Beauty production in heavy-ion collisions with ALICE at the LHC

Stefano Politanò on behalf of the ALICE Collaboration

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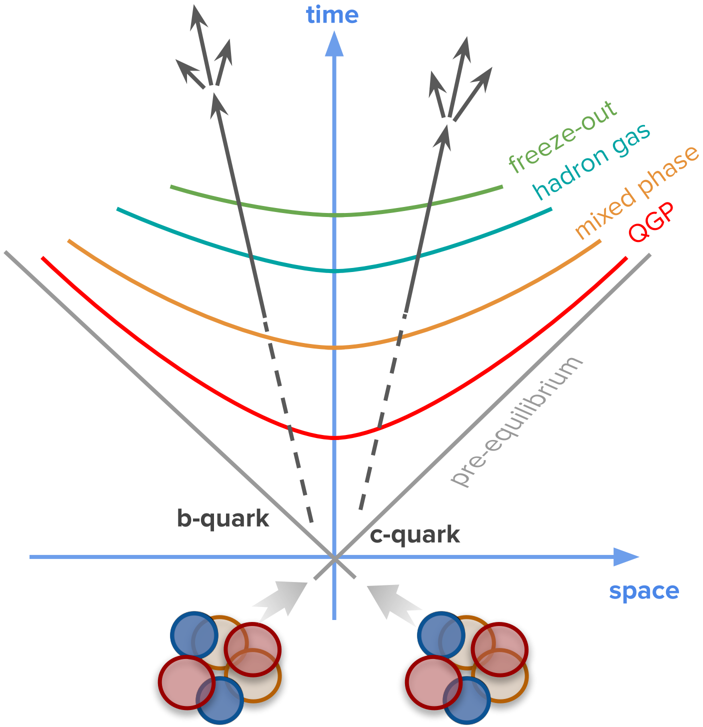
- Quantum chromodynamics calculations on lattice predict phase transition from ordinary nuclear matters to colour-deconfined medium: quark–gluon plasma (*QGP*)
  - ultrarelativistic heavy-ion collisions
  - high energy-density $\varepsilon > 15\ \mathrm{GeV/fm^3}$

- Heavy flavours (i.e. b and c quarks) produced in hard scattering processes during first stages of the collision
  - $\tau_b < \tau_c < \tau_{QGP} \sim 1\ \mathrm{fm}/c$ Novak, J.: PRC 89 034906 (2014)
  - probe the full system evolution



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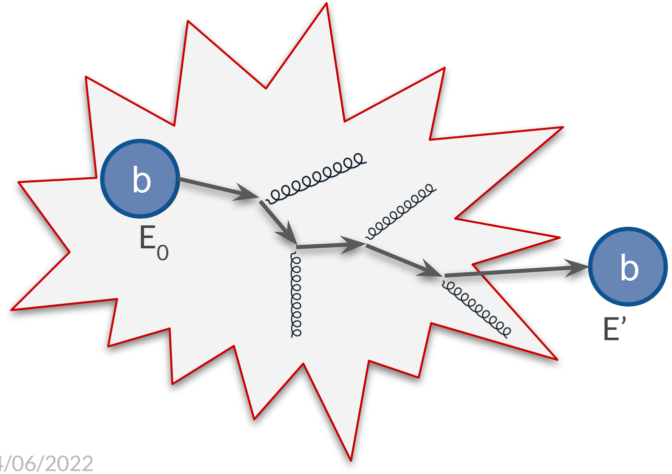
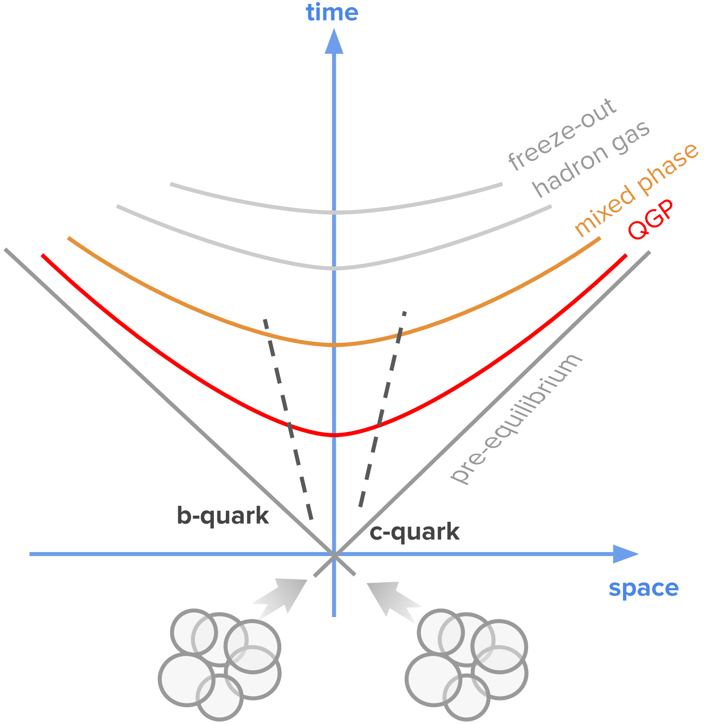
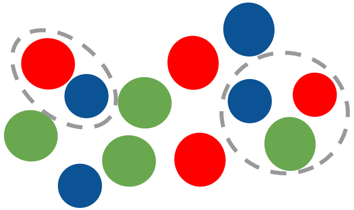
- HF propagate in the QGP with a Brownian motion
  - interact with medium constituents
  - lose energy via elastic collisions and radiative processes
    - ➡ in-medium energy-loss mass dependence
  - heavy-quark thermalisation in the QGP?

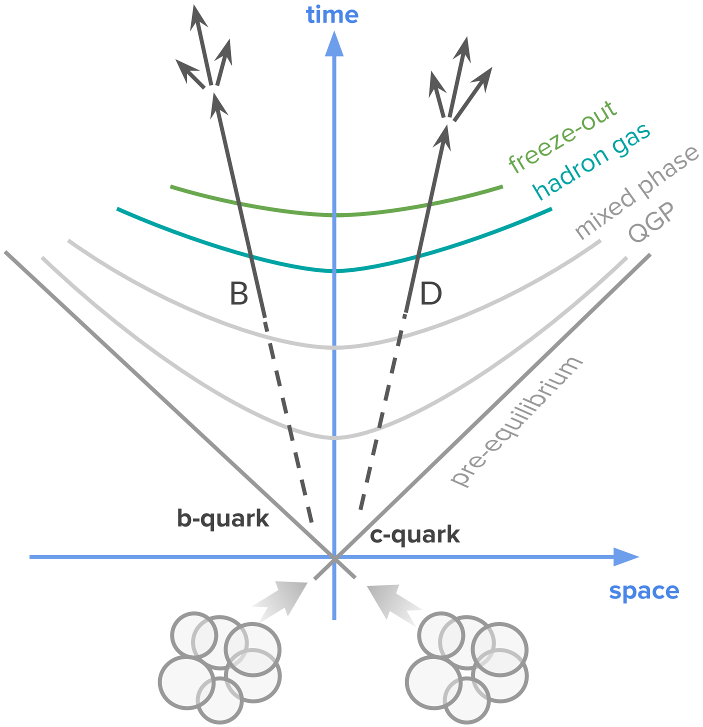




- HF hadronisation in the QGP
  - Fragmentation ($D_{q \rightarrow h}(z_q, Q^2)$)
    - ➡ partons energy-loss traversing QGP modifies z_q taken by the hadron



  - Coalescence
    - ➡ partons sharing velocity/position recombine into hadrons



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- HF hadronisation in the QGP
  - Fragmentation ($D_{q\to h}(z_q, Q^2)$)

Beauty measurements in this talk:

Beauty decay electron ($b \to e$)

Non-prompt D ($b \to D^0, D_s^+$) in hadronic decay ($K^-\pi^+, K^+K^-\pi^+$)

2015 Pb–Pb 5.02 TeV: $L^{int} \sim 13\ \mu b^{-1}$

2018 Pb–Pb 5.02 TeV: (0-10%) $L^{int} \sim 130\ \mu b^{-1}$

(30-50%) $L^{int} \sim 56\ \mu b^{-1}$

➡ partons sharing velocity/position recombine into hadrons

Analysis strategy: beauty-decay electrons

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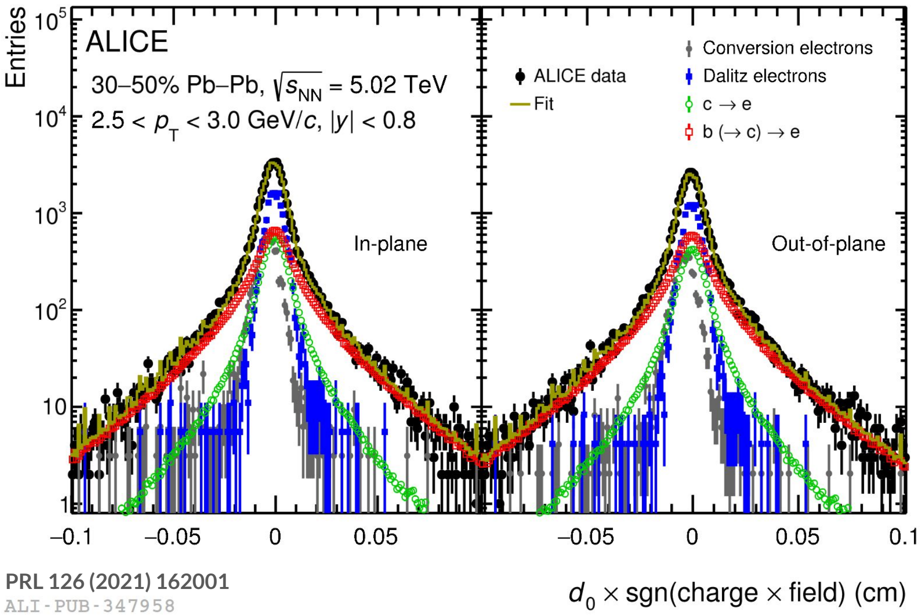
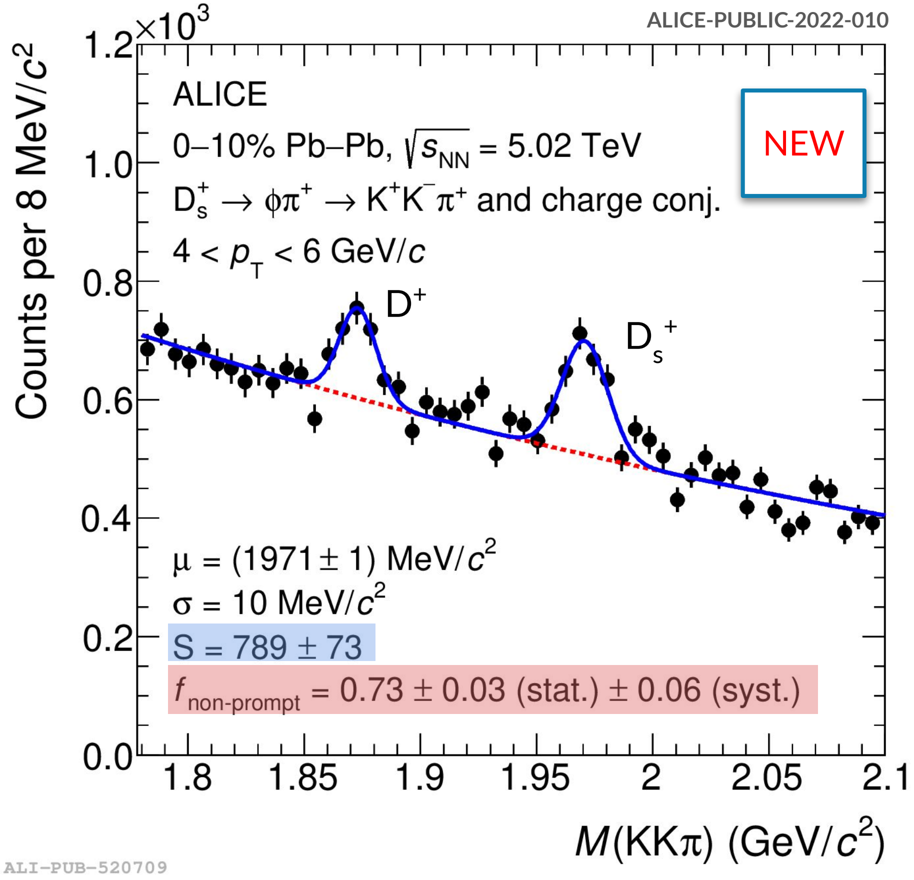


PRL 126 (2021) 162001
ALI-PUB-347958

- Large BR in semileptonic decay
  - $b \rightarrow e + X$ (~10%) , $b \rightarrow c \rightarrow e + X$ (~10%)
- longer lifetime than c-quark and other electron sources
  - τ_b ~ 500 μm/c; τ_c ~ 60-300 μm/c
  - larger impact parameter (d_0) w.r.t primary vertex
- yield obtained with template fit on impact parameter distributions

Analysis strategy: non-prompt D mesons (D^0, D_s)



- Large amount of combinatorial background
  - Machine Learning (ML) multiclass classification to enhance b → D contribution and reject combinatorial background
    - ➡ Signal from invariant mass fit
    - ➡ b → D fraction obtained via data-driven approach based on ML-based selection variation

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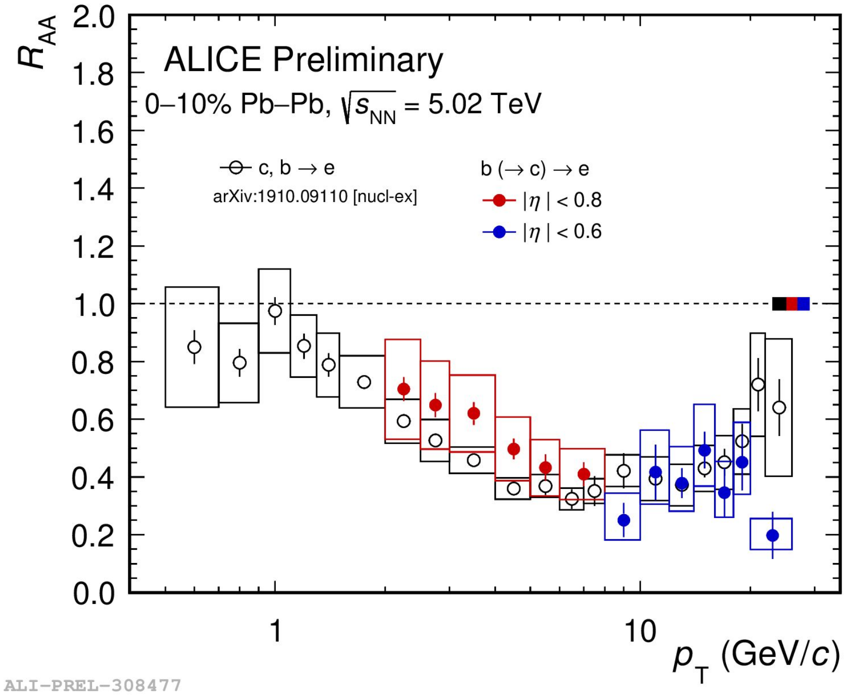
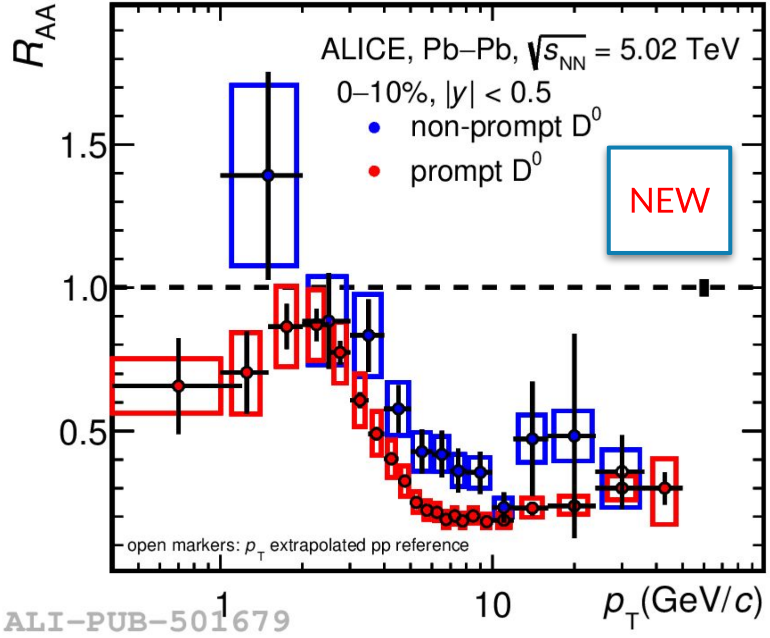
- b-quark R_{AA} can be studied via leptonic and hadronic decays





Non-prompt D^0: arXiv: 2202.00815

Prompt D^0: JHEP 01 (2022) 174

- beauty quark R_{AA} suppression

➡ Hint of R_{AA} (charm-hadron) < R_{AA}(beauty-hadron) at low p_T

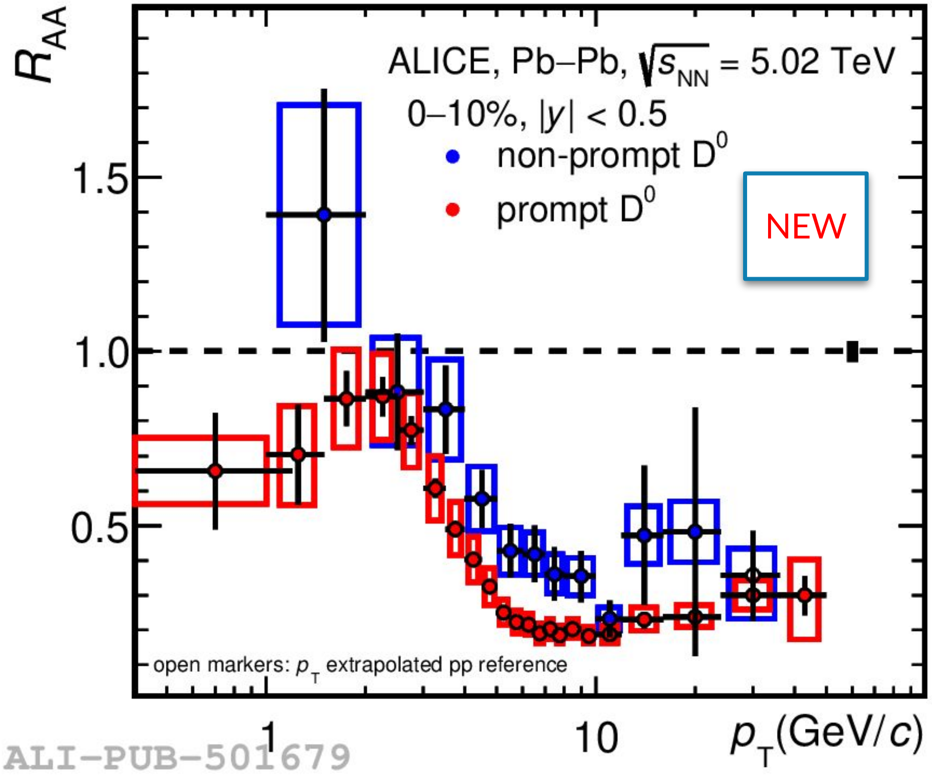
Martin Andreas Volkl
14 Jun 2022, 11:50

Non-prompt D^0 nuclear modification factor (R_{AA})

- R_{AA} (non-prompt D) > R_{AA} (prompt D) at intermediate p_T
  - integrated R_{AA}:

    R_{AA}^{prompt} (0–10%) = 0.689 ± 0.054 (stat.)$^{+0.104}_{-0.106}$(syst.)

    $R_{AA}^{non\text{-}prompt}$ (0–10%) = 1.00 ± 0.10 (stat.) ± 0.15 (syst.) $^{+0.08}_{-0.09}$(extr.) ± 0.02 (norm.)
  - compatible within less than 1.5σ
    - ➡ different shadowing or hadronisation via coalescence?



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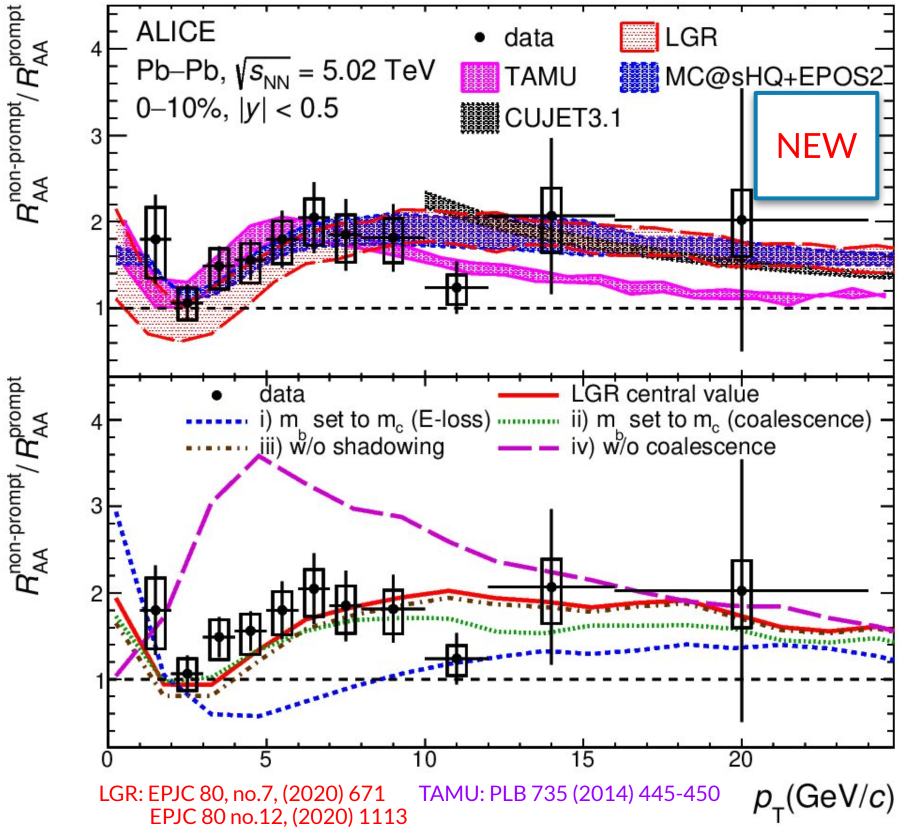


LGR: EPJC 80, no.7, (2020) 671
EPJC 80 no.12, (2020) 1113

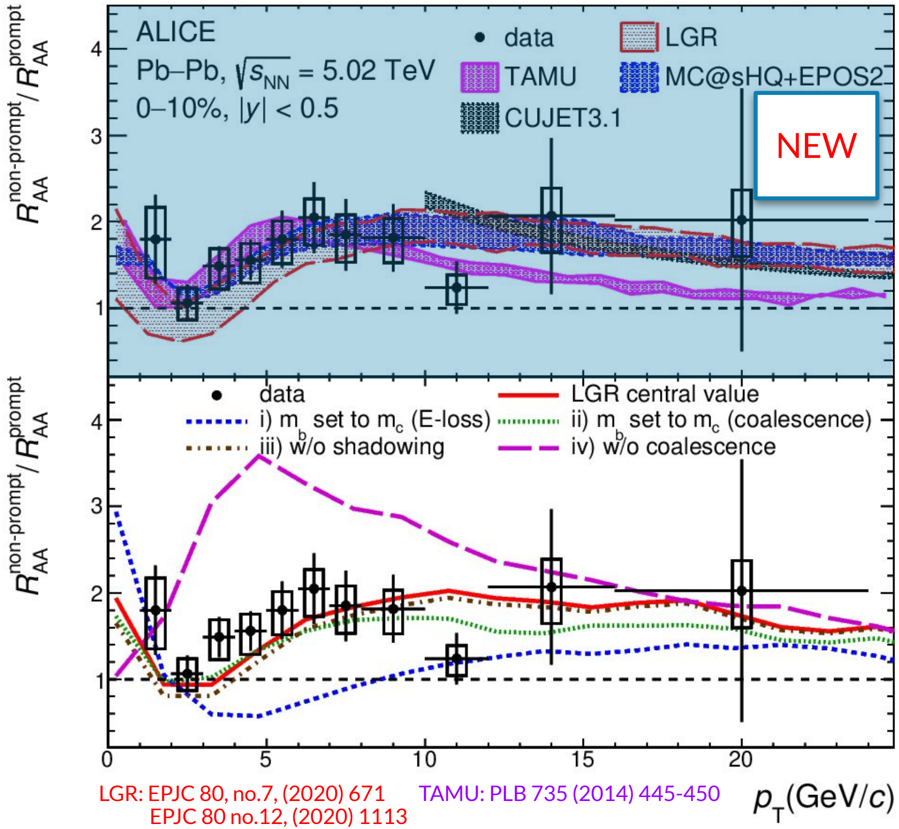
TAMU: PLB 735 (2014) 445-450

CUJET3.1: JHEP02(2016)169

MC@sHQ+EPOS2: PRC 89 (2014) 014905

ALI-PUB-501659

- R_{AA} (non-prompt D) / R_{AA} (prompt D) ratio comparison with models



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ALI-PUB-501659

- R_{AA} (non-prompt D) / R_{AA} (prompt D) ratio comparison with models
  - both collisional and radiative energy loss mechanisms important to describe data
  - low p_T (< 5 GeV/c): pattern hints difference in shadowing / flow / coalescence
  - high p_T (> 5 GeV/c): 3.9σ above unity → beauty less suppressed than charm

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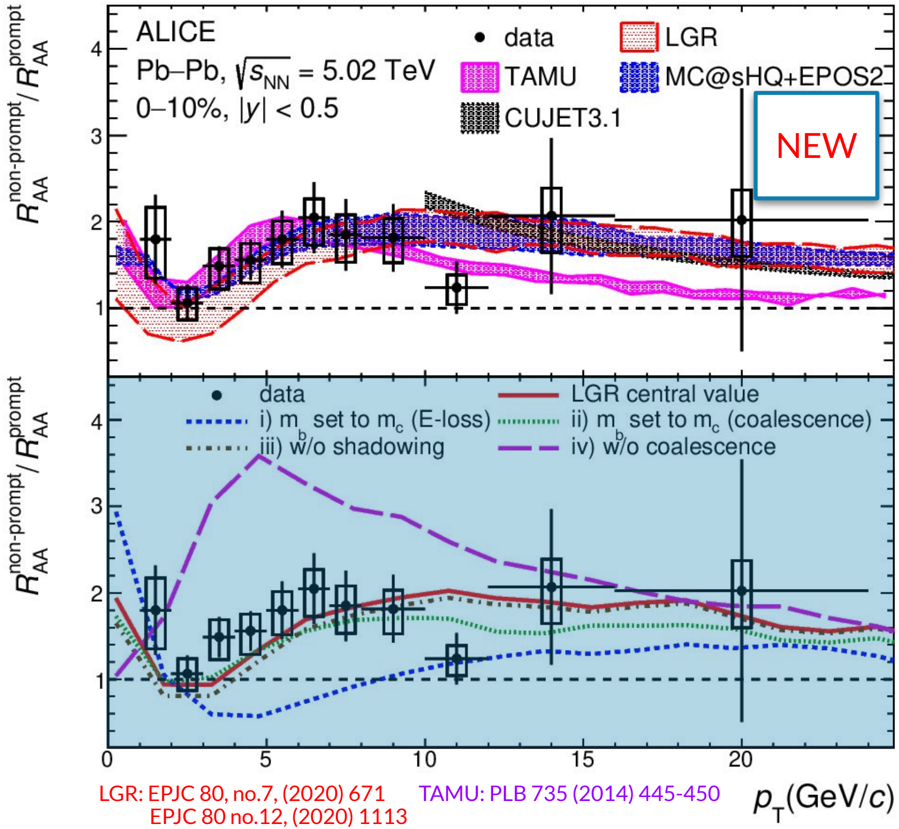

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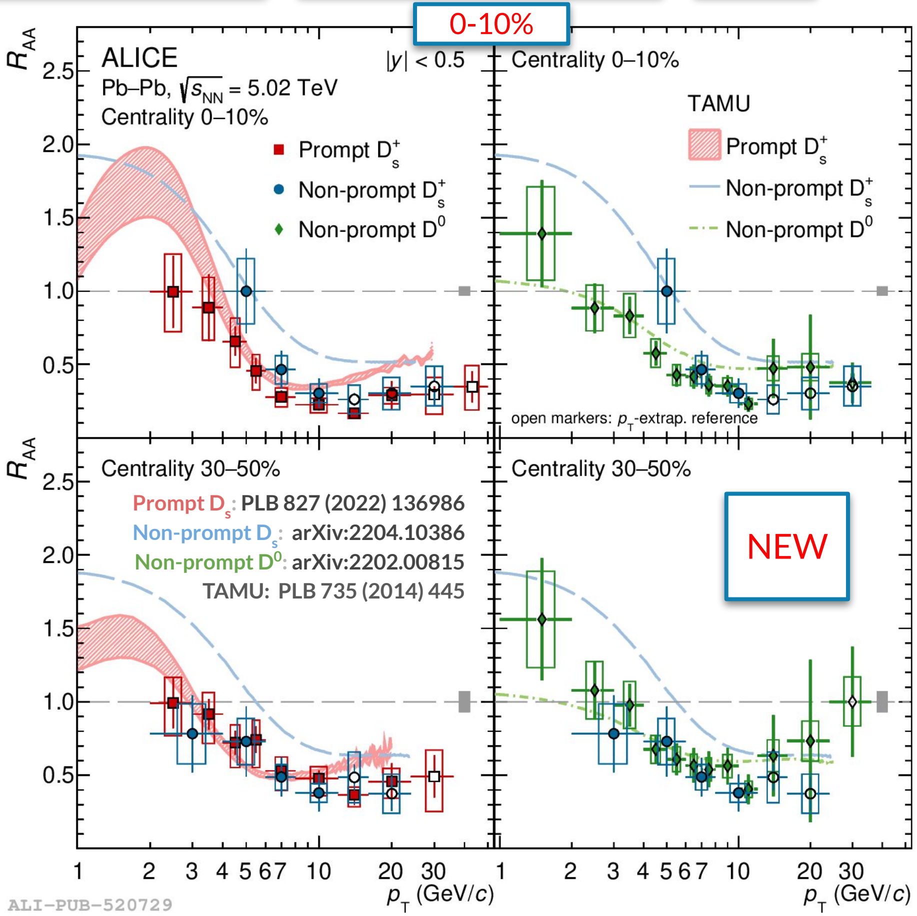
- Testing LGR ingredients effect
  - "valley" structure p_T < 5 GeV/c
    - ➡ charm coalescence (iv)
  - enhancement for p_T > 5 GeV/c
    - ➡ mass dependent quark in-medium energy loss effect (i)

- Central collisions (0–10%)
  - central values higher w.r.t those of prompt D_s, and non-prompt D^0 R_{AA} for p_T < 6 GeV/c, though compatible within uncertainties
    - ➡ interplay of different energy loss and recombination btw. charm and beauty



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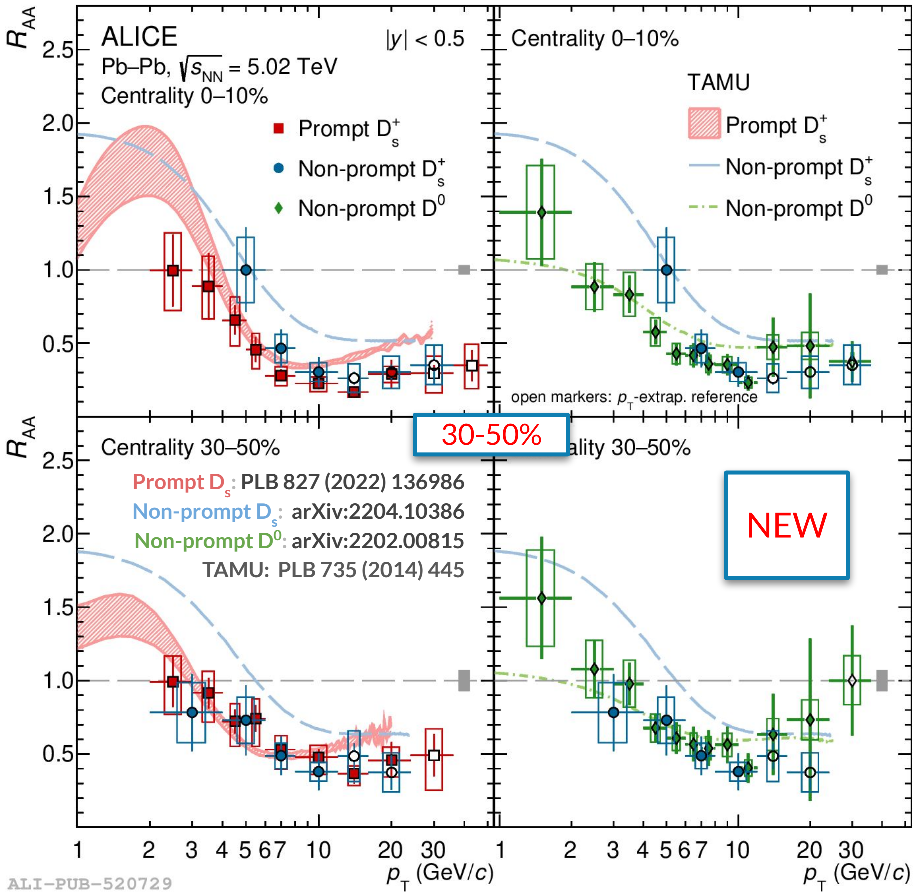
- Semicentral collisions (30–50%)
  - no sizeable medium-induced effect



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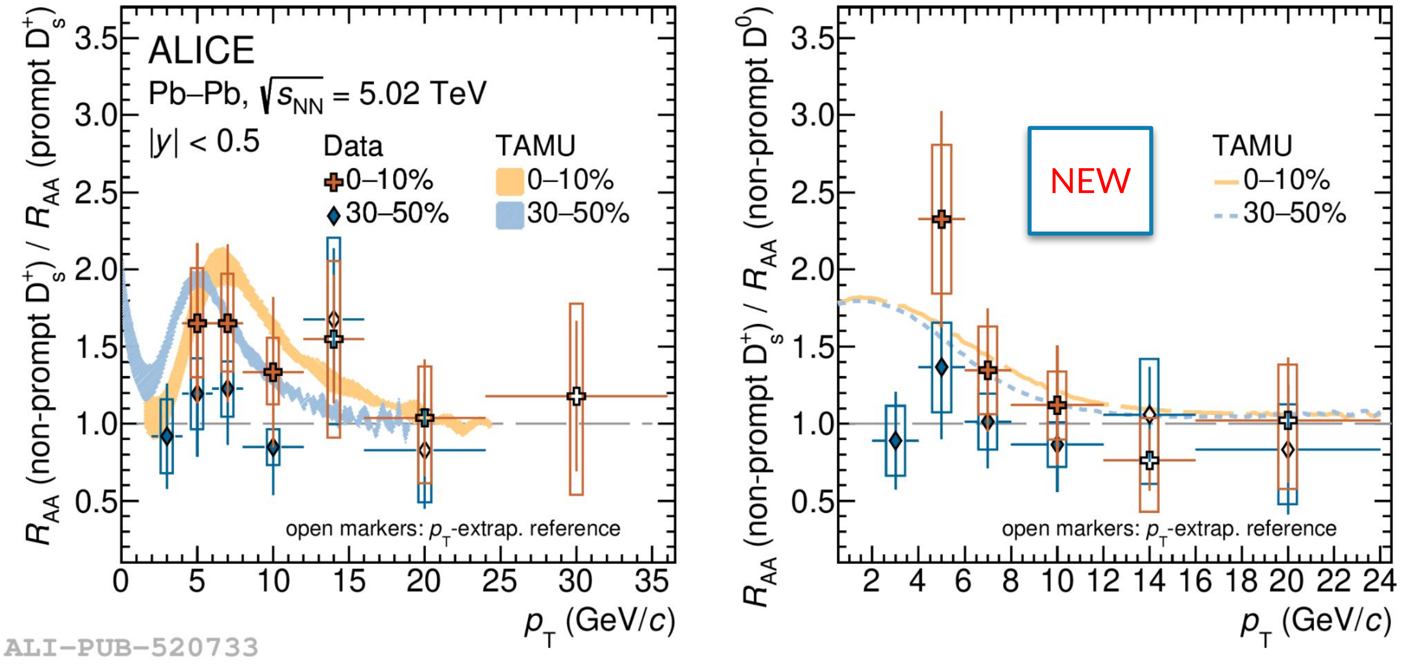
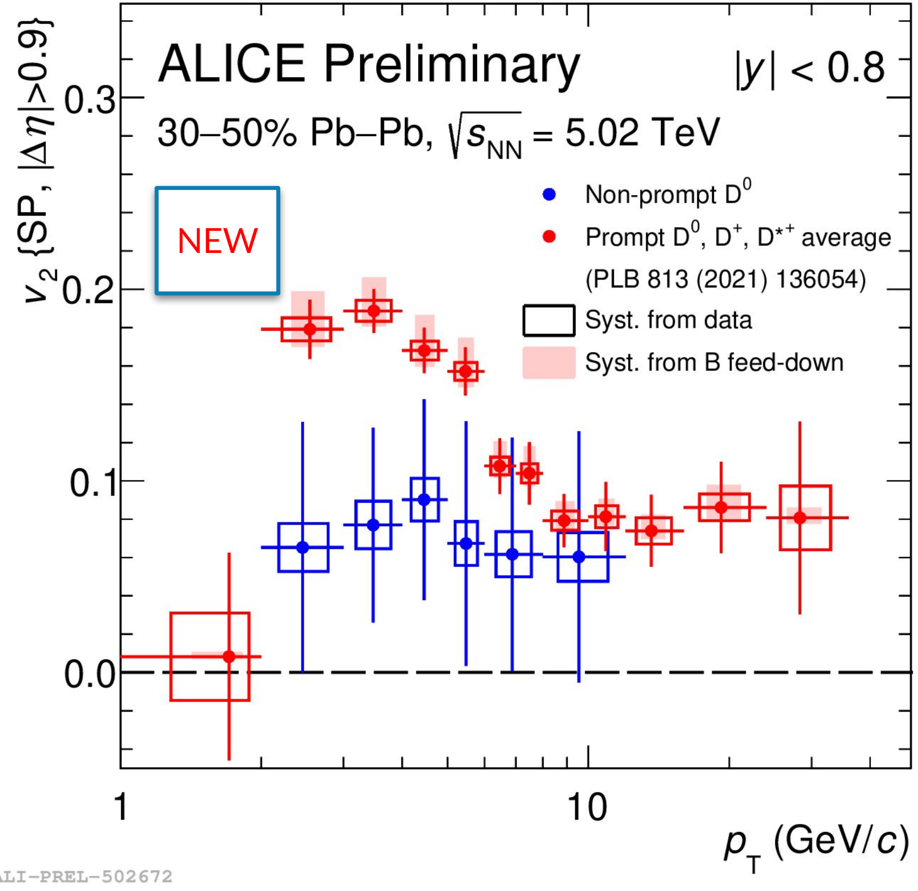


Data: arXiv:2204.10386

TAMU: PLB 735 (2014) 445

- Non-prompt/prompt R_{AA} D_s and non-prompt R_{AA} D_s/D^0 show hint of enhancement
  - 1.6σ (1.7σ) at $4 < p_T < 12$ GeV/c in 0–10%
    - ➡ coalescence + strangeness enhancement
  - TAMU qualitatively describes the result in 0–10%

Non-prompt D^0 v_2



- Non-prompt D^0 show non-zero v_2
  - 2.7σ significance for $2 < p_T < 12$ GeV/c
    - ➡ beauty partially thermalizes in the medium and/or recombines with light quarks
  - 3.2σ btw non-prompt D^0 and prompt non-strange D meson in $2 < p_T < 8$ GeV/c
    - ➡ charm and beauty quarks participate differently to collective motion

Beauty elliptic flow v_2

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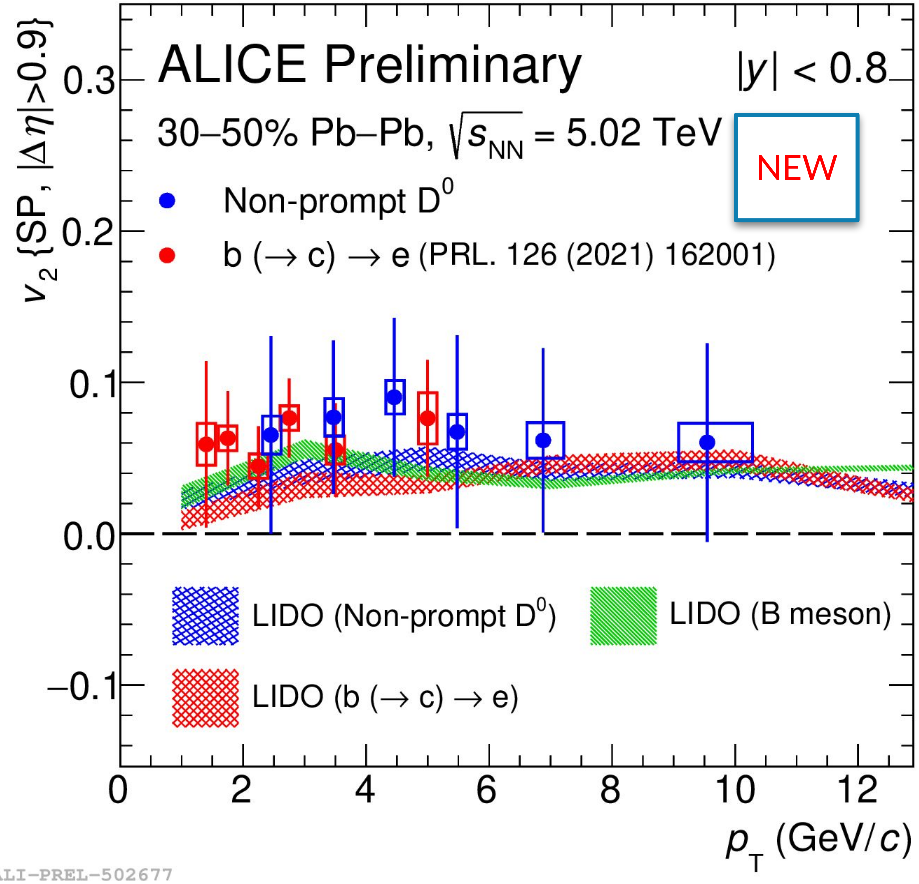
LIDO: PRC 98 (2018) 064901, PRC 100 (2019) 064911



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  - 2.7σ significance for $2 < p_T < 12$ GeV/c
    - ➡ beauty partially thermalizes in the medium and/or recombines with light quarks
  - 3.2σ btw non-prompt D^0 and prompt non-strange D meson in $2 < p_T < 8$ GeV/c
    - ➡ charm and beauty quarks participate differently to collective motion
  - Model describe data within uncertainties
    - ➡ compatible $b \rightarrow e$ and non-prompt D^0 v_2

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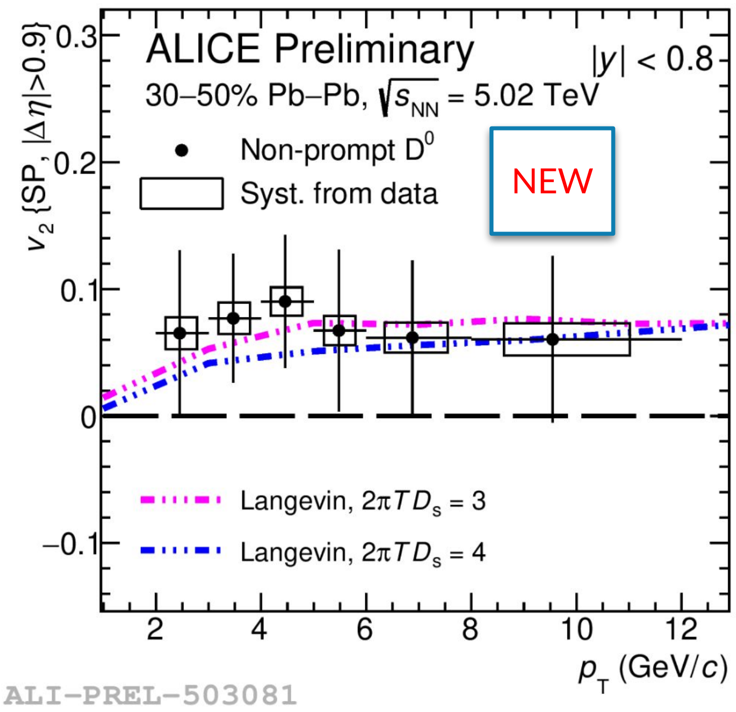
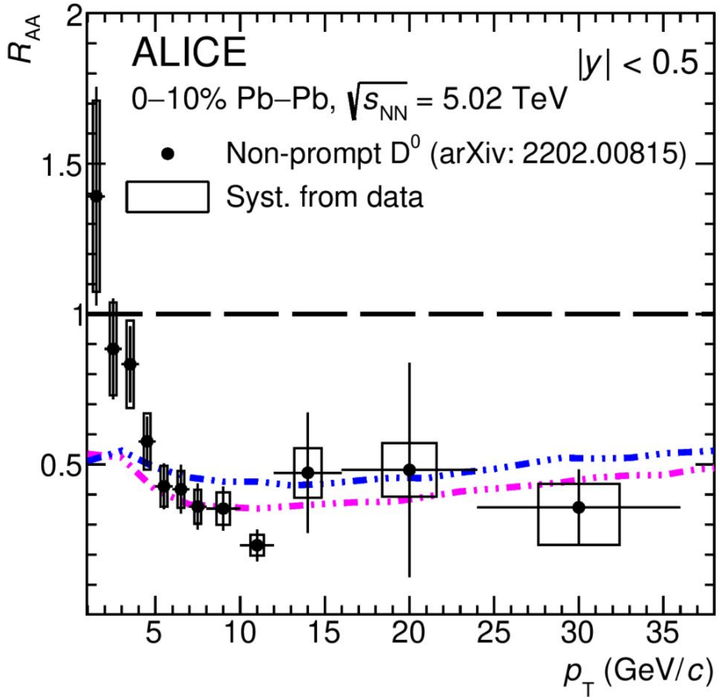
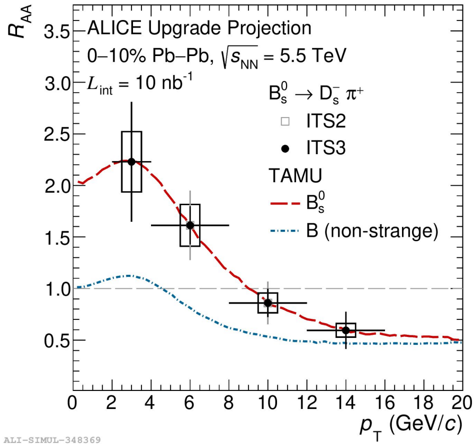
Langevin: S.Q Li et al., EPJC 81 (2021) 11, 1035

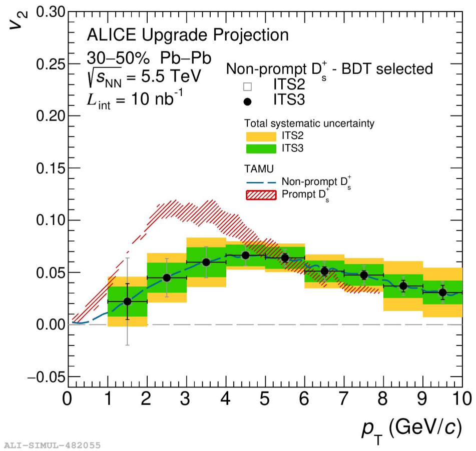




- Constrain b-quark spatial diffusion coefficient comparing v_2 and R_{AA} simultaneously
  - More precise measurements of exclusive beauty decay needed

- Beauty quarks undergo energy loss in the medium → important constraint of mass dependence energy loss
- Measurements described by models that include collisional and radiative energy loss
- Strange non-prompt D meson R_{AA} provides insights into beauty quarks hadronisation via coalescence
- Different non-prompt and prompt D^0 v_2
  - different degree of participation to collective motion and hadronisation between charm and beauty
- Beauty-strange meson and beauty-baryon production and azimuthal anisotropy measurements in Run 3





ADDITIONAL SLIDES

ALICE

1859

INFN

SQM 2022

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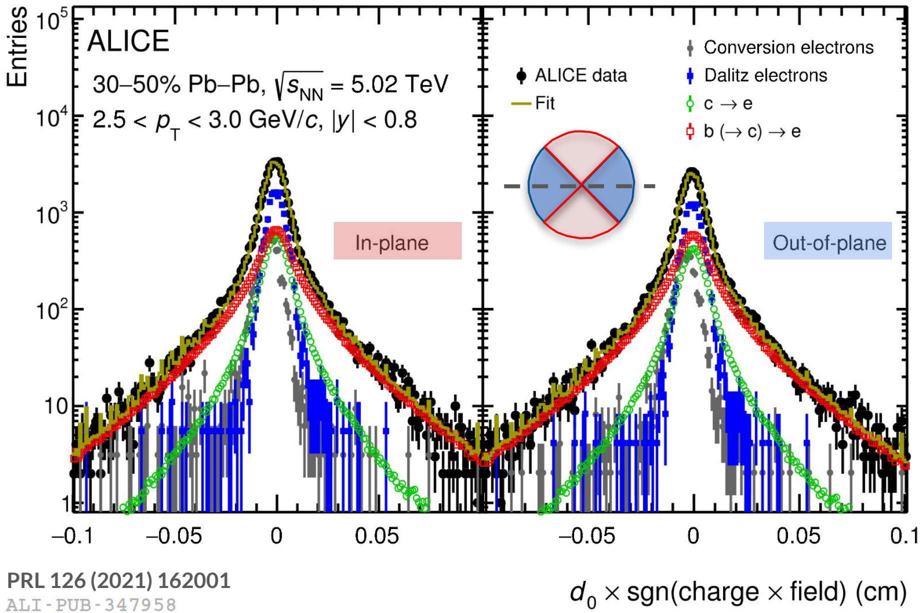
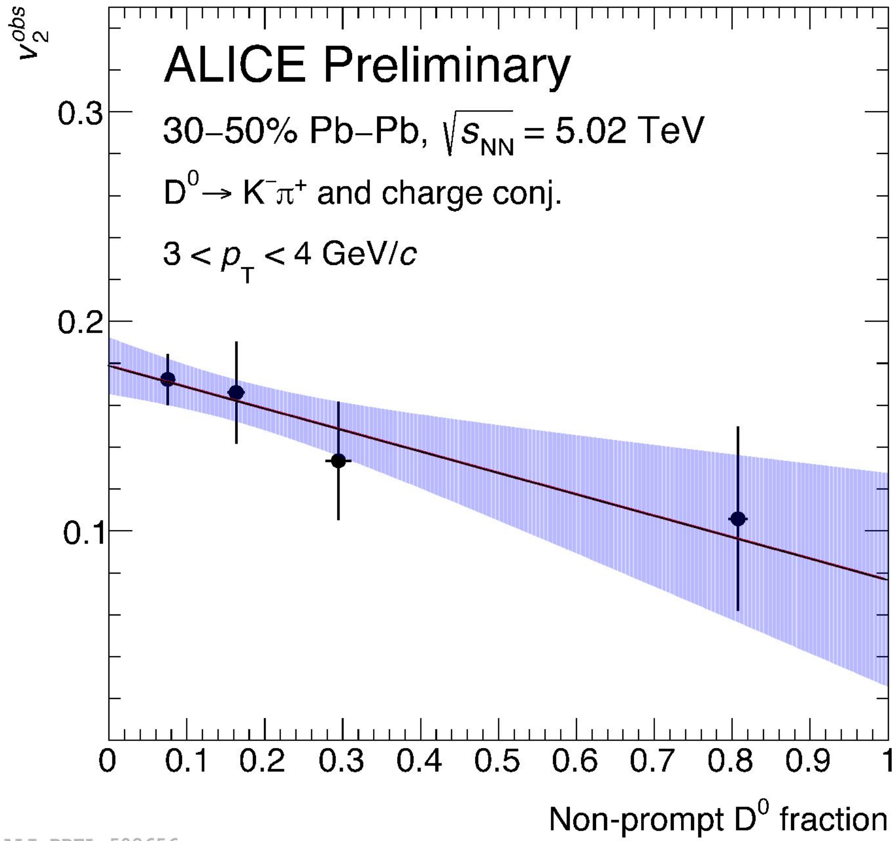
- v_2 measured with the Event-Plane (EP) method
  - computation of event-plane angle $$\psi_n = \frac{1}{n}\tan^{-1}\left(\frac{Q_{n,y}}{Q_{n,x}}\right) \quad \text{where} \quad \mathbf{Q}_n = \left(\sum_{k=0}^{N_{tracks}} \cos(n\varphi_k), \sum_{k=0}^{N_{tracks}} \sin(n\varphi_k)\right)$$



PRL 126 (2021) 162001
ALI-PUB-347958

- Yield extracted:
  - in-plane ((7π/4, π/4] U (3π/4,5π/4])
  - out-of-plane ((π/4, 3 π/4] U (5π/4, 7π/4])

$$v_2 = \frac{\pi}{4R_2}\frac{N_{in-plane} - N_{out-of-plane}}{N_{in-plane} + N_{out-of-plane}}$$

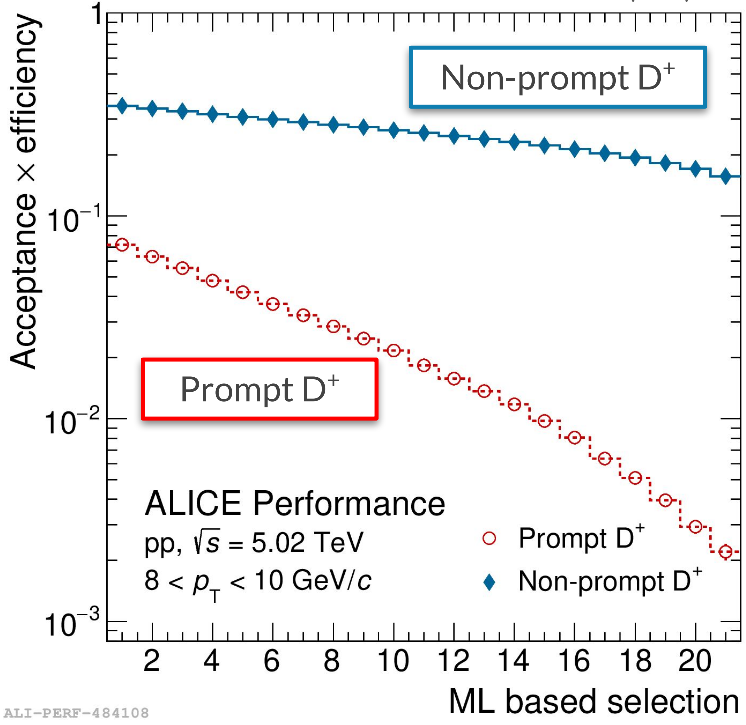


ALI−PREL−502656

- Large amount of combinatorial background
  - Machine Learning (ML) multiclass classification to enhance $b \rightarrow D$ contribution and reject combinatorial background
    - ➡ Signal from invariant mass fit
    - ➡ $b \rightarrow D$ fraction obtained via data-driven approach based on ML-based selection variation
  - $v_2^{\text{non-prompt}}$ obtained by linear fitting of $v_2^{\text{obs.}}$ vs. $f_{\text{non-prompt}}$, and extrapolate to $f_{\text{non-prompt}} = 1$

- Define *n* sets of ML-based selections with different prompt and non-prompt D-meson contributions

JHEP 05 (2021) 220



- Define *n* sets of ML-based selections with different prompt and non-prompt D-meson contributions
  - For each ML-based selection raw yield and efficiencies are related to the corrected yields of prompt and non-prompt D mesons

$$\epsilon^i_{\mathrm{P}} \cdot N_{\mathrm{P}} + \epsilon^i_{\mathrm{NP}} \cdot N_{\mathrm{NP}} = Y^i$$

➡ overdetermined algebraic system obtained

➡ solvable in approximated way

➡ f_{NP} obtained from the approximated solution

$$f^i_{\mathrm{NP}} = \frac{\varepsilon^i_{\mathrm{NP}} N_{\mathrm{NP}}}{\varepsilon^i_{\mathrm{NP}} N_{\mathrm{NP}} + \varepsilon^i_{\mathrm{P}} N_{\mathrm{P}}}$$

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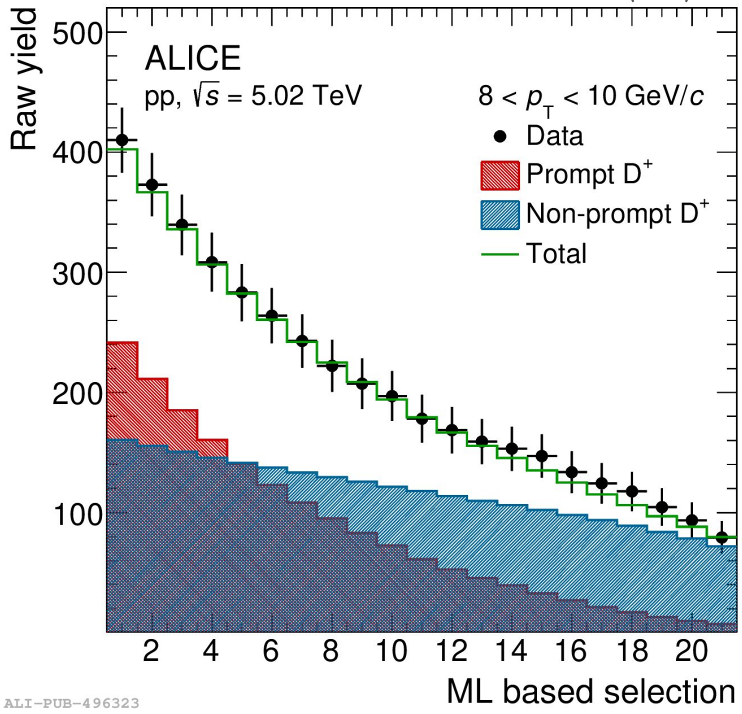
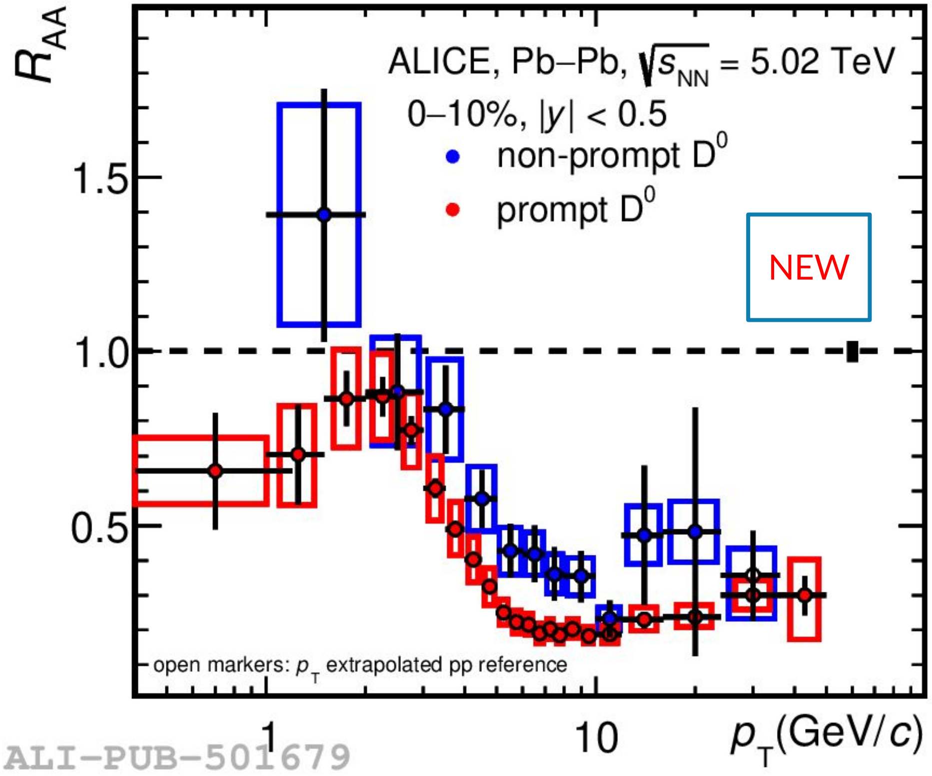


D^0 nuclear modification factor (R_{AA})

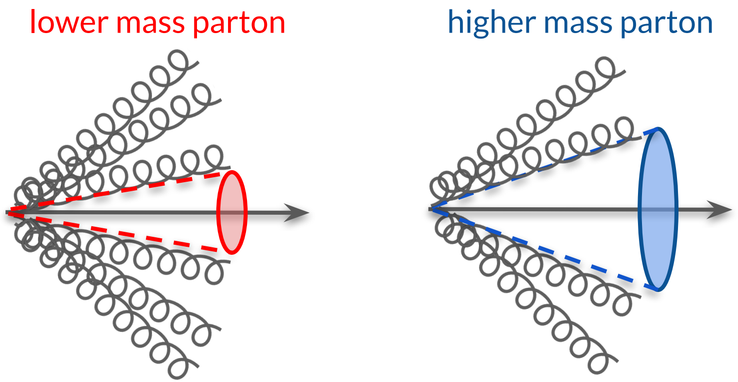


Non-prompt D^0: arXiv: 2202.00815

Prompt D^0: JHEP 01 (2022) 174

Antonio Carlos Oliveira Da Silva
14 Jun 2022, 14:20

- R_{AA} (non-prompt D) > R_{AA} (prompt D)
  - in-medium mass-dependent energy loss
    - ➡ dead cone effect: gluon radiation suppressed for small angles ($\vartheta < m_q/E$)
    - ➡ direct observation of dead cone effect with D^0-tagged jets in pp collisions

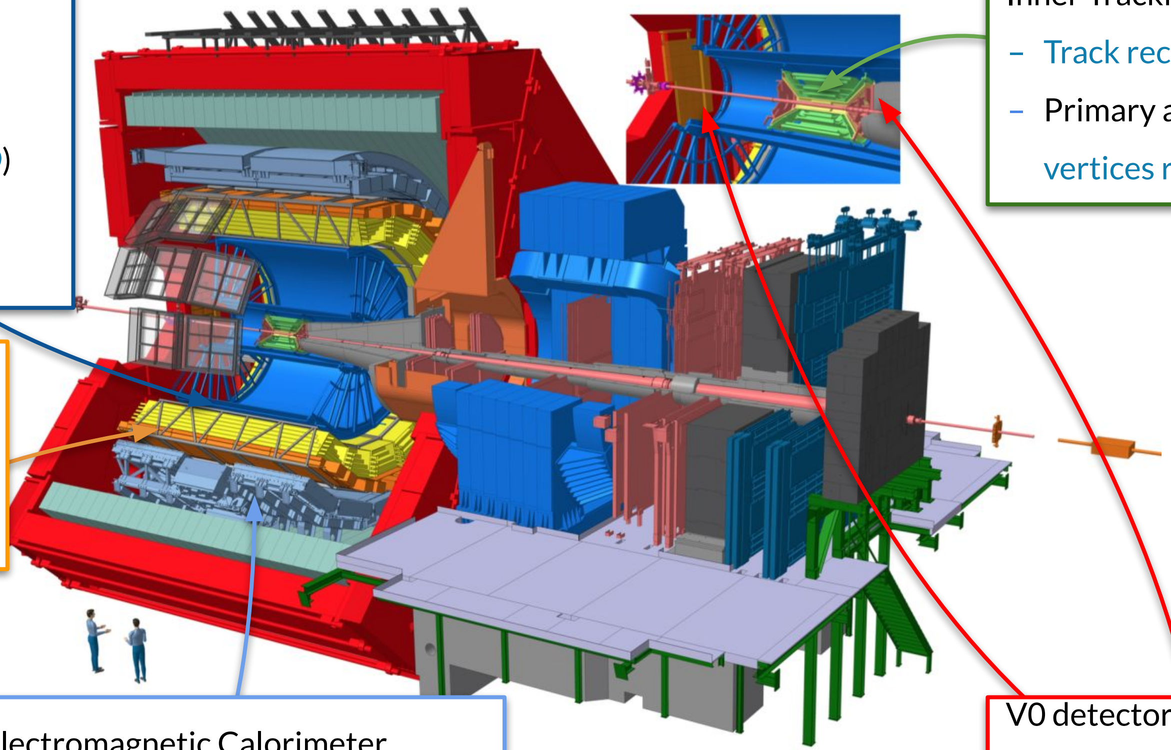


Time Projection Chamber:

- Track reconstruction
- Particle Identification (*PID*) via specific energy loss

Time Of Flight detector:

- PID via time-of -flight measurements



Inner Tracking System

- Track reconstruction
- Primary and decay vertices reconstruction

Electromagnetic Calorimeter

- PID via energy deposited
- Trigger

V0 detectors

- Trigger
- Centrality determination
- Event-plane estimation

ALICE in Run 3… and *beyond*

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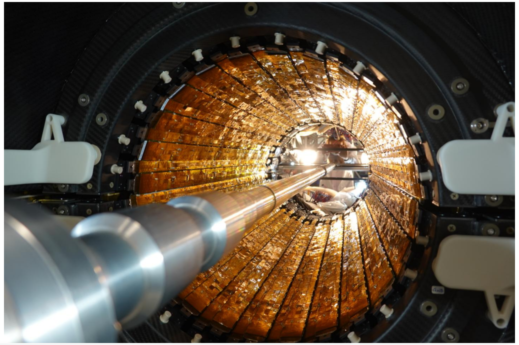
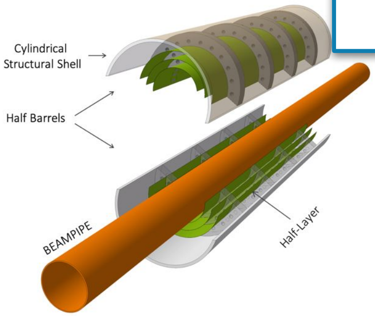
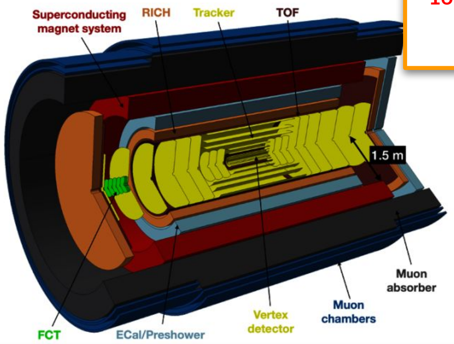
- ALICE upgrade for LHC Run 3 and 4 crucial for HF
  - increase collected Pb-Pb luminosity by more than one order of magnitude
  - new silicon Inner Tracking System (ITS)
    - ➡ Run 3: ITS2 (TDR: CERN-LHCC-2013-024)
    - ➡ Run 4: ITS3 (CERN-LHCC-2019-018 ; LHCC-I-034)
    - ➡ Run 5: all silicon ultra-light detector (ALICE 3)



A. Yuncu
15 Jun 2022,
08:40



R. Bailhache
16 Jun 2022,
12:05



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