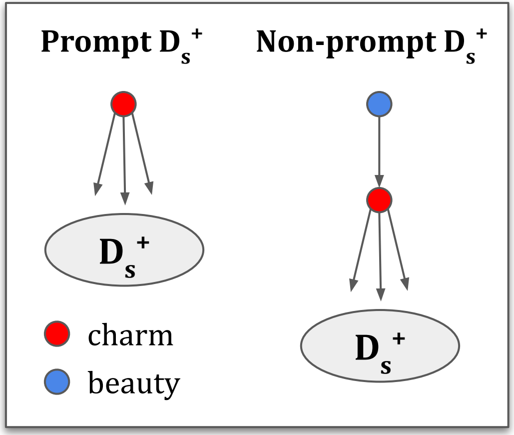
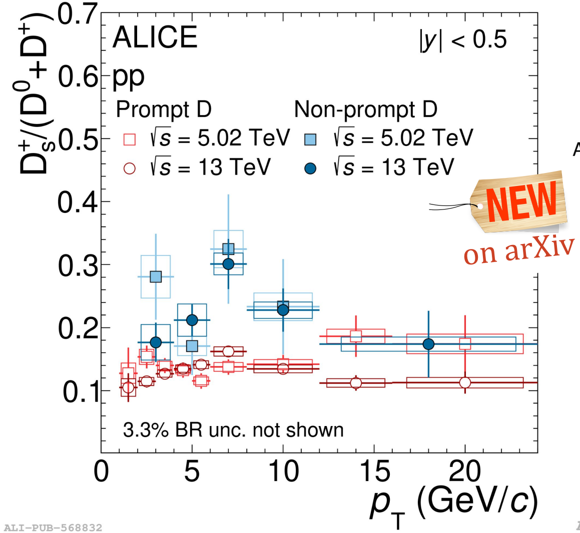
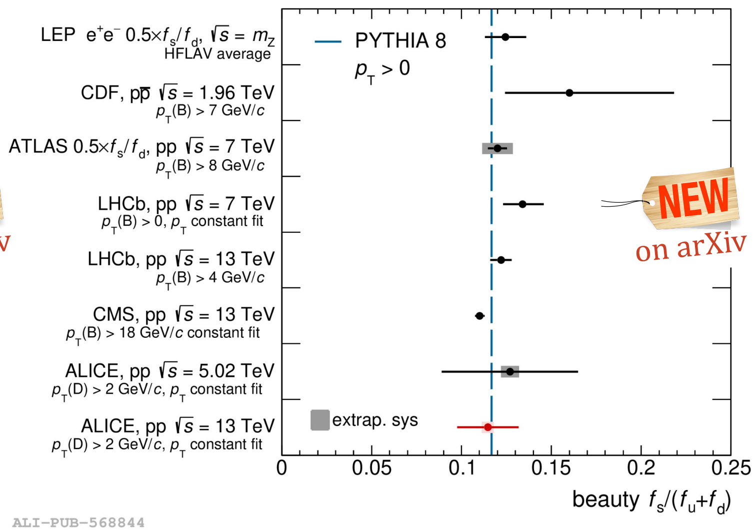




arXiv:2402.16417



- No strong p_T dependence for strange/non-strange D-meson ratios
- The measured yield ratios do not depend significantly neither on collision system nor collision energy

Valid for both prompt and non-prompt D mesons!

- Beauty $f_s/(f_u + f_d)$ fragmentation-fraction ratio from non-prompt $D_s^+/(D^0+D^+)$
  - FONLL+PYTHIA correction for D_s^+ from non-strange B-meson decays
- Beauty $f_s/(f_u + f_d)$ = charm $f_s/(f_u + f_d)$
- Beauty $f_s/(f_u + f_d)$ in line with SHM (~0.1) and PYTHIA 8

Strange/non-strange D-meson ratio

pp collisions

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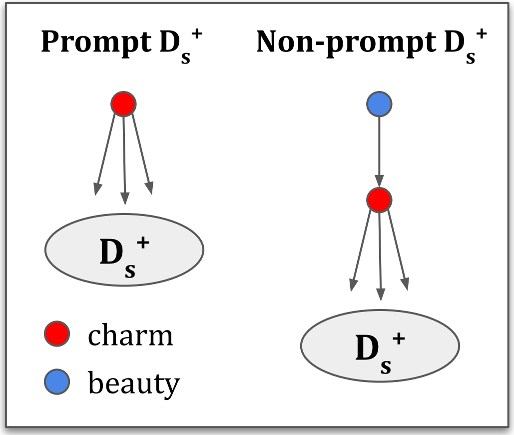
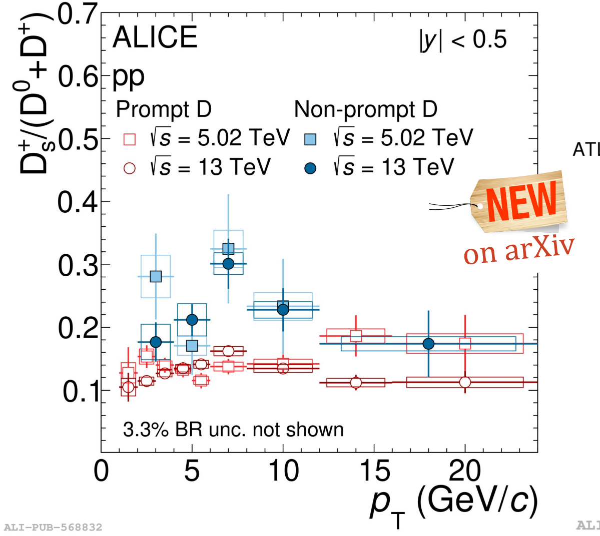
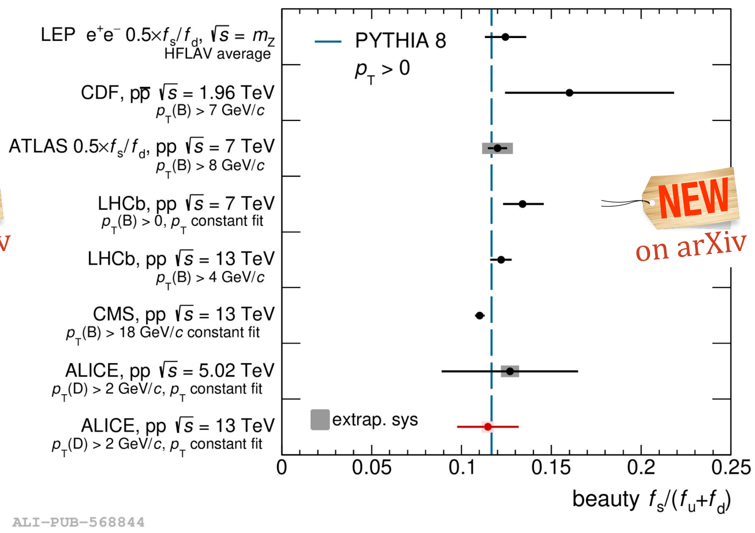
arXiv:2402.16417

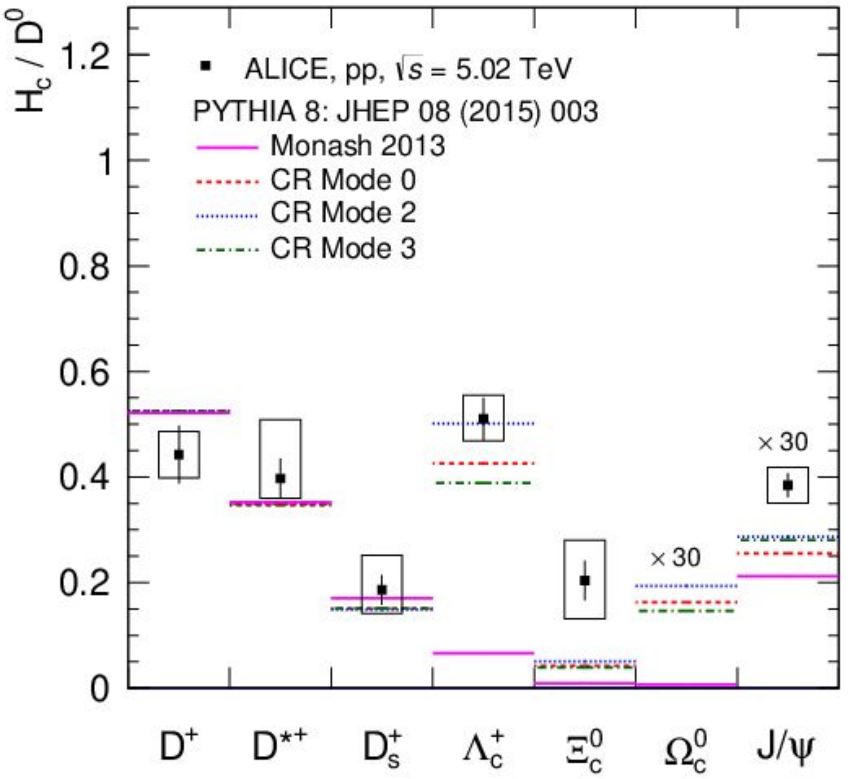






- Prompt and non-prompt $D_s^+/(D^++D^0)$ ratios do not depend significantly on p_T, collision system or energy
- No significant collision system and energy dependence of charm quark fragmentation function ratios into strange and non-strange D mesons

- Charm and beauty $f_s/(f_u+f_d)$ fragmentation-fraction ratio from prompt and non-prompt $D_s^+/(D^0+D^+)$ ratio, respectively
  - Beauty: FONLL+PYTHIA correction for D_s^+ from non-strange B-meson decays
- Beauty $f_s/(f_u+f_d)$ = charm $f_s/(f_u+f_d)$



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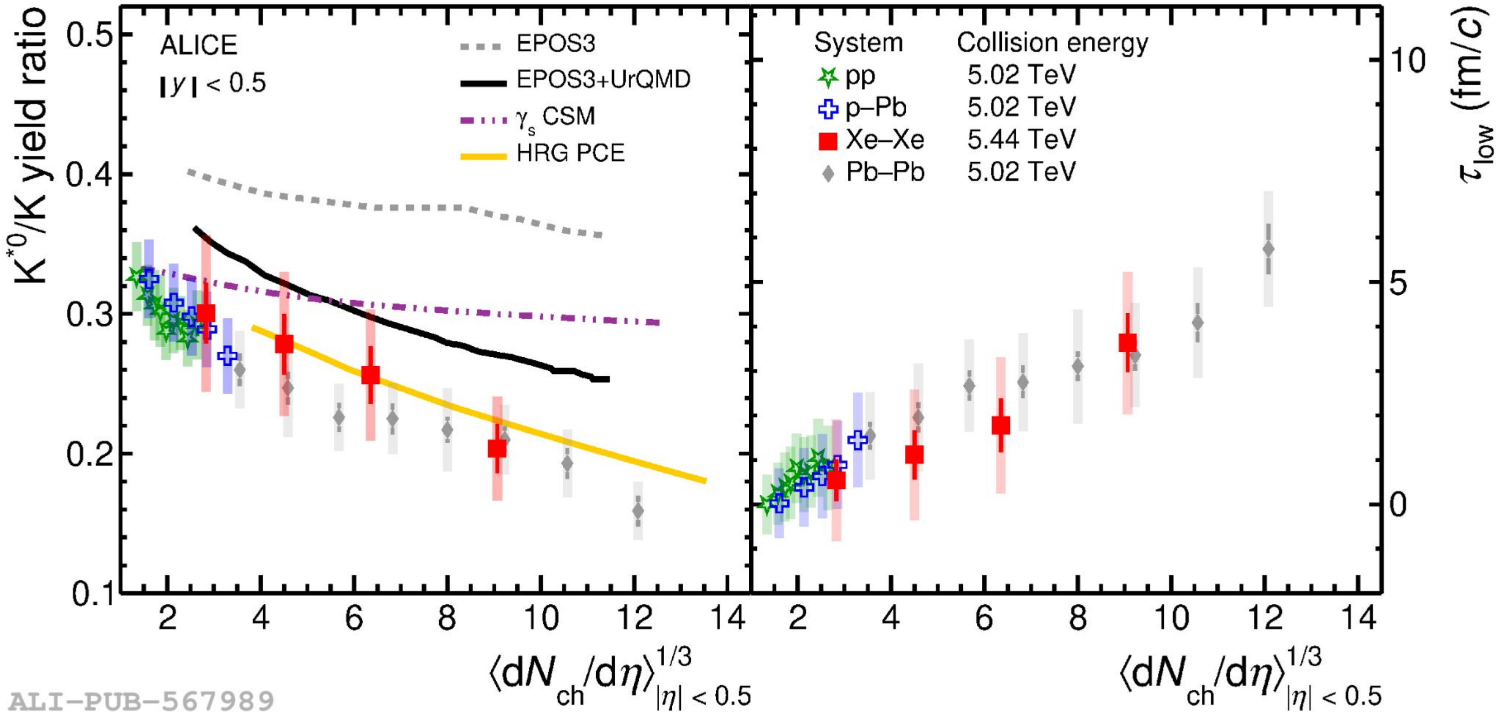
Phys. Rev. C 109, 014911 (2024)



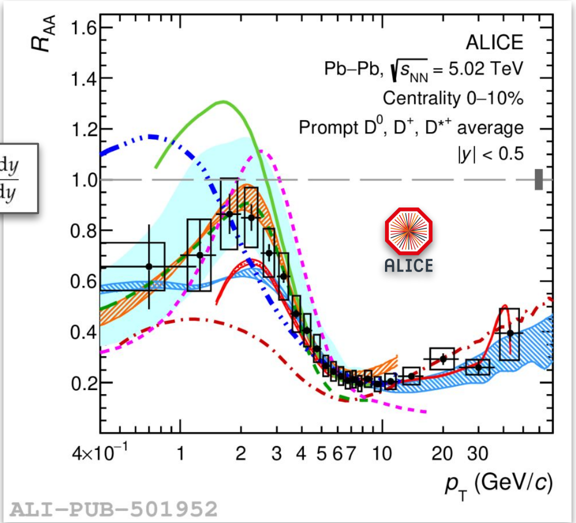
$\tau(D_{s,2}^{*+}) \sim 7\ \tau(K^*)$

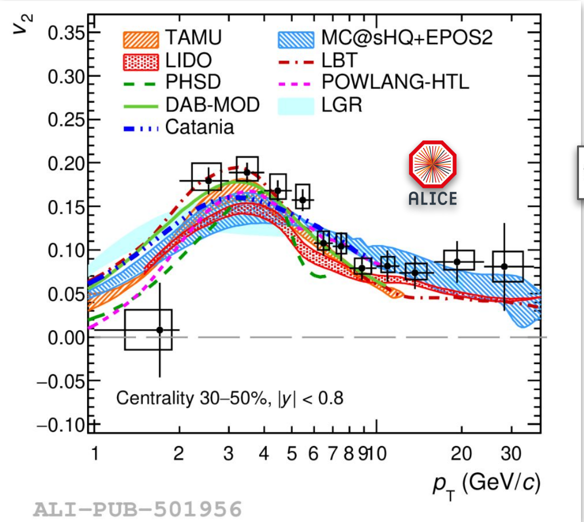
R_{AA} and v_2 compared to transport models

R_{AA}

$$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

ALICE: JHEP 01 (2022) 174





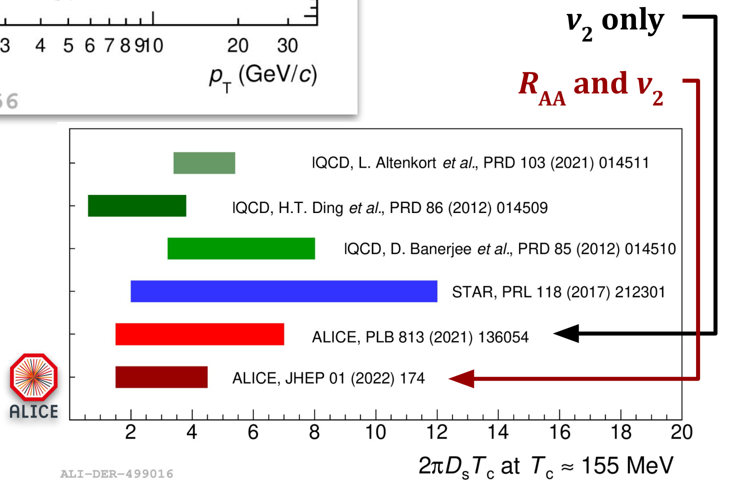
v_2

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

Measured R_{AA} and v_2 described by transport models

- **understanding** of **relevant effects** in different p_T intervals (next slides)
- sensitivity to transport regime (and charm-quark thermalization) at low p_T
    - **stronger constraint** to the **charm quark spatial diffusion coefficient** based on **data-to-model agreement**

$1.5 < 2\pi D_s T_c < 4.5 \leftrightarrow \tau_{charm} \simeq 3–8$ fm/c



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PHSD: PRC 93, 034906 (2016)
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MC@sHQ: PRC 91, 014904 (2015)
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LGR: EPJC 80 (2020) 7, 671
Catania: PRC 96, 044905 (2017)