QUARK MATTER KRAKÓW 2022
29TH INTERNATIONAL
CONFERENCE ON ULTRA – RELATIVISTIC
NUCLEUS - NUCLEUS COLLISIONS
APRIL 4-10, 2022
KRAKÓW, POLAND

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

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for the ALICE collaboration

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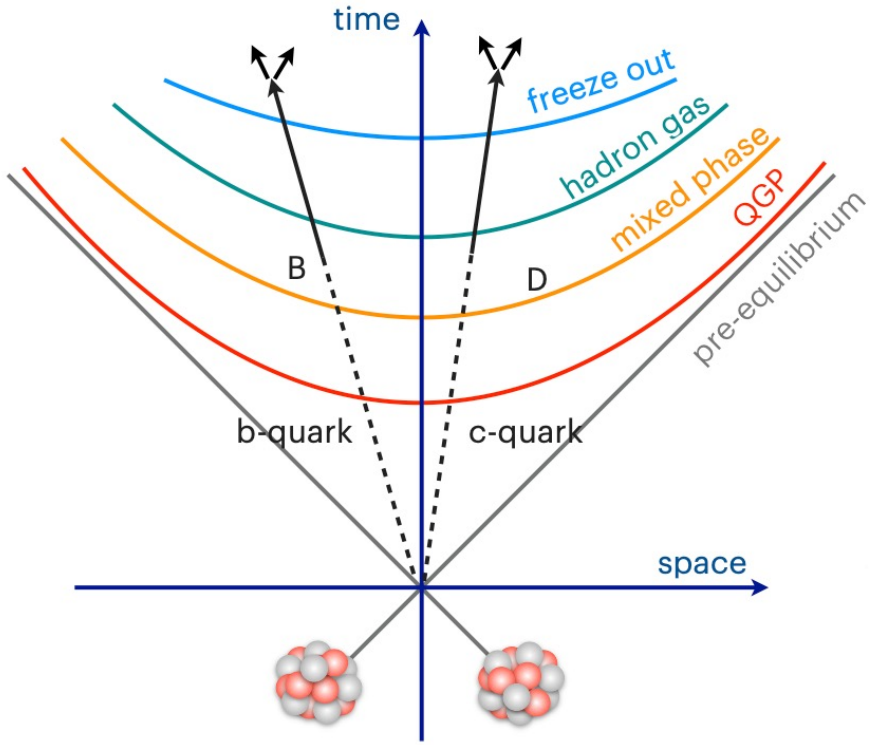
Motivation

- **Heavy quarks produced in hard scattering processes in the initial stages of the collision**
  - $\tau_b \sim 0.02 < \tau_c \sim 0.07 < \tau_{\mathrm{QGP}} \sim 0.1\text{-}1\ \mathrm{fm}/c$ [1]
  - Experience full system evolution interacting with the medium in Pb−Pb collisions → effective probe



[1] F.M Liu et al., PRC 89, 034906 (2014)

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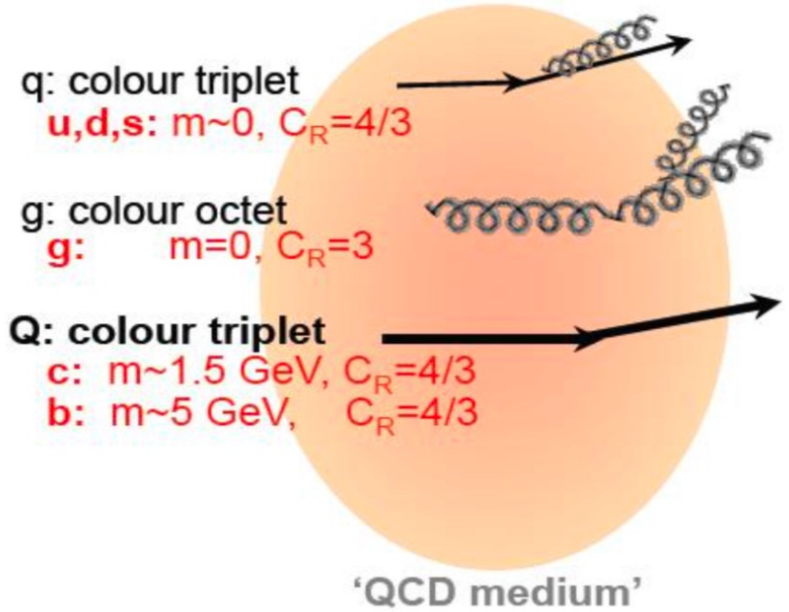
- **Beauty production in Pb−Pb collisions compared to charm**
  - Mass dependence energy loss: $m_{\mathrm{b}} > m_{\mathrm{c}} \rightarrow \Delta E_{\mathrm{c}} > \Delta E_{\mathrm{b}}$



Also directly observed in pp collisions for charm quark (arXiv:2106.05713)

Gluon emissions are suppressed in a cone with $\theta = \frac{m_Q}{\mathrm{E}_{Radiator}}$

Dead cone: Yu.L Dokshitzer et al., JPG17 (1991) 1602-1604

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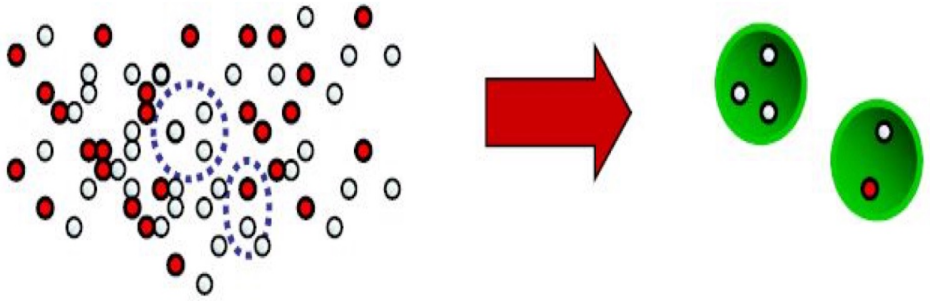
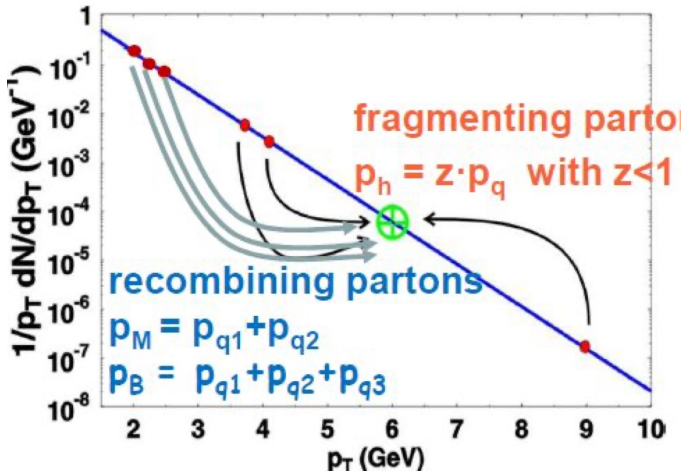
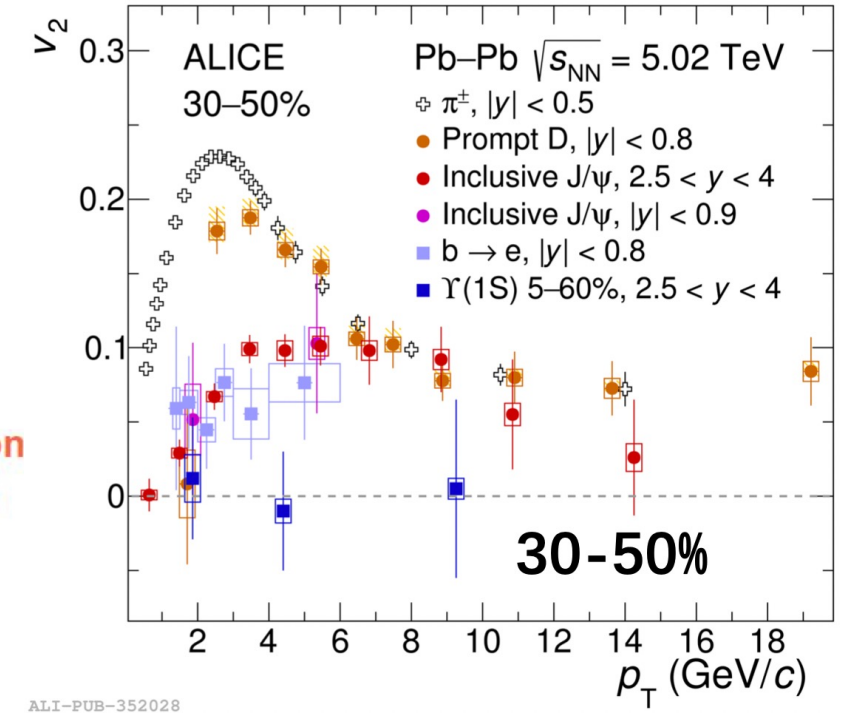
  - Different participation to collective expansion and hadronisation





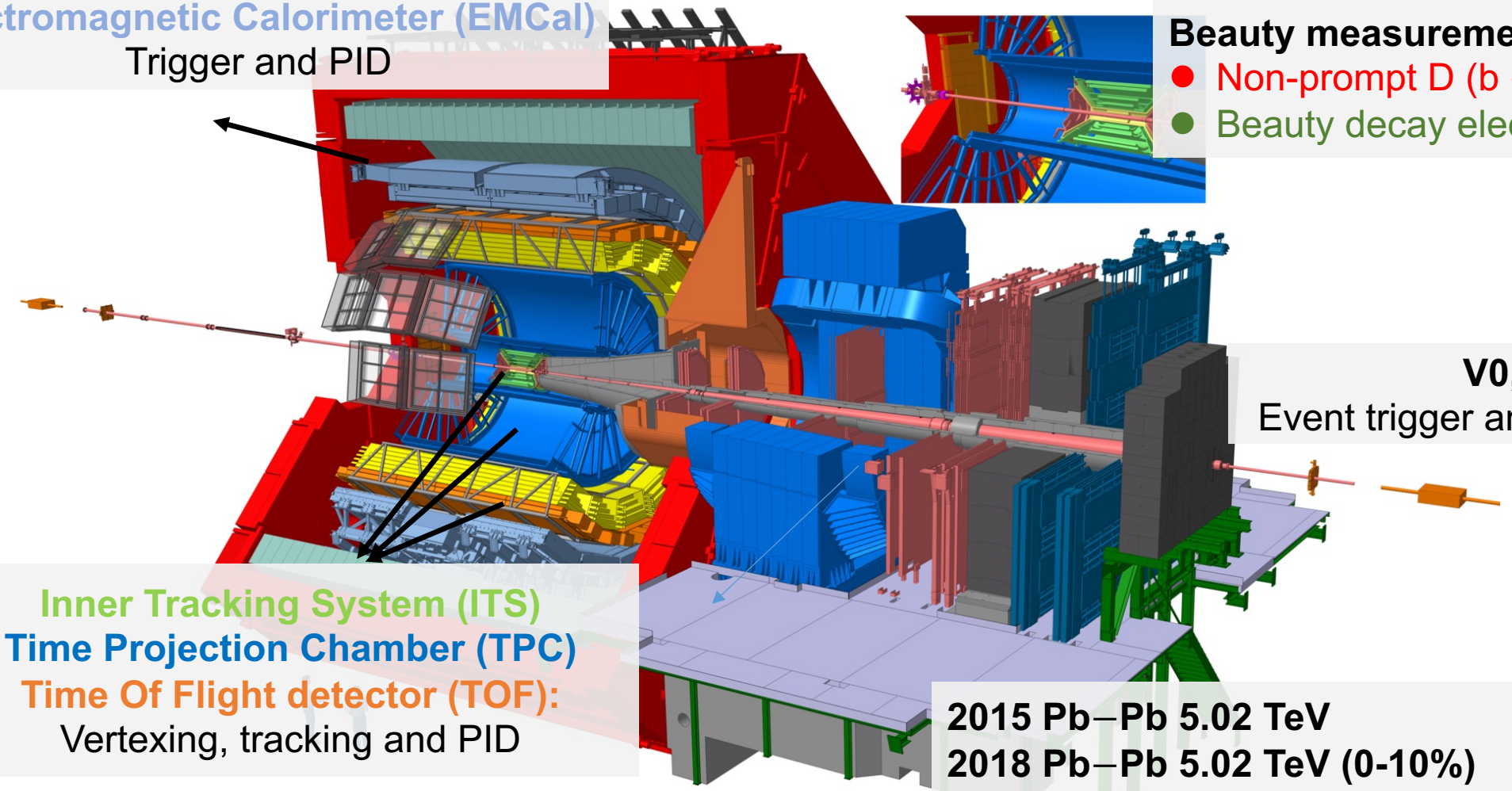
V. Greco et al., PRL 90 (2003) 202302



ALICE, PRL 126 (2021) 162001

The ALICE detector

Electromagnetic Calorimeter (EMCal)
Trigger and PID



Beauty measurements in this talk:
- Non-prompt D ($b \rightarrow D^0, D_s^+$)
- Beauty decay electron ($b \rightarrow e$)

V0, ZDC:
Event trigger and characterization

Inner Tracking System (ITS)
Time Projection Chamber (TPC)
Time Of Flight detector (TOF):
Vertexing, tracking and PID

2015 Pb–Pb 5.02 TeV	$\mathcal{L}_{int}$	$\sim 13\ \mu b^{-1}$
2018 Pb–Pb 5.02 TeV (0-10%)	$\mathcal{L}_{int}$	$\sim 130\ \mu b^{-1}$
(30-50%)	$\mathcal{L}_{int}$	$\sim 56\ \mu b^{-1}$

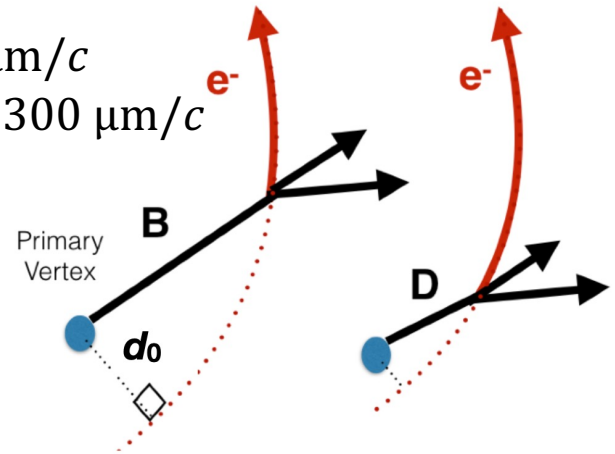
NEW New preliminary for QM Final On arXiv or released as PPS recently

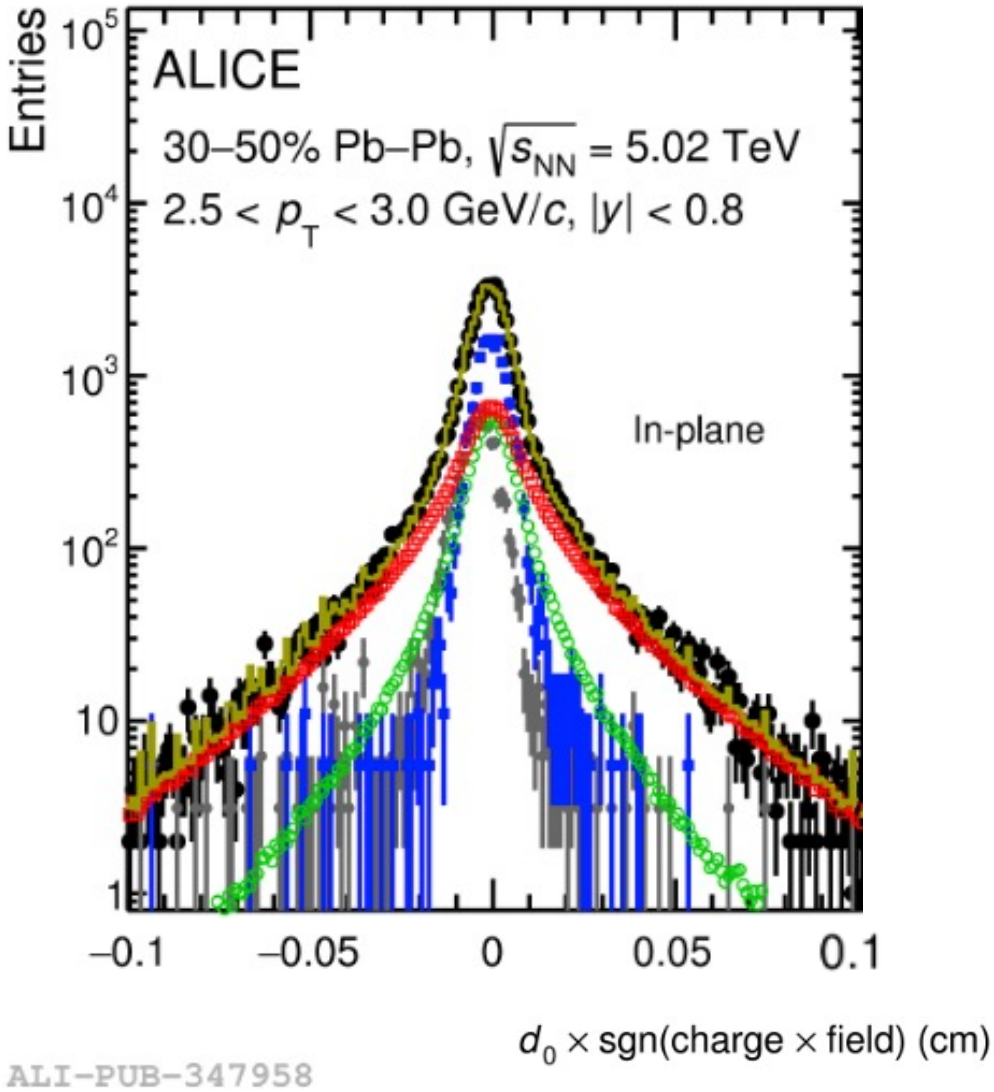
Analysis procedure

Beauty-decay electrons (b (→c) → e)

- Large branching ratios via semileptonic decays
  - ➢ b → e + X (~10%) , b → c → e + X (~10%)
- Longer lifetime than charm and other electron sources
  - ➢ Larger impact parameter (d_0) w.r.t primary vertex
- b → e yield obtained with template fit on impact parameter distributions

Beauty hadrons $\tau \sim 500\ \mu m/c$
Charm hadrons $\tau \sim 60 - 300\ \mu m/c$

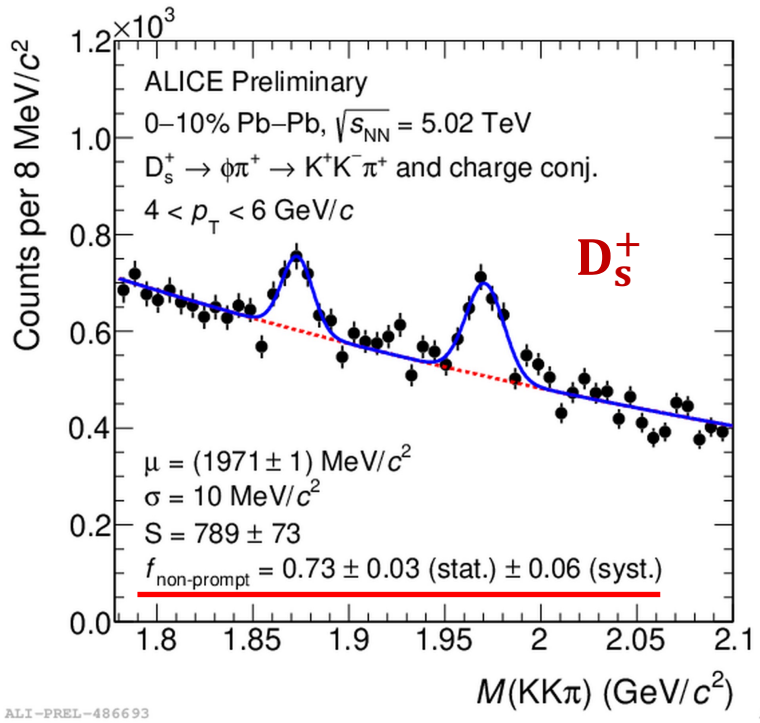


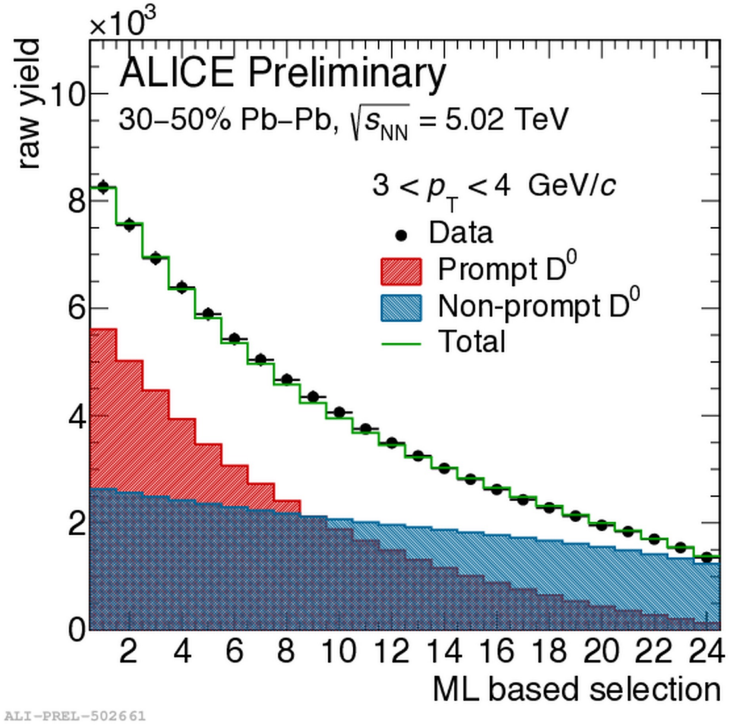


Analysis procedure

Non-prompt D mesons (D^0, D_s^+)

- Machine Learning method with a multiclassification by BDT[1] utilized to simultaneously increase the b → D fraction and suppress the combinatorial background
- Signal is extracted via an invariant-mass analysis
- b → D fraction obtained by min-χ^2 approach based on variation of ML-based selection





$$N_{raw}(x) \approx N_c \cdot \epsilon_c(x) + N_b \cdot \epsilon_b(x)$$

$\epsilon_{c,b}$ = efficiency for c,b → D

$$f_{np}(x) = \frac{N_b \cdot \epsilon_b(x)}{N_c \cdot \epsilon_c(x) + N_b \cdot \epsilon_b(x)}$$

[1] JHEP 05 (2021) 220

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- Signal is extracted via an invariant-mass analysis
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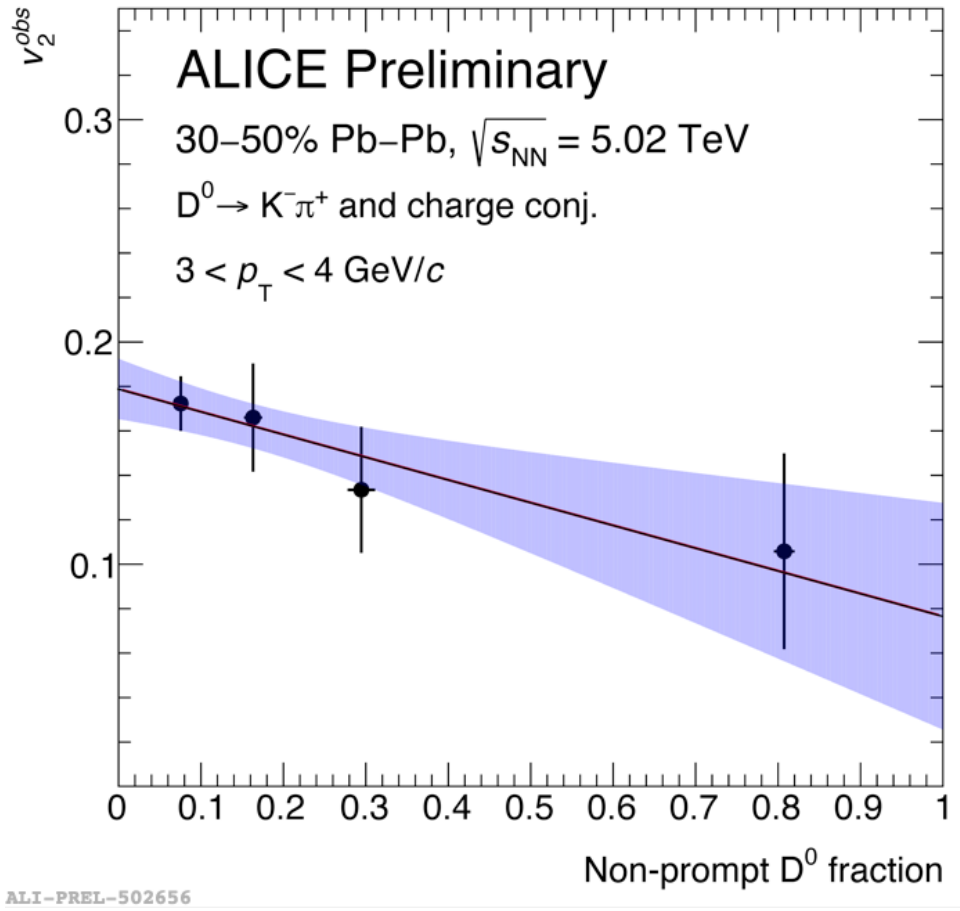
- $v_2^{\text{non-prompt}}$ obtained by Linear fitting of v_2^{obs} vs $f_{\text{non-prompt}}$, and extrapolate to $f_{\text{non-prompt}} = 1$[2]

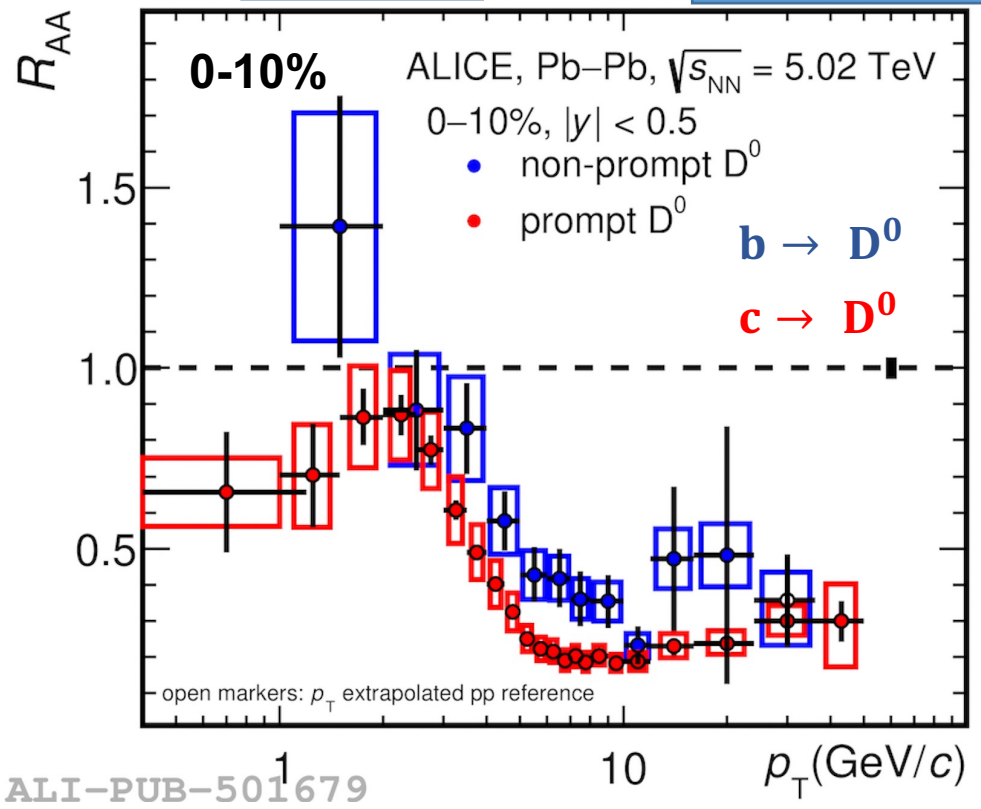


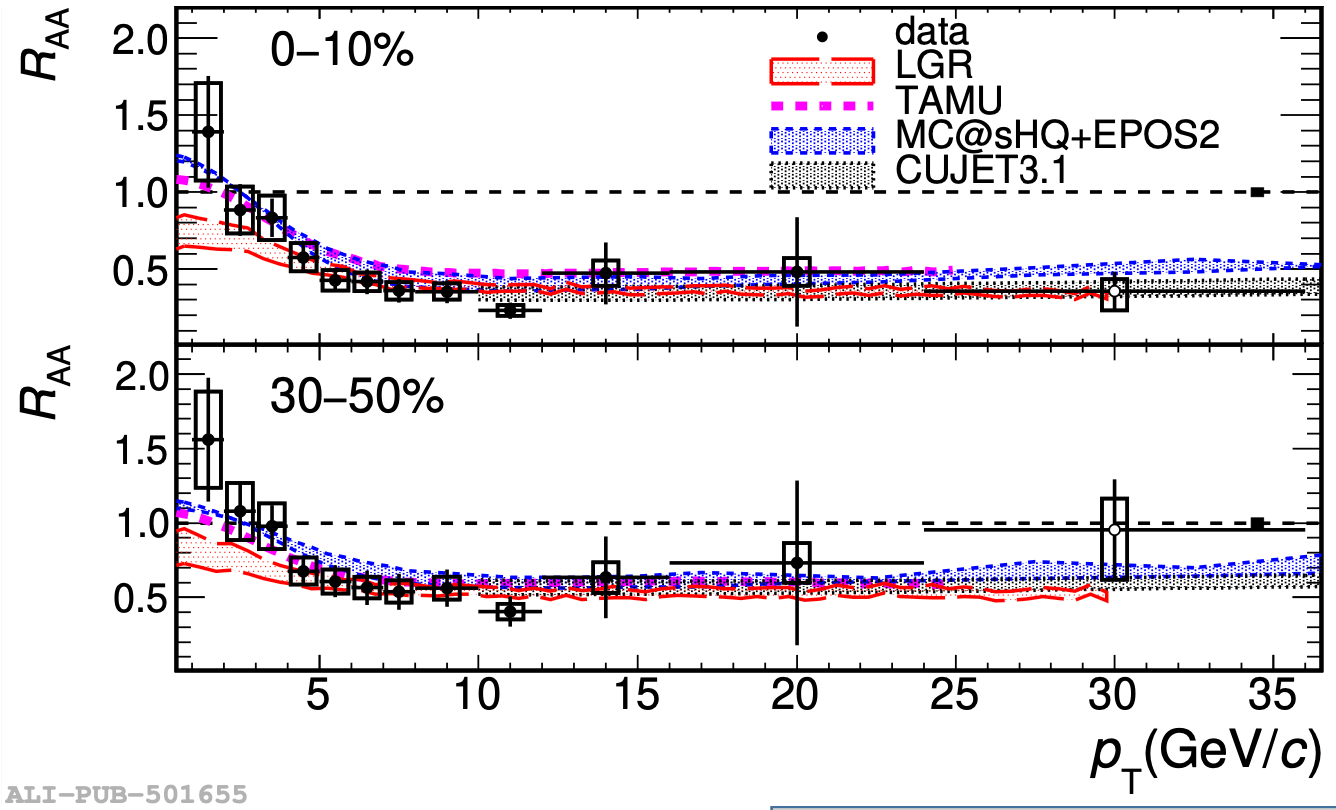
[1] JHEP 05 (2021) 220
[2] CMS PLB 813 (2021) 136036

Non-prompt D^0 R_{AA}

Final

arXiv: 2202.00815





- Suppression of $b \rightarrow D^0$ observed
- $R_{AA,\, b \rightarrow D^0} > R_{AA,\, c \rightarrow D^0}$ at intermediate p_T
- R_{AA} (0-10%) < R_{AA} (30-50%)
- Theoretical models that include collisional and radiative energy loss describe the data within uncertainties

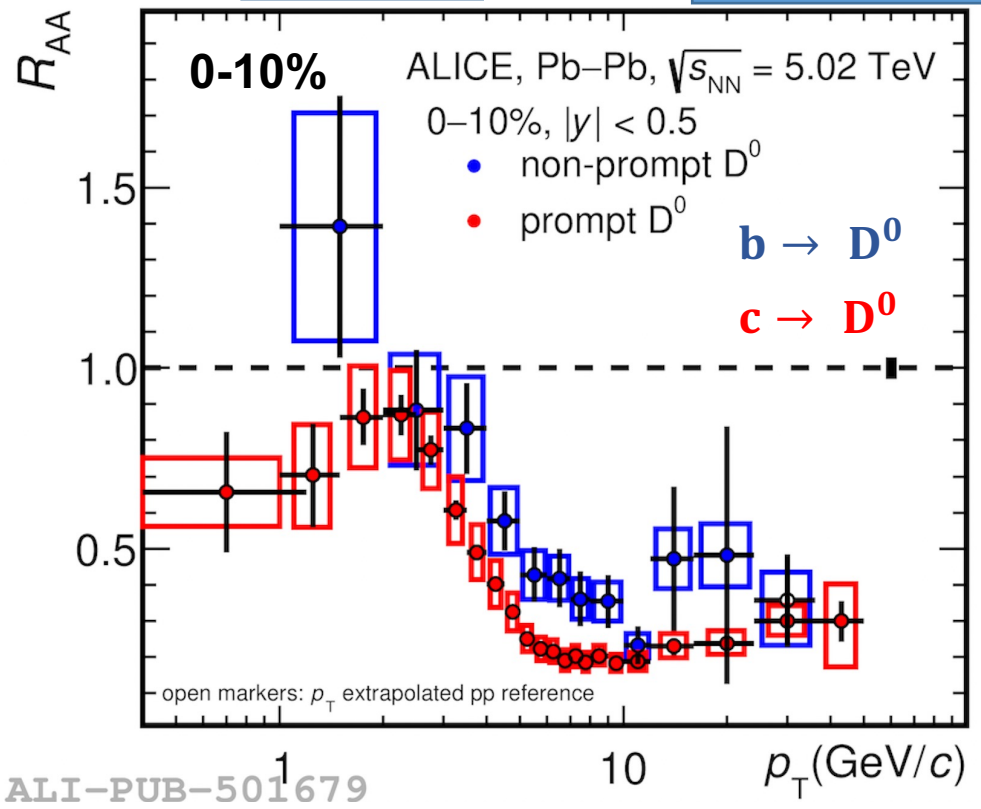
TAMU: PLB 735 (2014) 445
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: EPJC 80, no.7, (2020) 671
EPJC 80 no.12, (2020) 1113
CUJET3: CPC 43, no.4, (2019) 044101

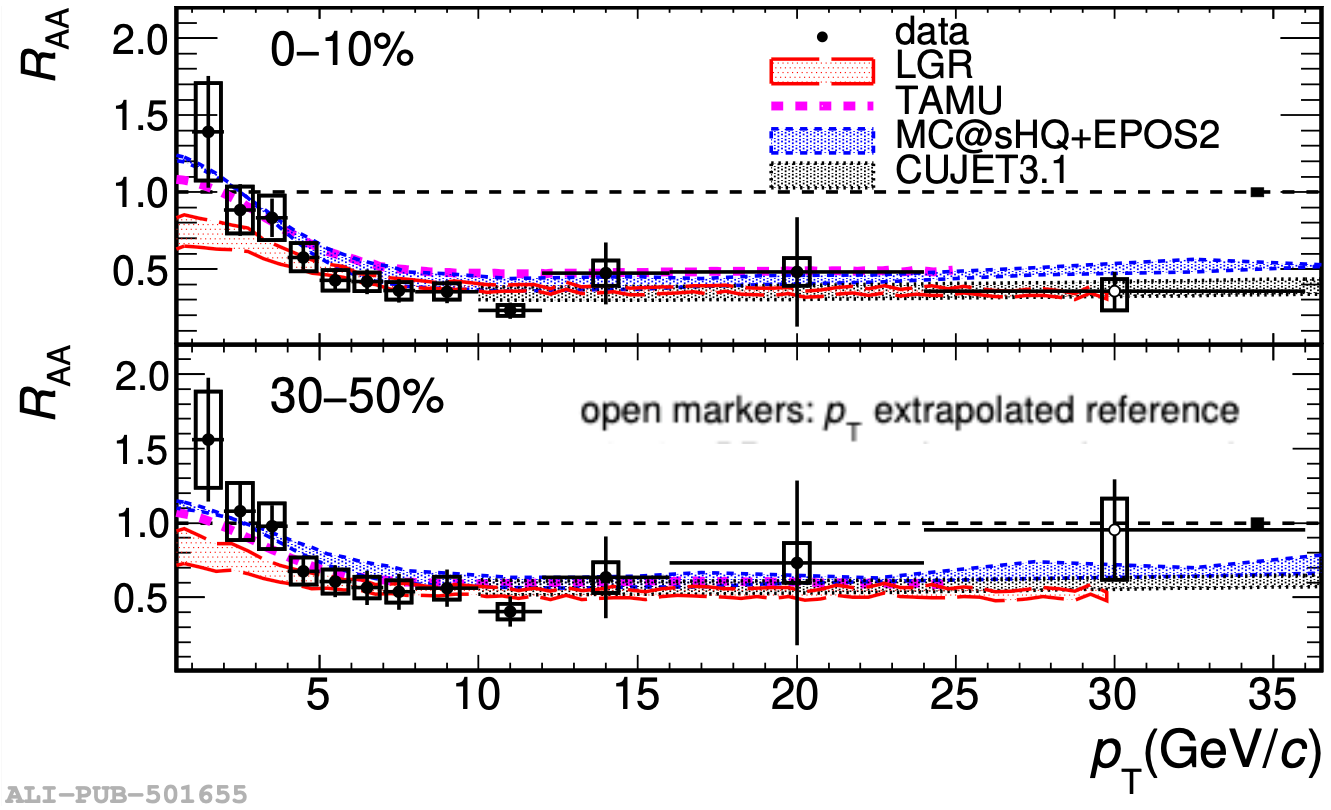
Prompt D^0 : parallel talk by L. Vermunt, 7 Apr 2022, 09:00

Non-prompt D^0 R_{AA}

Final

arXiv: 2202.00815





- For 1 < p_T < 2 GeV/c , the parent B-meson p_T distribution has a median of $p_T \approx 3.3$ GeV/c from simulation
- Integrated non-prompt D^0 R_{AA} :

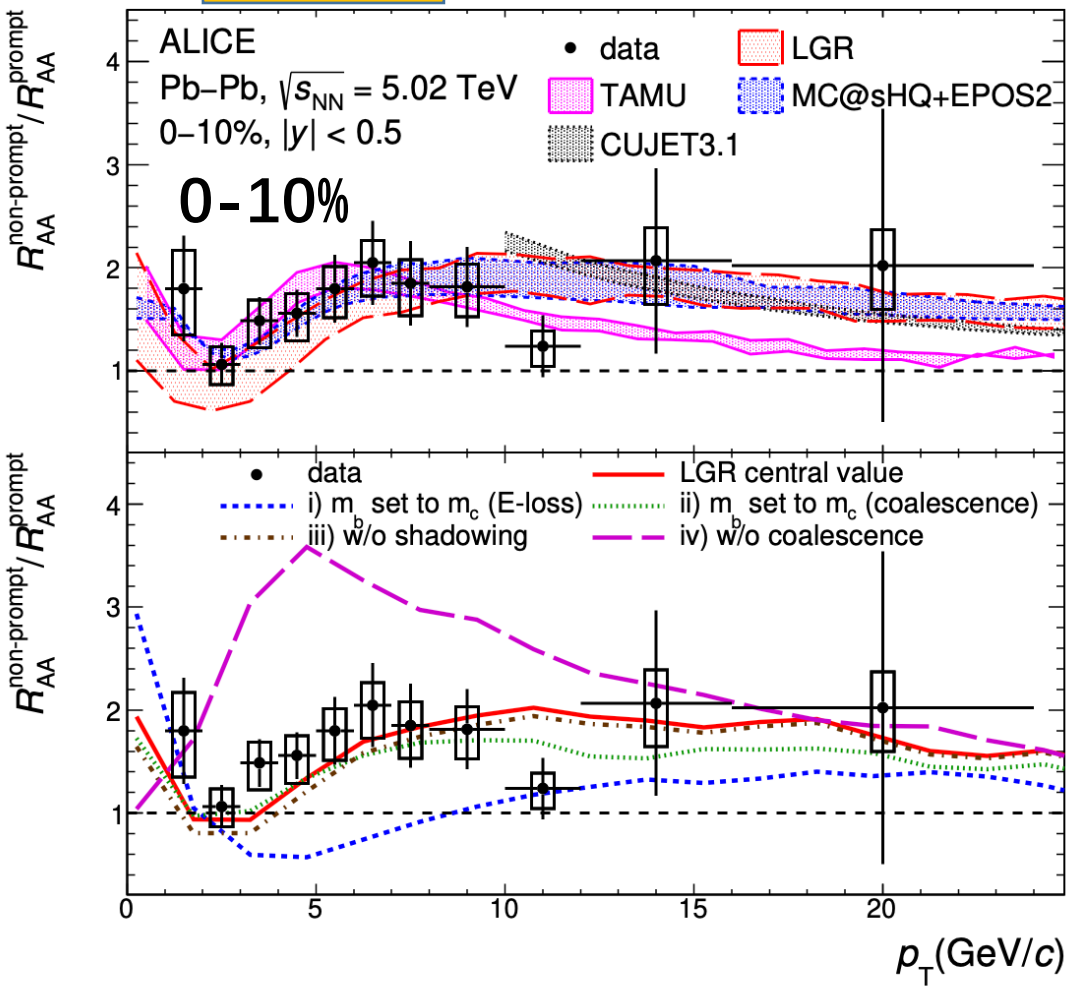
prompt D meson R_{AA}: JHEP 01 (2022) 174

$R_{AA}^{\text{non-prompt } D^0}$(0-10%) = 1.00 $\pm$ 0.10 (stat.) $\pm$ 0.15 (syst.) $^{+0.08}_{-0.09}$ (extr.) $\pm$ 0.02 (norm.)

$R_{AA}^{\text{prompt } D^0}$(0-10%) = 0.689 $\pm$ 0.054 (stat.) $^{+0.104}_{-0.106}$ (syst.) → **different shadowing or hadronisation via coalescence?**

Non-prompt/prompt D^0 R_{AA} ratio

Final



- Ratio of the R_{AA} of non-prompt to prompt D^0 (beauty/charm)
  - p_T < 5 GeV/c : pattern hints difference in shadowing / flow / decay kinematics for charm and beauty
  - p_T > 5 GeV/c : 3.9 σ above unity → beauty quarks undergo less suppression than charm quarks
- Test the double R_{AA} ratio with different LGR configurations
  - The "valley" structure is mainly due to the formation of prompt D-mesons via charm-quark coalescence (iv)
  - The significant enhancement of double ratio at high p_T is related to the mass dependent quark in-medium energy loss effect (i)

arXiv: 2202.00815

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

ALI-PUB-501659

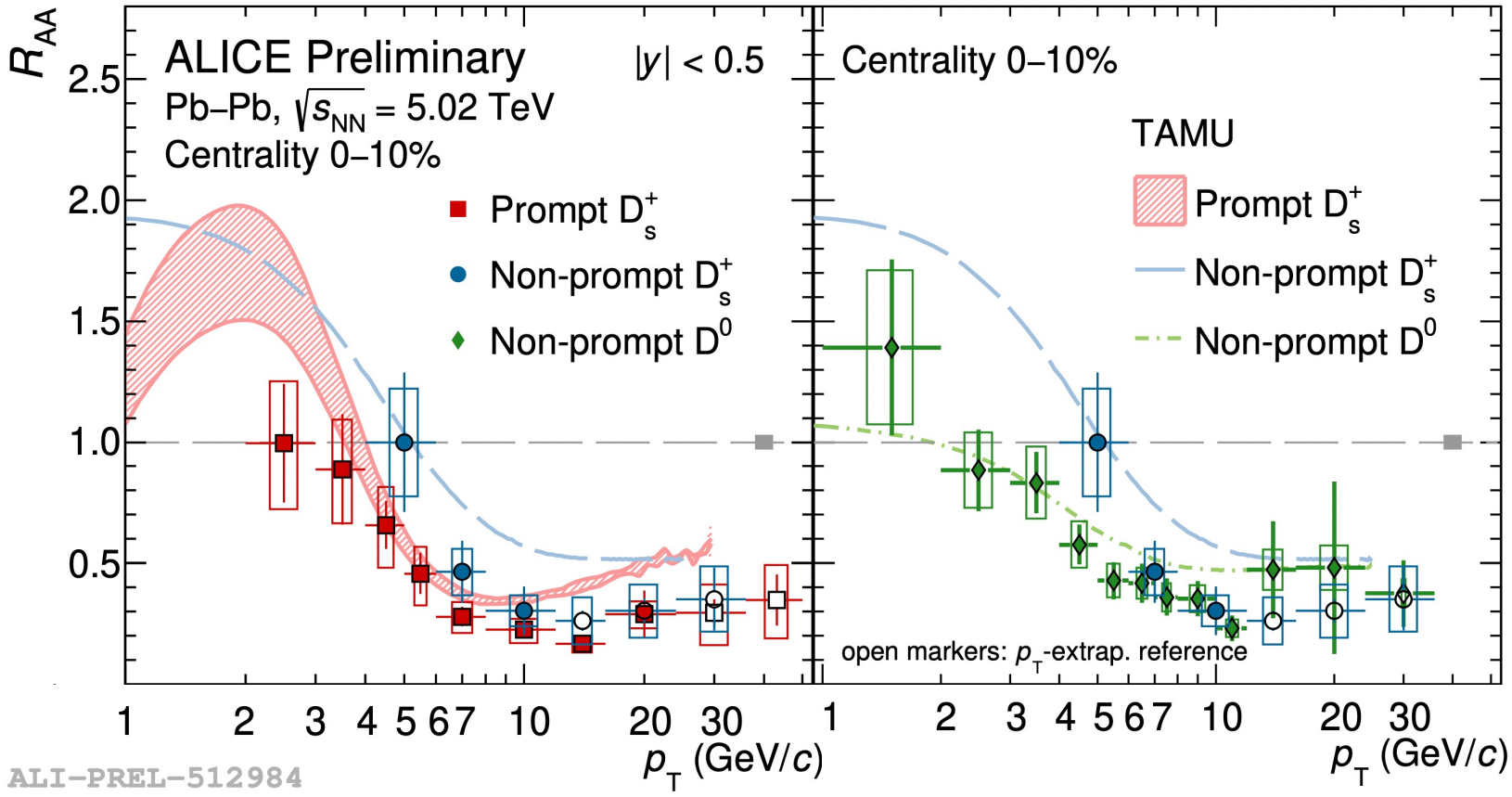
Non-prompt D_S R_{AA}

Final

$b \rightarrow D_s^+$

$b \rightarrow D^0$

$c \rightarrow D_s^+$



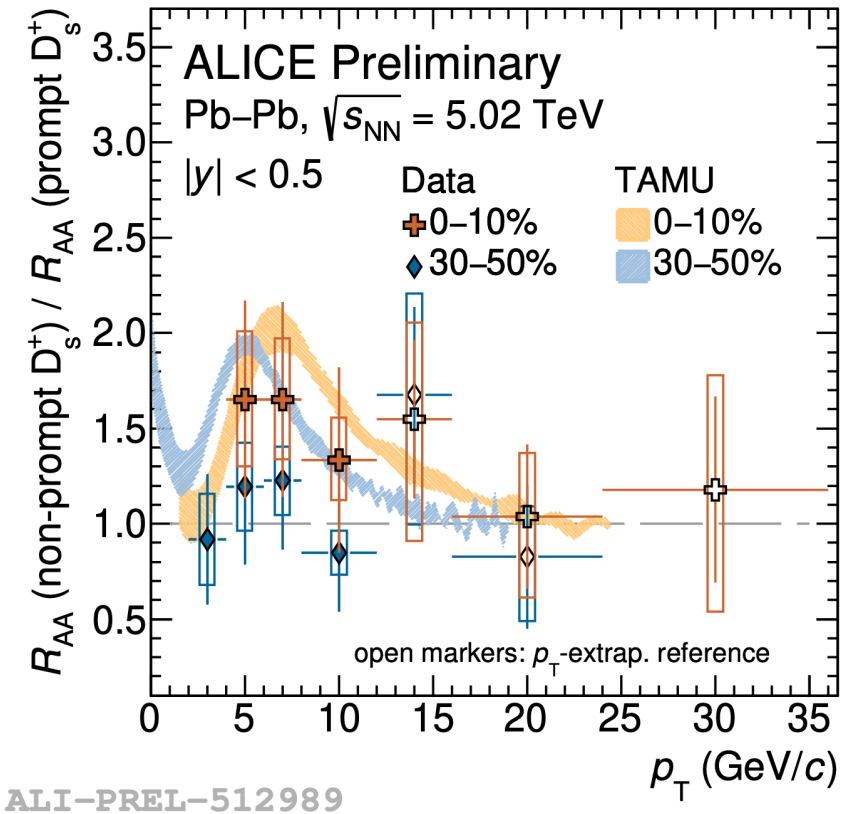
ALICE-PUBLIC-2022-010

TAMU: PLB 735 (2014) 445

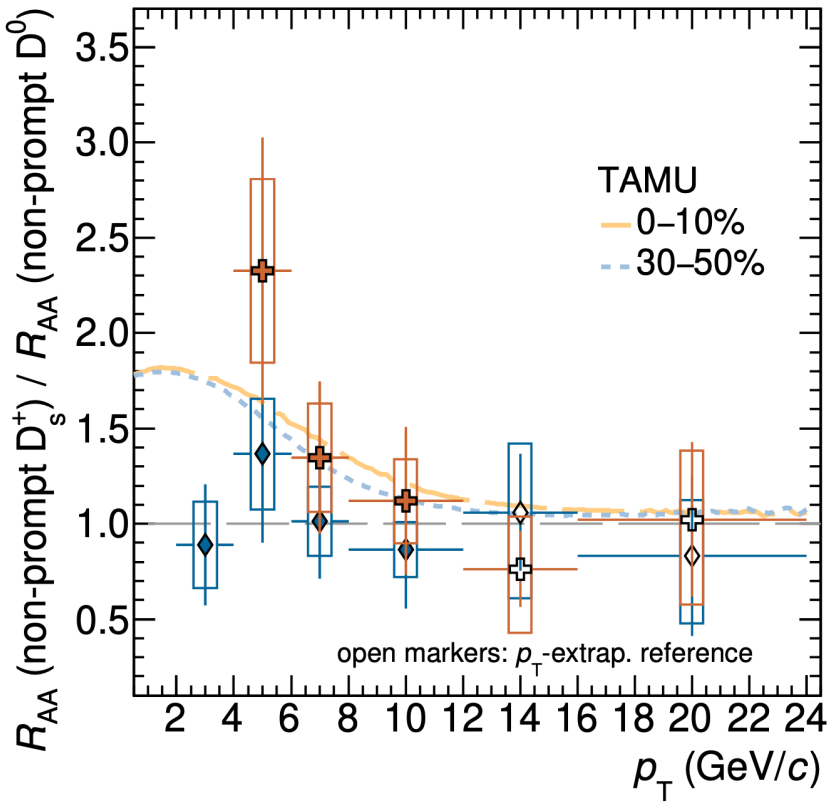
- Central values higher w.r.t those of prompt D_s^+ and non-prompt D^0 R_{AA} for p_T < 6 GeV/c, though compatible within uncertainties
  - Interplay of charm and beauty energy loss and recombination in the medium

Non-prompt D_S R_{AA} ratios

Final



ALI-PREL-512989



ALICE-PUBLIC-2022-010

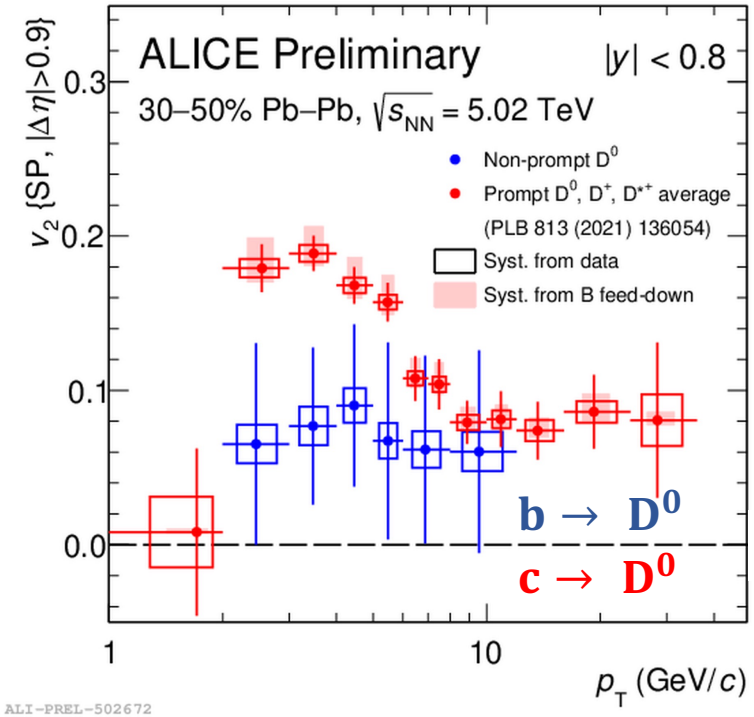
TAMU: PLB 735 (2014) 445

- Non-prompt/prompt $R_{AA}(D_s^+)$ ratio and $R_{AA}(D_s^+)/R_{AA}(D^0)$ ratio for non-prompt
  - Hint of enhancement (1.6 σ) in the 4 < p_T < 12 GeV/c interval in 0−10% for the ratios
    - ✓ **Effect of coalescence + strangeness enhancement?**
- TAMU predictions qualitatively describe the result for 0−10%, but overestimate the values for 30−50%

Poster (ID: 201) by B. Zhang and R. Bala, 8 Apr 2022, 14:12

Non-prompt D^0 v_2

NEW

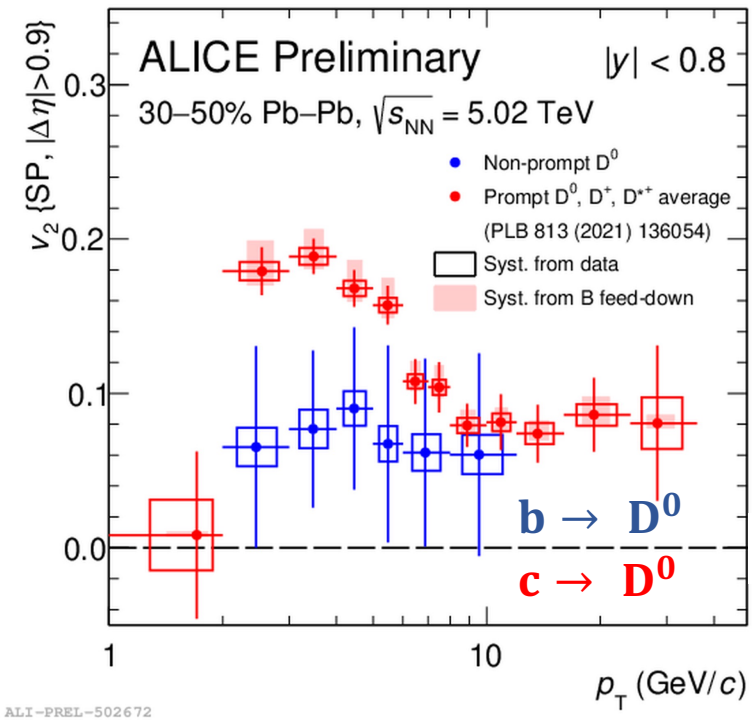


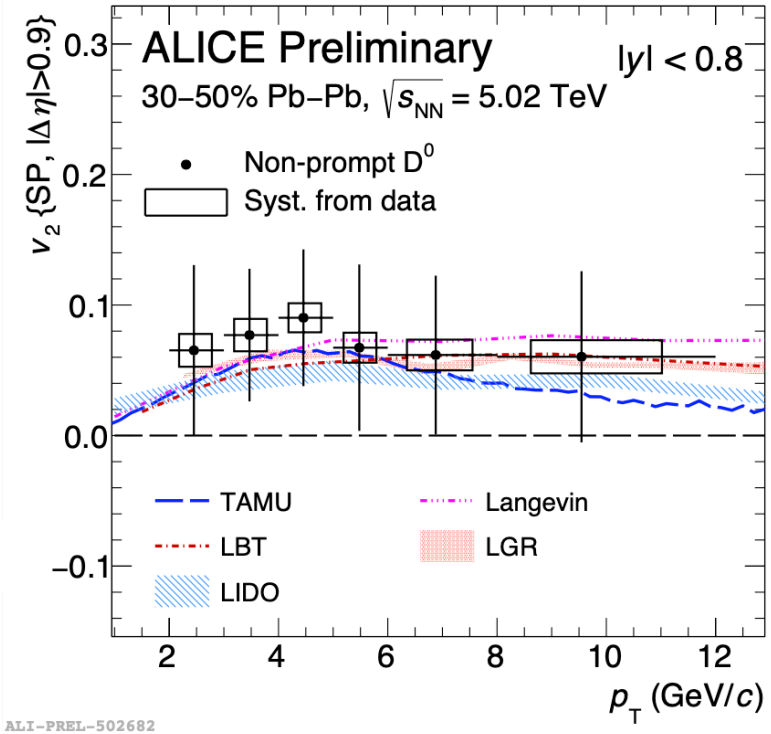
Average prompt D meson v_2: PLB 813 (2021) 136030

- Non-zero v_2 with 2.7 σ significance for 2 < p_T < 12 GeV/c
  - ✓ is beauty partially thermalized in the medium, and/or recombined with light quarks?
- 3.2 σ for the difference between non-prompt D^0 and prompt non-strange D meson v_2 in 2 < p_T < 8 GeV/c
  - ✓ Different degree of participation to collective motion and hadronisation between charm and beauty

Non-prompt D^0 v_2

NEW



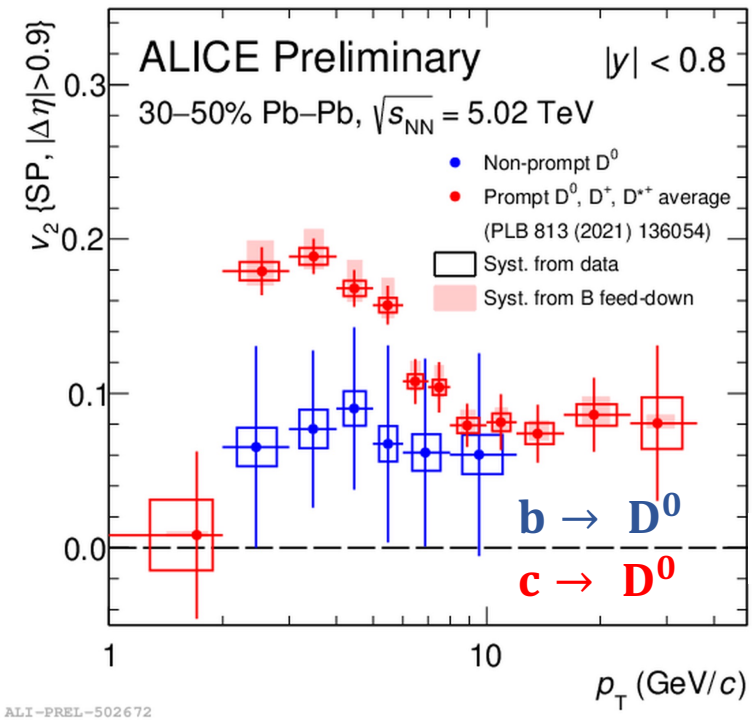


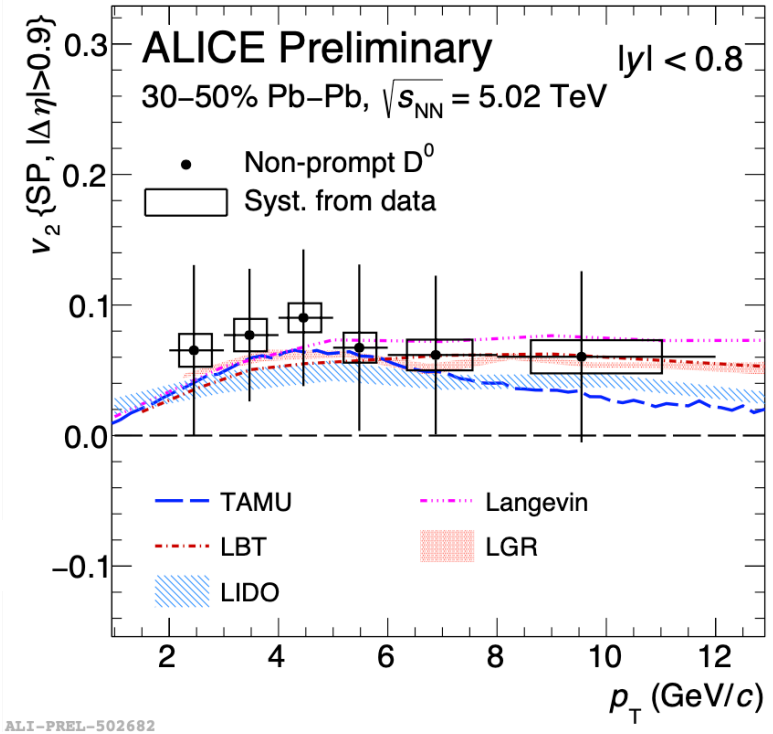
- Model predictions describe data within uncertainties

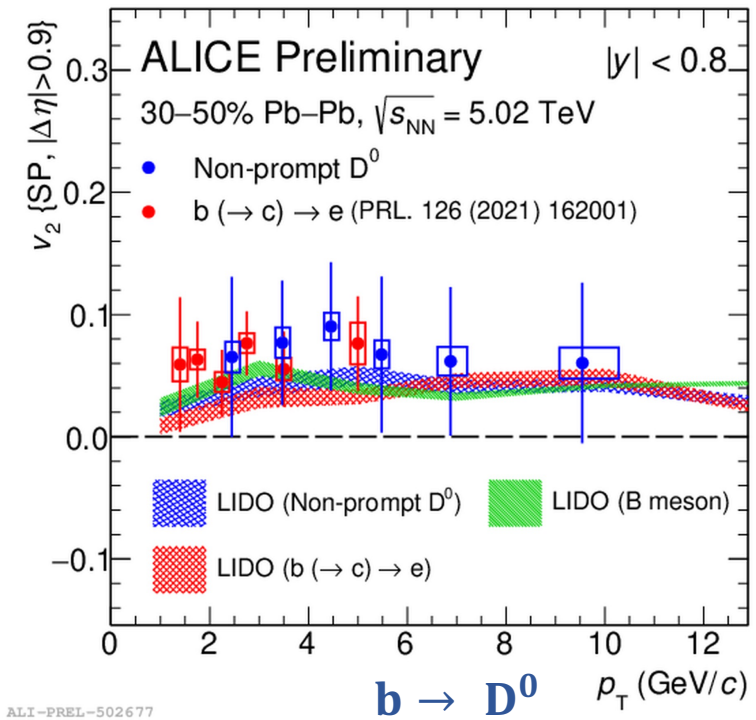
Langevin: S.Q Li et al., *EPJC* 81 (2021) 11, 1035, CPC 44 (2020) 11
PRC 88 (2013) 044907, PRC 92 (2015) 2, 024907
TAMU: PLB 813 (2021) 136054
LIDO: PRC 98 (2018) 064901, PRC 100 (2019) 064911
LGR: EPJC 80 (2020) 12, 1113
LBT: arXiv: 2112.15062, PLB 777 (2018) 255-259
PRC 94 (2016) 1,014909

Non-prompt D^0 v_2

NEW







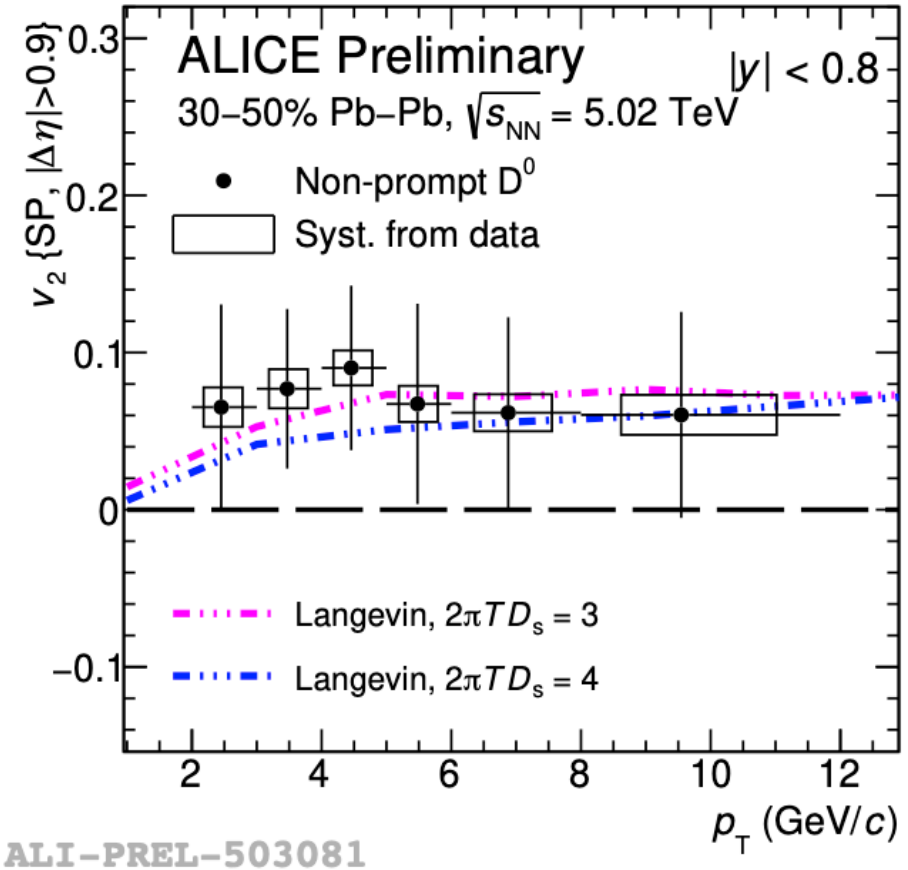
- Model predictions describe data within uncertainties
- b → e and non-prompt D^0 v_2 are compatible within uncertainties
  - ➢ Decay kinematic effect is small according to LIDO predictions

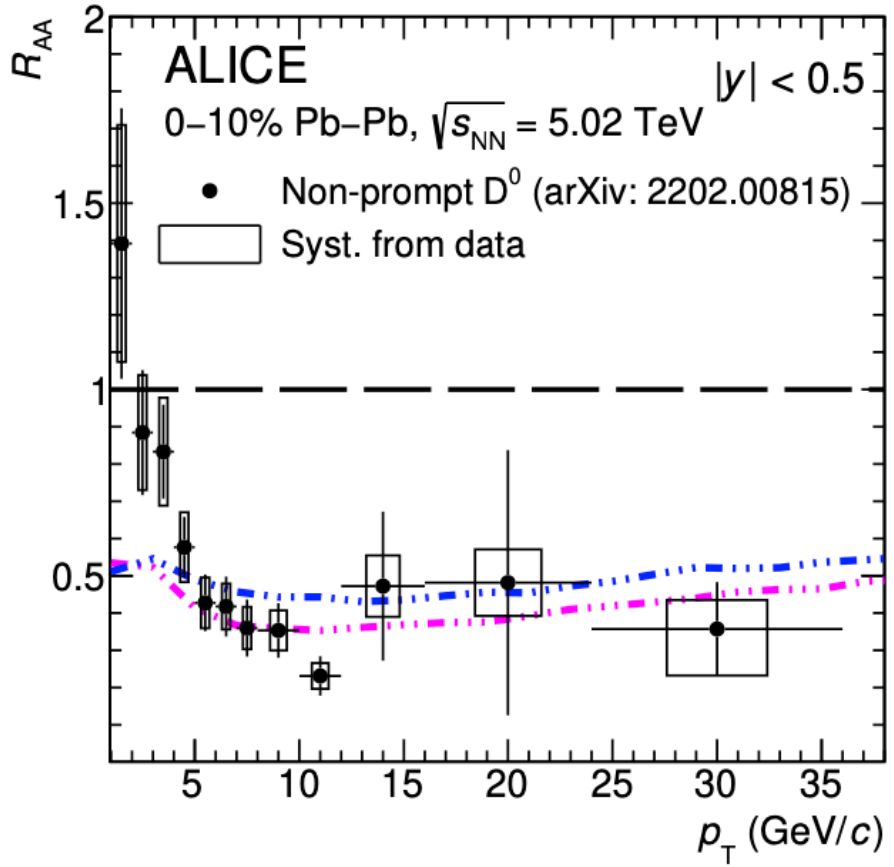
LIDO: PRC 98 (2018) 064901, PRC 100 (2019) 064911

Toward a constraint of beauty spatial diffusion coefficient

NEW

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





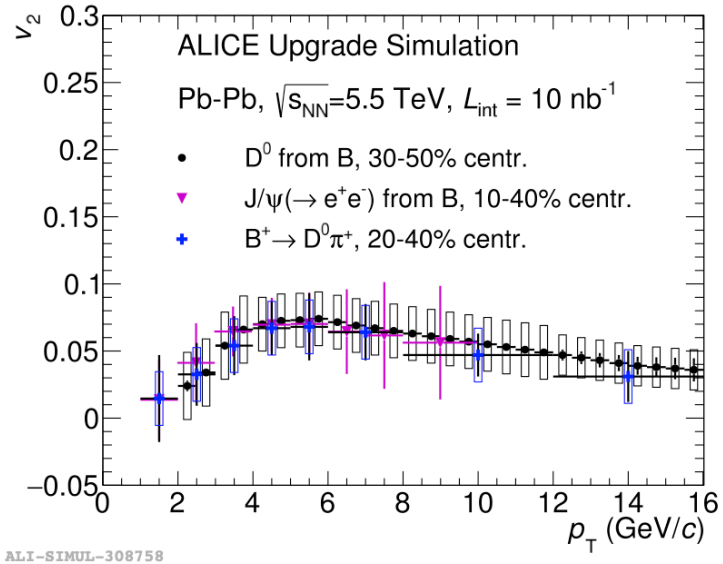
- Non-prompt D^0 R_{AA} and v_2 simultaneously compared with different Langevin configurations for $2\pi TD_{\mathrm{s}}$
  - $2\pi TD_{\mathrm{s}} = 3$ case is closer to data central values, though both cases compatible with data within uncertainties
- More precise data measurements will provide important constraint to beauty spatial diffusion coefficient

Summary

- Beauty quarks undergo energy loss in the medium → important constraint of mass dependence of ΔE
- Measurements described by models that include collisional and radiative energy loss
- Non-prompt $\mathrm{D_s^+}$ meson R_{AA} provides insights into beauty quarks hadronisation via recombination
- Different Non-prompt and prompt $\mathrm{D^0}$ v_2
  - Different degree of participation to collective motion and hadronisation between charm and beauty

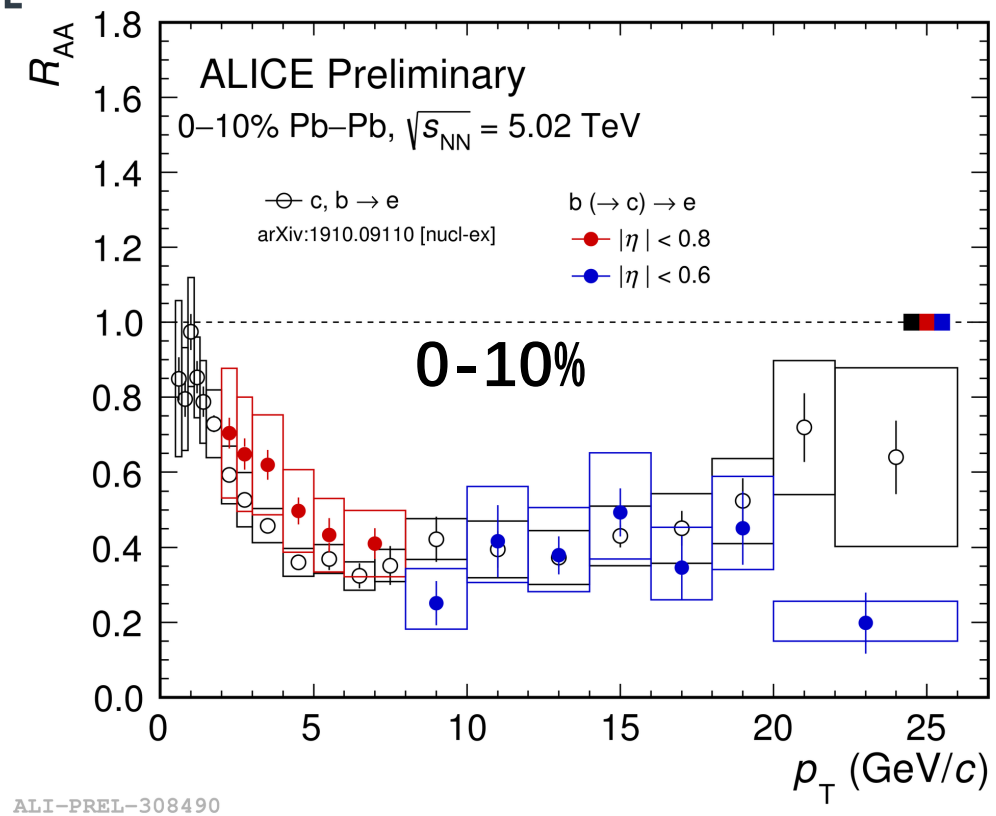
✓ New ITS detectors and increased integrated luminosity for LHC Run 3

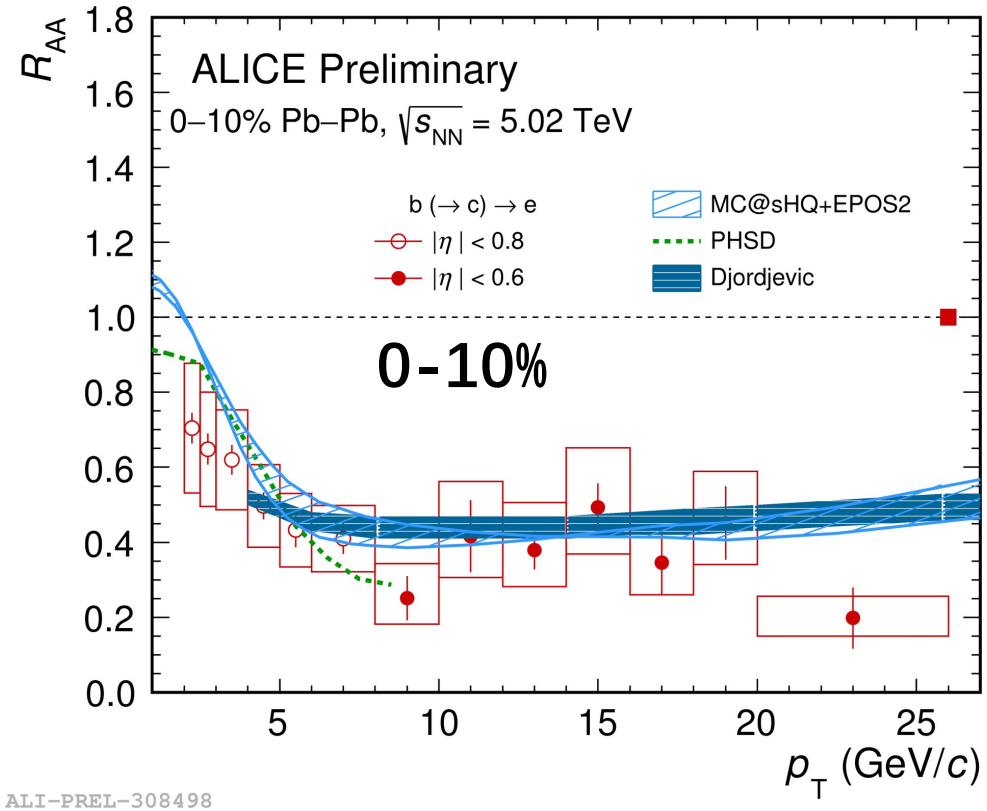
- Precise measurements of beauty hadrons at midrapidity



BACK UP

b → e R_{AA}





- Suppression of beauty decay electrons observed
- Comparison of b → e and b,c → e:
  - Hint of higher $R_{AA,\ b \to e}$ than $R_{AA,\ b,c \to e}$ at low p_T, while overlapping at high p_T (beauty decays dominate)
- Measurements described by models including collisional and radiative energy loss

MC@sHQ+EPOS2: PRC 89 (2014) 014905
PHSD: PRC 92 (2015) 014910
Djordjevic: PLB 791 (2019) 236-241