CLHCP 2021

Non-prompt charm meson measurements with ALICE

Xinye Peng

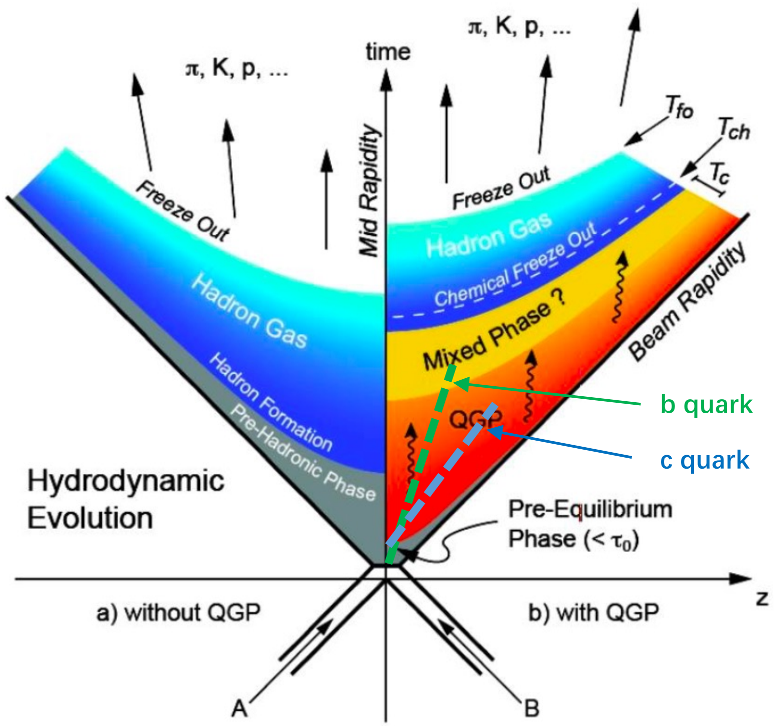
Central China Normal University, China

Outline

- Motivation and analysis technique
- Results
  - ✓ Preliminary or published results
- Summary

Motivation

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



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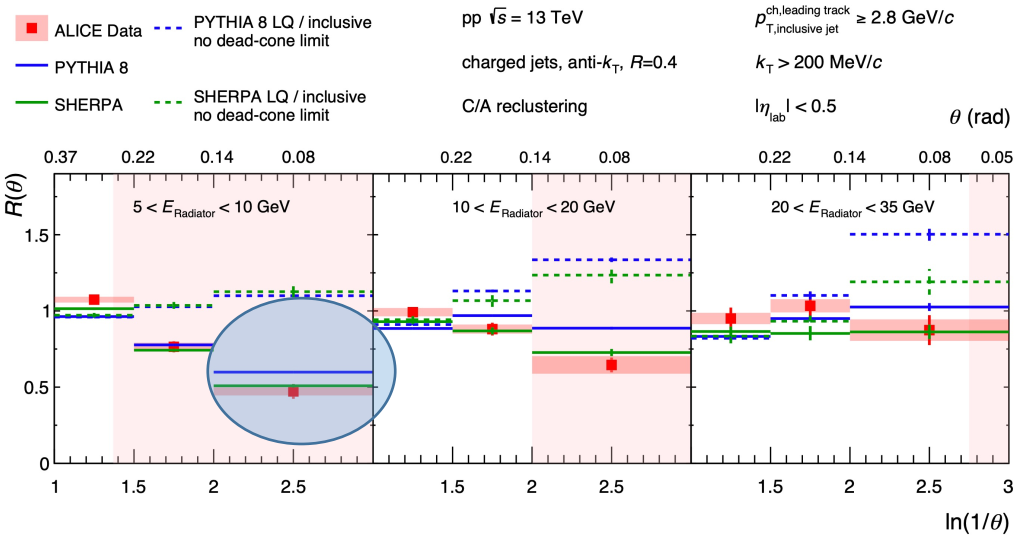
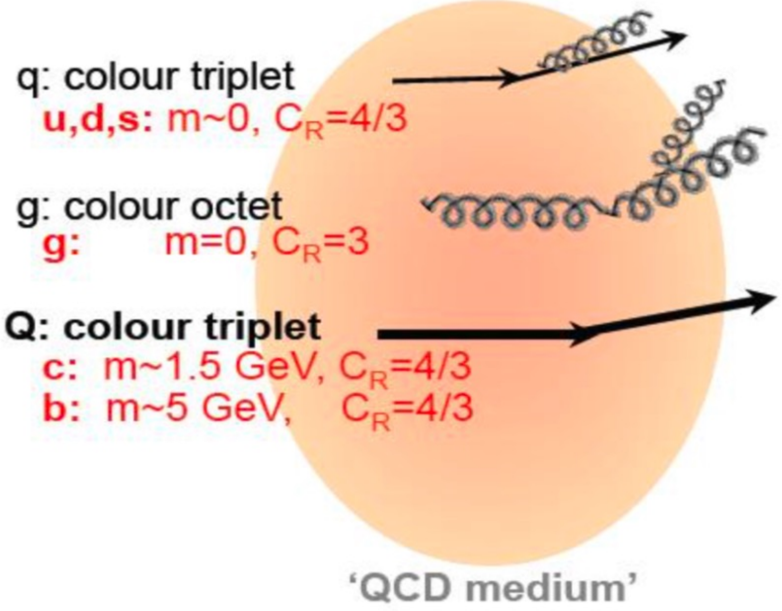
- **Beauty production in Pb-Pb collisions compared to charm quarks**
  - Mass dependence energy loss: $m_{\mathrm{b}} > m_{\mathrm{c}}$ -> $\Delta E_{\mathrm{c}} > \Delta E_{\mathrm{b}}$ (dead cone effect)



ALICE: arXiv:2106.05713 accepted by Nature



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

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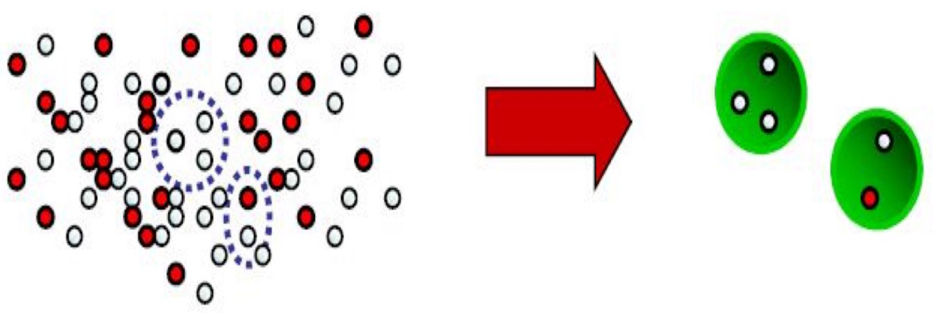
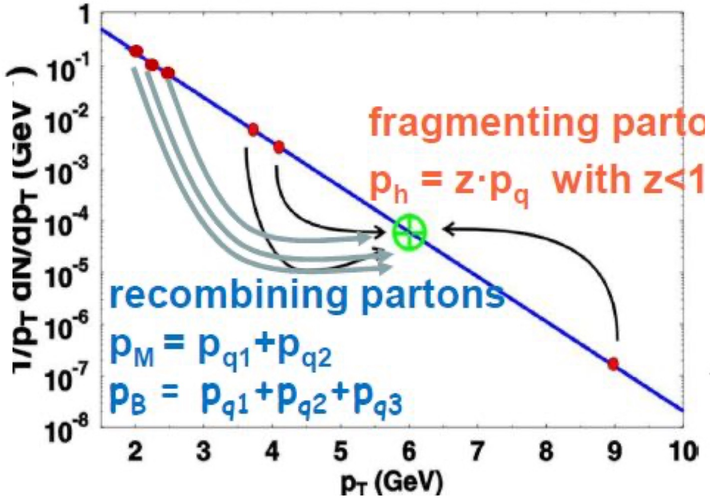
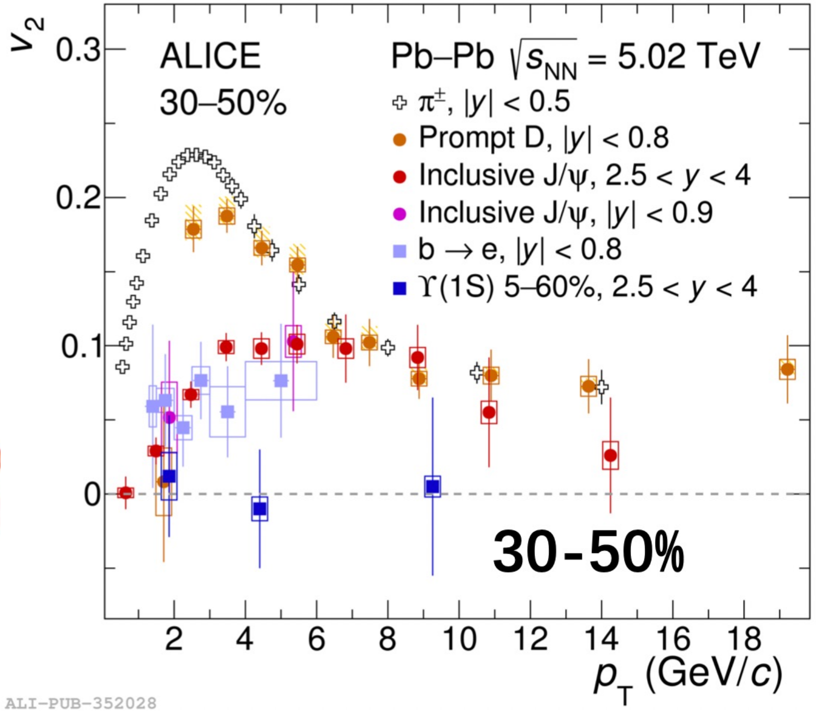




Greco et al., PRL 90 (2003) 202302
Fries et al., PRL 90 (2003) 202302



ALICE, PRL 126 (2021) 162001

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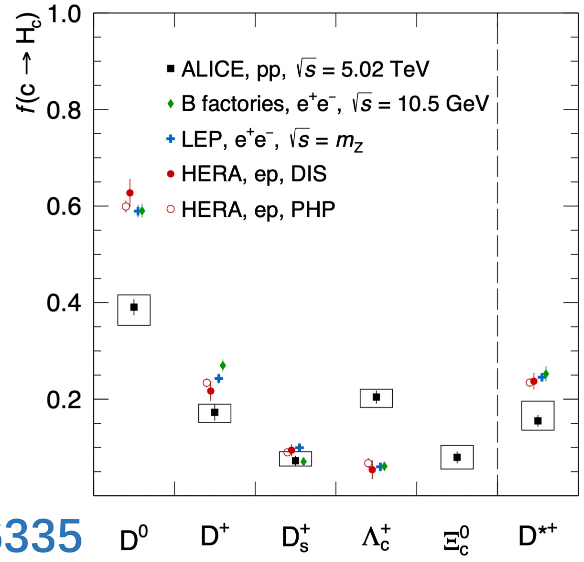
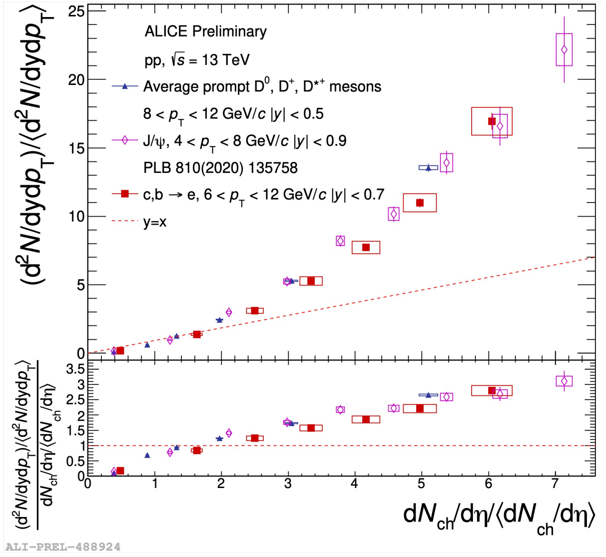
- **In pp collisions:**
  - Provide baseline for p-Pb and Pb-Pb collisions
  - Test pQCD calculations at LHC energies

- **In p-Pb collisions:**
  - Isolate initial state and cold nuclear matter (CNM) effects



ALICE, arXiv:2105,06335

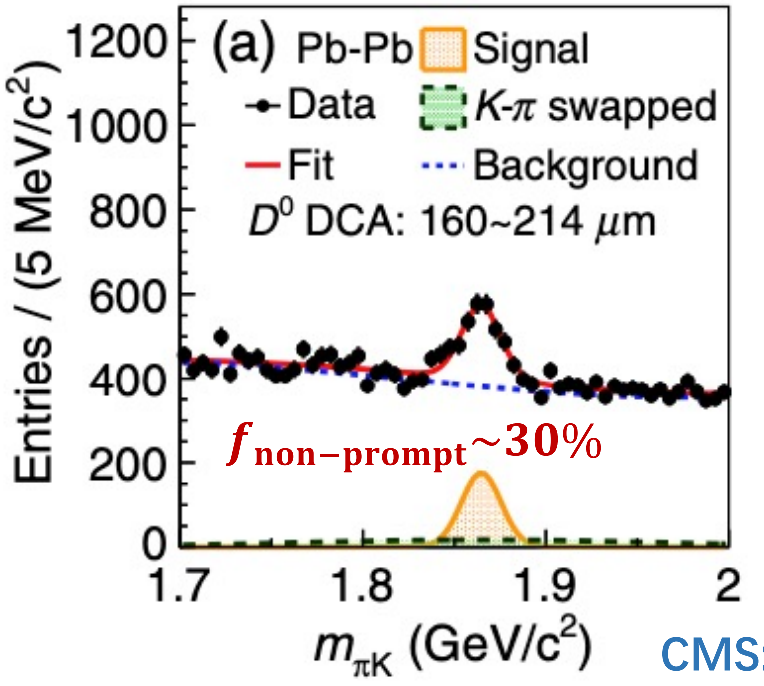


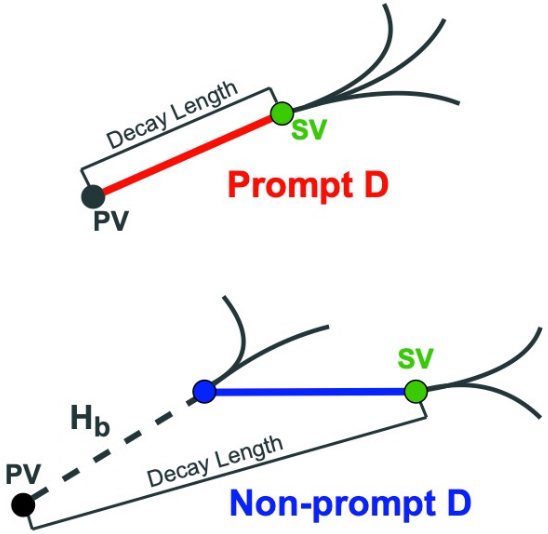
Why non-prompt charm measurements?

- **Non-prompt charm production originates from beauty-hadron decays**
  - ➢ no negligible at LHC energies (~5-20%)
  - ➢ more statistics w.r.t fully reconstructed B meson

Provide good opportunity to study the properties of beauty quark (i.e energy loss, collective flow and hadronisation)

- **Traditional analysis strategy**
  - ➢ Enhance Non-prompt fraction : selections based on the decay topological variables (such as decay length or impact parameter(DCA))
    - Even with ML optimization, the $f_{\mathrm{non-prompt}}$ can only reach up to 30%





CMS:PRL 123, 022001 (2019)

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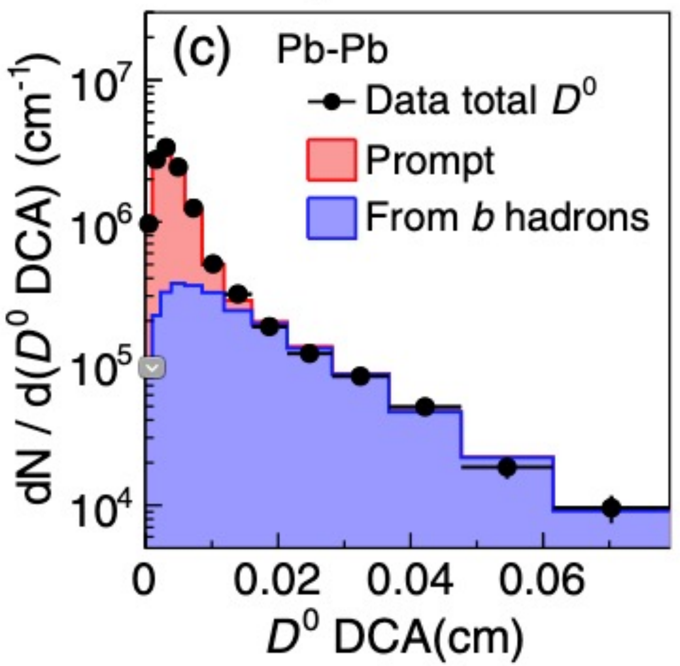
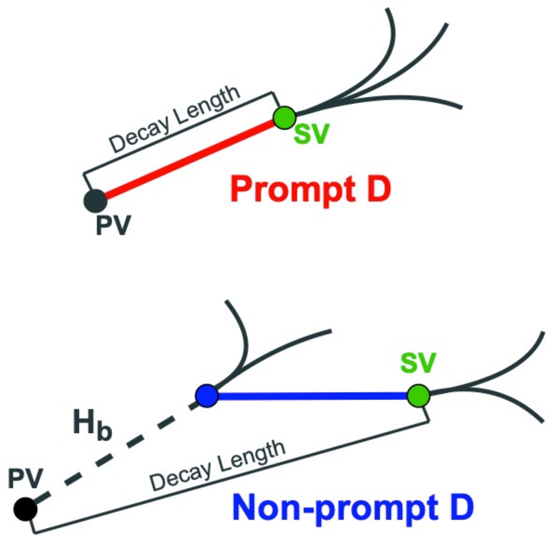
  - Non-prompt fraction calculation
    - Template fit of DCA to separate prompt and non-prompt component

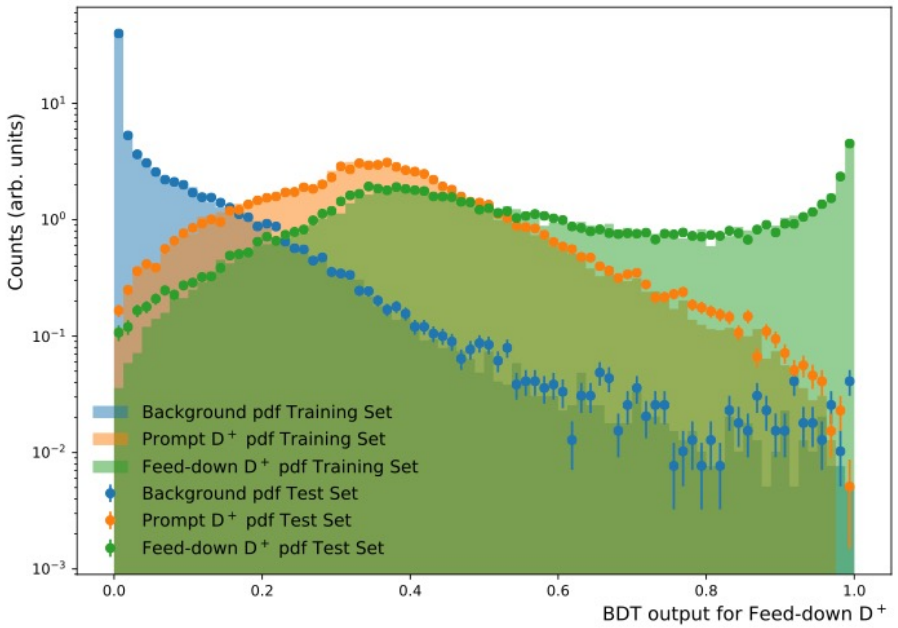


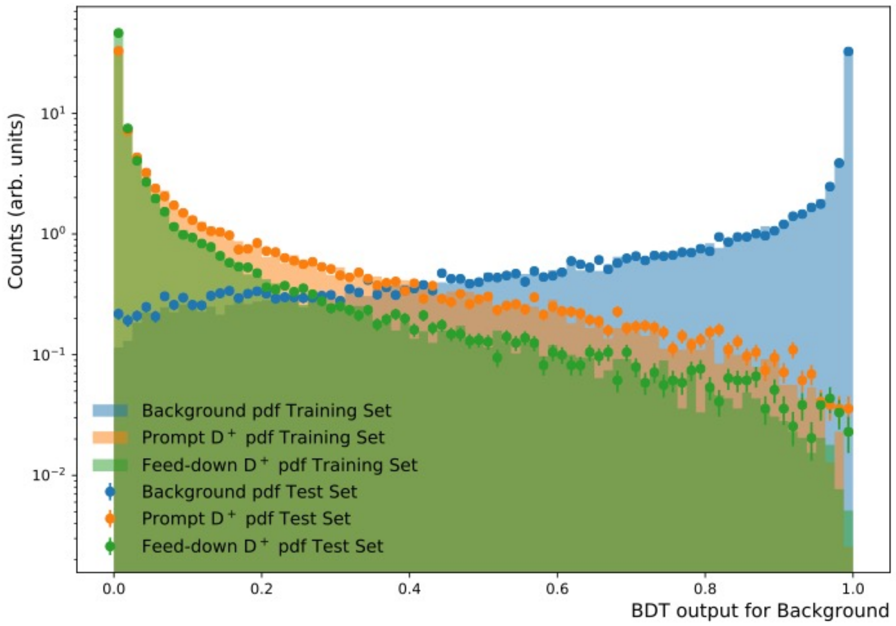


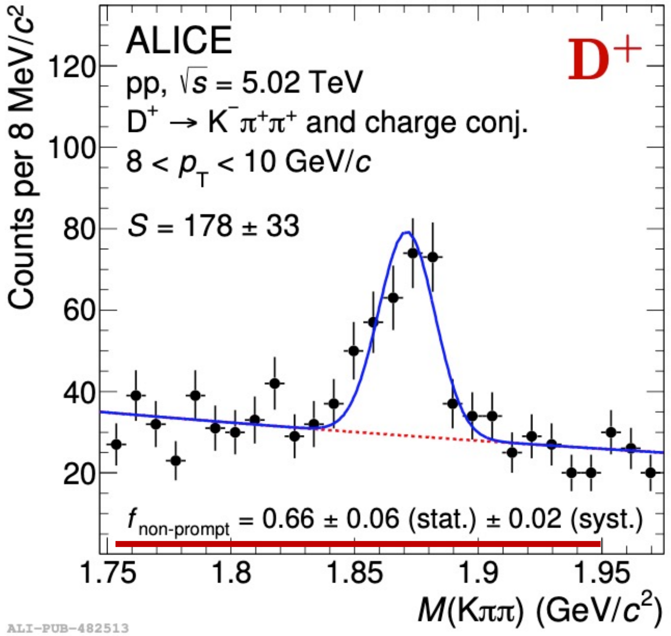
CMS:PRL 123, 022001 (2019)

New strategy of non-prompt selection

- Two individual ML trainings including topological variables are performed, aiming to simultaneously increase (control) the $b \to D$ fraction and suppress the combinatorial background







increase the $b \to D$ fraction

suppress the combinatorial background

JHEP05 (2021) 220

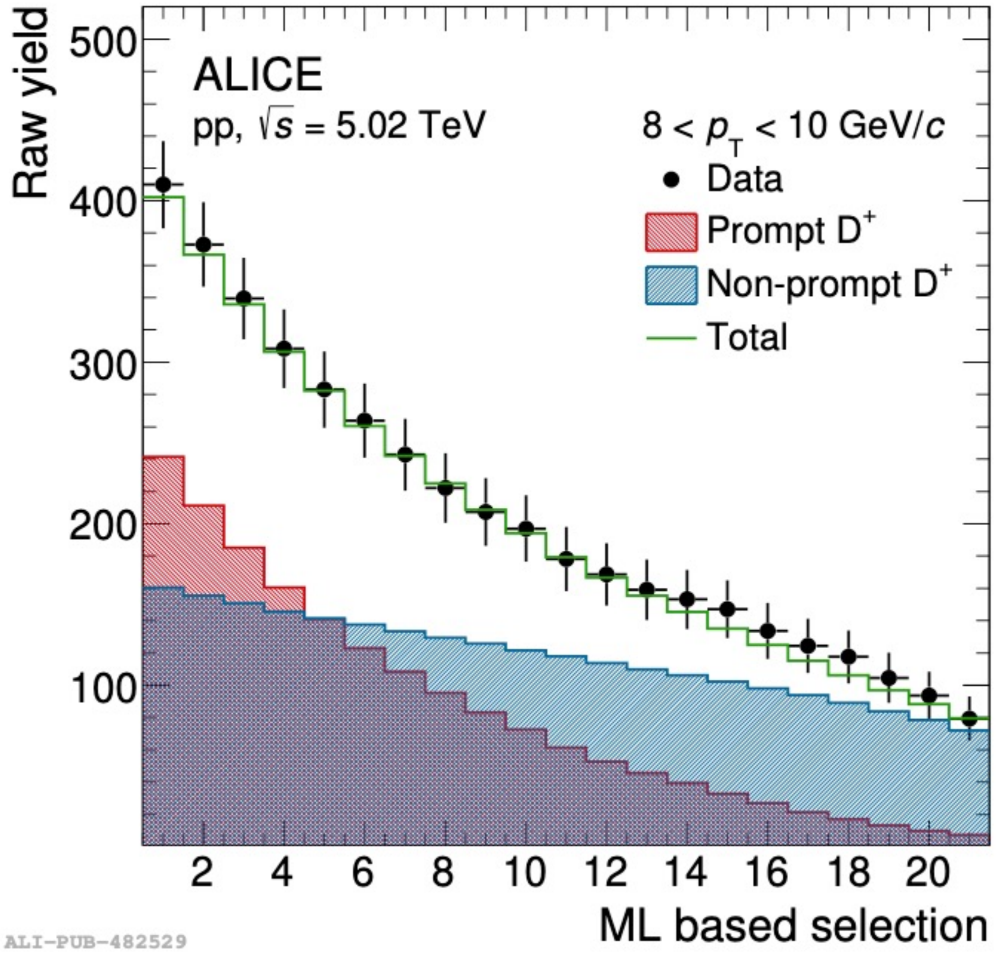
New data-driven $f_{\mathrm{non-prompt}}$ calculation

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

- An algebraic system can be obtained:

$$(\mathrm{Acc}\times\varepsilon)_{\mathrm{i}}^{\mathrm{prompt}}\cdot N_{\mathrm{prompt}}+(\mathrm{Acc}\times\varepsilon)_{\mathrm{i}}^{\mathrm{non\text{-}prompt}}\cdot N_{\mathrm{non\text{-}prompt}}-Y_{\mathrm{i}}=\delta_{\mathrm{i}}$$

- The system can be solved and obtain the $f_{\mathrm{non-prompt}}$ from χ^2 minimization of the system



Results in pp collisions: Non-prompt D mesons

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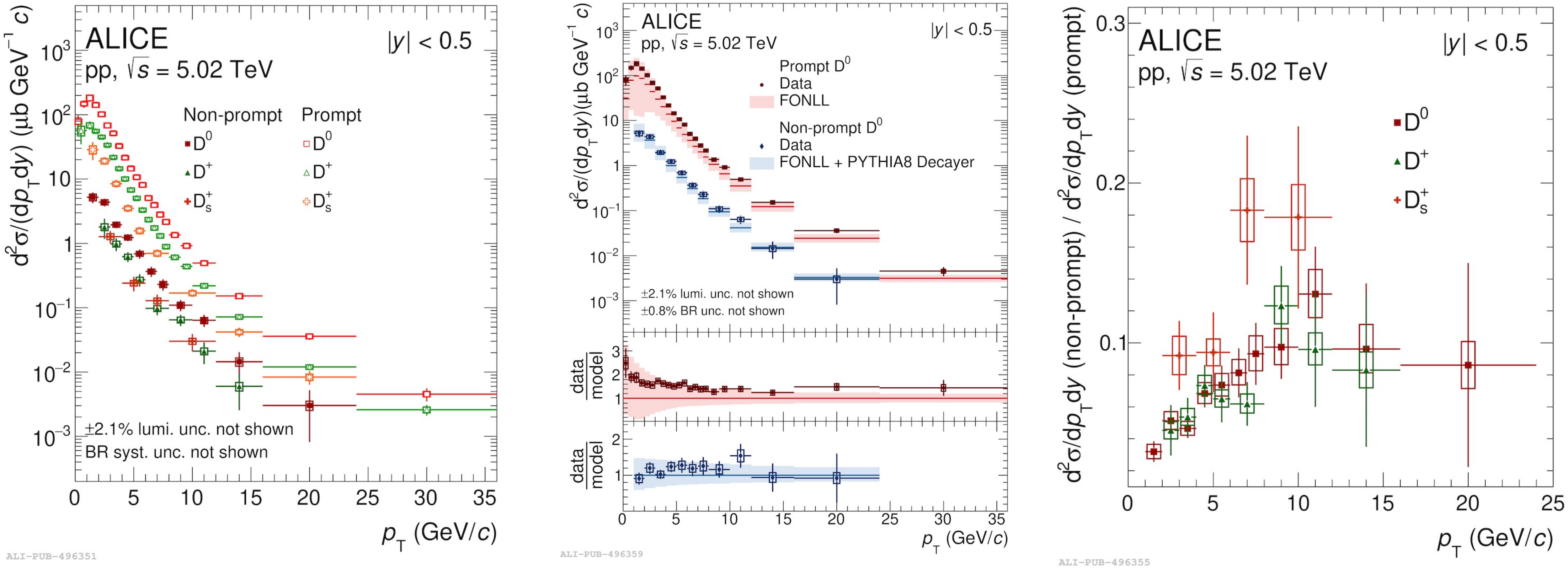

- Non-prompt $\mathrm{D^0}$,$\mathrm{D^+}$,$\mathrm{D_s^+}$ cross section measured in pp collisions down to low p_{T} at 5.02 TeV
- Measurements described by FONLL calculations within uncertainties
- Non-prompt/prompt ratio → different p_{T} shape / constraint on b → D decay branching ratio

Results in pp collisions: fragmentation fraction and total beauty cross section

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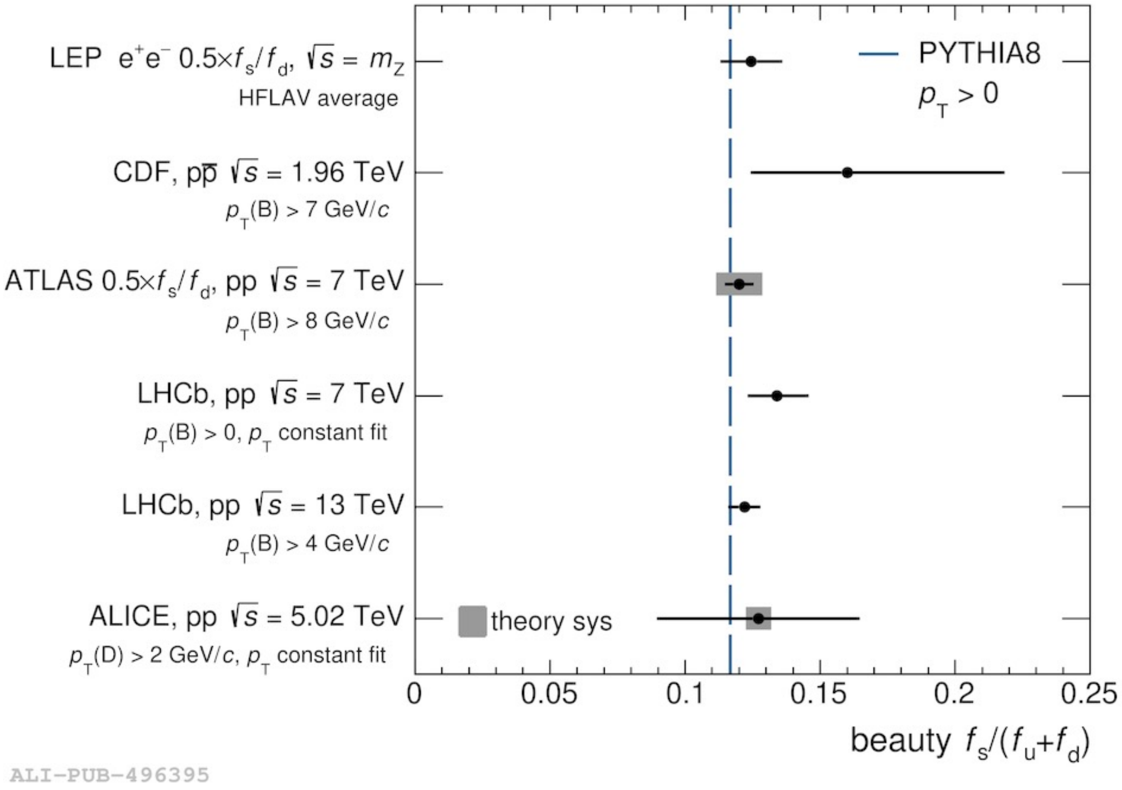
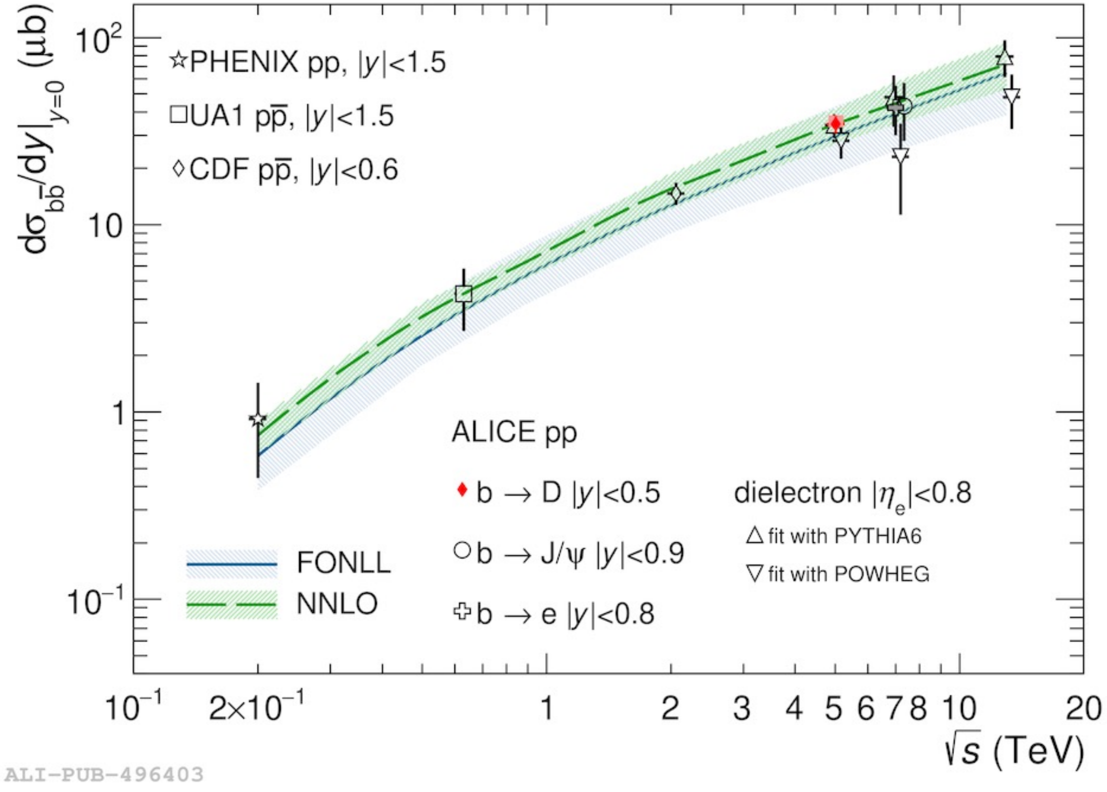
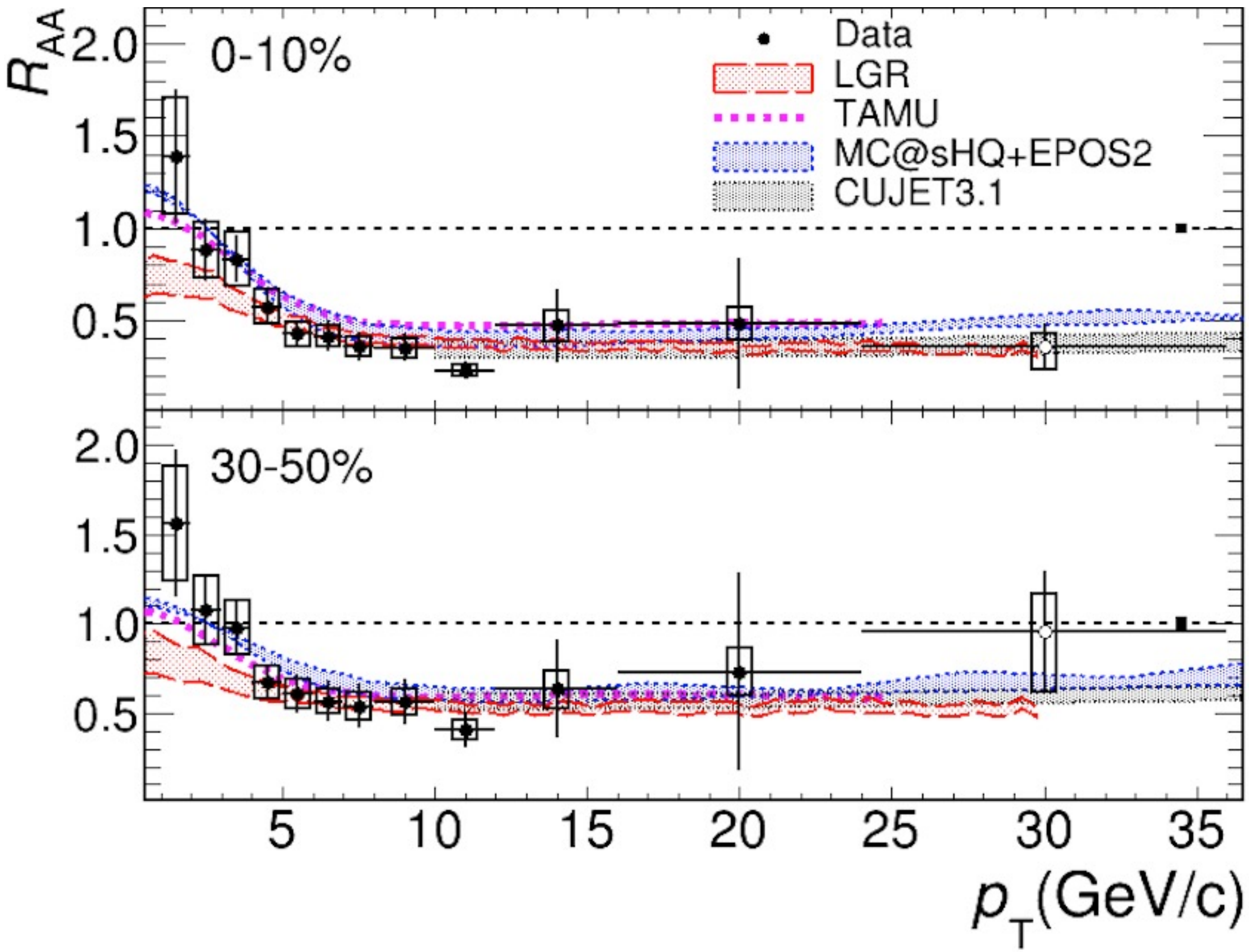




- Beauty $f_s/(f_u + f_d)$ has no significant dependence on energy and collisions system
- Most precise measurement measurement of $b\bar{b}$ cross section at 5.02 TeV with non-prompt D mesons
  - Described by FONLL and NNLO calculations

FONLL: JHEP 1210 137 (2012) NNLO: JHEP 03 (2021) 029

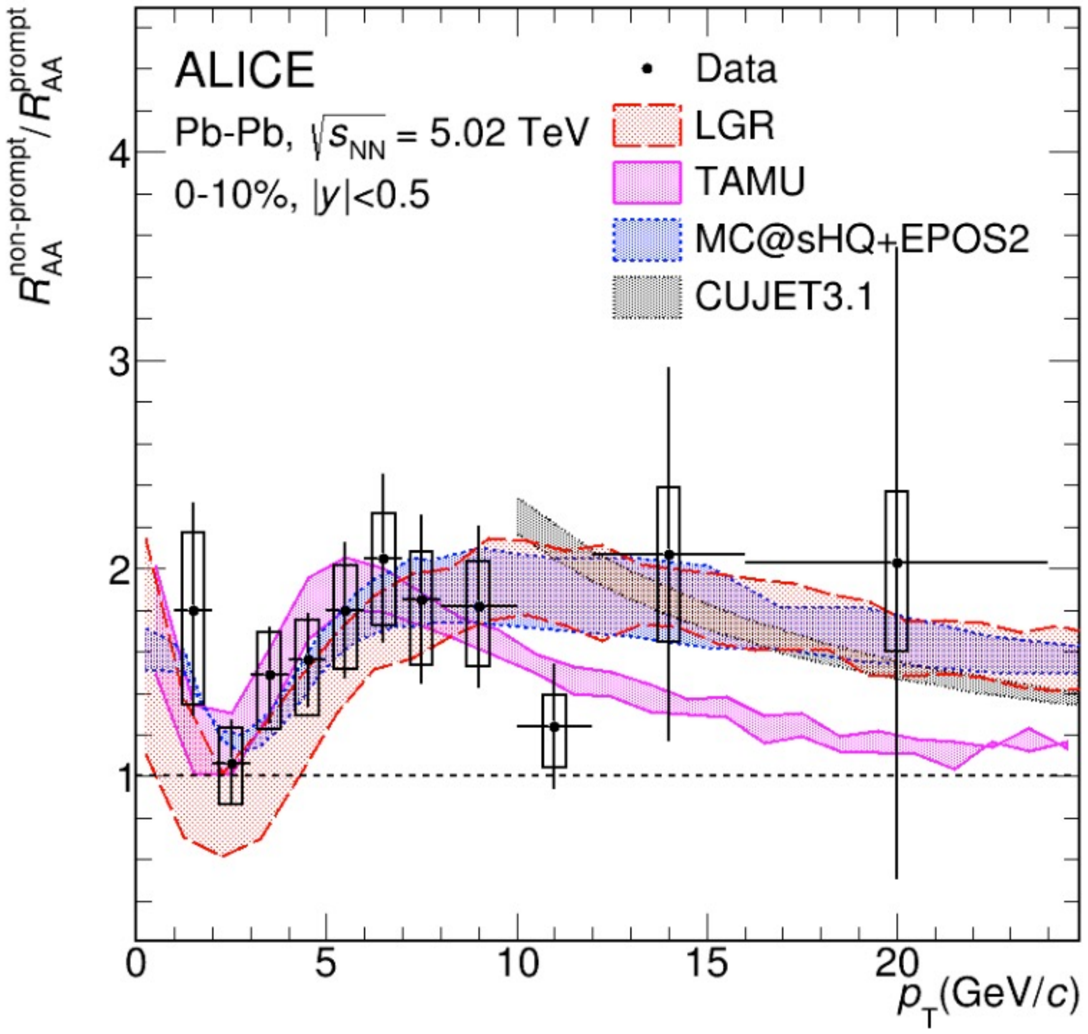
Results in Pb-Pb collisions: Non-prompt D^0 R_{AA}



- R_{AA} measured first time down to p_T = 1 GeV/c for b → D^0 in 0-10% and 30-50% Pb-Pb collisions at 5.02 TeV
- R_{AA} compatible with unity within uncertainties for p_T < 3 GeV/c in both 0-10% and 30-50%
- Theoretical models (LGR, MC@sHQ+EPOS2,CUTJET3.1) that include collisional and radiative energy loss describe the data within uncertainties
- TAMU included elastic collisions only, underestimate the suppression at 0-10%
  - Both radiative and collisional processes are important for beauty quark in-medium energy loss

TAMU: PLB 735 (2014) 445
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: EPJC 80 no.7, (2020) 671, EPJC 80 no. 12, (2020) 113
CUJET3.1: CPC 43 no.4, (2019) 044101

Results in Pb-Pb collisions: Non-prompt $\mathrm{D^0}$ R_{AA}



- Integrated non-prompt $\mathrm{D^0}$ R_{AA} compatible with unity within 1 σ, with prompt less than 1.5 σ -> shadowing or hadronization via coalescence

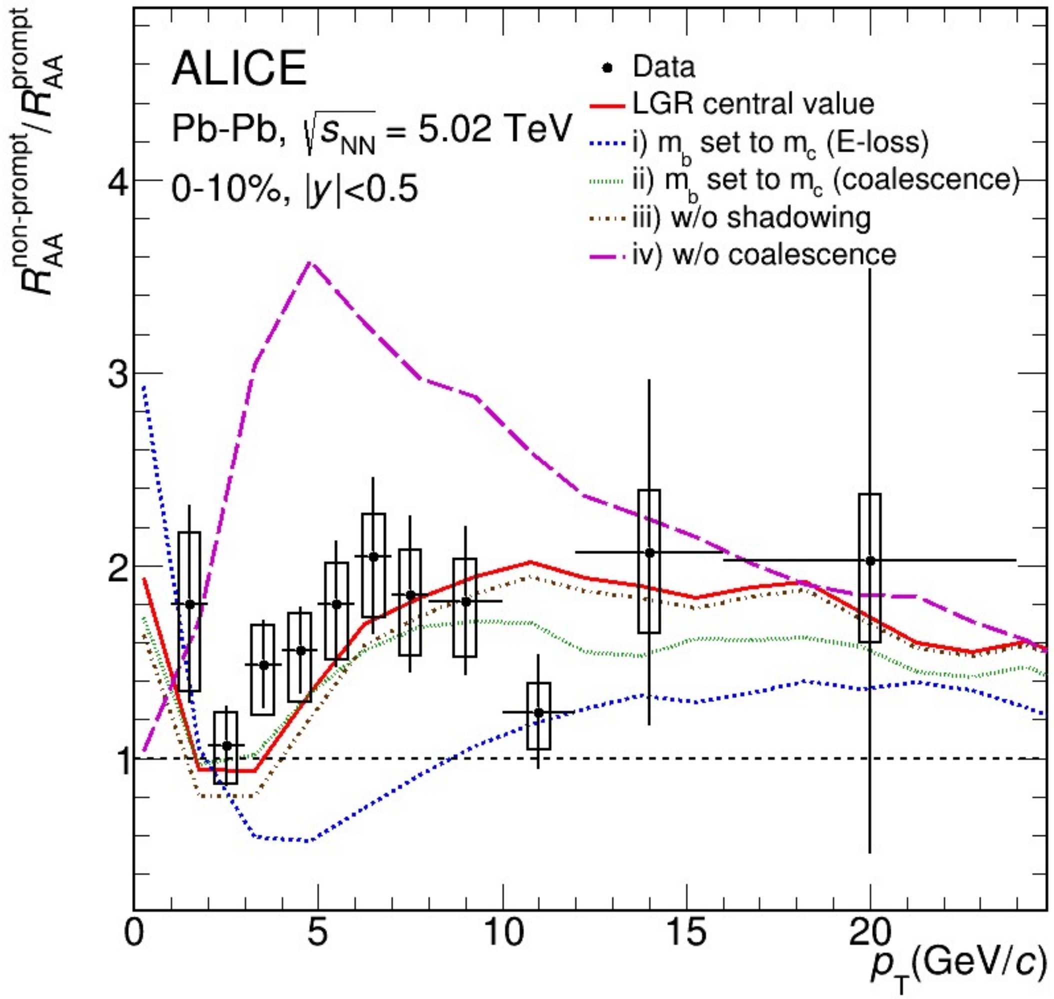
$$R_{\mathrm{AA}}^{\text{non-prompt}\,\mathrm{D^0}}(0\text{-}10\%) = 0.92 \pm 0.07\,(\text{stat.}) \pm 0.15\,(\text{syst.})$$

$$R_{\mathrm{AA}}^{\text{prompt}\,\mathrm{D^0}}(0-10\%) = 0.689 \pm 0.054\,(\text{stat.})^{+0.104}_{-0.106}\,(\text{syst.}).$$

- Ratio of the R_{AA} of non-prompt to prompt $\mathrm{D^0}$ (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 → mass dependence of energy loss

Uncertainties further reduced by simultaneously obtaining prompt and non-prompt

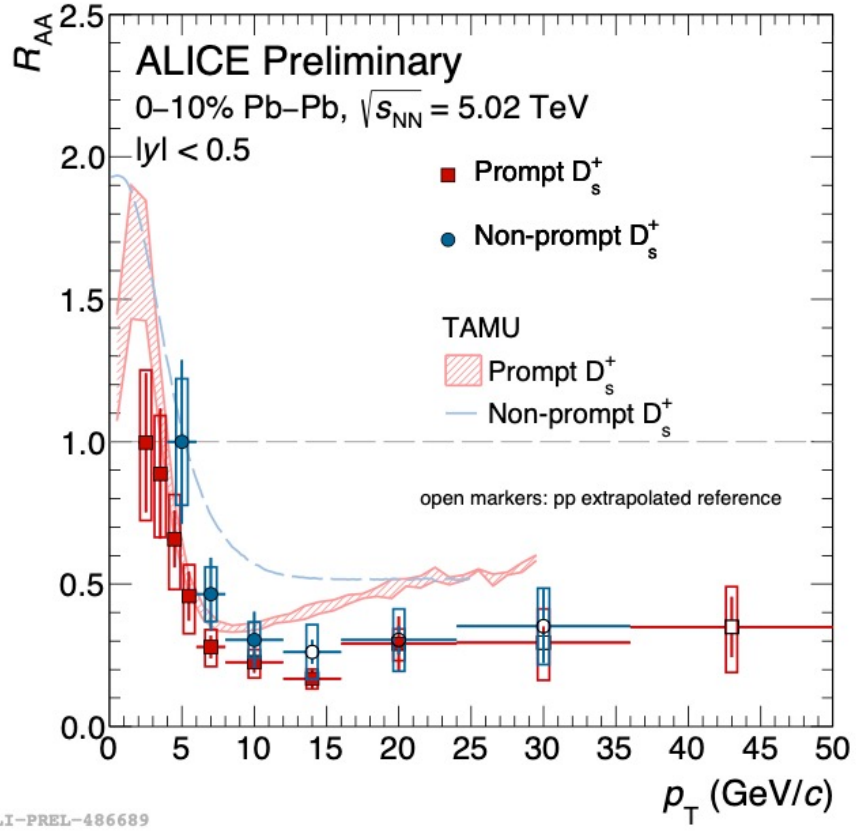
Results in Pb-Pb collisions: Non-prompt D^0 R_{AA}

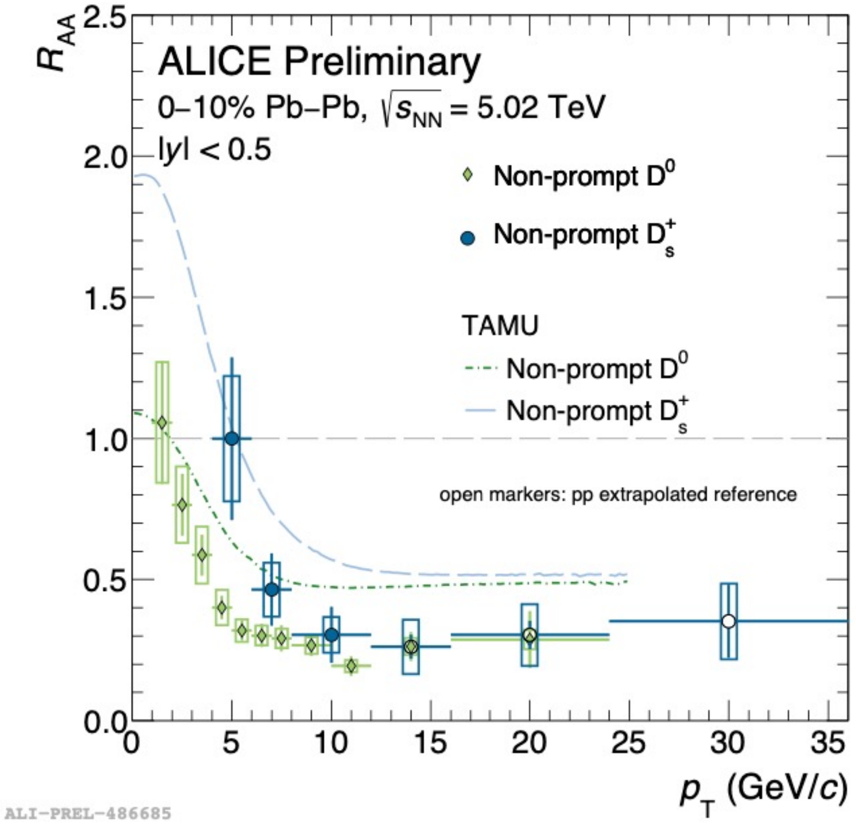


- Test the doube R_{AA} ratio with different LGR configurations
  - Shadowing effect largely cancelled for the double ratio
  - The "valley" structure is mainly due to the formation of prompt D-mesons via charm-quark coalescence
  - The significant enhancement of double ratio at high p_{T} is related to the mass dependent quark in-medium energy loss effect

LGR: including collisional and radiative processes

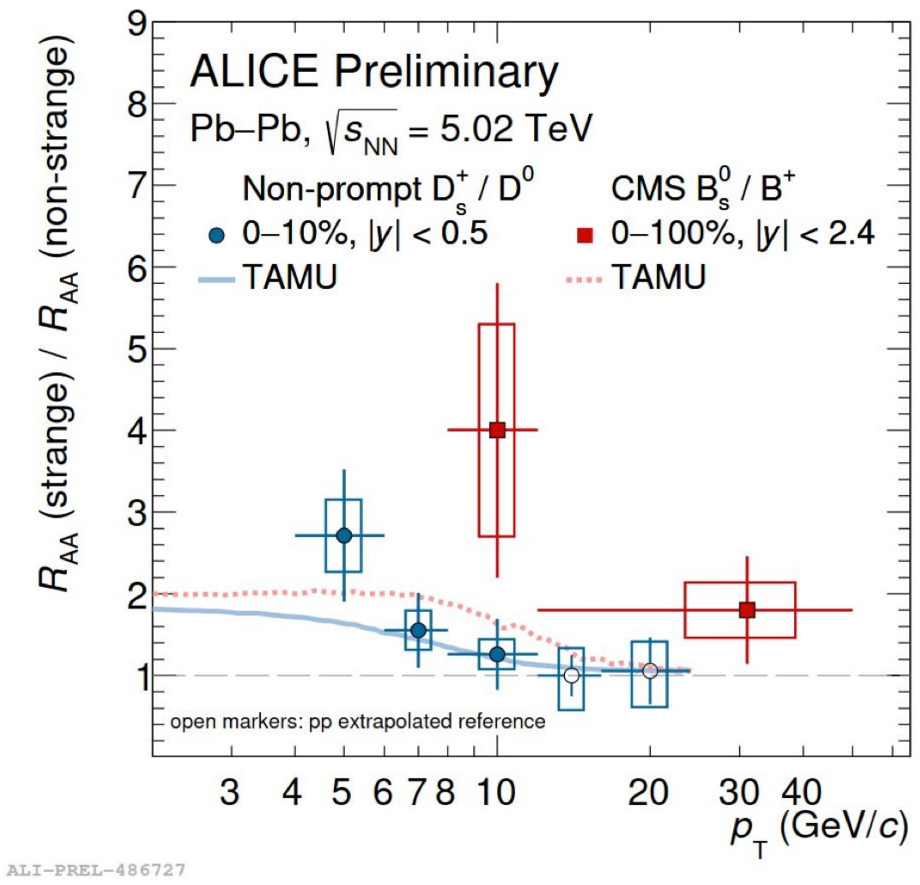
Results in Pb-Pb collisions: Non-prompt $\mathrm{D_S}$ R_{AA}

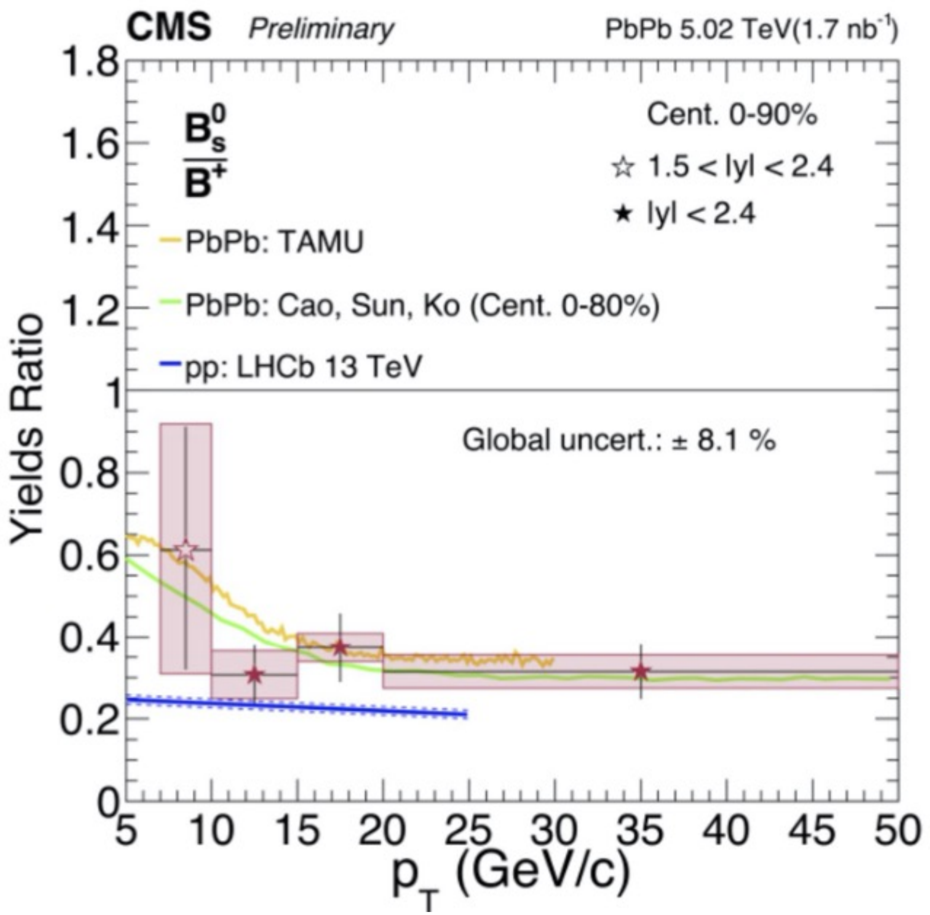




- First measurement of non-prompt $\mathrm{D_s^+}$ R_{AA} in central (0-10%) heavy-ion collisions
- Hint of larger R_{AA} than prompt $\mathrm{D_s^+}$ and non-prompt $\mathbf{D^0}$ mesons in the low p_{T} region
  - Non-prompt $\mathrm{D_s^+}$ mesons: about 50% originate from $\mathrm{B_s^0}$ meson decays -> Interplay of charm and beauty energy loss and recombination in the medium

Results in Pb-Pb collisions: Non-prompt $\mathrm{D_S}$ R_{AA}



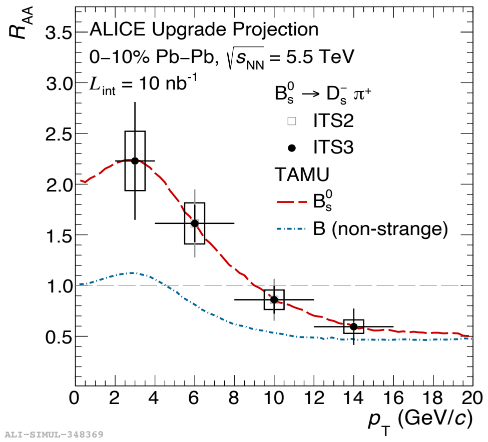


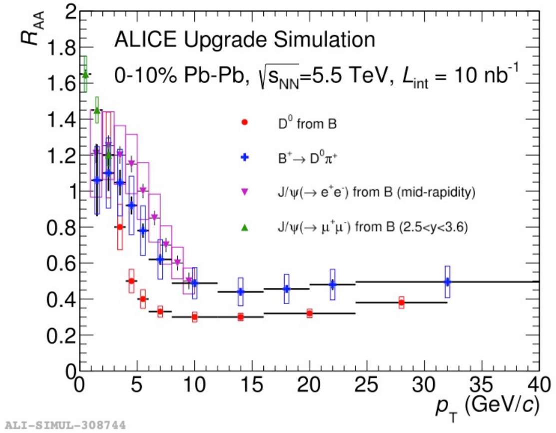
- $R_{\mathrm{AA}}(\mathrm{D_s^+})/R_{\mathrm{AA}}(\mathrm{D^0})$ ratio for non-prompt above one at low p_{T}
  - ➢ Non-prompt $\mathrm{D_s^+}$ mesons: about 50% originate from $\mathrm{B_s^0}$ meson decays -> beauty hadronisation via coalescence

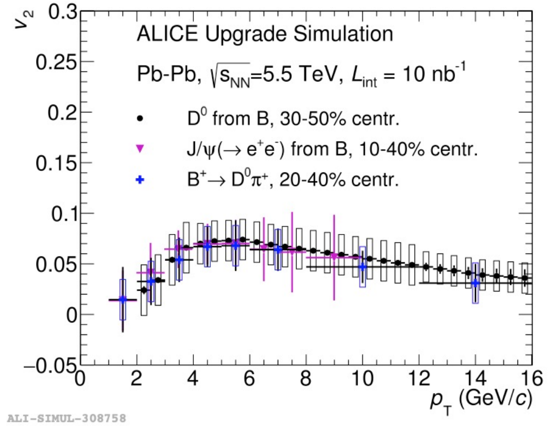
➢ Larger $R_{\mathrm{AA}}(\mathrm{B_s^0})/R_{\mathrm{AA}}(\mathrm{B^+})$ ratio w.r.t non-prompt D -> B to D decay kinematics or $\mathrm{D_s^+}$ from non-strange B-meson decay

Summary

- Beauty production studied via non-prompt measurements in different systems
  - pp collisions:
    - ➢ Beauty-quark production described by FONLL and NNLO calculations over a wide interval of center-of-mass energies
  - Pb-Pb collisions:
    - ➢ Beauty quarks undergo energy loss in the medium → important constraint of mass dependence of ΔE
    - ➢ Measurement described by models that include collisional and radiative energy loss
- Even at the end of Run2 , several interesting non-prompt measurements are still ongoing
  - ➢ Non-prompt Λ_c^+, $f_{\mathrm{non-prompt}}$ vs multiplicity , non-prompt D^0 v_2 in Pb-Pb (foreseen in QM 2022)
- Looking forward to see more precise and fully reconstructed beauty production in Run3

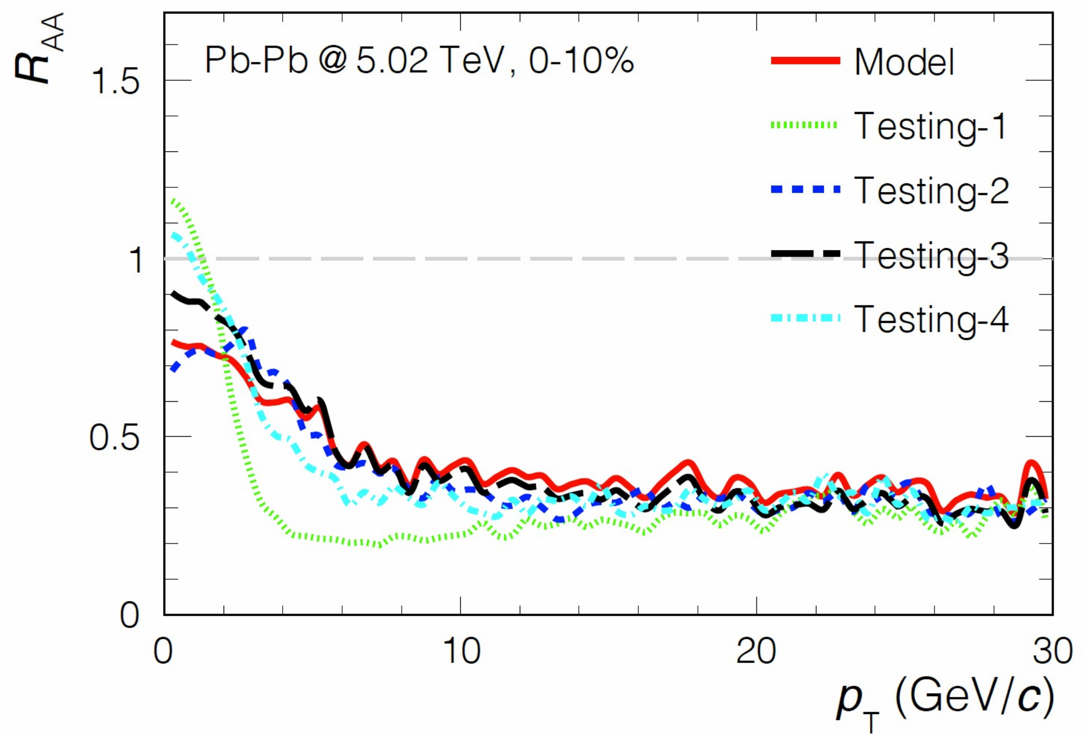


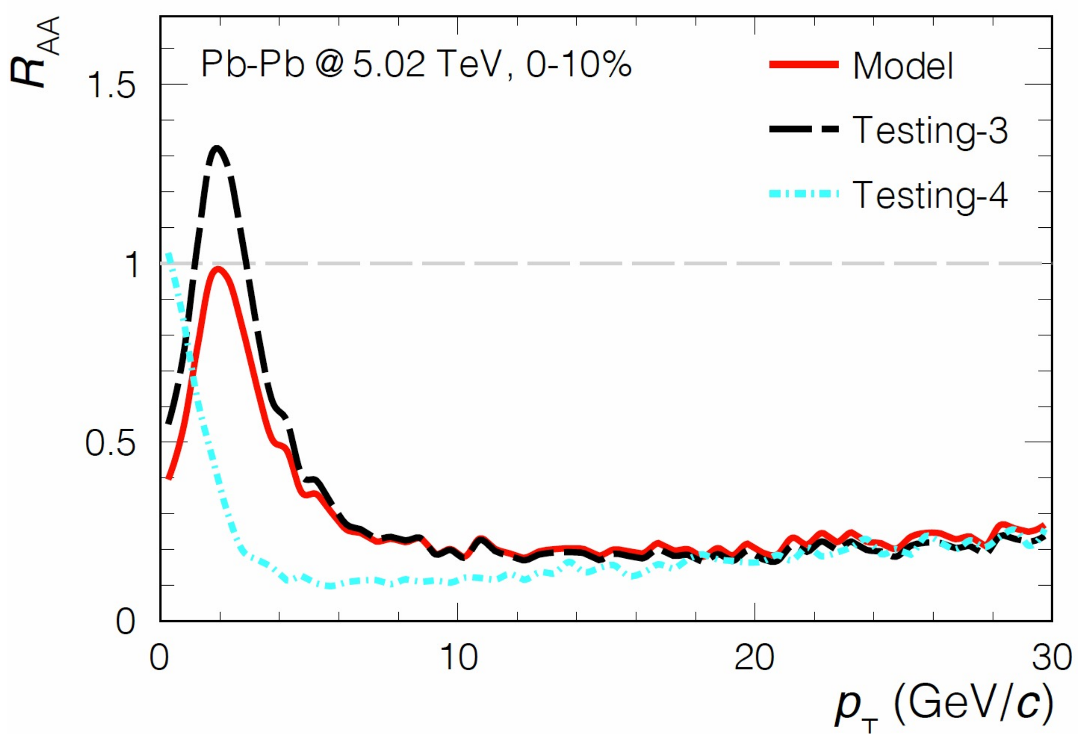




BACK UP

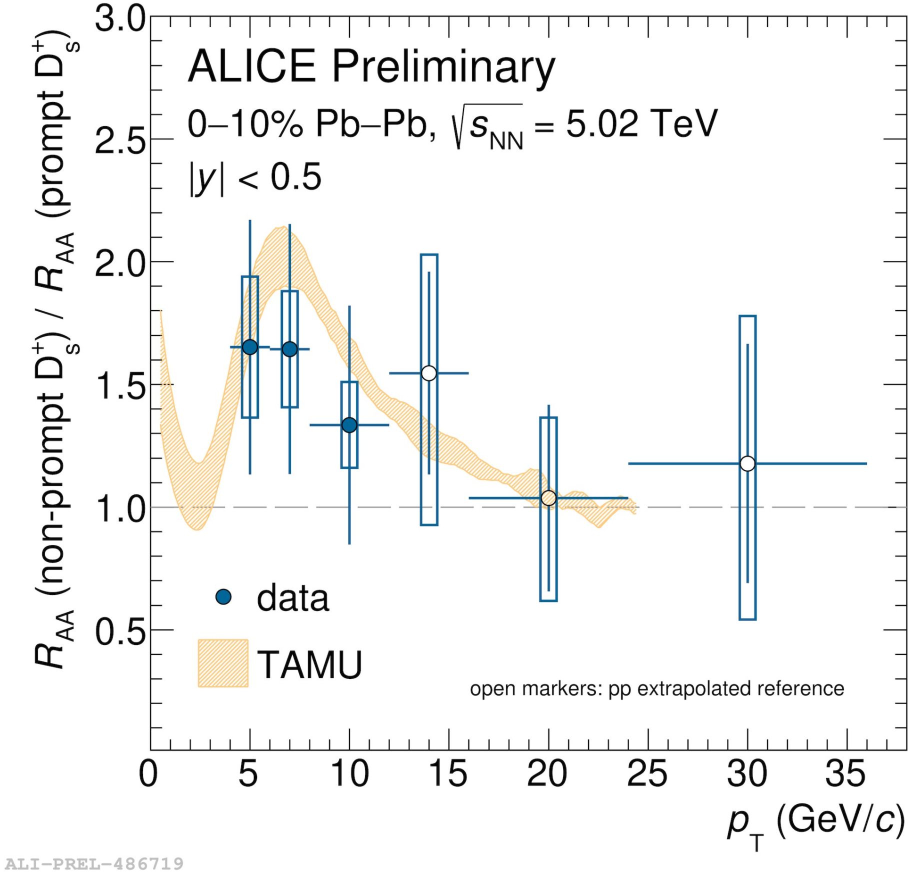
LGR prediction for prompt and non-prompt D^0 R_{AA}





Testing-1: b quark energy loss using mass of charm (keep b quark coalesce unchanged)
Testing-2: b quark coalesce using mass of charm (keep b quark energy loss unchanged)
Testing-3: Calculate the double ratio without shadowing (but keep all other parameters, e.g., quark masses, unchanged)
Testing-4: Calculate double ratio without recombination in hadronization

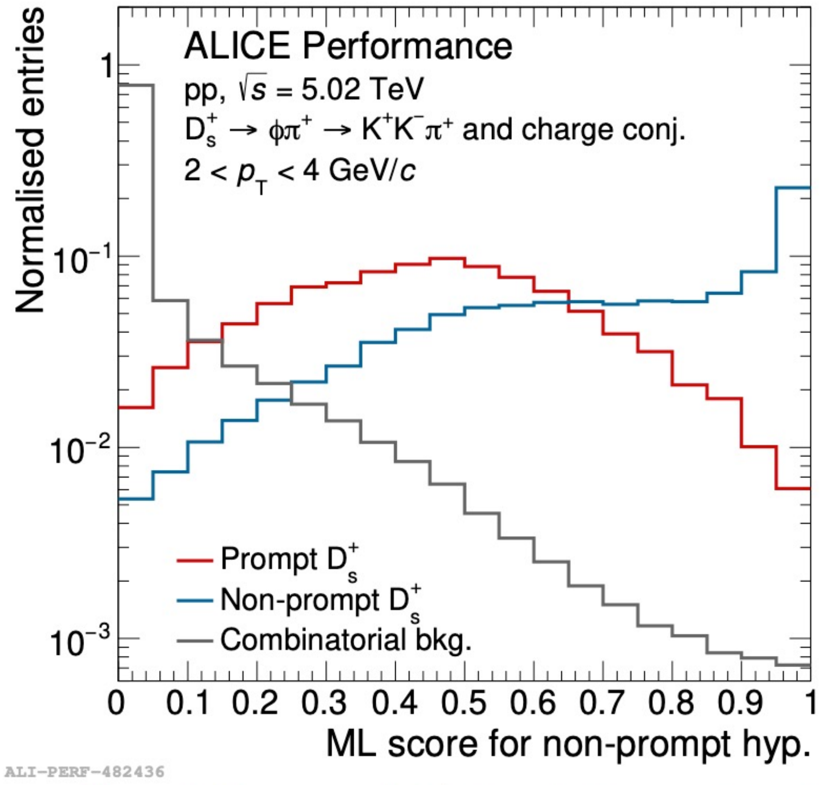
Ratio of the D_s R_{AA} of non-prompt to prompt



- Ratio of the R_{AA} of non-prompt to prompt D_s (beauty/charm)
  - Described by the TAMU prediction within uncertainties

New strategy of non-prompt selection

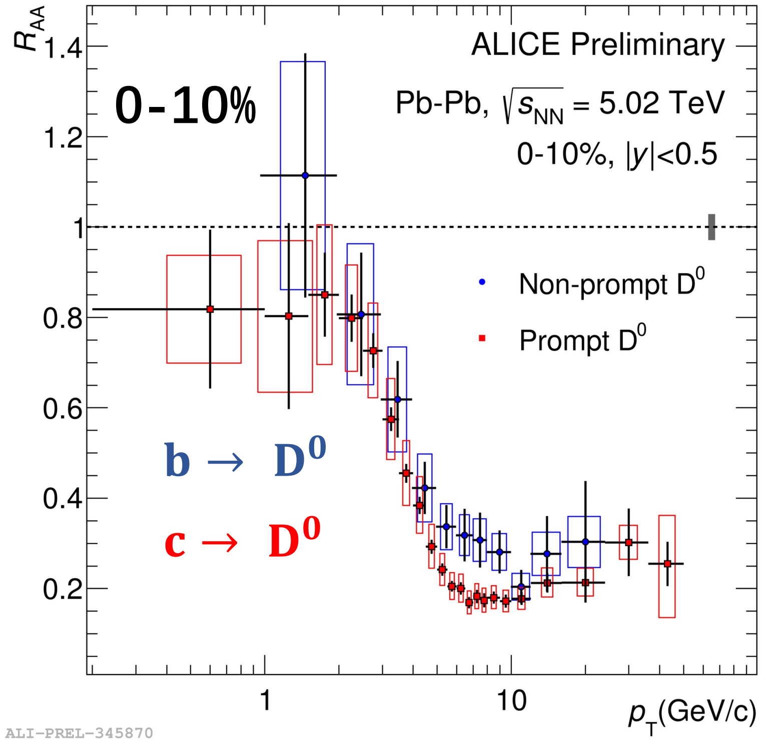
- Multi-class Boosted Decision Trees (BDT) employed to separate prompt D mesons, non-prompt D mesons and combinatorial background
  - different BDTs for D^0, D^+ and $\mathrm{D_s^+}$ mesons and for different transverse-momentum (p_T) intervals

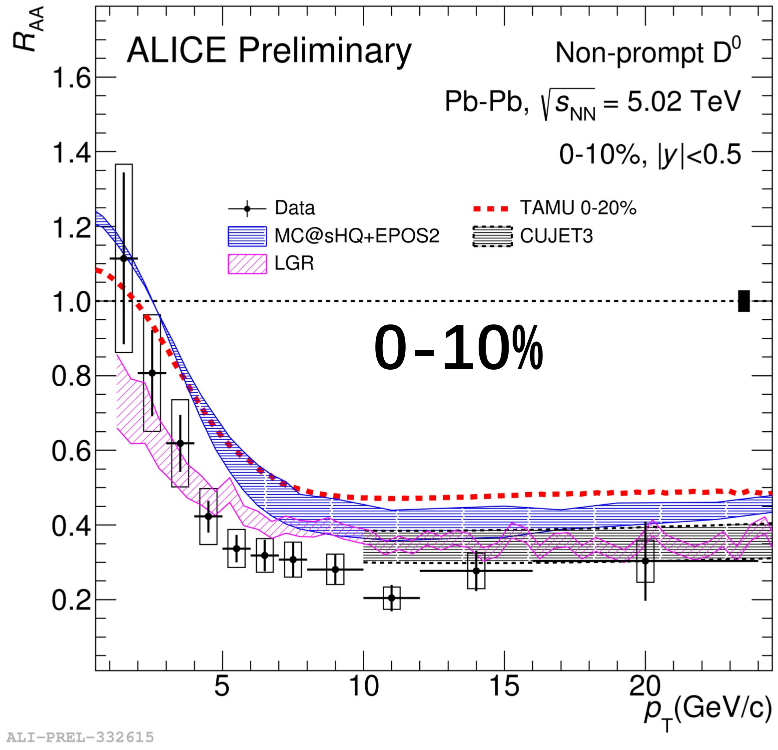


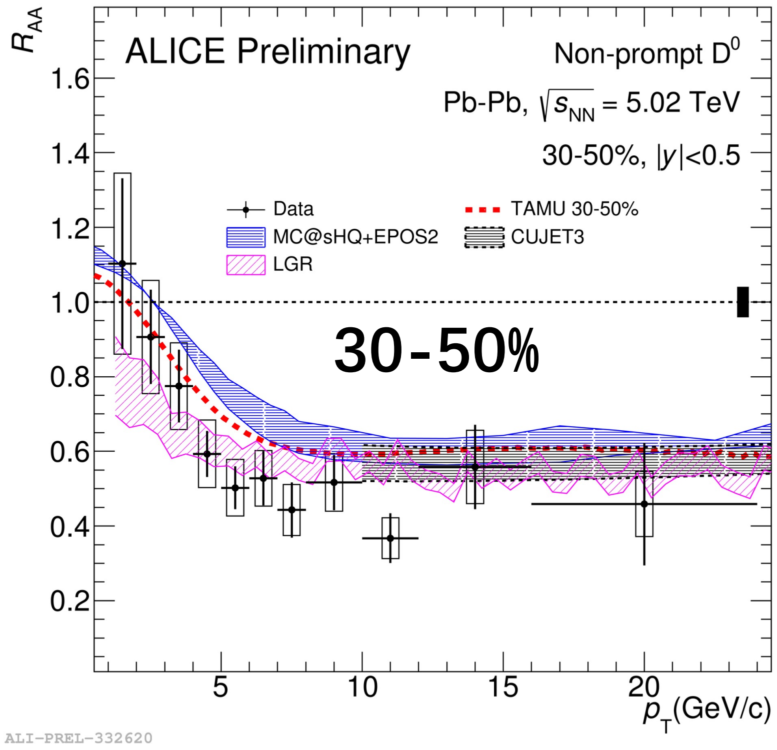
Prompt/Non-prompt $\mathrm{D_s^+}$ from MC, bkg. from data

- BDT input: candidate kinematic, geometrical and PID quantities
- BDT output: 3 scores related to the candidate probability to be prompt, non-prompt and background
- Selections applied on these scores to reduce combinatorial background and reject prompt or non-prompt D mesons

Results in Pb-Pb collisions: Non-prompt D^0 R_{AA}







- R_{AA} measured for $b \rightarrow D^0$ in 0-10% and 30-50% Pb-Pb collisions at 5.02 TeV
  - ➢ Suppression of $b \rightarrow D^0$ observed
- Hint of ordering $R_{AA,\, b \rightarrow D^0} > R_{AA,\, c \rightarrow D^0}$ 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 arXiv:1901.04600; 1805.05807
CUJET3: arXiv:1411.3673; 1508.00552; 1804.01915; 1808.05461