

Charm and beauty production measurements to constrain transport models with ALICE

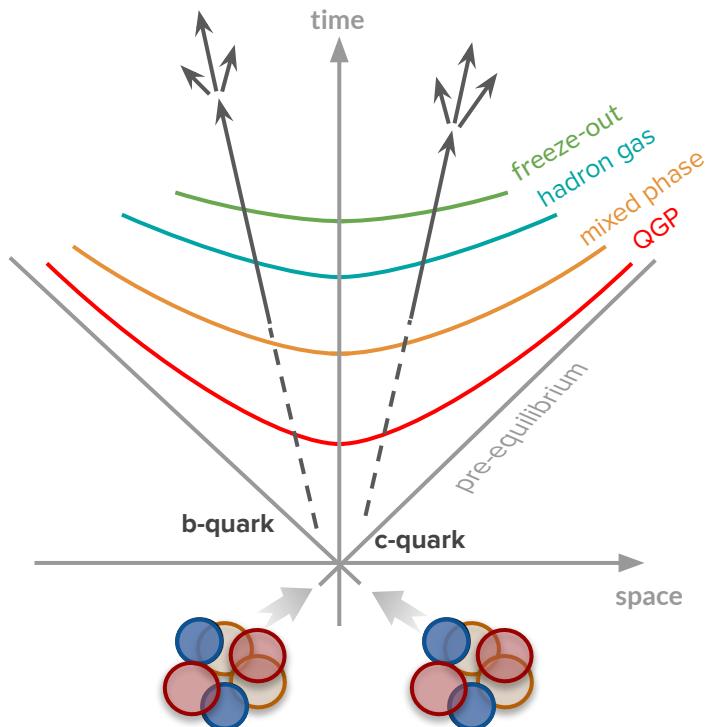


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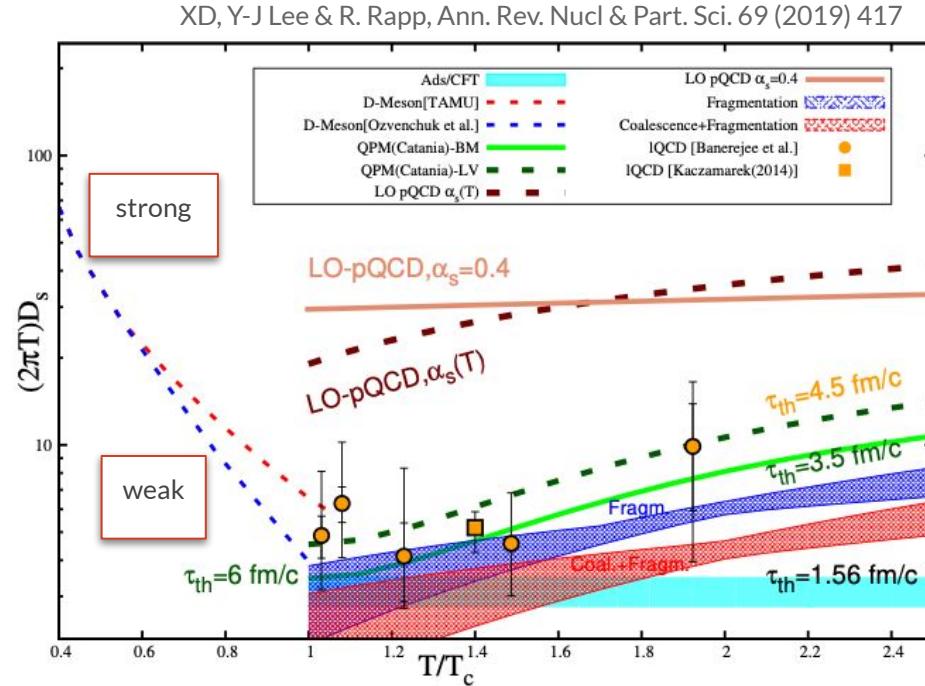
Politecnico and INFN Torino, on behalf of the **ALICE Collaboration**

EuNPC, Santiago de Compostela - 27/10/2022

- Quantum chromodynamics calculations on lattice predict phase transition from ordinary nuclear matters to colour-deconfined medium: quark-gluon plasma (QGP)
 - ultra-relativistic heavy-ion collisions
 - $\epsilon > 15 \text{ GeV/fm}^3$
- Heavy flavours (i.e. b and c quarks) produced in hard scattering processes during first stages of the collision
 - $T_b < T_c < T_{QGP} \sim 0.3 \text{ fm}/c$
Phys. Rev. C 89, 034906
 - probe the full system evolution



- HF propagating in the QGP
 - interact with medium constituents
 - lose energy via **elastic collisions** and **radiative processes**
 - low- p_T HF interactions described by transport models in terms **diffusion coefficient (D_s)**
 - investigate strong/weak coupling regime
 - direct access to HF **relaxation time**
 - heavy-quark **thermalisation** in the QGP?
 - constrain D_s !



A Large Ion Collider Experiment

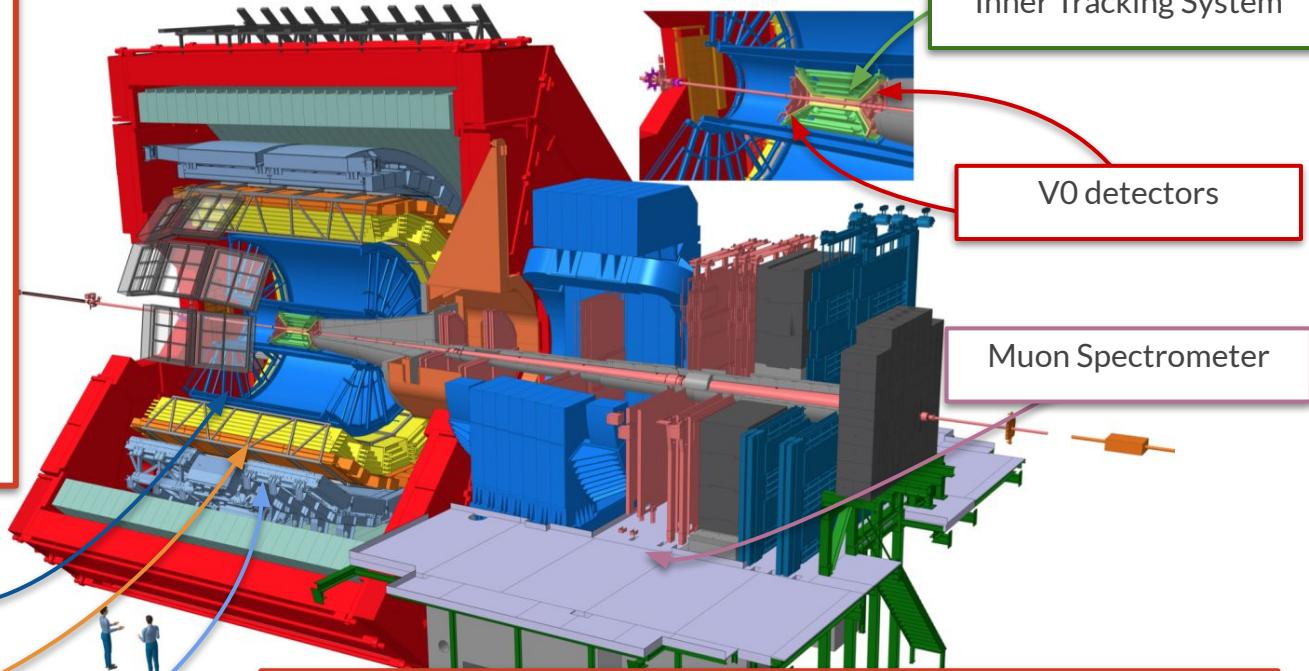
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Open HF hadrons fully
reconstructed via hadronic
decays in Pb-Pb collisions

- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$
- $D^{**} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
- $\Lambda_c^+ \rightarrow K_s^0 p \rightarrow \pi^- \pi^+ p$
- $c, b \rightarrow e/\mu^\pm X$



Time Projection Chamber

Time Of Flight detector

Electromagnetic Calorimeter

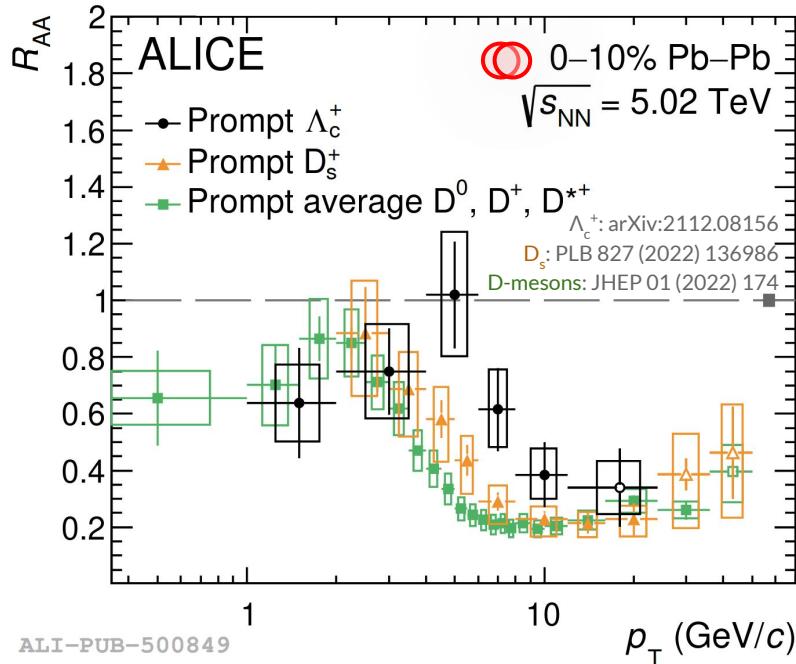
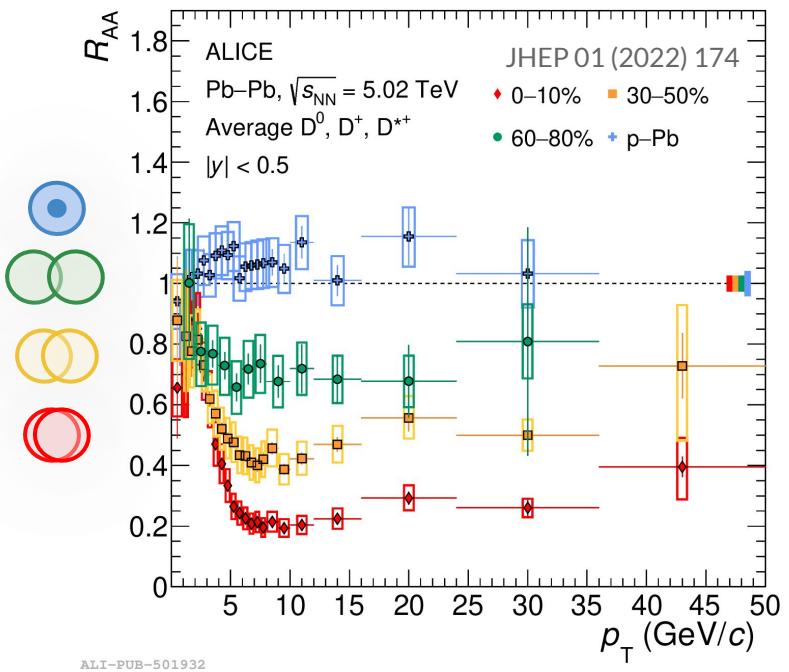
Data samples

- Pb-Pb $\sqrt{s} = 5.02$ TeV
 - 2015: $L_{\text{int}} \sim 13 \mu\text{b}^{-1}$ (MB)
 - 2018: $L_{\text{int}} \sim 130 \mu\text{b}^{-1}$ (0-10%), $\sim 56 \mu\text{b}^{-1}$ (30-50%)

Charm in-medium energy loss

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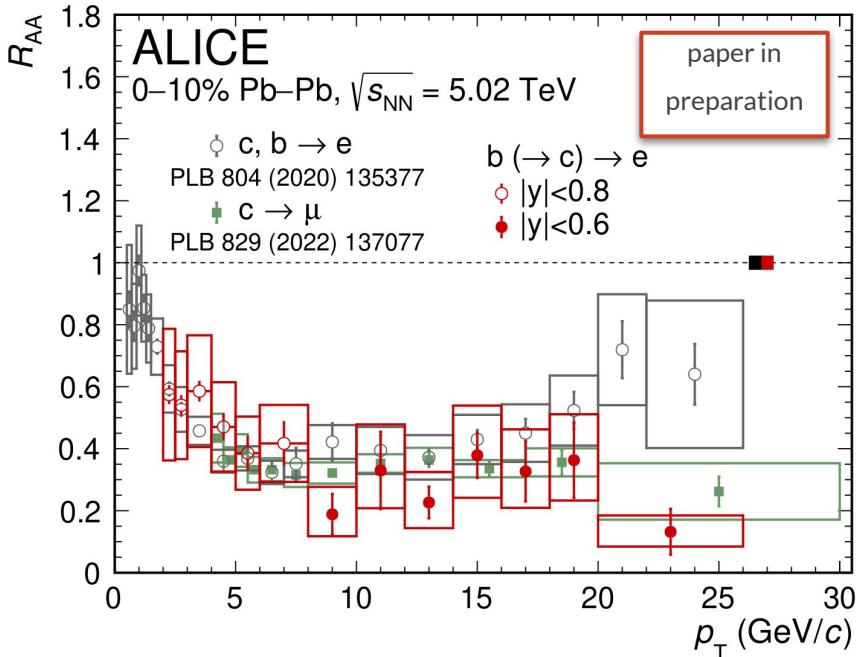
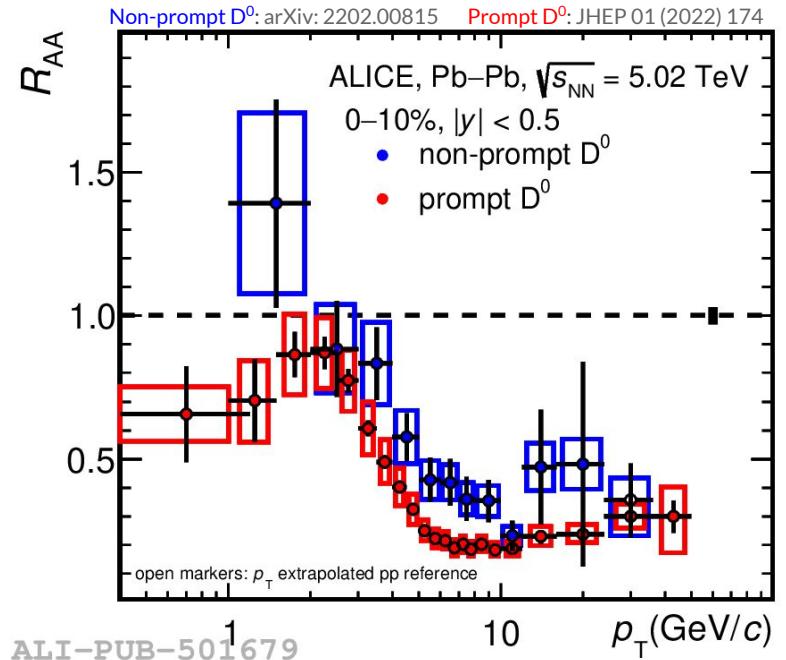
- From semicentral to central collisions:
 - clear p_{T} dependence: minimum at $p_{\text{T}} = 6 - 8 \text{ GeV}/c$
 - significant centrality hierarchy

- Hint of hierarchy, $R_{\text{AA}}(\Lambda_c^+) > R_{\text{AA}}(D_s^+) > R_{\text{AA}}(D)$ for $p_{\text{T}} > 4 \text{ GeV}/c$ in most central collisions
 - modified hadronisation mechanisms? Interplay with radial flow?

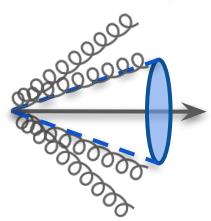
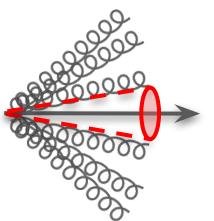
Beauty in-medium energy loss

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- Direct B measurements not accessible
 - beauty study via non-prompt D and leptons from b quark
- R_{AA} (charm-hadron) $<$ R_{AA} (beauty-hadron) at low p_{T}
 - in-medium energy-loss mass dependence (dead cone effect)

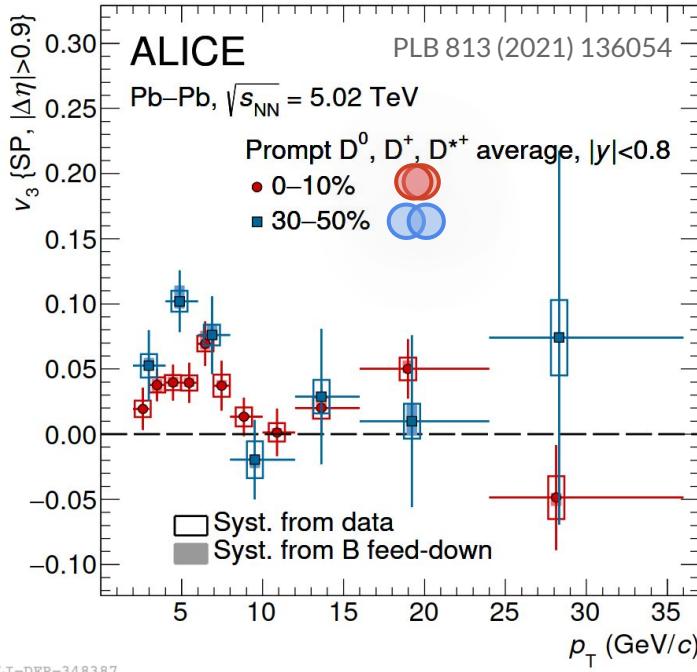
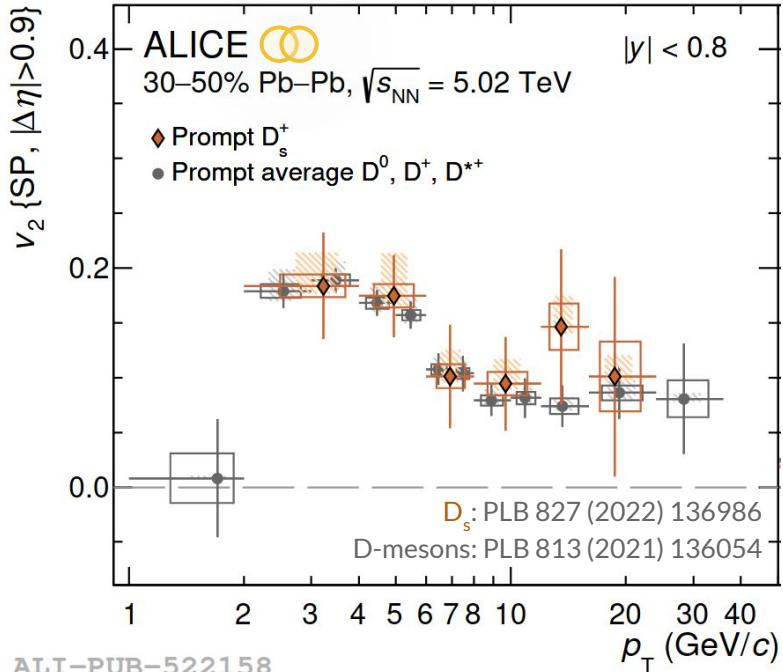


Charm thermalization in QGP medium

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- Significant elliptic (v_2) and triangular (v_3) flow for charm
 - positive $D_s^+ v_2 (6.4\sigma)$: charm participation to collective expansion
 - potential difference w.r.t. non-strange D?
 - charm thermalisation with the surrounding medium

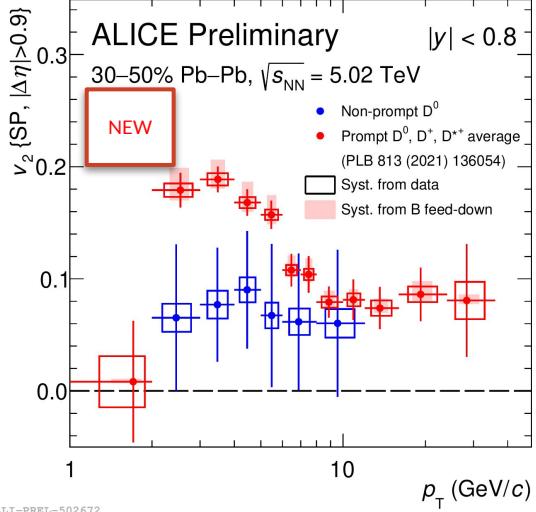
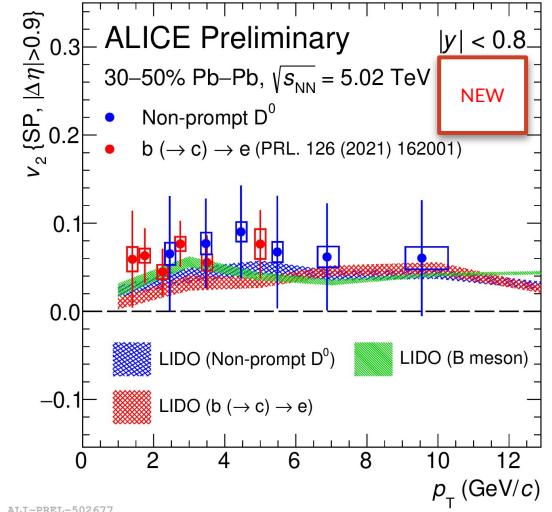
Beauty quark collectivity

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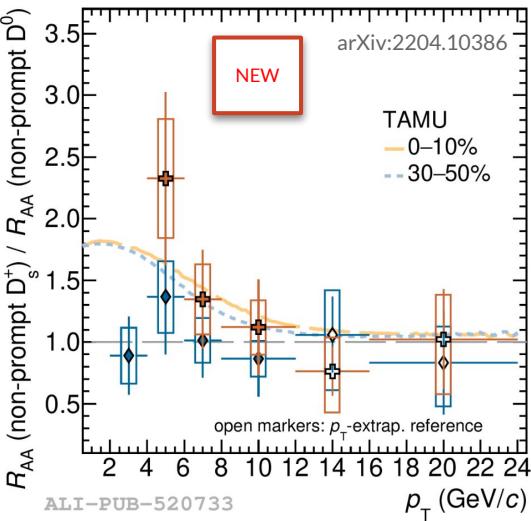


Phys. Rev. Lett. 126 (2021) 162001



- Non-prompt $D_s^+ / D^0 R_{AA}$ ratio show **hint of enhancement** (1.6σ)
 - strangeness-rich environment + coalescence
 - still compatible with **no-enhancement scenario**
 - Run 3 crucial to study b-sector

- Positive non-prompt D^0 and $b \rightarrow e v_2$:
 - 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 $2 < p_T < 8 \text{ GeV}/c$**
 - charm and beauty quarks participate differently to collective motion



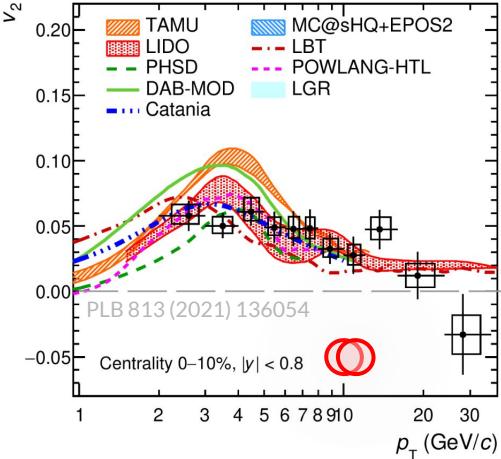
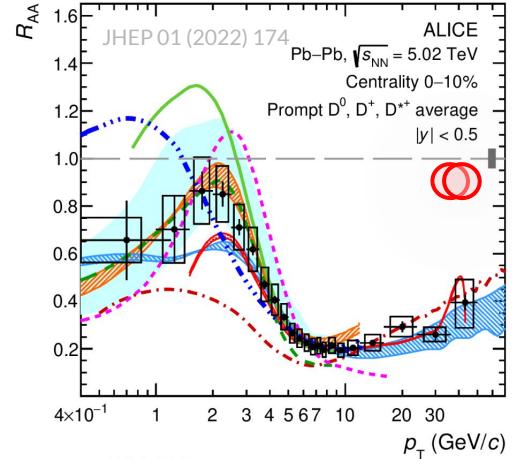
Constraining charm quark diffusion coefficient

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TAMU: PRL 124, 042301 (2020) DAB-MOD: PRC 96, 064903 (2017) LBT: PLB 777 (2018) 255-259 LIDO: PRC 98, 064901 (2018) Catania: PRC 96, 044905 (2017)
POWLANG: EPJC 75 (2015) 3, 121 PHSD: PRC 93, 034906 (2016) MC@sHQ: PRC 91, 014904 (2015) LGR: EPJC 80 (2020) 7, 671



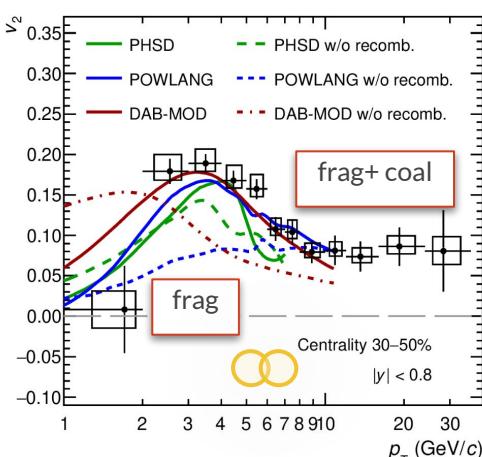
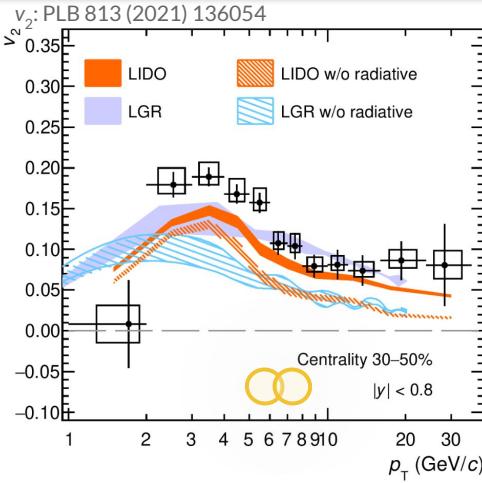
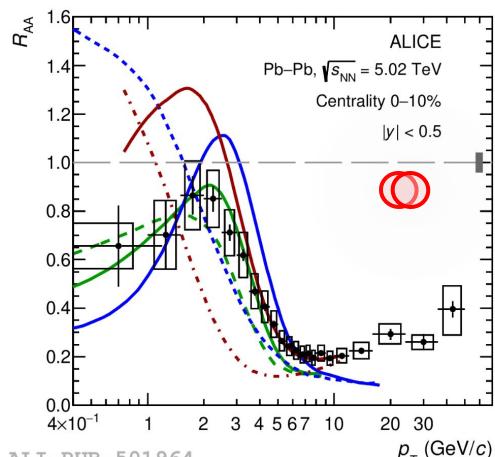
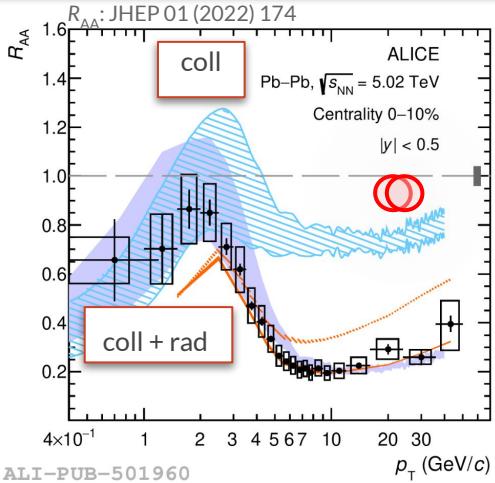
- Constrain c-quark D_s comparing v_2 and R_{AA} simultaneously
 - very challenging for transport models

ALI-PUB-501952

Constraining charm quark diffusion coefficient

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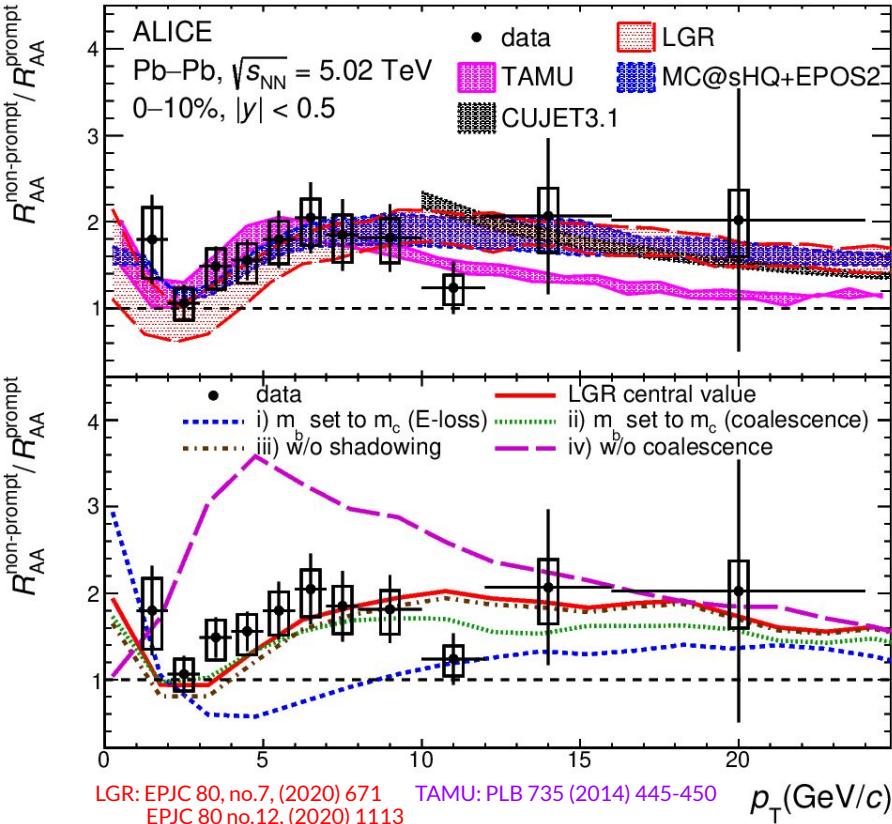


- Constrain c-quark D_s comparing v_2 and R_{AA} simultaneously
 - very challenging for transport models
- More differential comparisons available
 - radiative energy loss
 - no significant effect in low p_T region
 - fragmentation + coalescence necessary
 - important to describe low-intermediate p_T

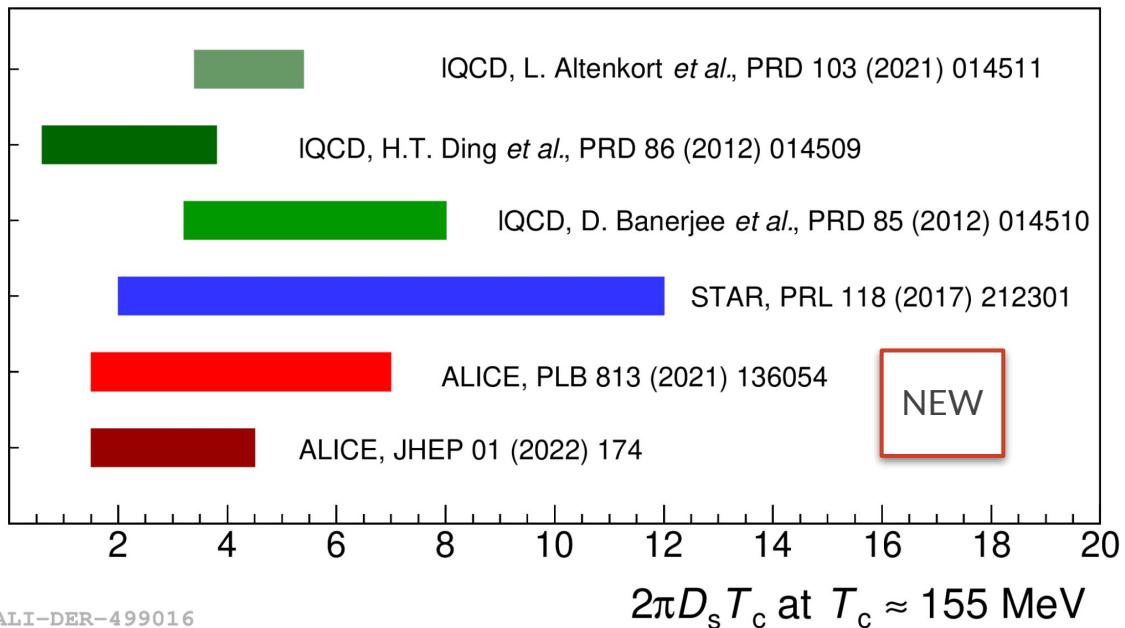
Addressing beauty energy loss via non-prompt D⁰

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- 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**
- 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)**



- Data-to-model agreement
 - χ^2/ndf analysis performed for R_{AA} ($\chi^2/\text{ndf} < 5$) and v_2 ($\chi^2/\text{ndf} < 2$) non-strange D measurements
 - TAMU, MC@sHQ, LIDO, LGR, and Catania “selected”
 - $1.5 < 2\pi D_s T_c < 4.5$
 - $T_{\text{charm}} = 3\text{--}8 \text{ fm}/c$

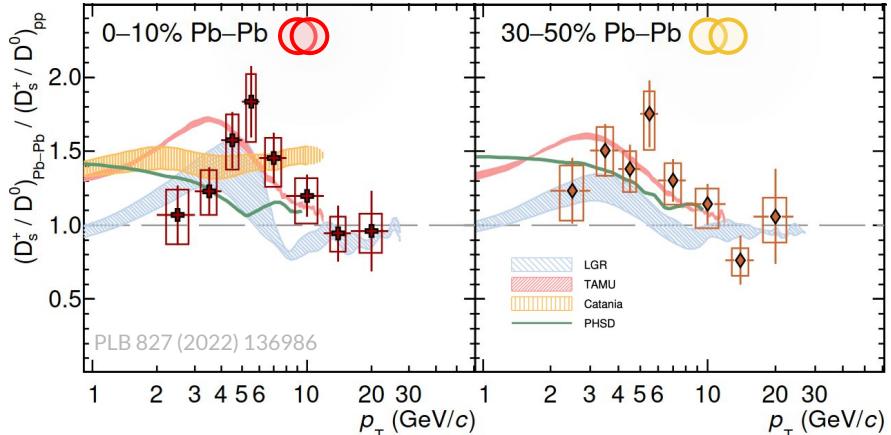
Probe HF hadronisation

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

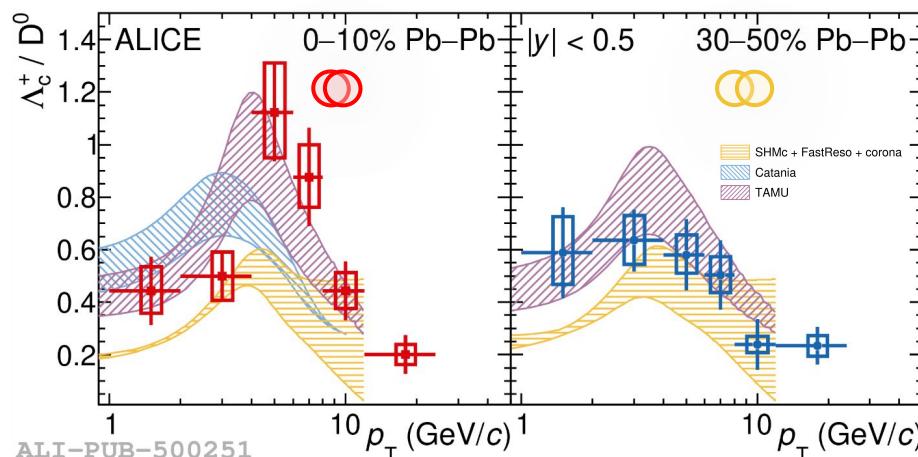


- **Baryon-to-meson ratio**

- Λ_c^+ / D^0 ratio is enhanced in $4 < p_T < 8$ GeV/c for central Pb-Pb wrt pp collisions by 3.7σ
- Data described by TAMU, Catania, and SHMc predictions agree qualitatively
- different redistribution of p_T between baryons and mesons?

- **Meson-to-meson ratio**

- D_s^+ / D^0 ratio is higher in $2 < p_T < 8$ GeV/c in 0-10% (30-50%) Pb-Pb by 2.3σ (2.4σ)
- Described by models including strangeness enhancement and fragmentation + recombination



TAMU: PRL 124, 042301 (2020) Catania: PRC 96, 044905 (2017) SHMc: JHEP 07 (2021) 035

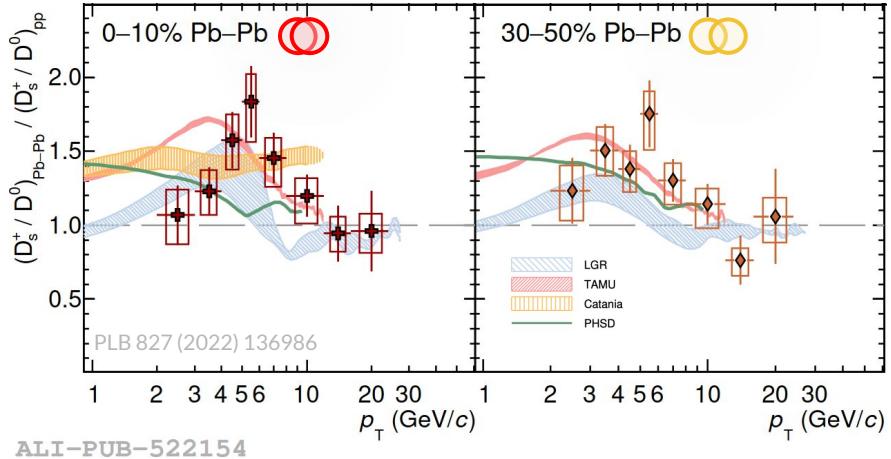
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TAMU: PRL 124, 042301 (2020) LGR: EPJC 80 (2020) 7, 671 Catania: PRC 96, 044905 (2017) PHSD: PRC 93, 034906 (2016)

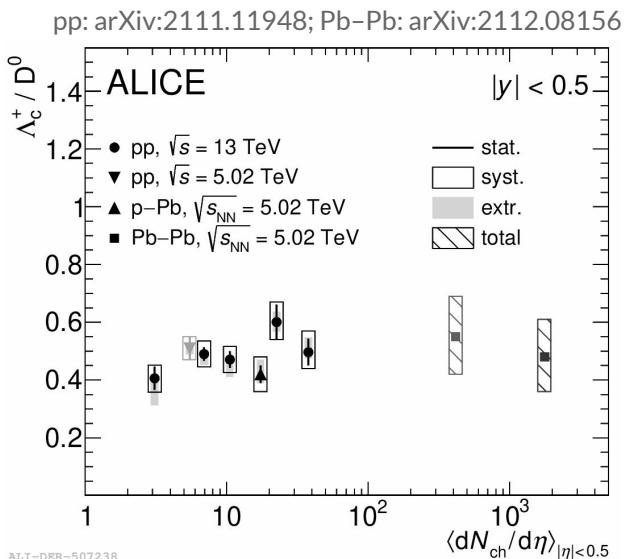


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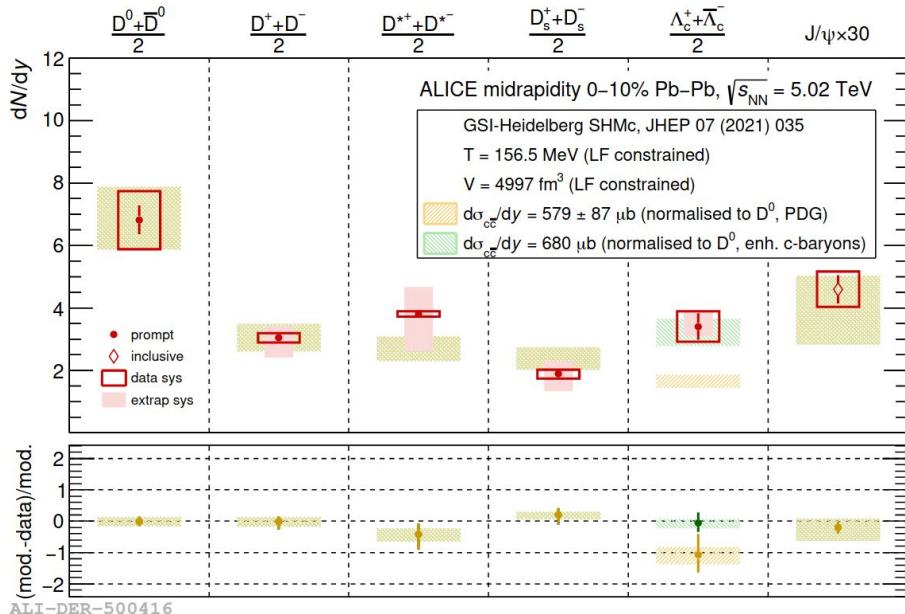
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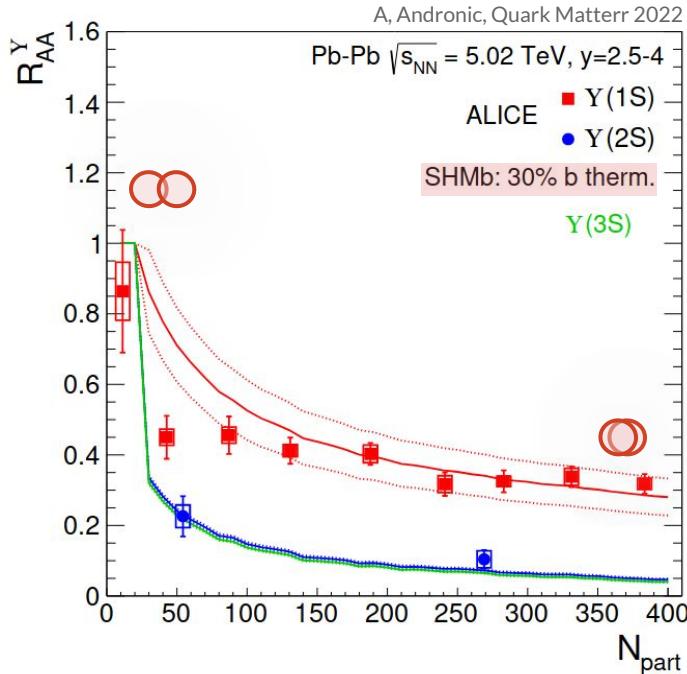
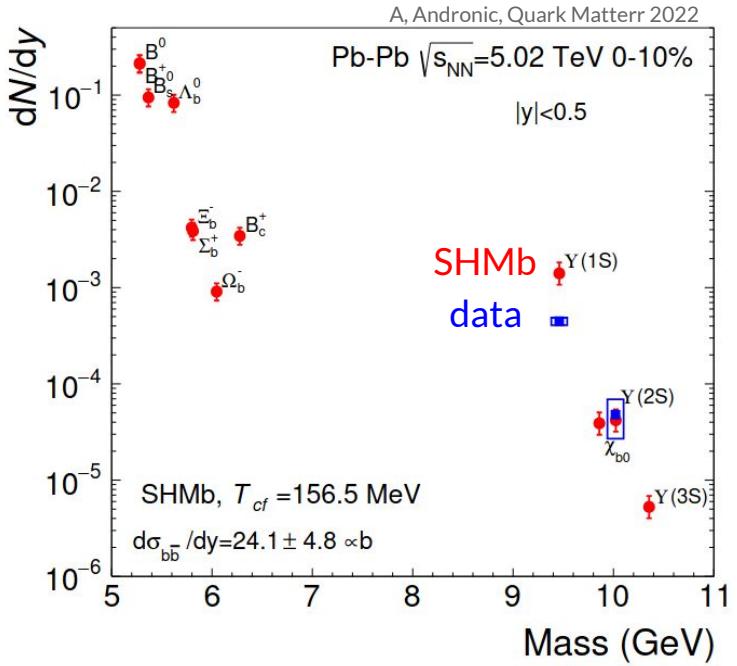
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- SHMc successfully describe charm-hadron abundances
 - c-quark thermal production suppressed
 - c-quark thermalise in QGP medium
 - Λ_c^+ not really described
 - compatible with additional high-mass charm baryon resonances scenario





- SHMb largely overestimate b-mesons (x 3)
 - unless b-quark partially thermalize (30%)
 - high precision b at low- p_T region needed
 - new observables?

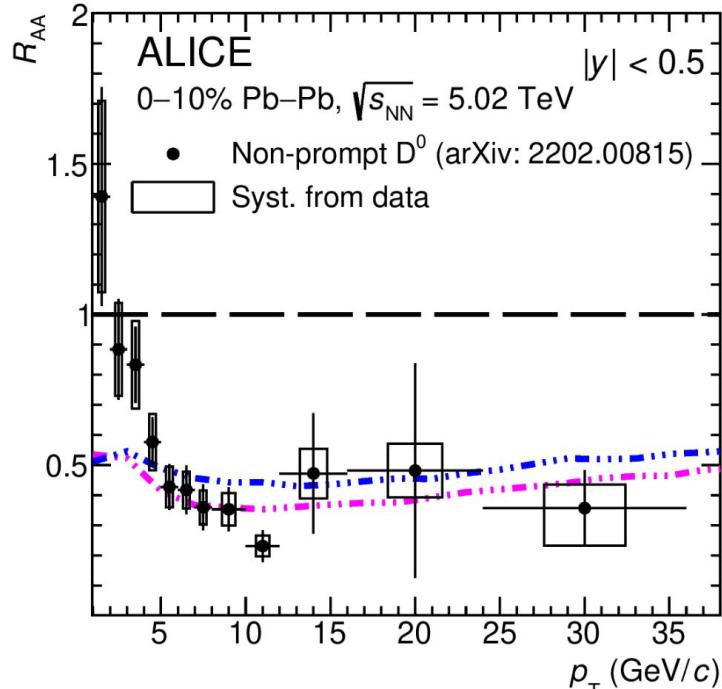
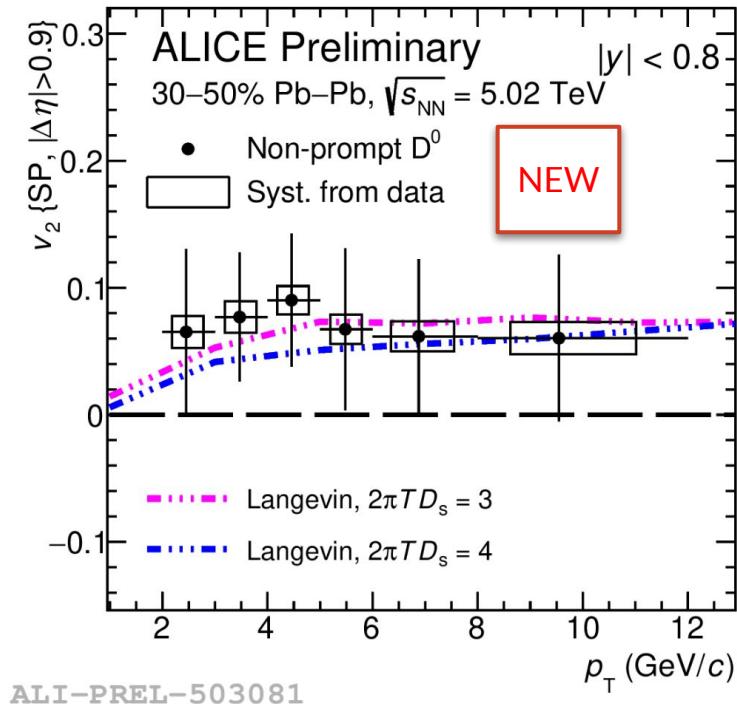
Constrain of beauty spatial diffusion coefficient

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

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

- HF quarks undergo **energy loss in the medium** → mass dependence in-medium energy loss
- Measurements described by models that include **collisional and radiative energy loss** → $1.5 < 2\pi D_s T_c < 4.5$
- HF quarks **hadornise via coalescence (+ fragmentation)**
- Different degree of thermalization between charm and beauty quarks
- **What's Next? Run 3!**

