Heavy-Flavour production, propagation, and hadronisation in QGP

LHCP 2024 on behalf of LHC Collaborations, Boston – 05/06/2024

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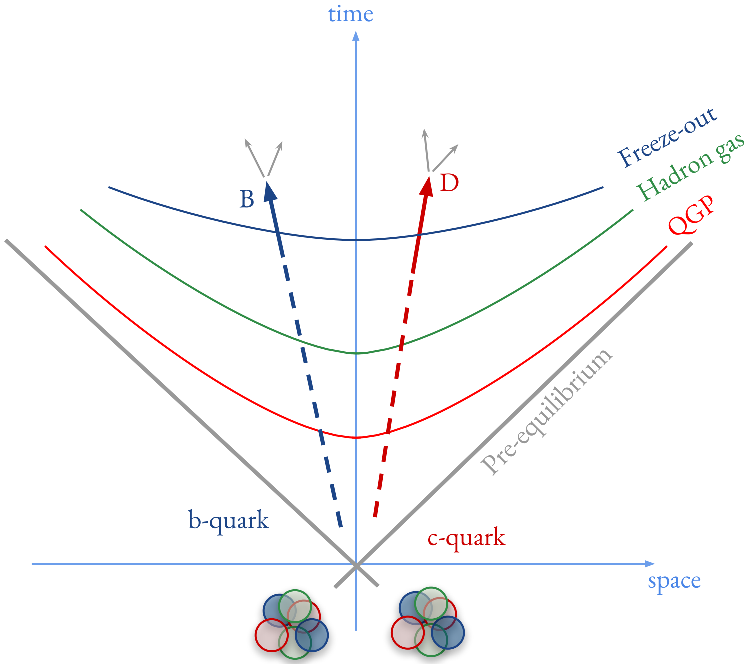
- Heavy quarks produced via hard scattering processes before quark-gluon plasma (QGP) formation
  - $\tau(\mathrm{HF}) \lesssim 0.1\ \mathrm{fm}/c < \tau(\mathrm{QGP}_{\mathrm{form.,\,LHC}}) \approx 0.3\ \mathrm{fm}/c$ (PRC 89 (2014) 034906)



Heavy quarks energy loss in QGP

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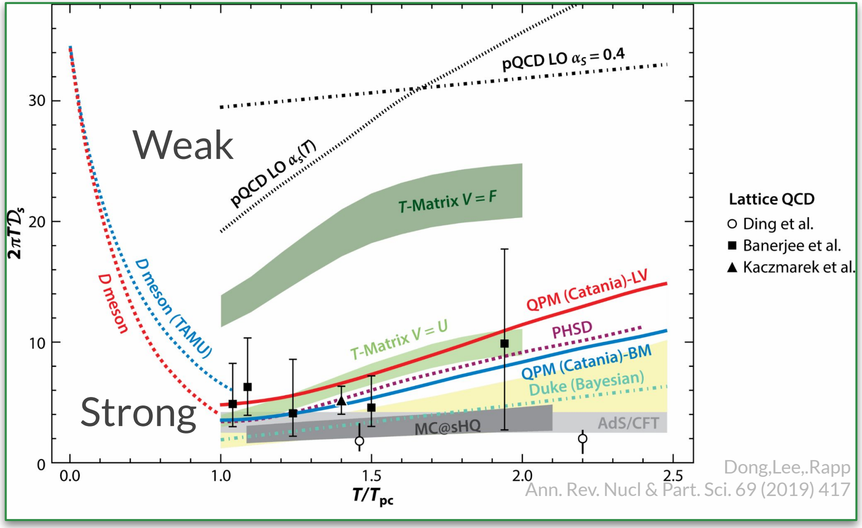
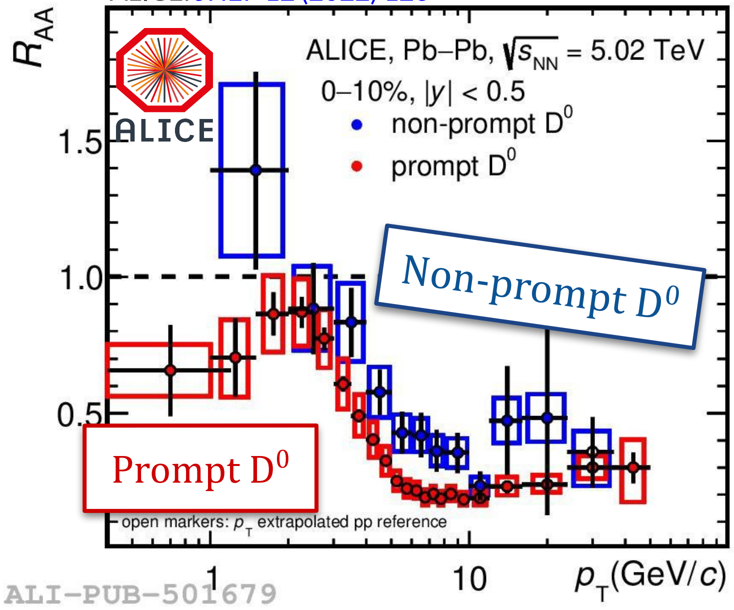
  - τ(HF) $\lesssim$ 0.1 fm/c < τ($QGP_{form., LHC}$) ≈ 0.3 fm/c (PRC 89 (2014) 034906)
  - Elastic interactions: HQs diffuse in QGP medium (Boltzmann, Fokker-Planck or Langevin)
    ➡ *Degree of thermalisation of heavy-quarks in the medium? Spatial diffusion coefficient (D_s)?*
  - Radiative interactions: energy loss of charm and beauty quarks in the medium
    ➡ *Colour-charge and quark-mass dependence?*
- Key observables: nuclear modification factor (R_{AA}) and elliptic flow (v_2)

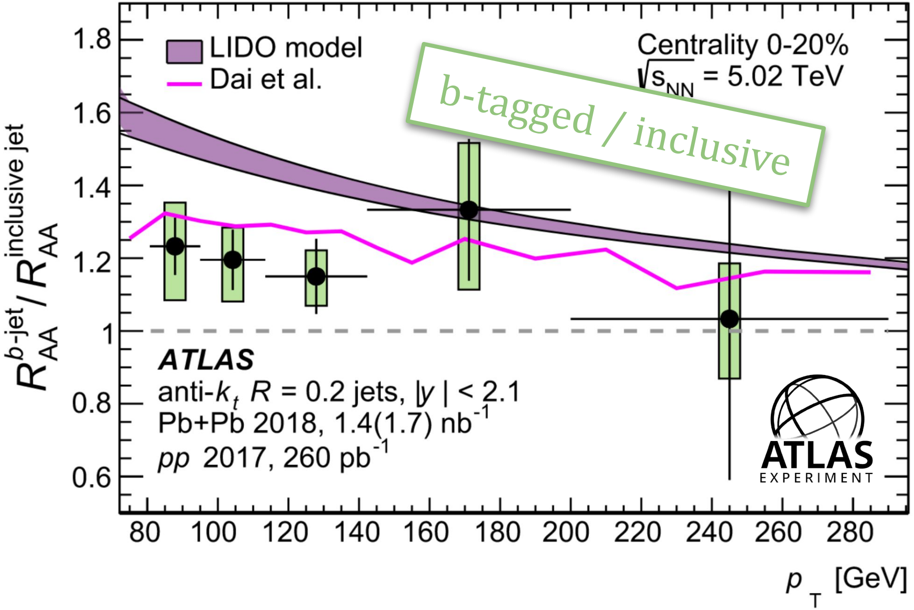


Dong,Lee,,Rapp
Ann. Rev. Nucl & Part. Sci. 69 (2019) 417

ALICE: JHEP 12 (2022) 126



ATLAS: EPJC (2023) 83:438



- R_{AA} (charm-hadron) < R_{AA}(beauty-hadron) at low p_T
- Different effects: flow, shadowing, recombination
  - Gluon radiation suppressed at angles smaller than $\theta < m_Q/E$
- b-tagged jets less suppressed than inclusive jets in central and midcentral Pb—Pb collisions
  - Not only mass effects, smaller suppression than gluon jets also due to colour factor

B-jet structure in heavy-ion collisions

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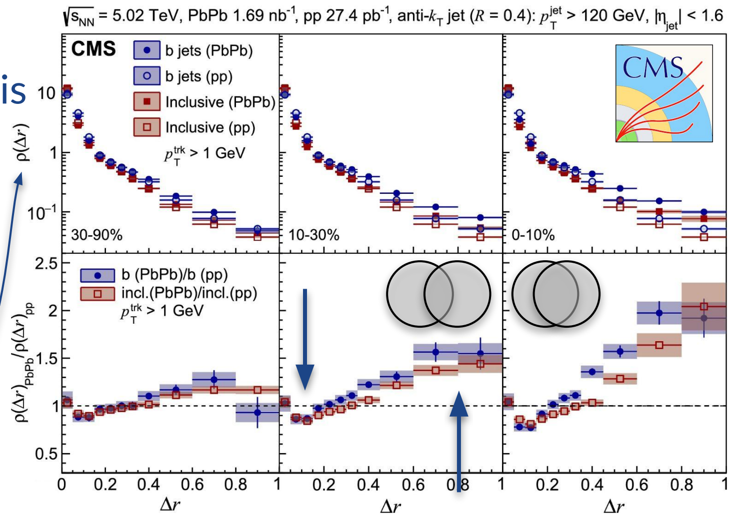
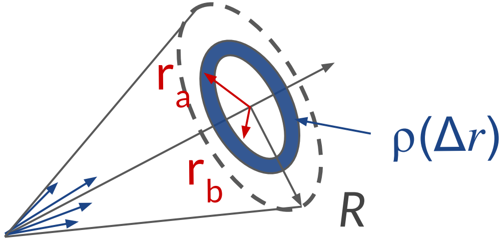
- Gain additional info studying jet shape: measure of charged-particle p_T profile w.r.t. radial distance from jet axis
  - ➡ Depletion of p_T at small Δr from jet axis compared to inclusive jet shapes, already present in pp
  - ➡ Enhancement at intermediate-large Δr which increases with centrality



$$\rho(\Delta r) = \frac{P(\Delta r)}{\Sigma_{\text{jets}} \Sigma_{\text{trk}\in(\Delta r<1)} p_T^{\text{trk}}}$$

$$P(\Delta r) = \frac{1}{\Delta r_b - \Delta r_a} \frac{1}{N_{\text{jet}}} \Sigma_{\text{jets}} \Sigma_{\text{trk}\in(\Delta r_a, \Delta r_b)} p_T^{\text{trk}}$$

Don't miss P. Das talk! (06/06)



CMS: PLB 844 (2023) 137849

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- Gain additional info studying jet shape: measure of charged-particle p_T profile w.r.t. radial distance from jet axis
  - ➡ Depletion of p_T at small Δr from jet axis compared to inclusive jet shapes, already present in pp
  - ➡ Enhancement at intermediate-large Δr which increases with centrality
  - ➡ Quantitative measurement of dead-cone effect for b-jets

$$\rho(\Delta r) = \frac{P(\Delta r)}{\Sigma_{jets} \Sigma_{trk \in (\Delta r < 1)} p_T^{trk}}$$

$$P(\Delta r) = \frac{1}{\Delta r_b - \Delta r_a} \frac{1}{N_{jet}} \Sigma_{jets} \Sigma_{trk \in (\Delta r_a, \Delta r_b)} p_T^{trk}$$

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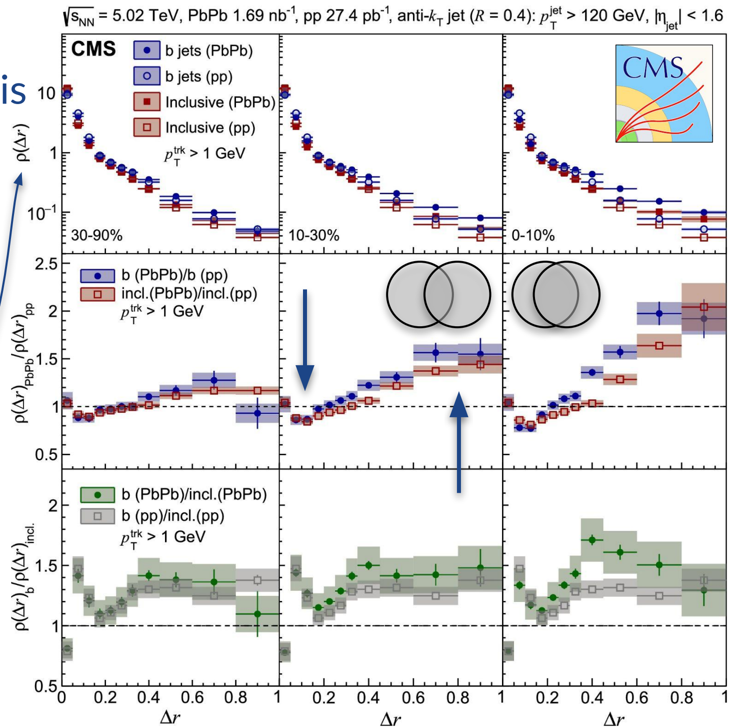

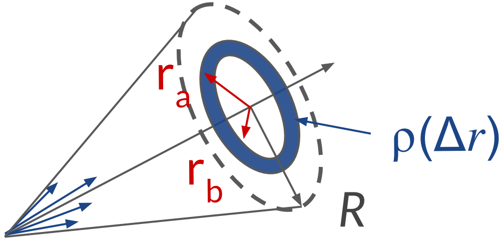

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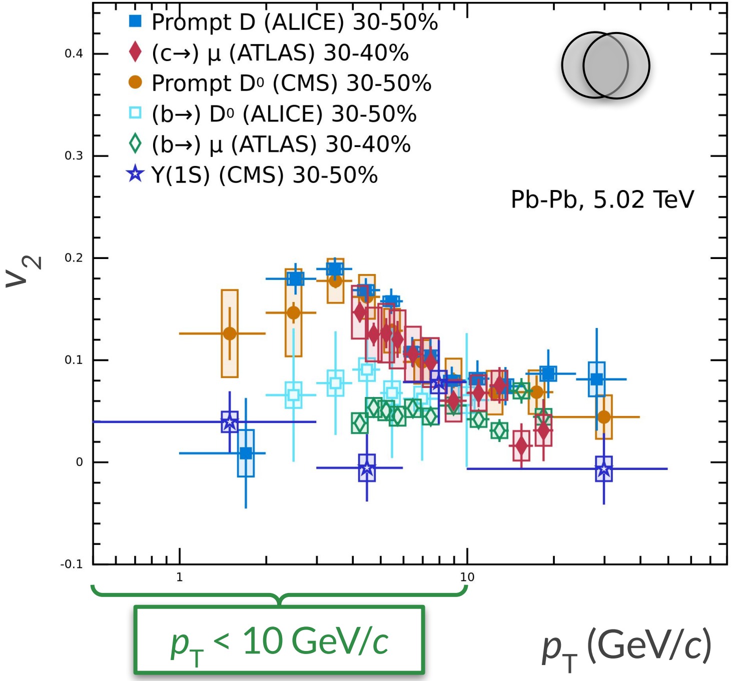

boundino.github.io/hinHFplot

Don't miss A. Dobrin talk! (07/06)

- Positive v_2 of HF hadrons and leptons from HQ decays
  - Participation to the collective motion of the system
  - Beauty v_2 lower than charm one for p_T < 10 GeV/c
    - ➡ Partial thermalisation of open beauty in QGP?

Prompt D ALICE (30–50%):
PLB 813 (2021) 136054
c→μ ATLAS (30–40%):
PLB 807 (2020) 135595
Prompt D^0 CMS (30–50%):
PLB 816 (2021) 136253
b→D^0 ALICE (30–40%):
EPJC 83 (2023) 1123
b→μ ATLAS (30–40%):
PLB 807 (2020) 135595
Υ(1S) CMS (30–50%):
PLB 819 (2021) 136385

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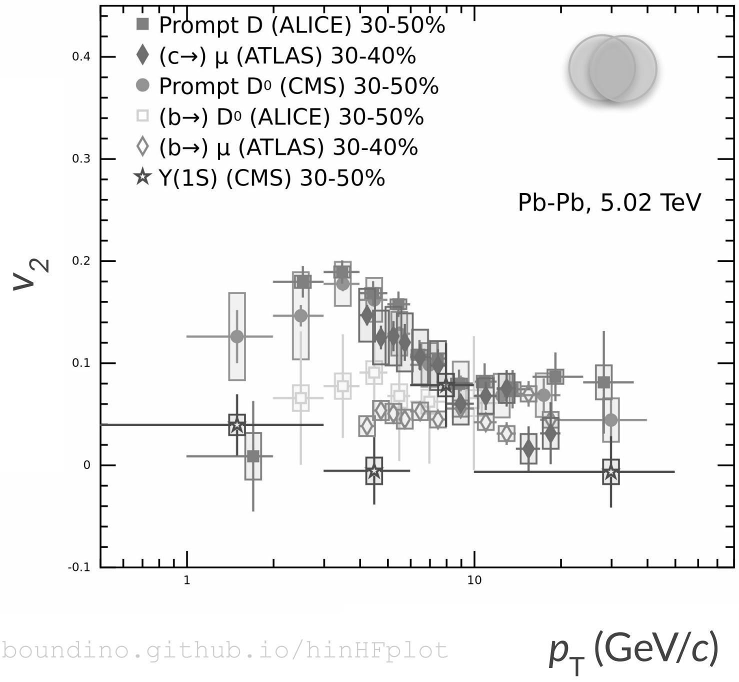

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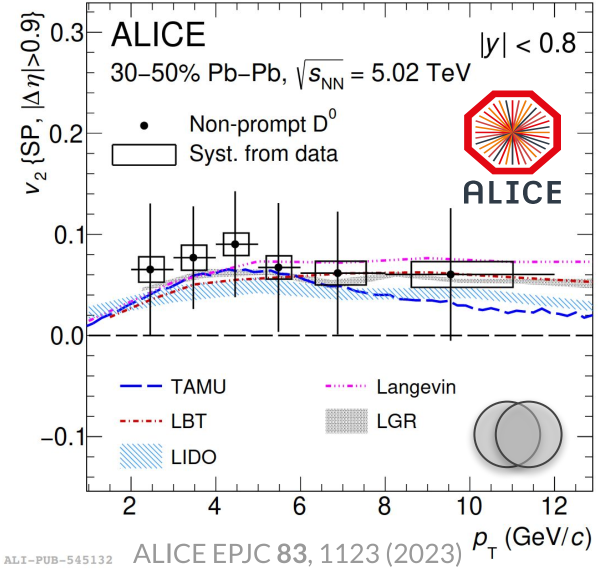

ALICE EPJC **83**, 1123 (2023)

- Transport models in hydrodynamical expanding QGP including collisional energy loss + coalescence describe data

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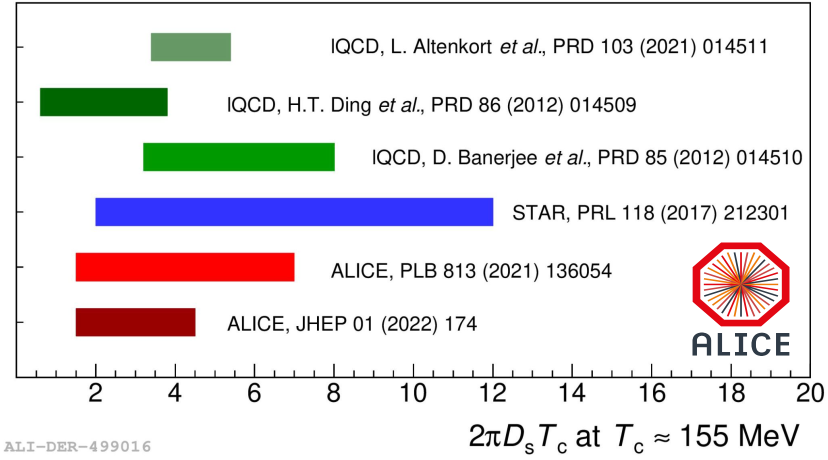
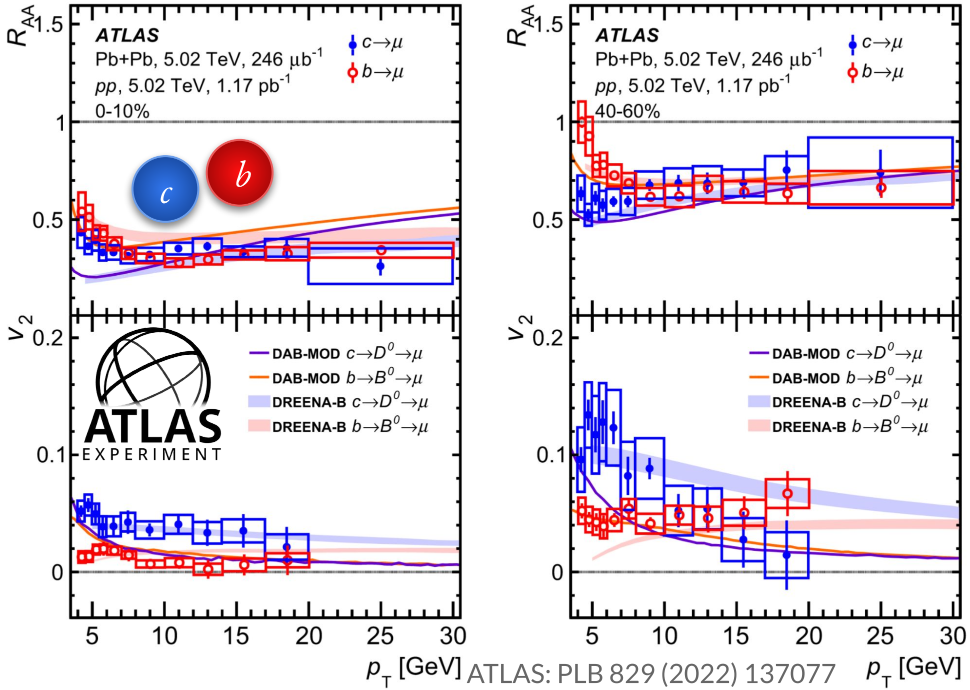


- R_{AA} and v_2 of muons from HF hadron decays from ATLAS
  - Charm: $2\pi D_s T_c$=2.23, Bottom: $2\pi D_s T_c$= 2.79
    - ➡ Compatible results between ATLAS and ALICE

- Constraining spatial diffusion coefficient D_s via D meson measurements
- Simultaneous fit to R_{AA} (χ^2/ndf < 5) and v_2 (χ^2/ndf < 2)
  - $1.5 < 2\pi D_s T_c < 4.5 \rightarrow \tau_{charm}$ = 3–8 fm/c



ATLAS: PLB 829 (2022) 137077

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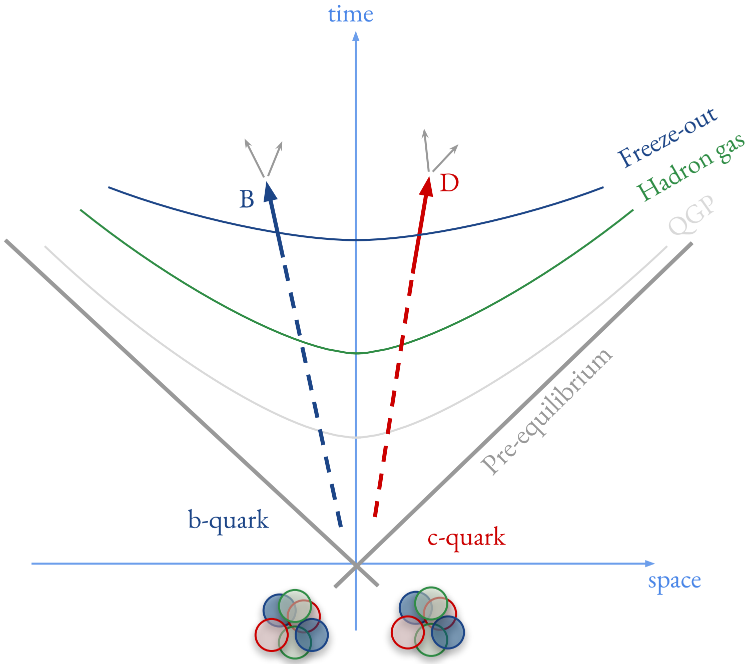
  - $\tau(\mathrm{HF}) \lesssim 0.1$ fm/c < $\tau(\mathrm{QGP}_{\mathrm{form., LHC}}) \approx 0.3$ fm/c (PRC 89 (2014) 034906)

- *Modification of hadronisation mechanism in presence of QGP?*



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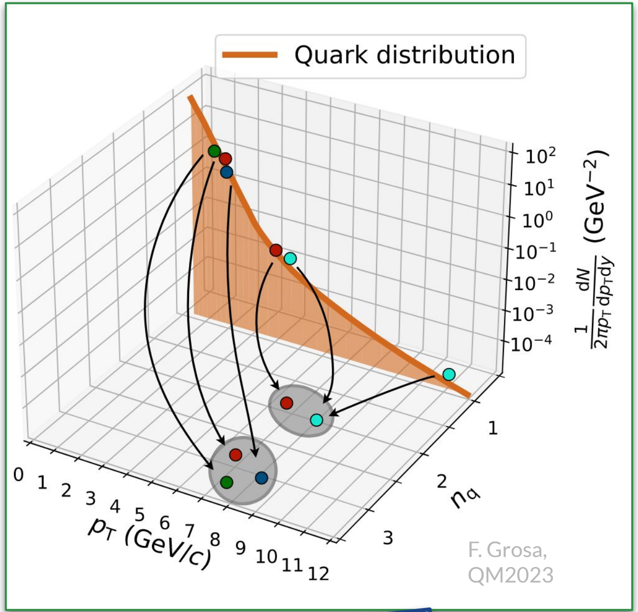
- *Modification of hadronisation mechanism in presence of QGP?*
  - Fragmentation $D_q \rightarrow H(z_q, Q^2)$: parton shares fraction of its momentum z_q with hadron H (dominant at high p_T)
  - Coalescence/Recombination: partons close in phase space recombine into higher p_T hadron (dominant at low p_T)

    ➡ *Higher baryon–to–meson ratio at intermediate p_T*

- Key observables: relative hadron production



Don't miss V. Feuillard talk! (05/06)

HF hadronisation: meson–to–meson ratios

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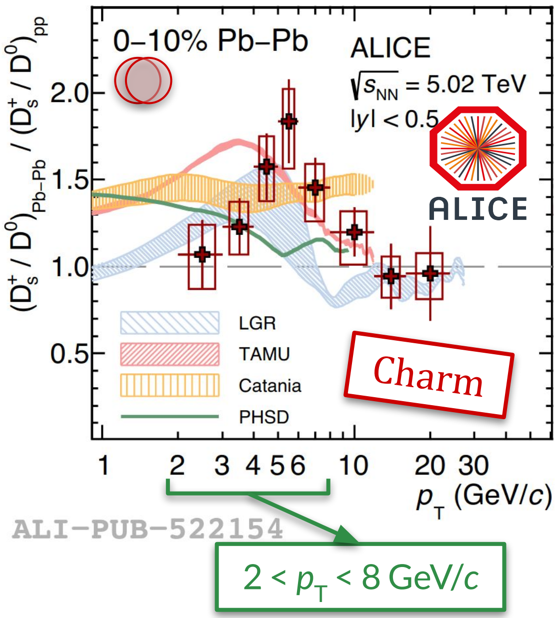
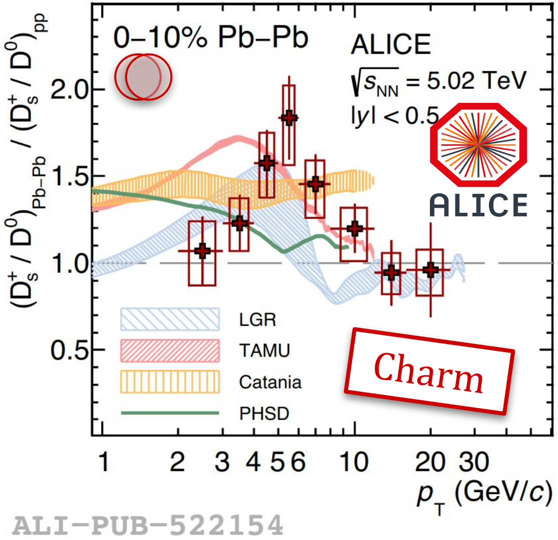
ALICE: PLB 827 (2022) 136986, TAMU: PRL 124, 042301 (2020), LGR: EPJC 80 (2020) 7, 671, Catania: PRC 96, 044905 (2017), PHSD: PRC 93, 034906 (2016)



- Higher D_s^+/D^0 in central Pb–Pb wrt pp in 2 < p_T < 8 GeV/c by 2.3σ
  - Hadronisation via recombination + strangeness enhancement
    - ➡ (Partial) thermal equilibrium required
- Described by transport models including strangeness enhancement and fragmentation + recombination

ALICE: PLB 827 (2022) 136986, TAMU: PRL 124, 042301 (2020), LGR: EPJC 80 (2020) 7, 671, Catania: PRC 96, 044905 (2017), PHSD: PRC 93, 034906 (2016)



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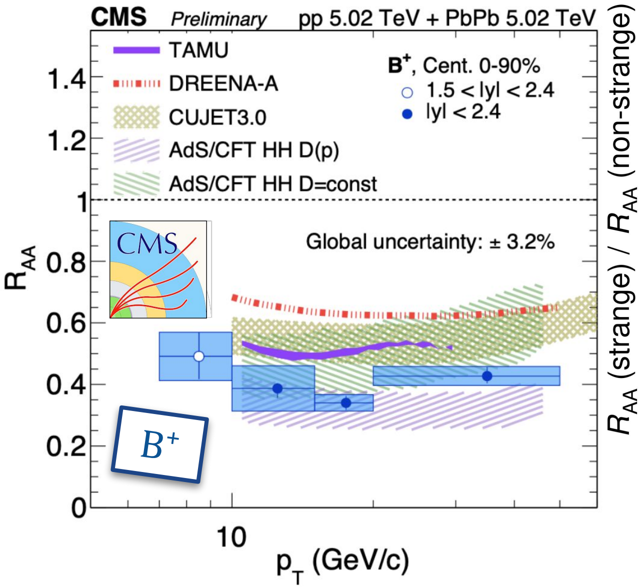
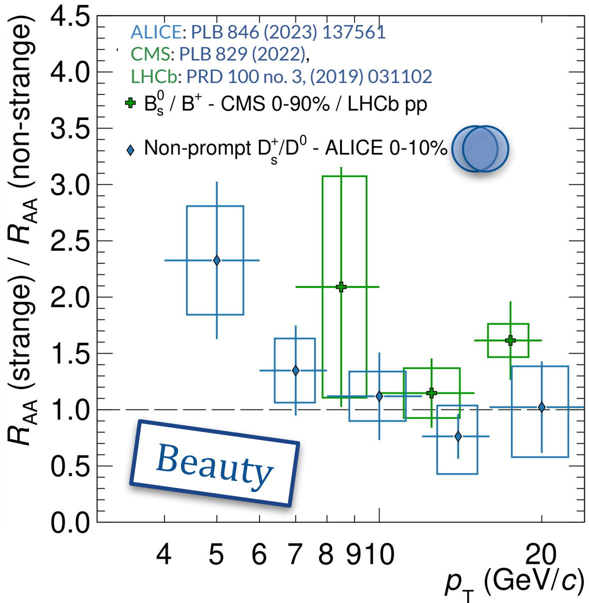
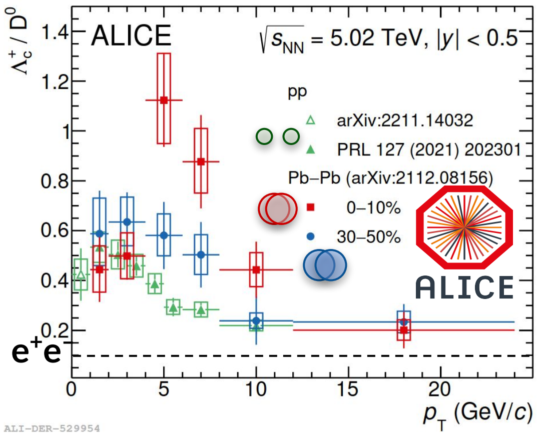
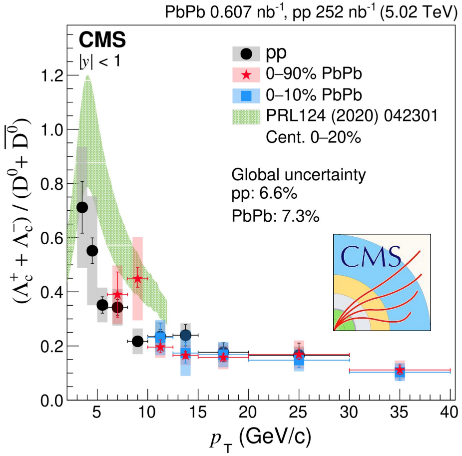
- Beauty measurements compatible with transport models implementing strangeness enhancement + recombination
  - ➡ More precise measurements and lower p_T reach needed



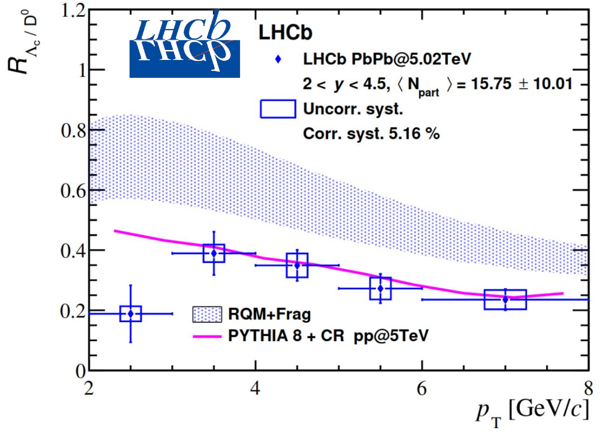




CMS: JHEP 01 (2024) 128



LHCb: JHEP06 (2023) 132



- Enhanced charm baryon-to-meson ratio wrt e^+e^-
  - Modification increasing from pp to central Pb–Pb collisions

    ➡ Similar results between ALICE and CMS

- First measurement of prompt Λ_c^+/D^0 at forward rapidities in Pb–Pb by LHCb in 65–90%
  - Similar to ALICE/CMS but lower in absolute values

    ➡ *Rapidity dependence? Specific for 65–90%?*

    ➡ PYTHIA8+CR compatible

    ➡ Down to 30% centrality in Run 3

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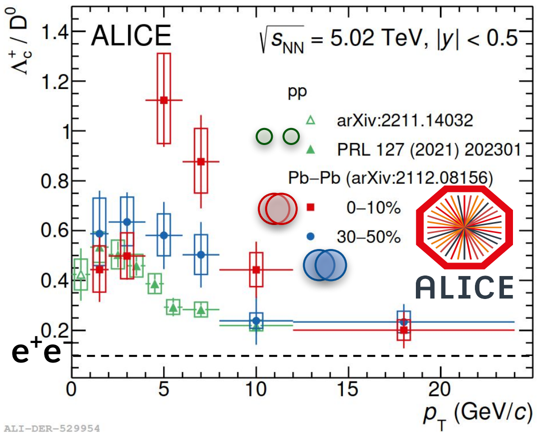
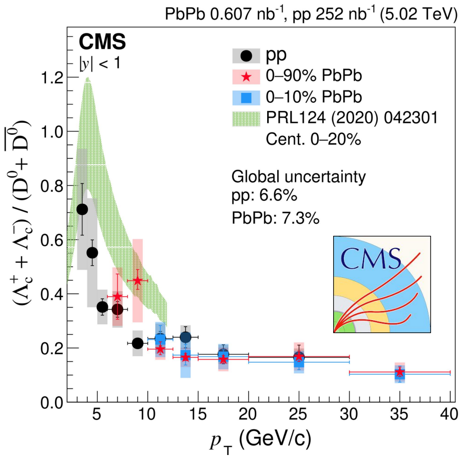
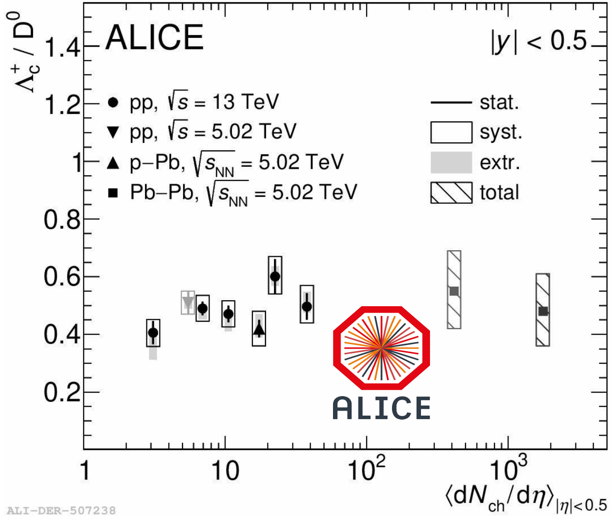


CMS: JHEP 01 (2024) 128





- Enhanced charm baryon-to-meson ratio wrt **e$^+$e$^-$**
  - Modification increasing from pp to central Pb–Pb collisions

  ➡ Similar results between ALICE and CMS

- p_T-integrated Λ_c^+/D^0 ratio as function of average charged-particle multiplicity
  - Similar values from pp, p–Pb, to Pb–Pb

  ➡ Different p_T redistribution between baryons and mesons?

Summary

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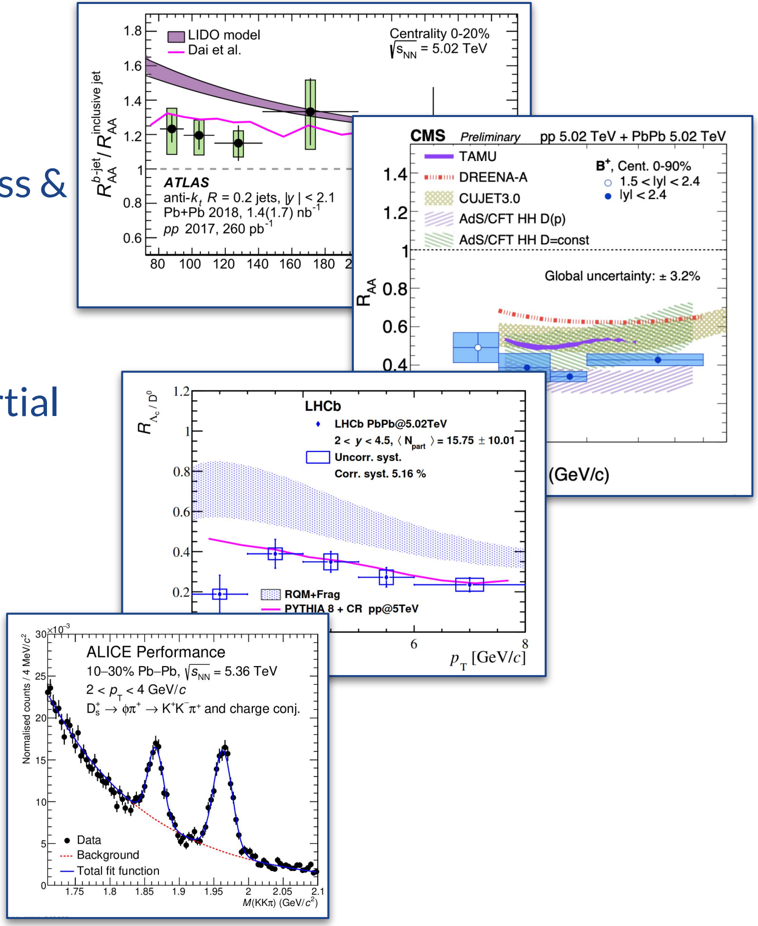
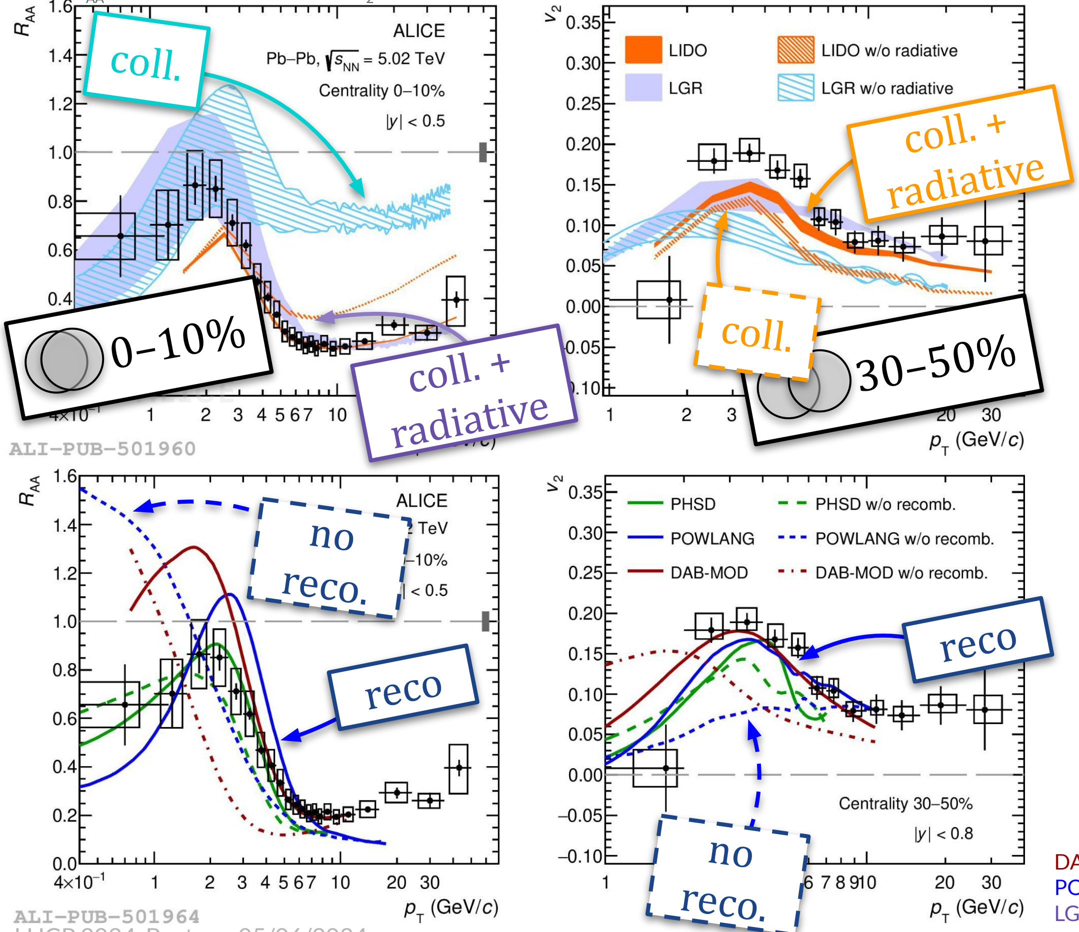
- Many HF observables measured at LHC
  - Nuclear modification factor R_{AA}
    - ➡ HF quarks undergo energy loss in the medium → mass & color-charge dependence of in-medium energy loss
  - Azimuthal anisotropy
    - ➡ Positive beauty v_2 observed →lower than charm, partial beauty thermalisation?
  - Baryon/meson and meson/meson ratios
    - ➡ Role of coalescence in charm-baryon formation
    - ➡ Room for improvements in beauty sector
- *What's next? Run 3!*



Additional material

R_{AA}: JHEP 01 (2022) 174 v_2: PLB 813 (2021) 136054



- Constrain c-quark D_s by comparing v_2 and R_{AA} simultaneously
  - very challenging for transport models
- Differential comparisons:
  - radiative energy loss
    - ➡ no significant effect at low pT
  - fragmentation + coalescence necessary
    - ➡ important to describe low-intermediate p_T

DAB-MOD: PRC 96, 064903 (2017) LIDO: PRC 98, 064901 (2018)
POWLANG:EPJC 75 (2015) 3, 121 PHSD: PRC 93, 034906 (2016)
LGR: EPJC 80 (2020) 7, 671

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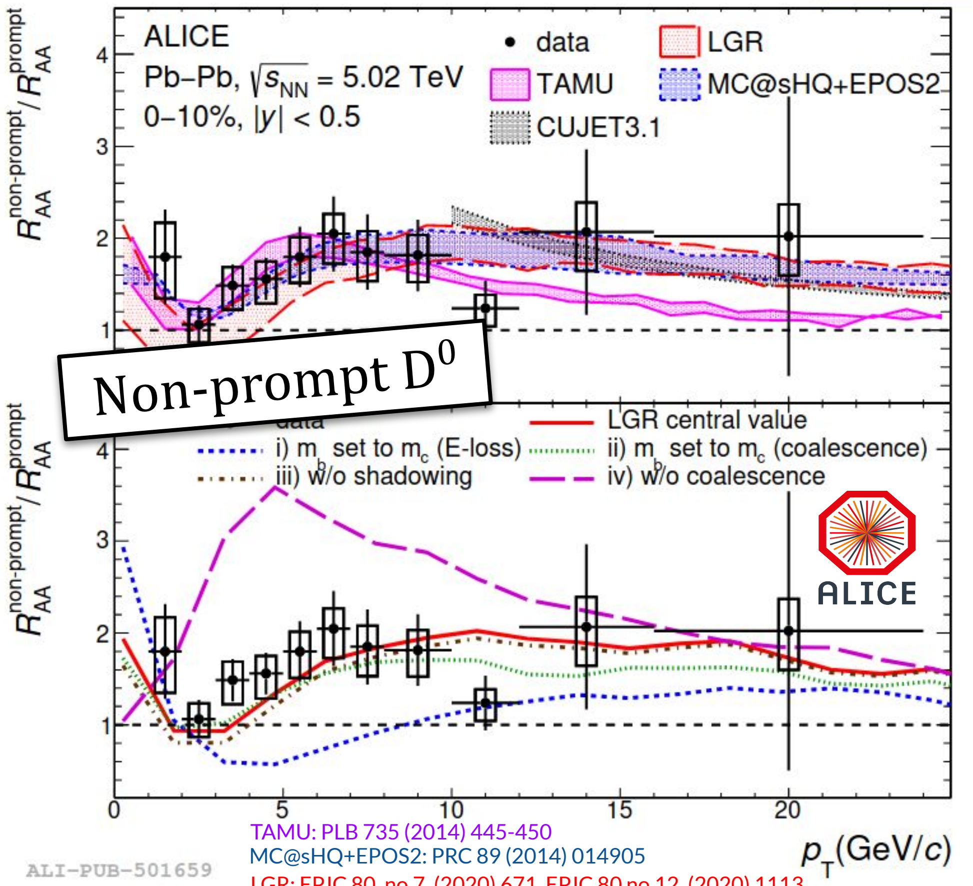

TAMU: PLB 735 (2014) 445-450
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: EPJC 80, no.7, (2020) 671, EPJC 80 no.12, (2020) 1113
CUJET3.1: JHEP02(2016)169

- R_{AA}(non-prompt D^0) / R_{AA} (prompt D^0) 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
- Testing LGR ingredients effect
  - "valley" structure pT < 5 GeV/c
    - ➡ charm coalescence (iv)
  - enhancement for p_T > 5 GeV/c
    - ➡ mass dependent quark in-medium energy loss effect (i)

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- Boltzmann equation for HQ phase-space distribution (f_1)

$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{E}\cdot\vec{\nabla}_r - (\vec{\nabla}_r V)\cdot\vec{\nabla}_p\right) f_1(\vec{r},\vec{p},t) = I_{\mathrm{coll}}(f_1)$$

— collision term: semiclassical simulation of medium + HQ quasiparticles

— consider $p^2 \sim m_Q T >> q^2 \sim T^2$ (e.g. HF)

- Fokker-Planck equation

$$\frac{\partial f_Q(p,t)}{\partial t} = \frac{\partial}{\partial p_i}\left[A_i(p) + \frac{\partial}{\partial p_j}B_{ij}(p)\right] f_Q(p,t)$$

— impose the $p \to 0$ limit

$$\frac{\partial f_Q}{\partial t} = \gamma\frac{\partial}{\partial p_i}(p_i f_Q) + D\frac{\partial}{\partial p_i}\frac{\partial}{\partial p_i} f_Q$$

arXiv:0803.0901v2

— relaxation time: $t_Q = 1/\gamma$

— spatial diffusion coefficient: $D_s = T/[\gamma(p{=}0)m_Q] \to \gamma = Tm_Q/D_s$

Transport models

Models	Bulk	nPDFs	HQ interactions	Hadronization	Hadron phase	D_s	Ref.
CATANIA	Boltzmann quasi-particles		Langevin	Recomb. (ICM) + Frag.	No	3.5-4.5	Phys. Rev. C 96 (2017) 044905 (R_{AA}) Phys. Lett. B 805 (2020) 135460 (v_2)
DAB-MOD (M&T)	Hydro viscous (v-USPhydro)		Langevin	Recomb. (ICM) + Frag.	No	2.5	Phys. Rev. C 102, 024906 (2020)
LBT	Hydro viscous (VISHNew)	Yes	Boltzmann coll+rad	Recomb. (ICM) + Frag.	No	2	Phys. Rev. C 94 (2016) 014909 Phys. Lett. B 777 (2018) 255
LIDO	Hydro viscous		Boltzmann Langevin coll+rad	Recomb. (ICM) + Frag.	Yes	2-4	Phys. Rev. C 100, 064911
LGR	Hydro viscous (3+1 HLLE)	Yes	Langevin coll+rad	Recomb. + Frag.		2-4	Eur. Phys. J. C, 80 (2020) 671
MC@sHQ+ EPOS2	Hydro ideal (EPOS)	Yes	Boltzmann coll+rad	Recomb. (ICM) + Frag.	No	1.5	Phys. Rev. C 89 (2014) 014905
PHSD	off-shell parton transport	Yes	Collisional	Recomb. (ICM) + Frag.	Yes	4	Phys. Rev. C 93, 034906 (2016) (LHC) Phys. Rev. C 92, 014910 (2015)
POWLANG	Hydro viscous (ECHO-QGP)	Yes	Langevin coll	In-medium strings	No	7	Eur. Phys. J. C 75 (2015) 121 (R_{AA}) JHEP 02 (2018) 043 (v_2)
TAMU	Hydro ideal	Yes	Langevin T-matrix (coll)	Recomb. (RRM) + Frag.	Yes	4	Phys. Rev. Lett. 124, 042301 (2020)