Medium-induced yield enhancement in small and large collision systems

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On behalf of the ALICE, ATLAS, CMS, LHCb Collaborations

14th International workshop on Multiple Parton Interactions at the LHC
MPI@LHC 2023
22nd November 2023

Heavy quarks: a unique probe for high-density QCD

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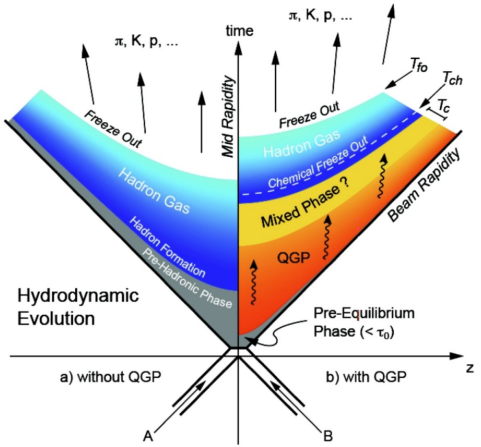
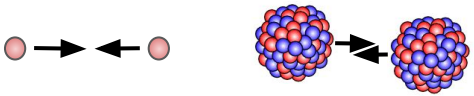


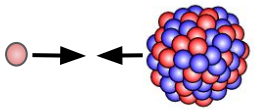


pp collisions

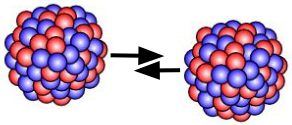
- **Charm** and **beauty** quarks: $m_c \sim 1.3$ GeV/c^2, $m_b \sim 4.2$ GeV/c^2
- **Produced** in **hard scattering** processes among partons

- **Ultrarelativistic heavy-ion** collisions at the LHC: quark-gluon plasma (**QGP**)
  - state of matter expected in the first ~ 10 μs after the Big Bang
  - heavy quarks experience the **full evolution** of the system

Charm- and **beauty- quarks dynamics** tested via **measurements** of **charm-** and **beauty- hadron production**



p–Pb collisions



Pb–Pb collisions

- Reference for Pb–Pb collisions
- Test of pQCD calculations

Cold nuclear-matter effects

- Modification of parton distribution functions (PDFs) in bound nuclei

Hot nuclear-matter effects

- Energy loss in the medium
- Collective motion
- Hadronization modified in QGP

Charm and beauty hadronization from e^+e^- to Pb–Pb

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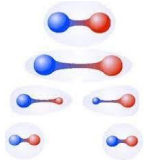
Hadronization: a key ingredient in all collision systems!

- "**Point-like**" object interaction
- **Fragmentation** in the vacuum



Fragmentation

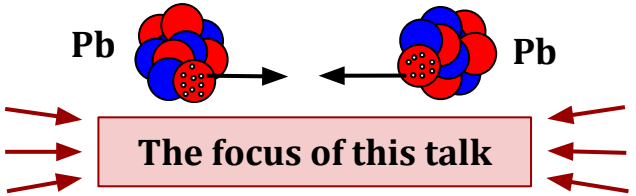
- Hard scattering: $e^+e^- \rightarrow qq$
- Color string: $V_{Cornell}(r) \sim \kappa r$
- New qq pairs from multiple string breaking (confinement)

What happens in pp collisions?

A. Rossi, Monday at 10:10

"Heavy-quark production and hadronisation as a function of event multiplicity with ALICE"

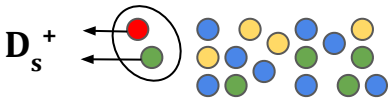
DO NOT MISS OUT!



- **QGP**: complex system with **partonic d.o.f**
- Hadronization can be influenced by **coalescence** and **strangeness enhancement**

Coalescence

- Heavy quark recombinates with light quarks in the QGP
- Expected increase of hadrons at intermediate-low p_T
- QGP: interplay with fragmentation



The observables in Pb–Pb collisions

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1 Production spectra and R_{AA}

$$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

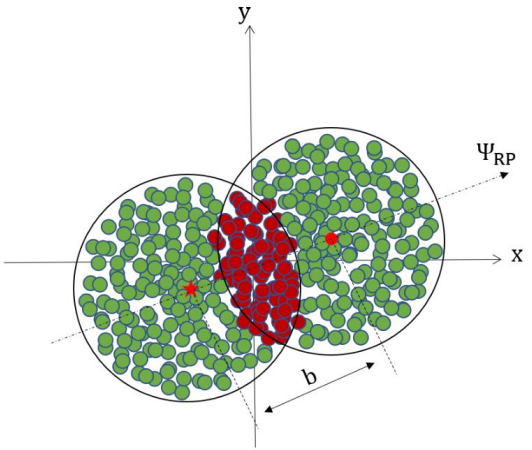
$\langle N_{coll} \rangle$: average number of binary nucleon-nucleon collisions

$R_{AA} = 1$: no modifications
$R_{AA} \neq 1$: nuclear effects

2 Anisotropic flow

$$v_n(p_T) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(1 + 2\sum_{n=1}^{\infty} v_n(p_T) \cos[n(\varphi - \Psi_n)]\right)$$



Reaction plane (Ψ_{RP}): between z axis and centers of nuclei

3 … and particle ratios!

The observables in Pb–Pb collisions

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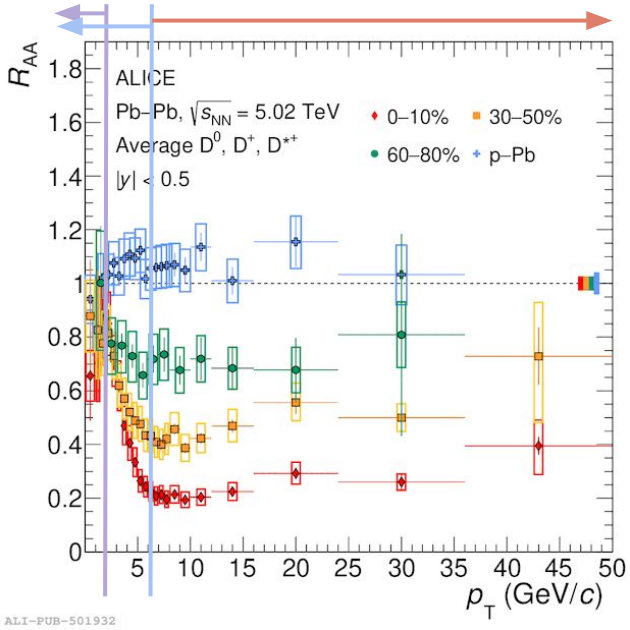
1 Production spectra and R_{AA}

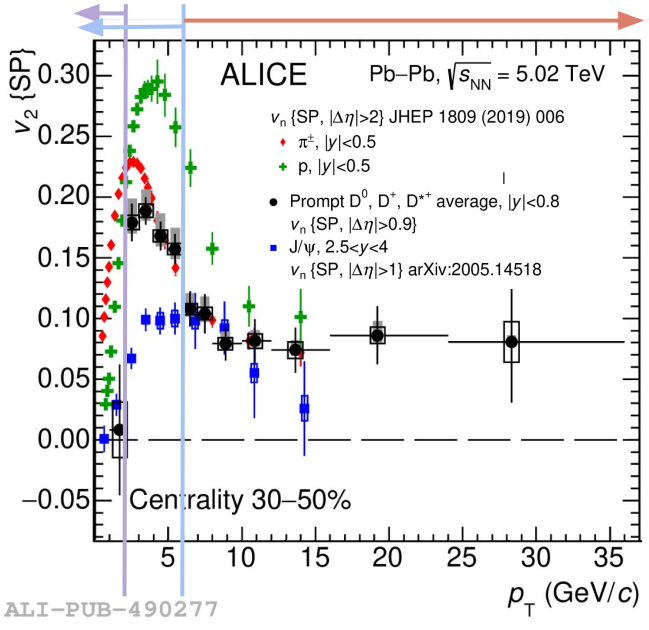
$$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$



ALICE: JHEP 01 (2022) 174

2 Anisotropic flow

$$v_n(p_T) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$



ALICE: Phys. Lett. B 813 (2021) 136054

Low p_T

- Elastic scatterings
- Diffusion via Langevin dynamics
- nPDF and shadowing

Intermediate p_T

- Charm- and beauty-quark hadronization

High p_T

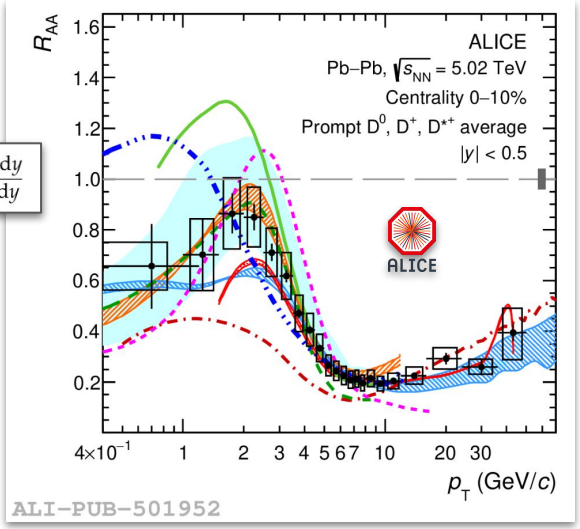
- Radiative E-loss
- Quark-mass and path length dependent E-loss

R_{AA} and v_2 compared to transport models

R_{AA}

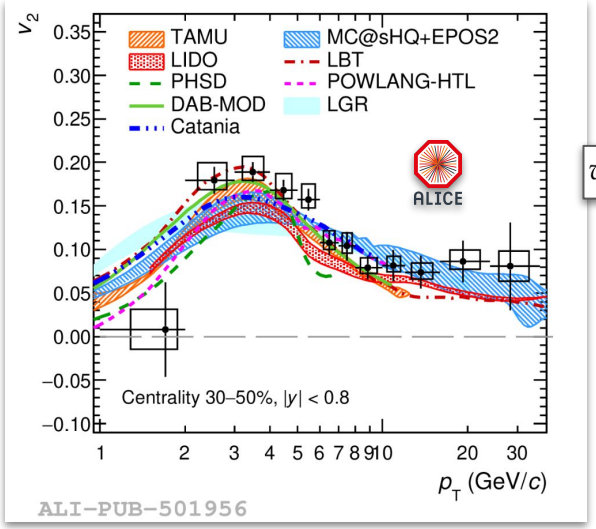
$$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

ALICE: IHEP 01 (2022) 174



v_2

$$v_n(p_T) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$



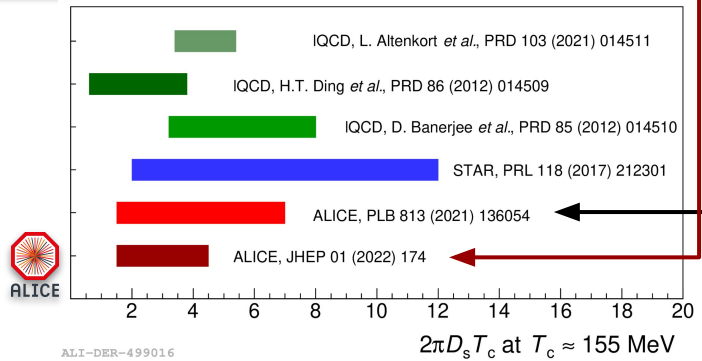
Measured R_{AA} and v_2 described by transport models

- **understanding** of **relevant effects** in different p_T intervals (<u>next slides</u>)
- sensitivity to transport regime (and charm-quark thermalization) at low p_T
  - **stronger constraint** to the **charm quark spatial diffusion coefficient** based on **data-to-model agreement**

$$1.5 < 2\pi D_s T_c < 4.5 \leftrightarrow \tau_{charm} \simeq 3\text{–}8 \text{ fm}/c$$

v_2 only

R_{AA} and v_2



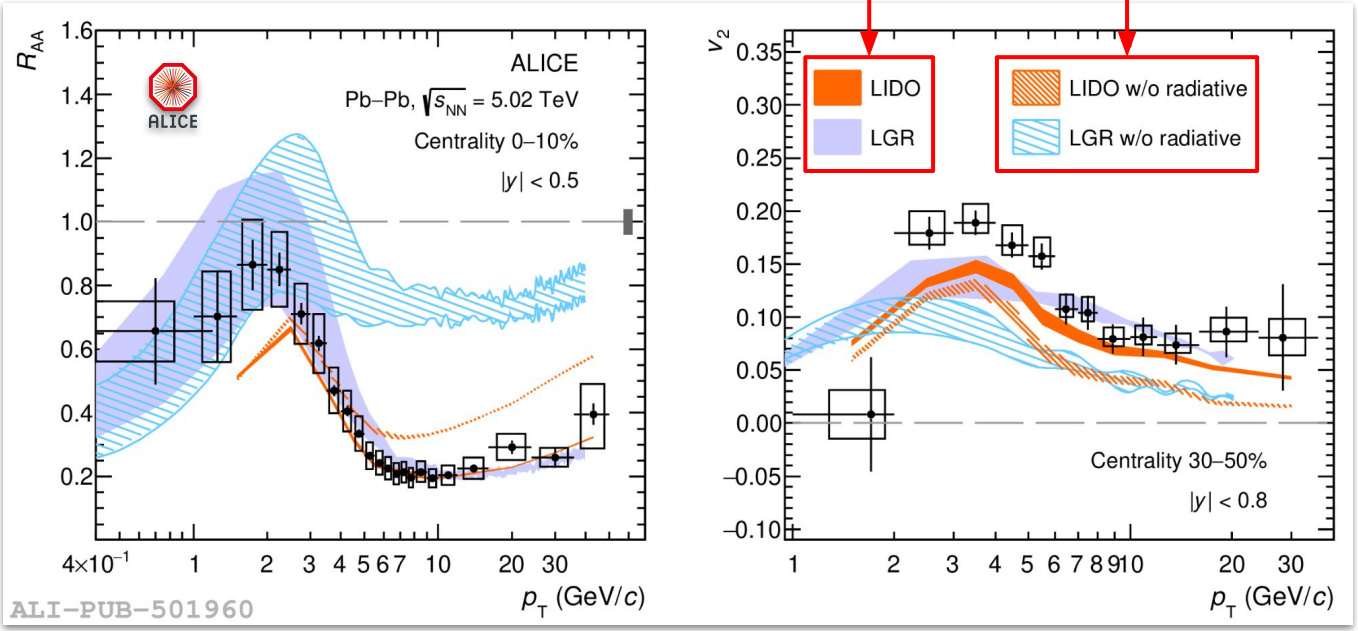
TAMU: PRL 124, 042301 (2020) DAB-MOD: PRC 96, 064903 (2017) LBT: PLB 777 (2018) 255-259 LIDO: PRC 98, 064901 (2018) Catania: PRC 96, 044905 (2017)
POWLANG: EPJC 75 (2015) 3, 121 PHSD: PRC 93, 034906 (2016) MC@sHQ: PRC 91, 014904 (2015) LGR: EPJC 80 (2020) 7, 671

Radiative energy loss

with

without

R_{AA}



v_2

Measured R_{AA} **and** v_2 compared to transport models to **understand** the **relevant effects** on **charm-quark dynamics** in **QGP**

- **Radiative energy loss** important to describe the results at **high** p_T, while it is less relevant at low p_T

ALICE: JHEP 01 (2022) 174

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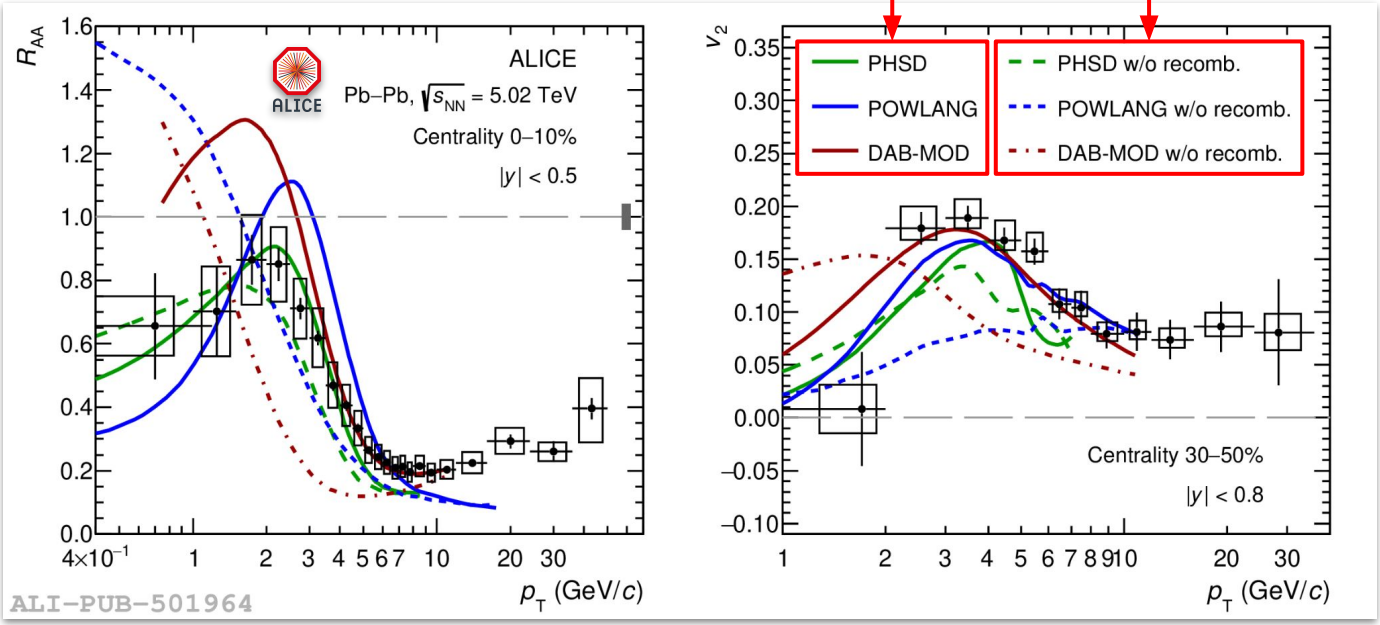
Hadronization via coalescence

with without

R_{AA}



v_2

Measured R_{AA} **and** v_2 compared to transport models to **understand** the **relevant effects** on **charm-quark dynamics** in **QGP**

- Radiative energy loss important to describe the results at high p_T, while it is less relevant at low p_T
- **Hadronization** via **coalescence** important to describe the results at **low** and **intermediate** p_T

ALICE: JHEP 01 (2022) 174

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Beauty-quark dynamics from non-prompt D mesons

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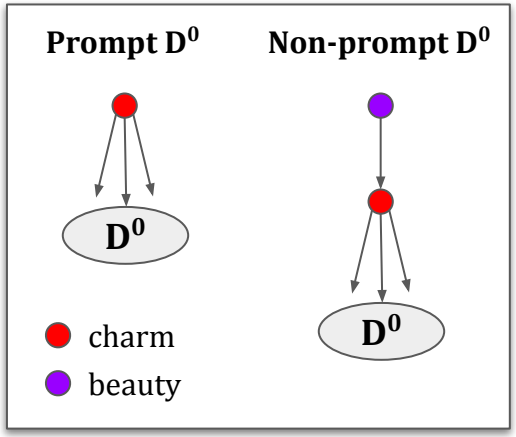
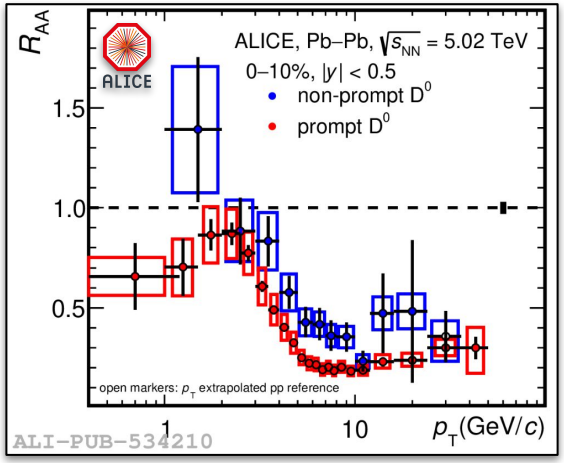
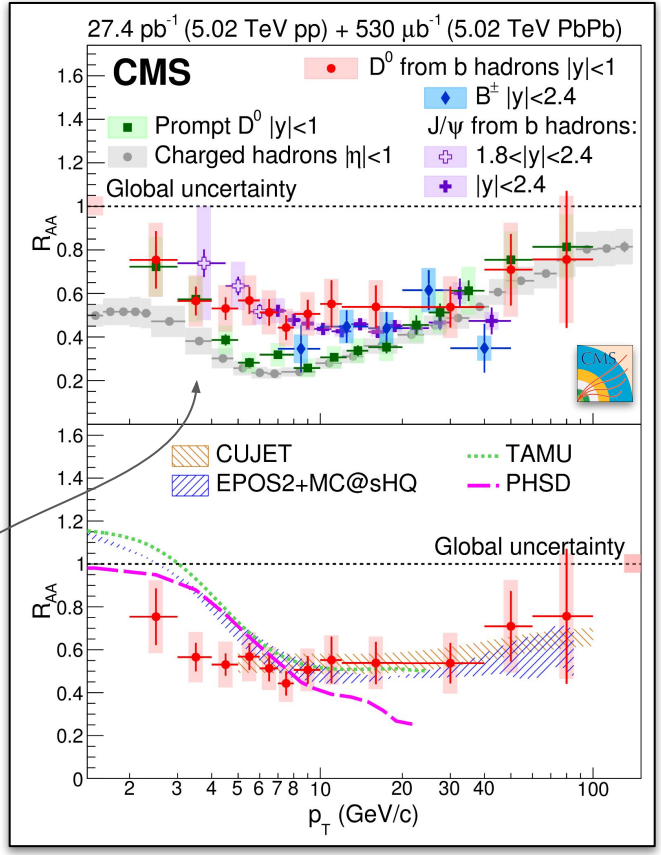


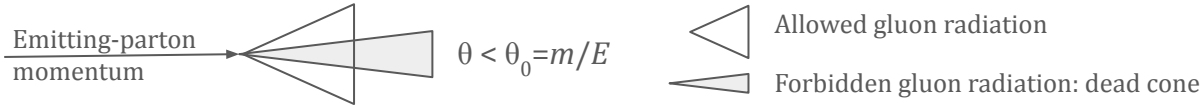




- R_{AA}(non-prompt D^0) described by models including radiative E-loss for $p_T > 5$ GeV/c
- The hierarchy

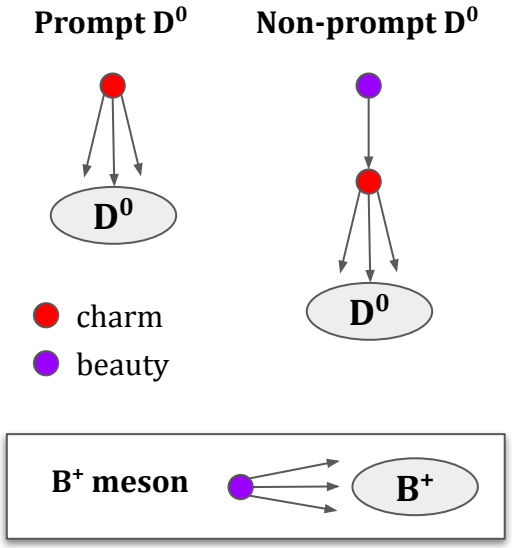
R_{AA}(non-prompt D^0) ~ R_{AA}(non-prompt J/ψ) ~ R_{AA}($B^{\pm}$) > R_{AA}(prompt D) > R_{AA}(ch. hadrons)

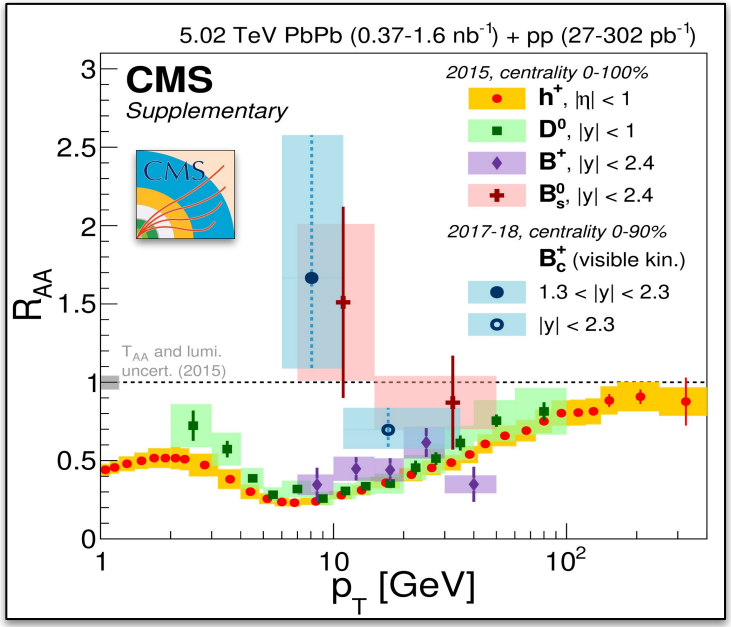
can be explained with the $m_b > m_c$ hierarchy and the **dead-cone effect**



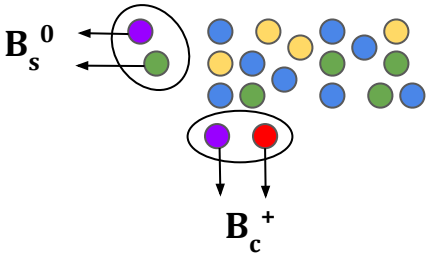
ALICE: JHEP 12 (2022) 126
CMS: PRL 123, 022001 (2019)

Beauty-quark hadronization from B mesons R_{AA}





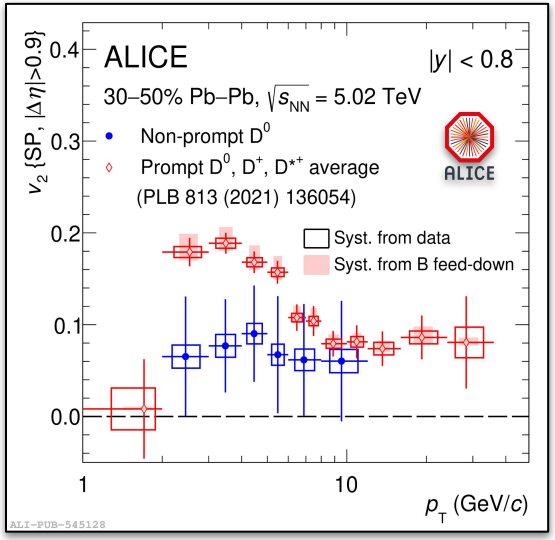
CMS: PRL 128 (2022) 252301
CMS: PRL 123, 022001 (2019)



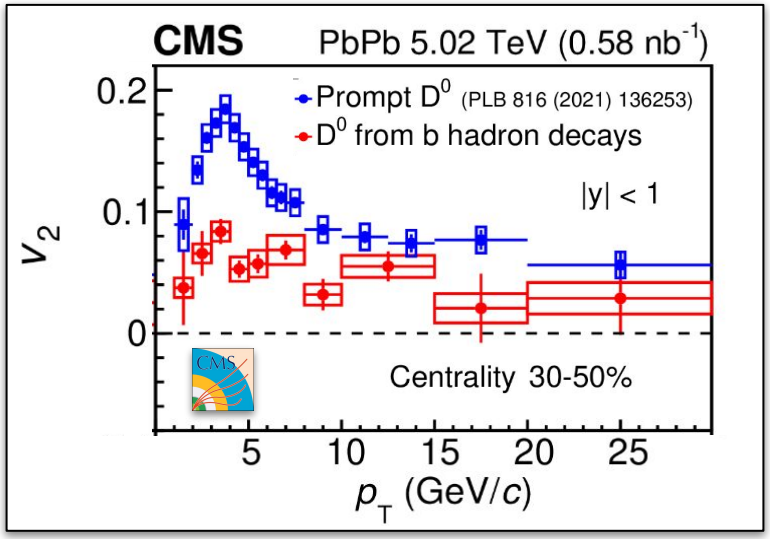
R_{AA} of **B_s^0** (bottom-strange) and **B_c^+** (bottom-charm) **larger** than that of other B mesons at **intermediate p_T**

- B_s^0: coalescence between b-quark and s-quark from the QGP
- B_c^+: **recombination** between **c-quark and b-quark**, despite they are not thermally produced?
  - B_c^+: new particle to study the interplay between enhancement (hadronization at intermediate p_T) and suppression (E-loss at high p_T)

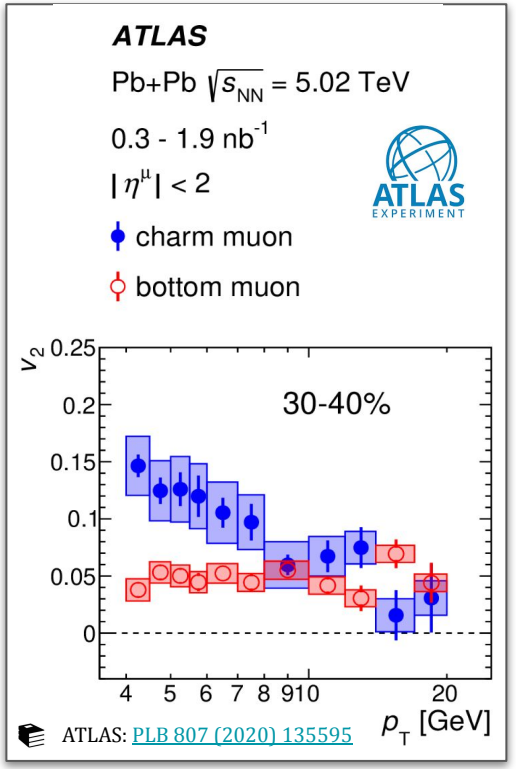
Beauty-hadron flow from non-prompt D-meson v_2



ALICE: arXiv:2307.14084 [nucl-ex]



CMS: arXiv:2212.01636 [nucl-ex]



ATLAS: PLB 807 (2020) 135595

- **Flow larger than 0** for **non-prompt D^0** mesons (ALICE: 2.7σ)
  - Indication of strong interaction of b-quark with the QGP
- v_2 **lower than** that of **prompt** D mesons (ALICE: 3.2σ)
  - **Different degree of participation** to the QGP collective motion between **charm** and **beauty quarks**
  - Consistent with the expectation of a **weaker interaction** for b-quark than c-quark

Heavy-strange-meson production

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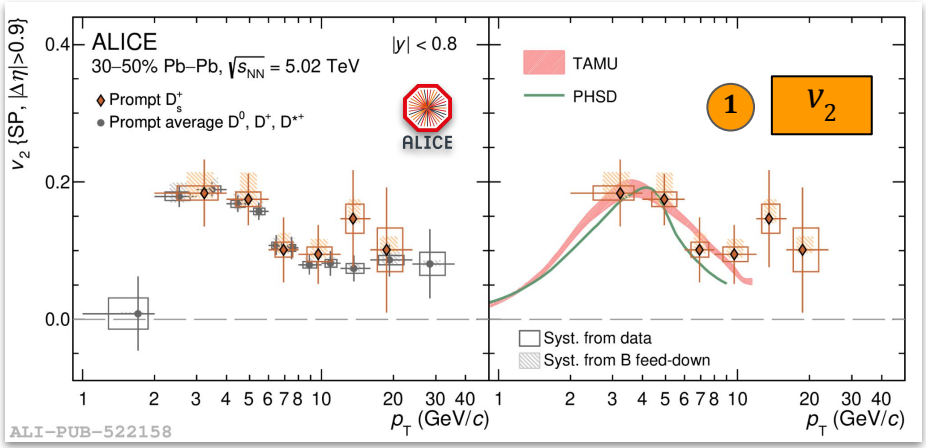
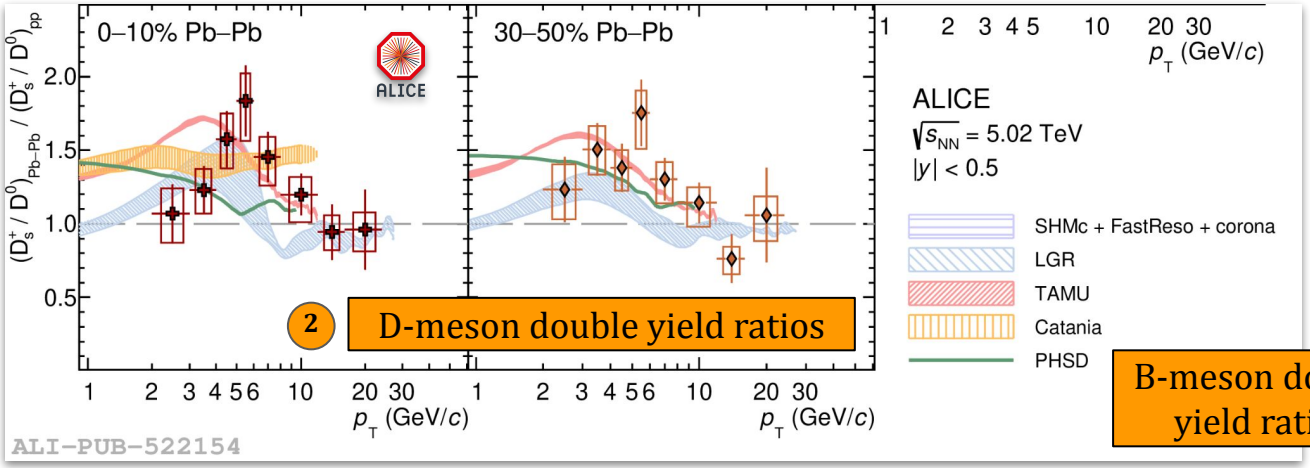


1 v_2

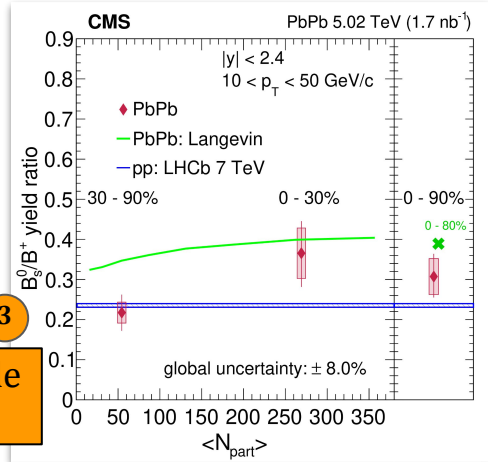
ALICE: PLB 827 (2022) 136986 CMS: PLB 829 (2022) 137062

Sensitivity to **coalescence** and **strangeness enhancement**

1. v_2 described by models including charm-quark coalescence with strange quarks flowing in the QGP
2. Hint of higher D_s^+/D^0 ratio in Pb-Pb collisions than that in pp collisions (2.3-2.4σ at intermediate p_T)
3. Similar for B_s^0/B^+, with a hint of dependence vs. centrality



2 D-meson double yield ratios



3

B-meson double yield ratios

D_s^+ enhancement in high-multiplicity p–Pb collisions

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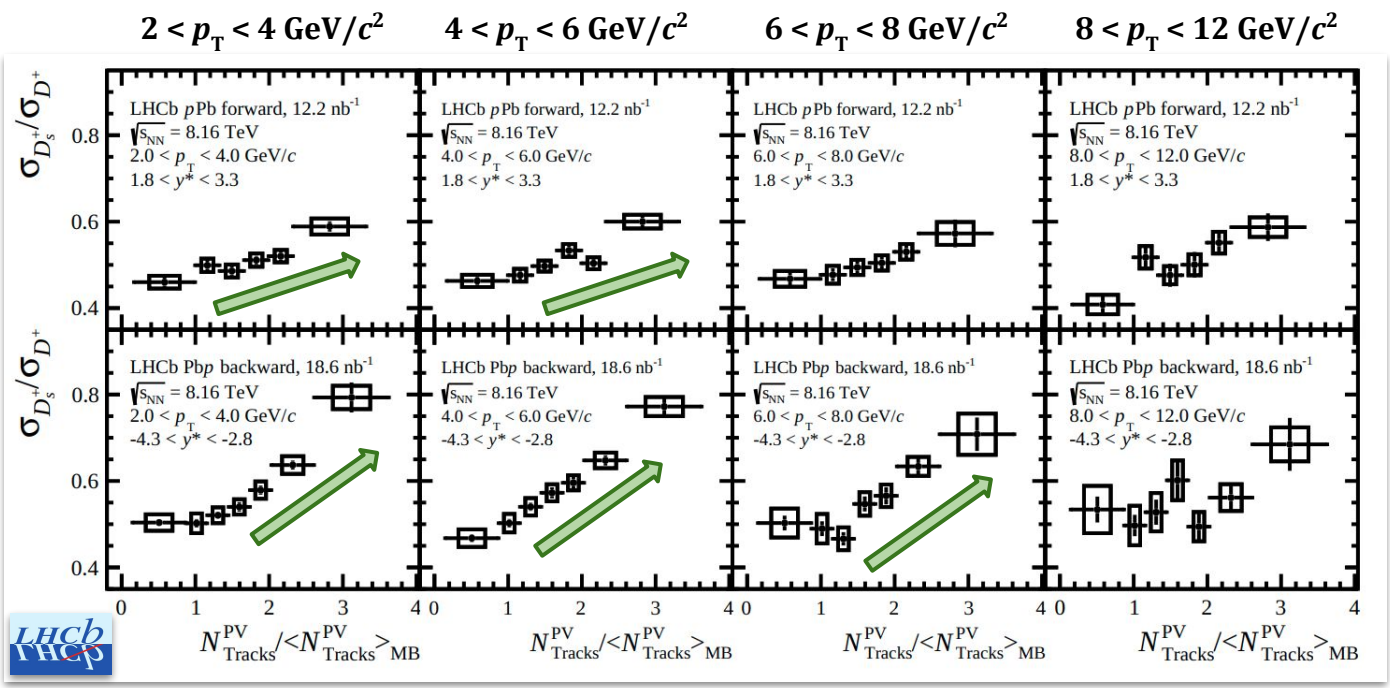
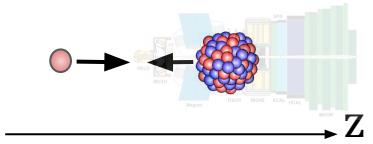
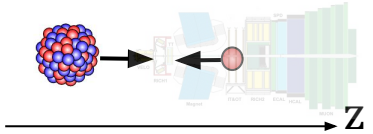
LHCb: arXiv:2311.08490



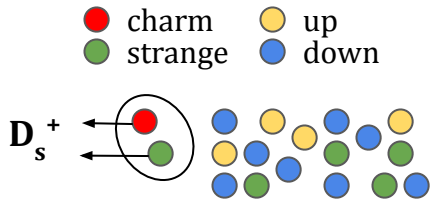
p–Pb (forward y^*)



Pb–p (backward y^*)



- Significant **increase vs. multiplicity** of prompt $\mathbf{D_s^+/D^+}$ ratio in **p–Pb** collisions
  - **more pronounced** for **backward** collisions
- In line with a scenario including hadronization via **coalescence** and **strangeness enhancement** in **high-multiplicity p–Pb** collisions



Nuclear modification factor of Λ_c^+ baryon

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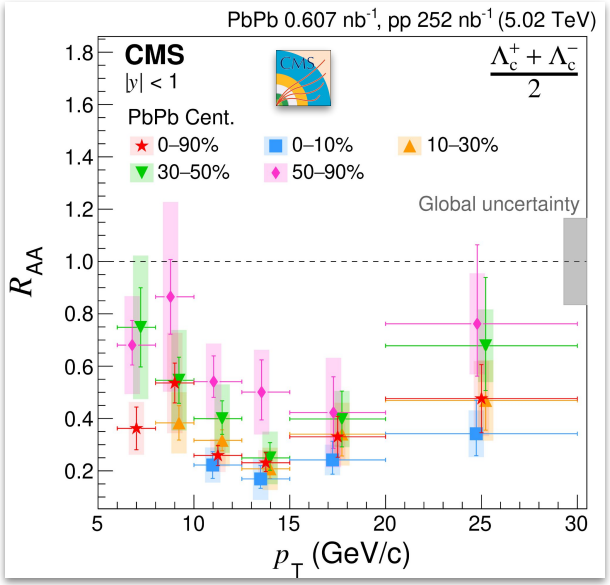

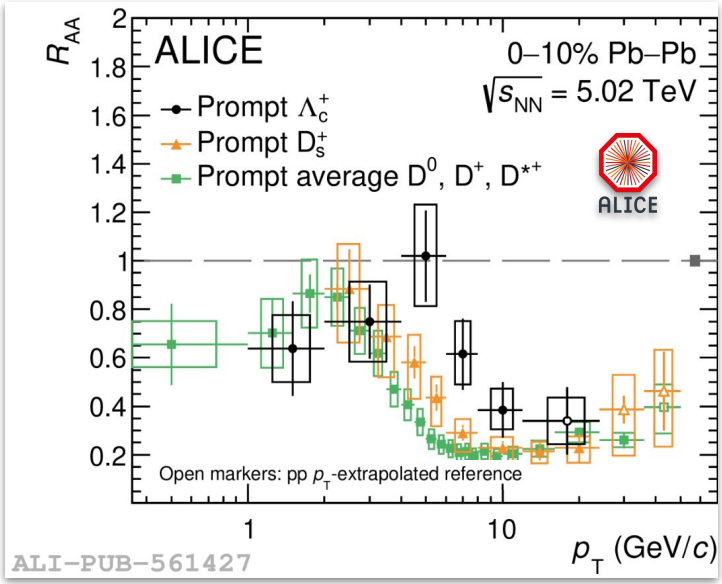

- Hint of $R_{AA}^{central}(\Lambda_c^+) < R_{AA}^{peripheral}(\Lambda_c^+)$ → sensitivity to **different system size** and **energy density**
- Minimum value of $R_{AA}^{central}(D^0)$ at around p_T = 6-8 GeV/c, which is lower than that of $R_{AA}^{central}(\Lambda_c^+)$
- Hint of hierarchy $R_{AA}(\Lambda_c^+) > R_{AA}(D_s^+) > R_{AA}$(**non-strange D**) for $4 < p_T < 12$ GeV/c in most central collisions
  - Indication of larger enhancement for baryons due to **coalescence**
  - Interplay with **radial flow**?

ALICE: PLB 839 (2023) 137796
CMS: arXiv:2307.11186 [nucl-ex]

Λ_c^+/D^0 ratio in Pb–Pb collisions

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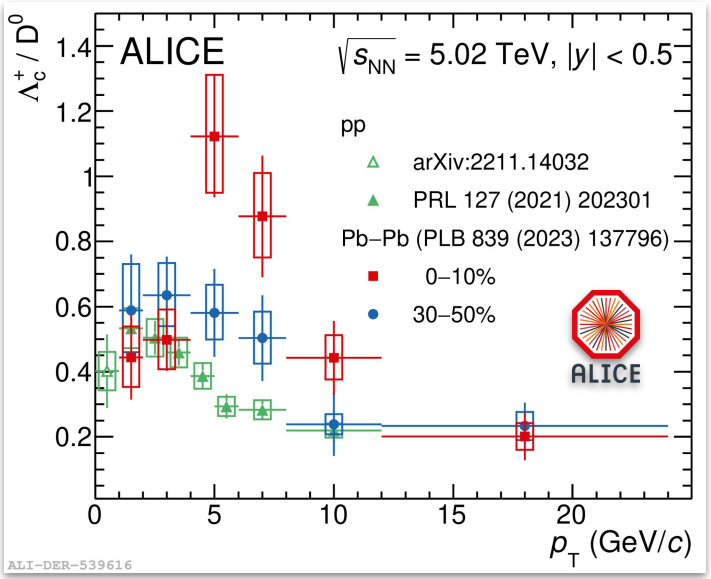
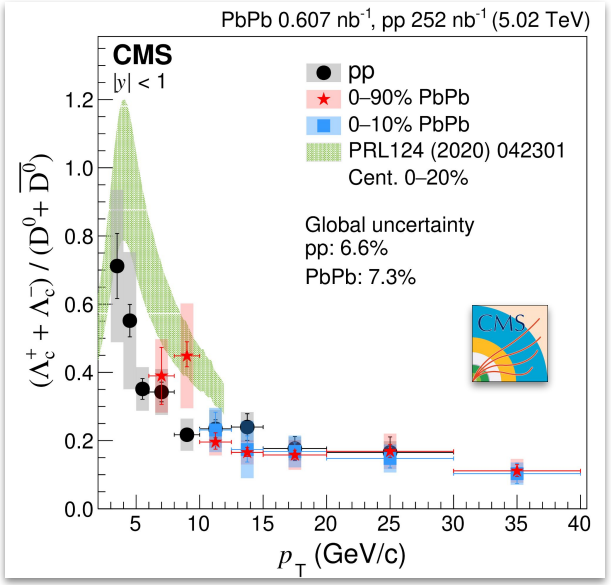
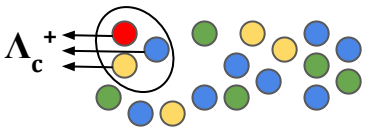




- Λ_c^+/D^0 baryon-to-meson ratio ***at midrapidity*** significantly **higher** (ALICE: 3.7σ) in **central Pb-Pb** collisions than in **pp** collisions in the interval $4 < p_T < 8$ GeV/c
  - Measurement in central Pb-Pb collisions described by **transport models** with **recombination**

- No significant collision-system and centrality dependence for $p_T > 12$ GeV/c

charm
strange
down
up



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Charm-baryon production at the LHC - open points (1/2)

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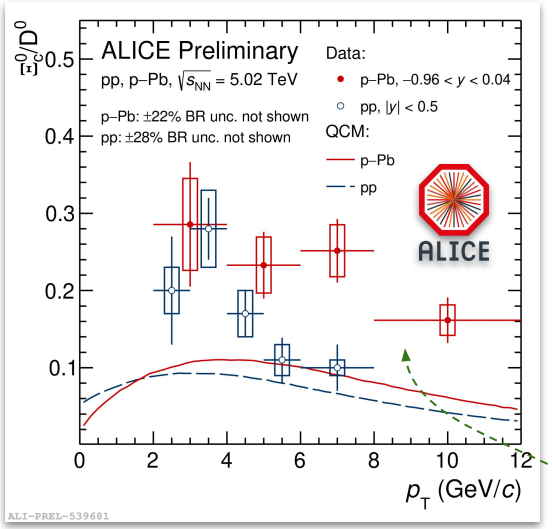

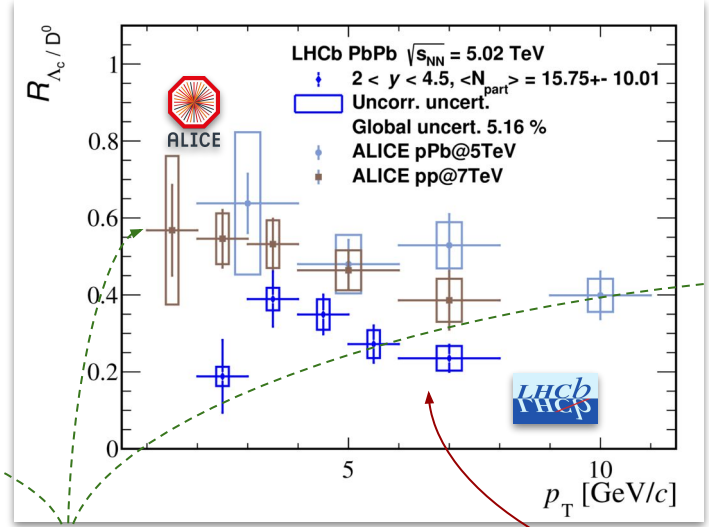

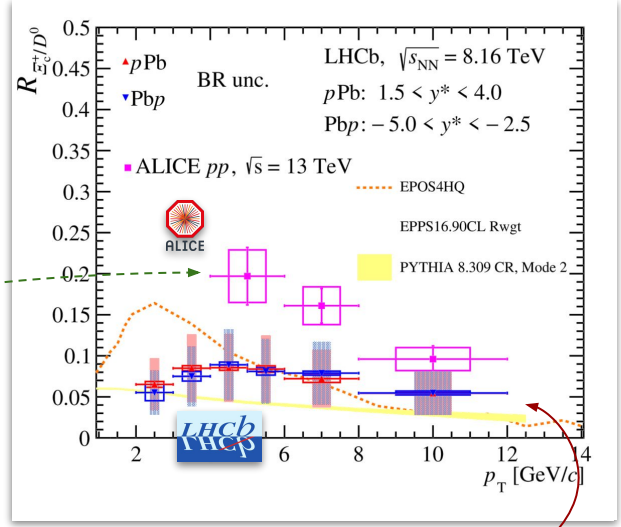

Midrapidity (|*y*| < 0.5) **Forward rapidity**

- Baryon-to-meson ratio at midrapidity compatible in pp and p–Pb collisions
  → hint of larger Ξ_c^0/D^0 in p–Pb collisions at $p_T > 4$ GeV/c

LHCb: JHEP 06 (2023) 132
LHCb: https://arxiv.org/abs/2305.06711

- **Baryon-to-meson ratio** at **forward rapidity** systematically **lower** than those at **midrapidity** across collision systems
  - influence of different parton and/or heavy-flavour quark densities in different rapidity ranges?

Charm-baryon production at the LHC - open points (2/2)

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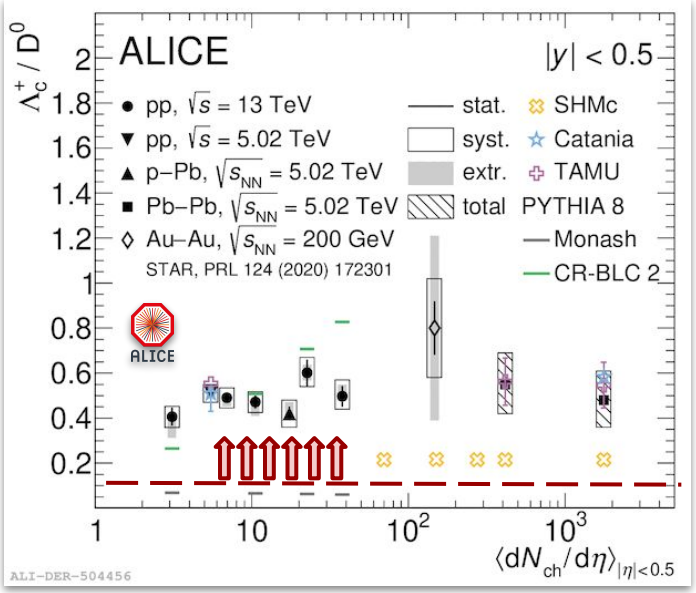

LEP: EPJC 75, 19 (2015)

ALICE: PLB 839 (2023) 137796

Charm baryon-to-meson ratio

e^+e^-: **0.113 ± 0.013 ± 0.006**

- **No** significant **dependence vs. multiplicity** of the **p_T-integrated Λ_c^+/D^0** ratio at **mid-y across collision systems**
- Ratio described by Catania (fragmentation + coalescence) and TAMU (SHM+RQM + 4-momentum conserving coalescence in Pb–Pb)
- PYTHIA 8 CR-BLC prediction does not reproduce the trend vs. multiplicity in pp collisions

→ Is the **p_T-differential Λ_c^+/D^0 enhancement** just a consequence of **radial flow** and **recombination**?

Charm-baryon production at the LHC - open points (2/2)

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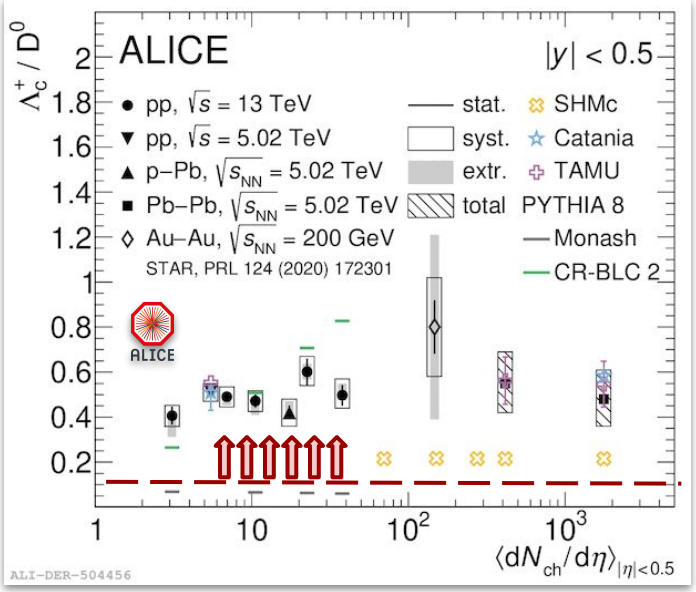
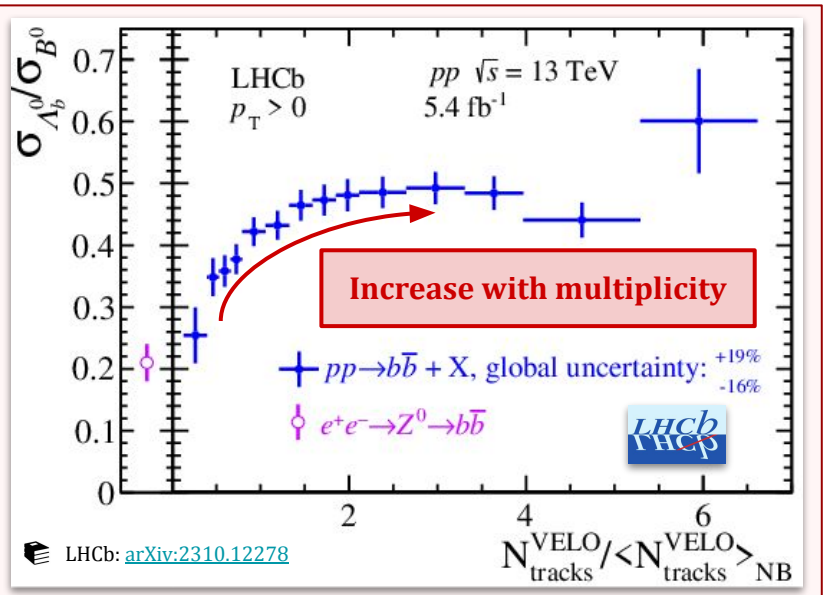


e⁺e⁻

pp collisions

Beauty
baryon-to-meson ratio



- **No** significant **dependence vs. multiplicity** of the **p_T-integrated Λ_c^+/D^0** ratio **across collision systems**
- **Significant dependence versus multiplicity** of the **p_T-integrated Λ_b^0/B^0** ratio **at forward-*y*** in **pp** collisions
  - increase of about a factor 2 from low to high multiplicity

→ ***Influence of different parton and/or heavy-flavour quark densities in different rapidity ranges?***
→ Is the p_T-differential Λ_c^+/D^0 enhancement just a consequence of radial flow and recombination?

Charm-baryon production across collision systems

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Baryon enhancement in all collision systems at the LHC compared to e^+e^-

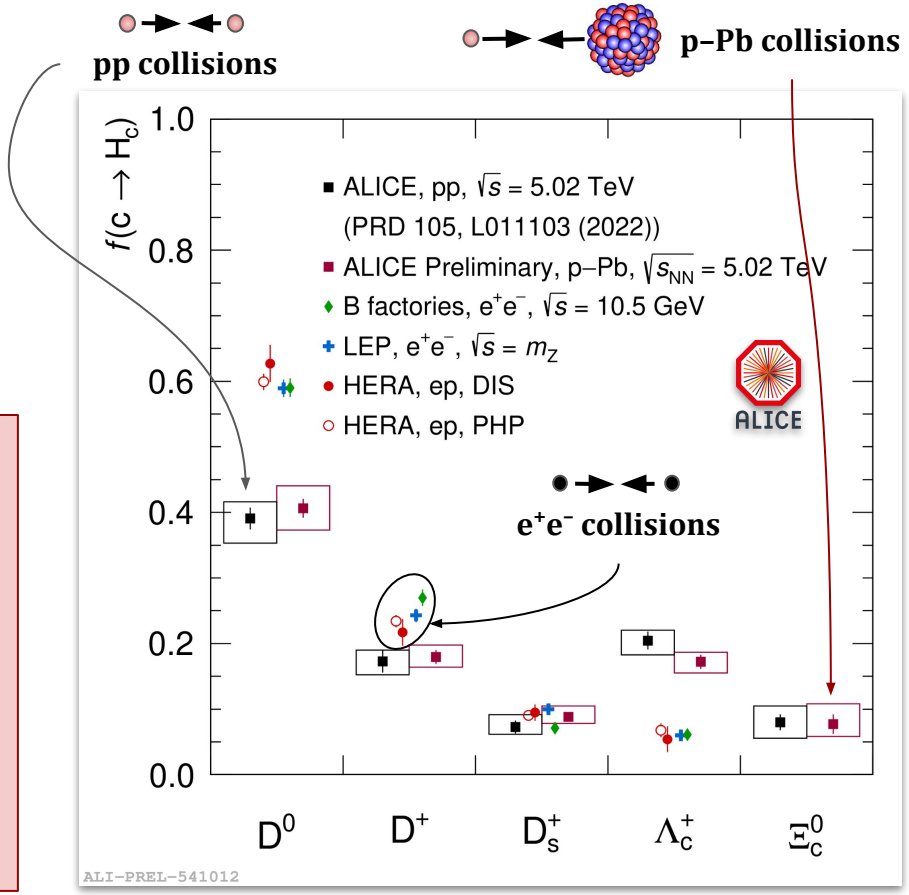
- D mesons: ↓↓↓ ✕1.4-1.6 with respect to e^+e^-
- Λ_c^+ baryon: ↑↑↑ ✕~ 3 with respect to e^+e^-
- **No** significant **system dependence** of charm **fragmentation fractions**

Modification of **hadronization** mechanisms **already** in pp and p-Pb collisions, i.e. **without QGP formation**?

DO NOT MISS OUT!

A. Rossi, Monday at 10:10

"Heavy-quark production and hadronisation as a function of event multiplicity with ALICE"



ALICE: Phys. Rev. D 105, L011103 (2022)

Conclusions

A lot of **experimental results** from the **ALICE**, **ATLAS**, **CMS** and **LHCb** Collaborations at the LHC to shed light on the **c-quark** and **b-quark dynamics** in the **QGP**

- **c- and b-quark** lose energy via **gluon radiation**
- indications of c- and b-quark **participation** to the **collective motion**
- **hadronization** via **recombination** crucial to explain the particle production hierarchy at intermediate p_T

More results coming from Run 3 at the LHC!

*"This work is **(partially)** supported by ICSC – Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, funded by European Union – NextGenerationEU".*

Backup

Charm and beauty hadronization from e^+e^- to Pb–Pb

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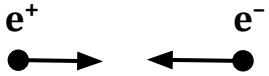
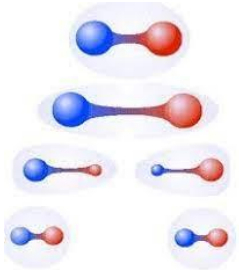
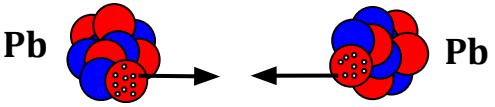


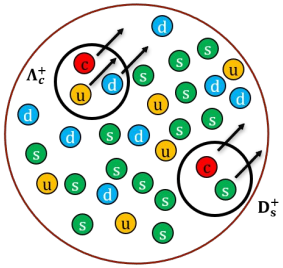
- "**Point-like**" object interaction
- **Fragmentation** in the vacuum



Hadronization: a key ingredient in all collision systems!

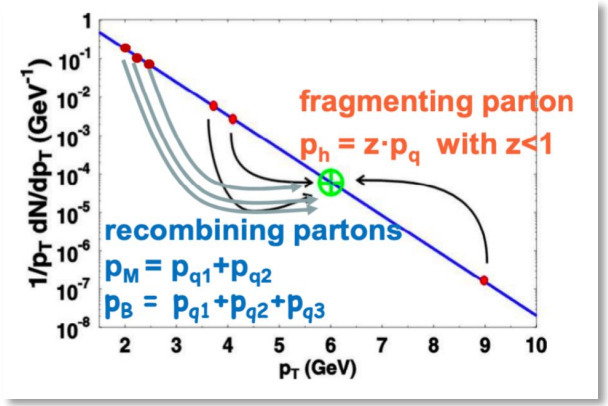


- **QGP**: complex system with **partonic d.o.f**
- Hadronization can be influenced by **coalescence** and **strangeness enhancement**



Fragmentation

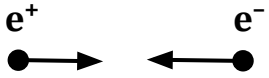
- Hard scattering: $e^+e^- \rightarrow \bar{q}q$
- Color string: $V_{Cornell}(r) \sim \kappa r$
- New $q\bar{q}$ pairs from multiple string breaking (confinement)

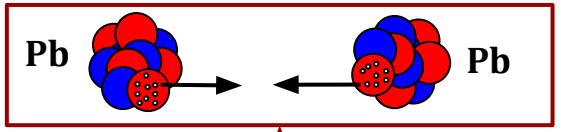


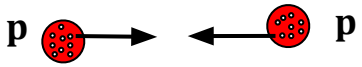
Coalescence

- Heavy quark recombinates with light quarks in the QGP
- Expected increase of hadrons at intermediate-low p_T
- QGP: interplay with fragmentation

Charm and beauty hadronization from pp collisions







- Superposition of many "e^+e^-" collisions
- Changes in hadronization due to the surrounding color charges and those from MPI?
- **Do the model calculations based on the factorization approach describe the experimental results?**

DO NOT MISS OUT!

A. Rossi, Monday at 10:10

"Heavy-quark production and hadronisation as a function of event multiplicity with ALICE"

This talk: more focused on results in **heavy-ion collisions**

Spatial diffusion coefficient

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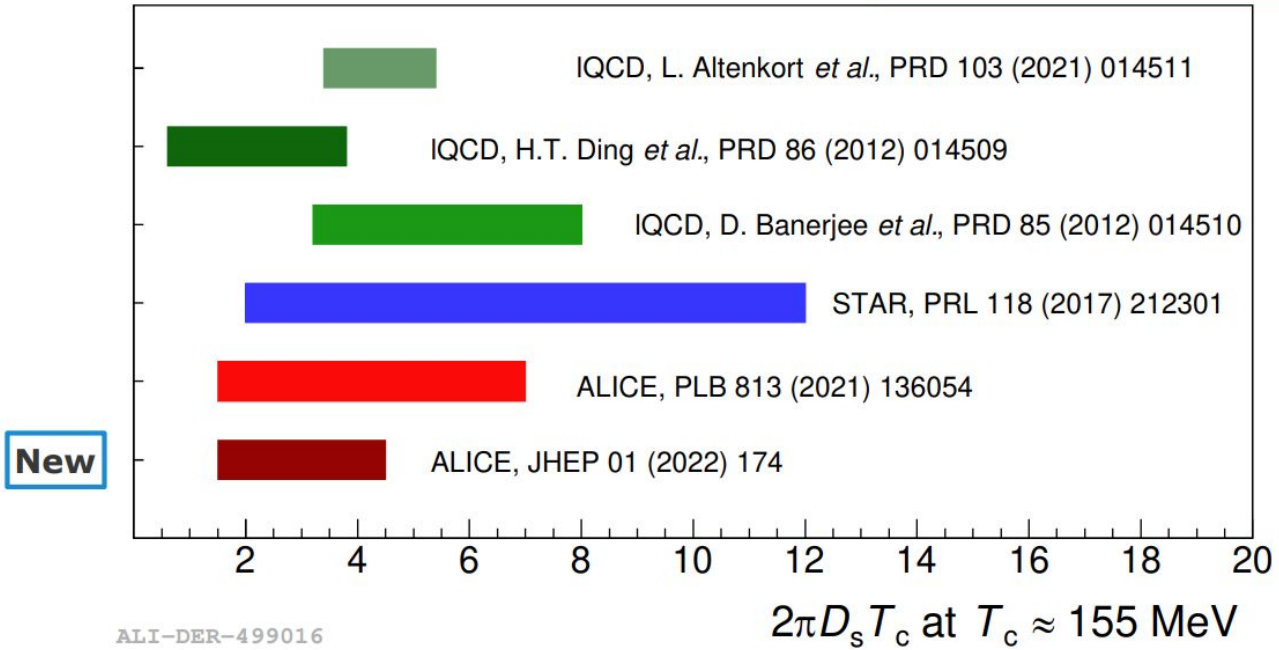
Constraining the spatial diffusion coefficient via the **data-to-model agreement**

→ Using R_{AA} (with $\chi^2/\mathrm{ndf} < 5$) and v_2 (with $\chi^2/\mathrm{ndf} < 2$) non-strange D measurements

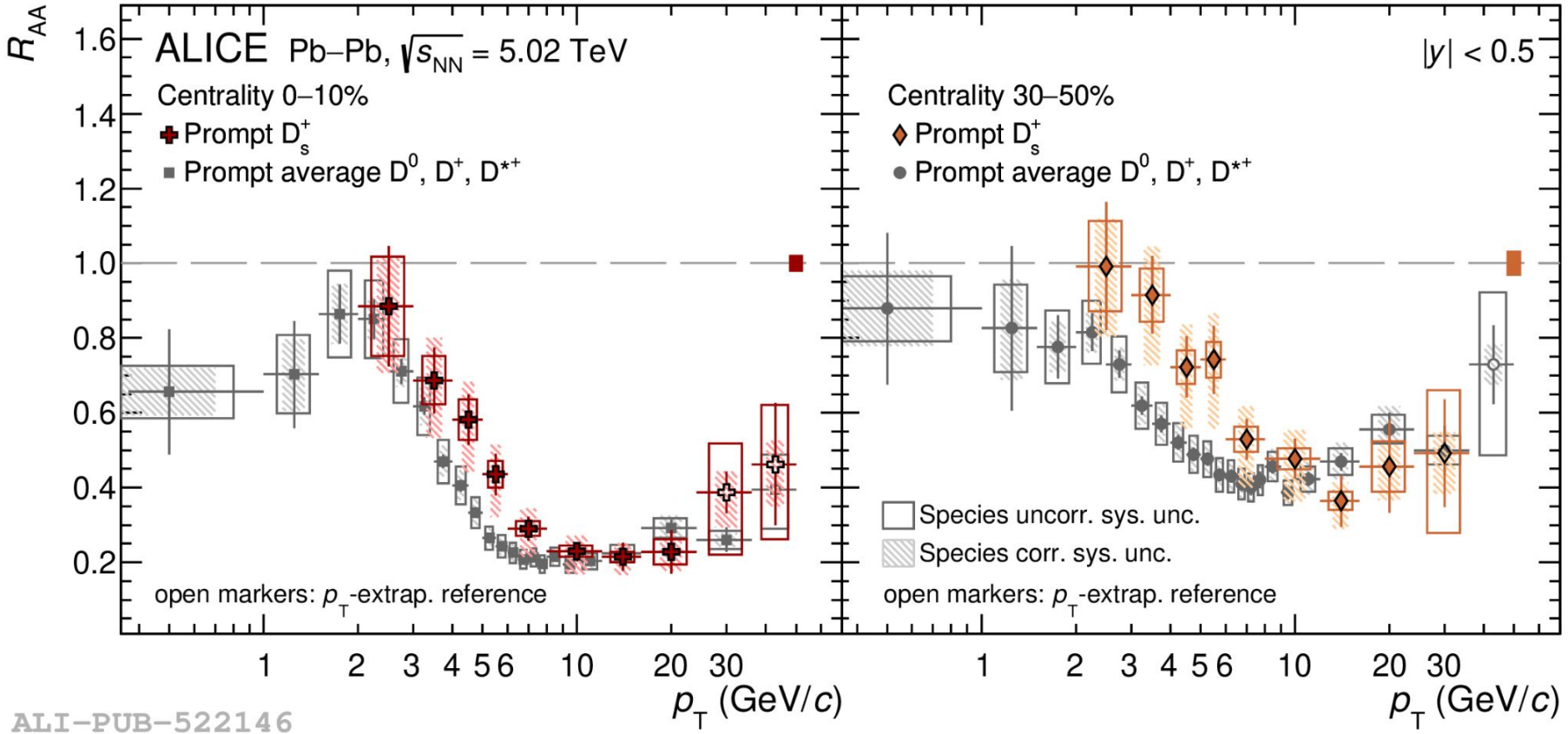
→ TAMU, MC@sHQ, LIDO, LGR, and Catania "selected"

→ $1.5 < 2\pi D_s T_c < 4.5$

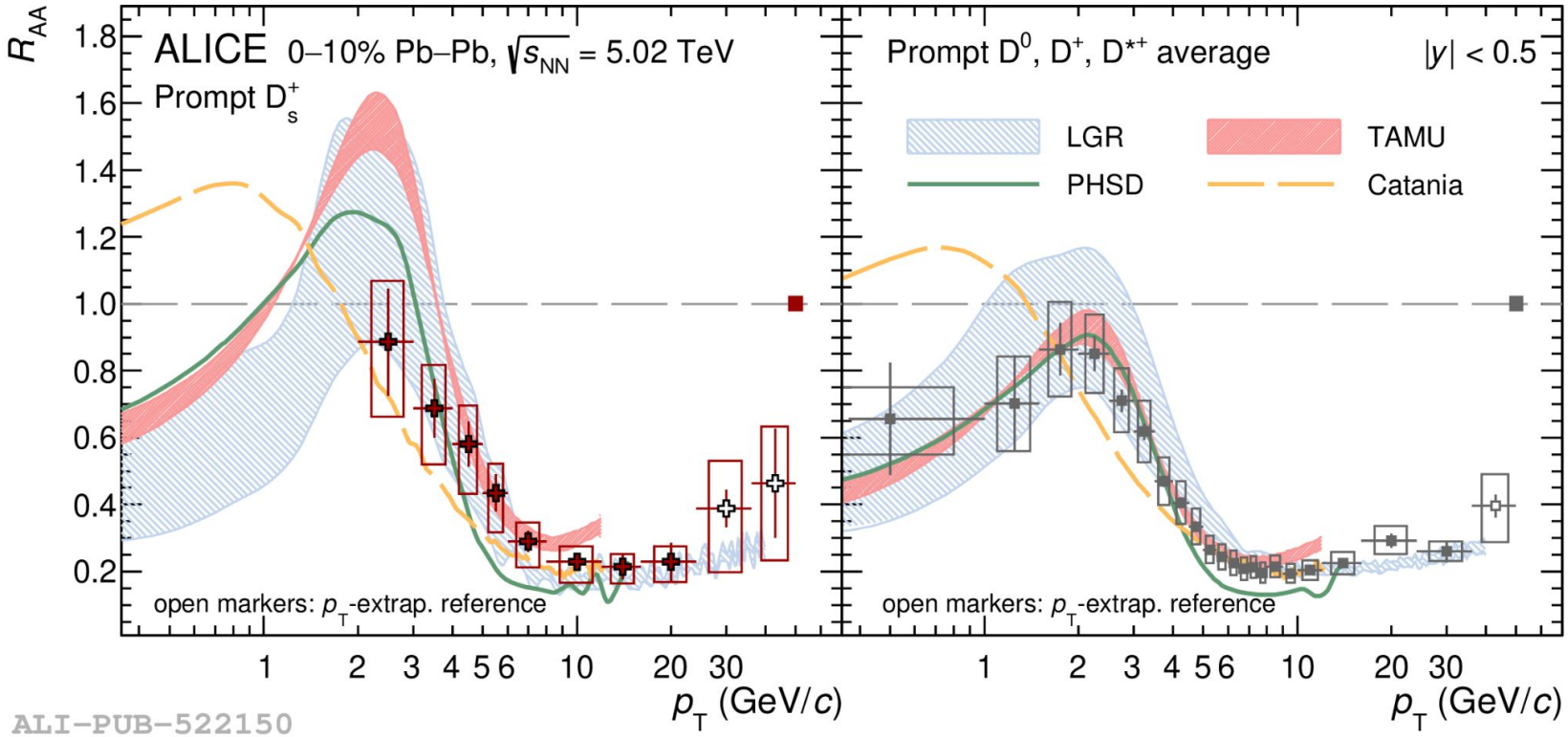
→ $\tau_{\mathrm{charm}} \simeq 3\text{–}8$ fm/c



ALI-DER-499016



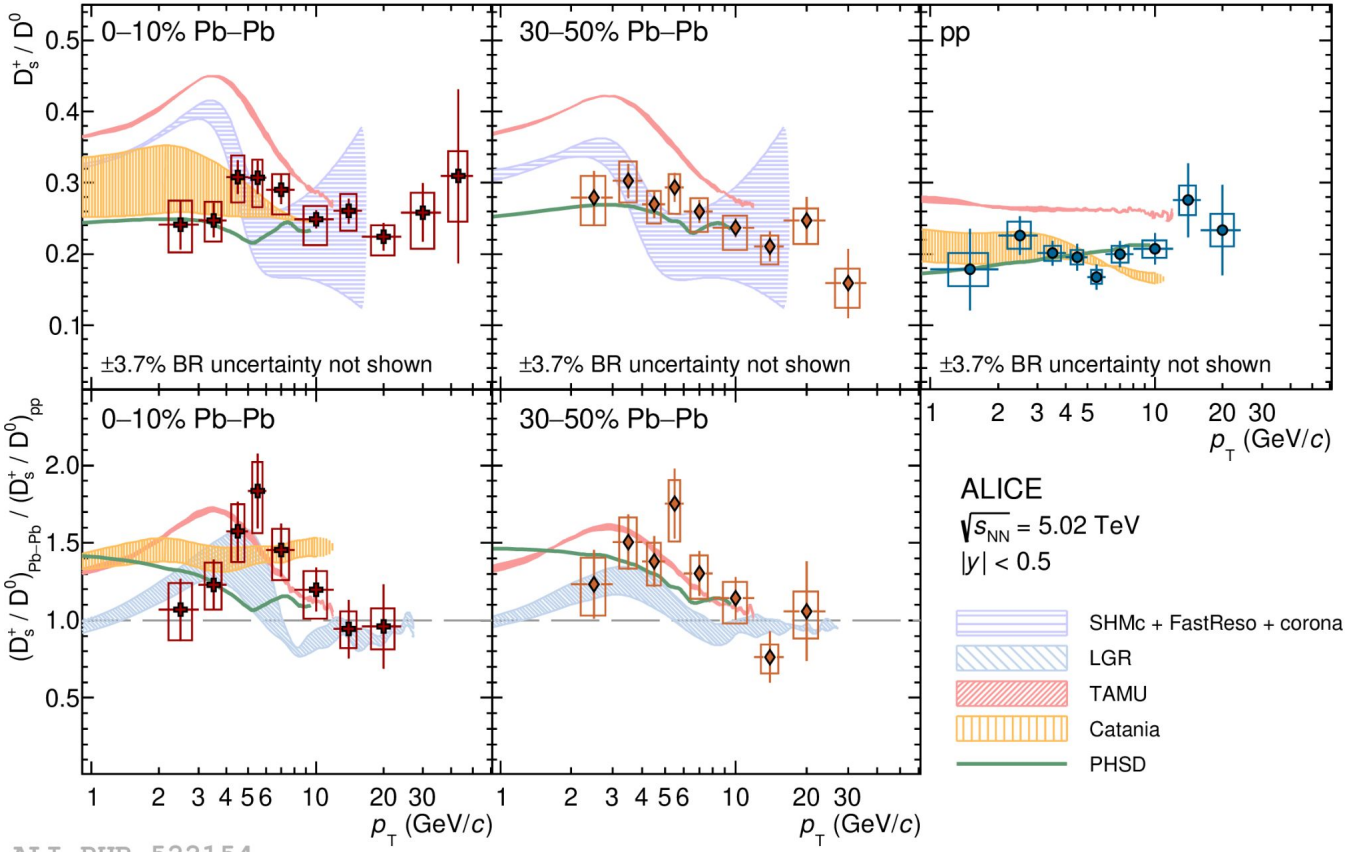
ALI-PUB-522146



ALI-PUB-522150

Prompt Ds+

ALICE: https://arxiv.org/pdf/2010.10006.pdf



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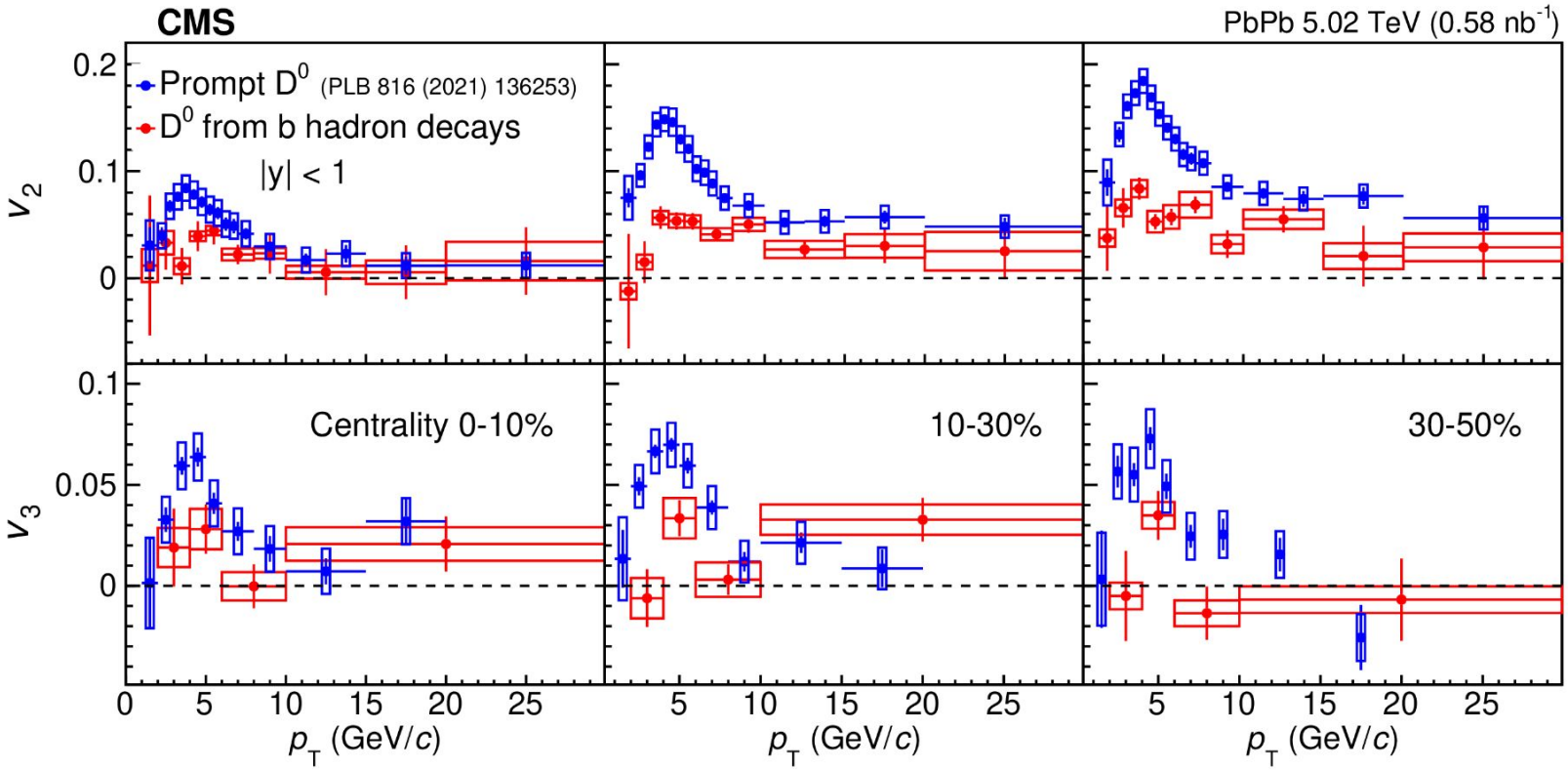
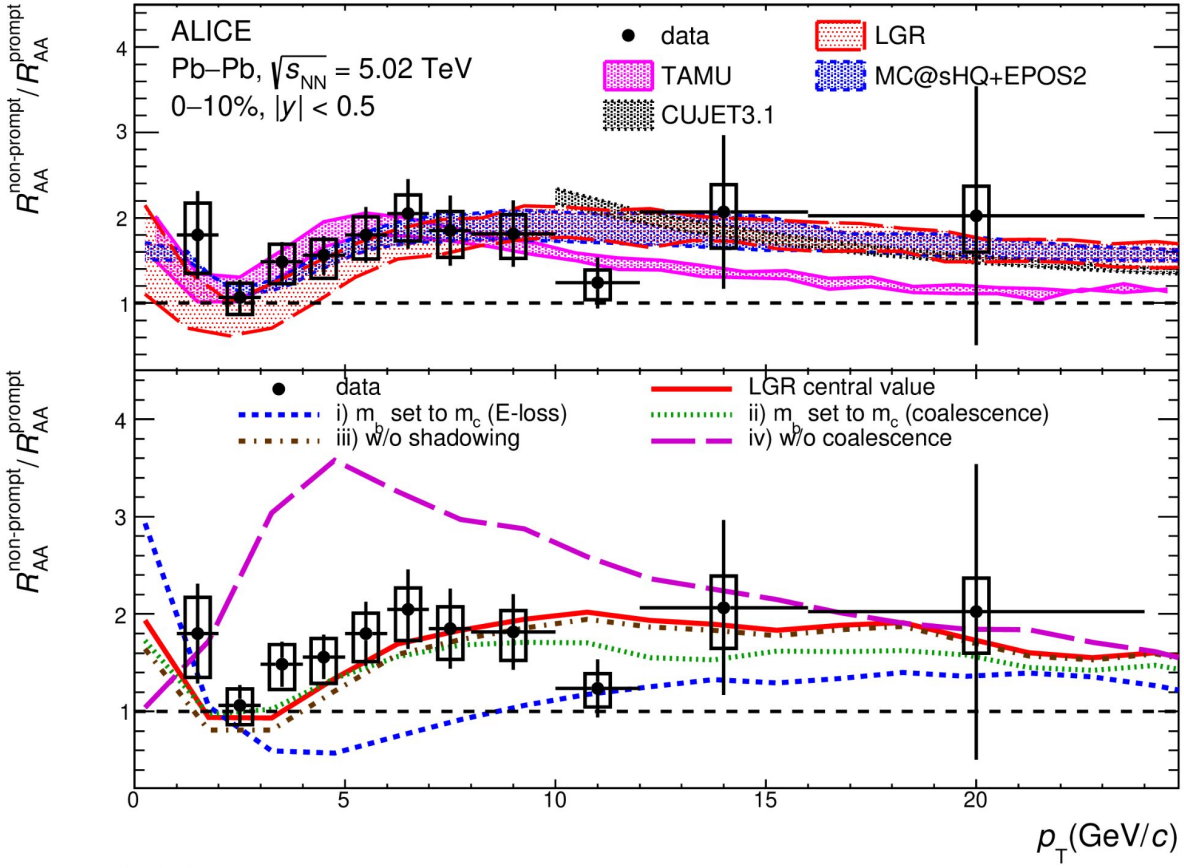

CMS
PbPb 5.02 TeV (0.58 nb^{-1})
Prompt D^0 (PLB 816 (2021) 136253)
D^0 from b hadron decays
|y| < 1
Centrality 0-10%
10-30%
30-50%
v_2
v_3
p_T (GeV/c)



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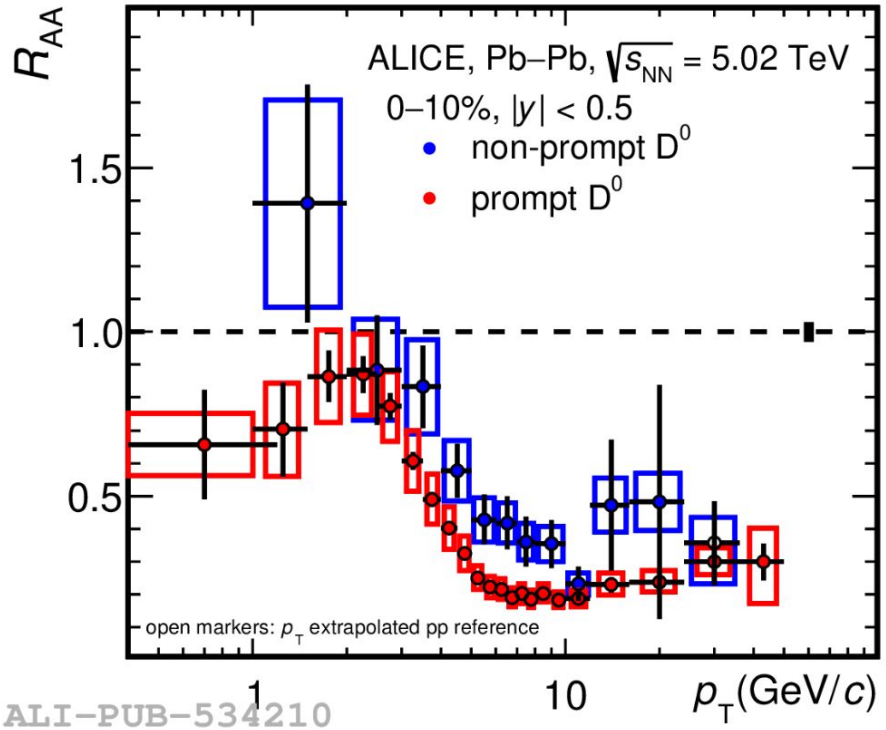
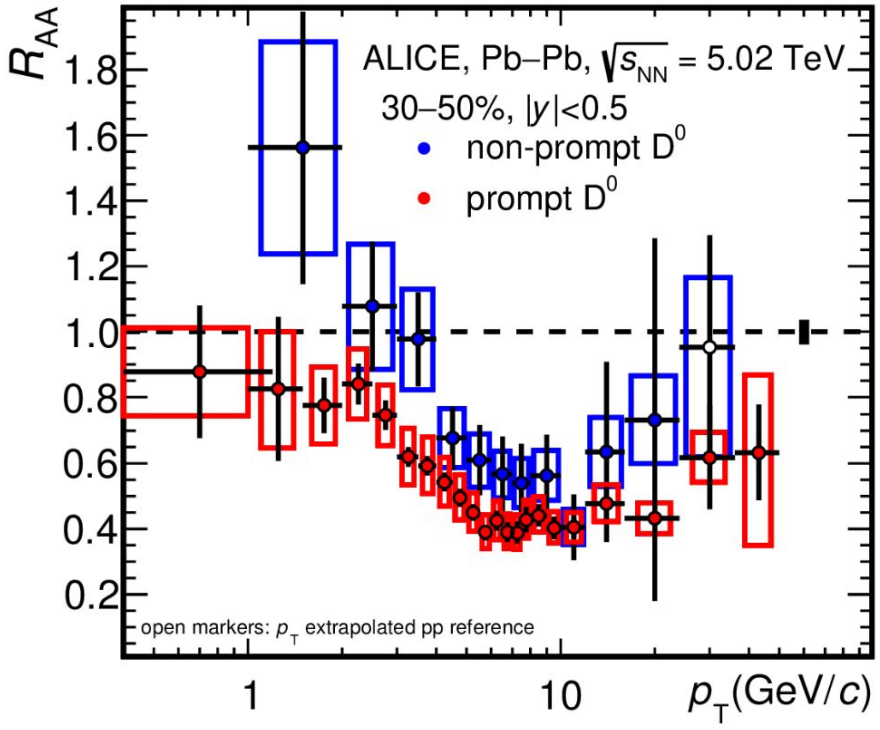
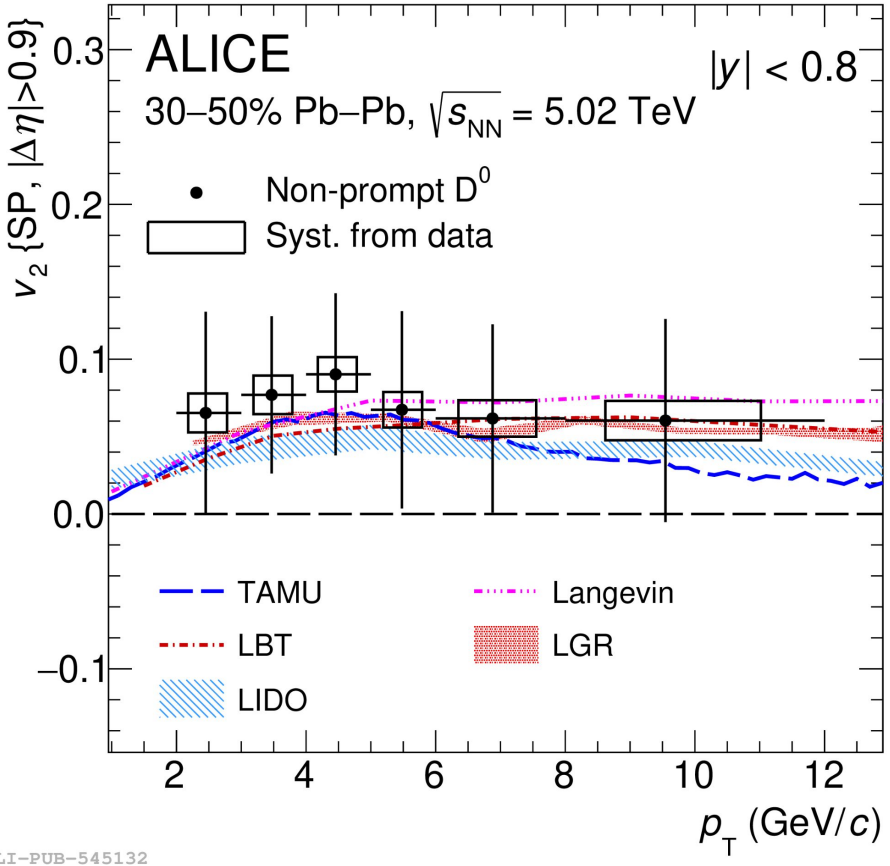
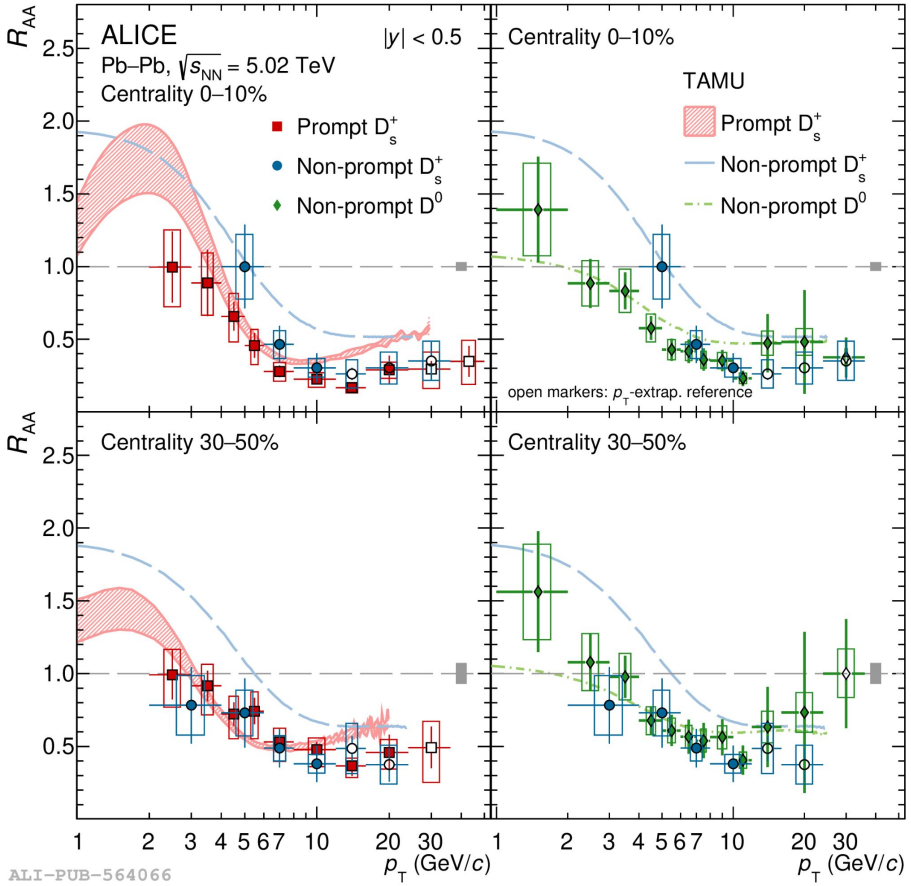


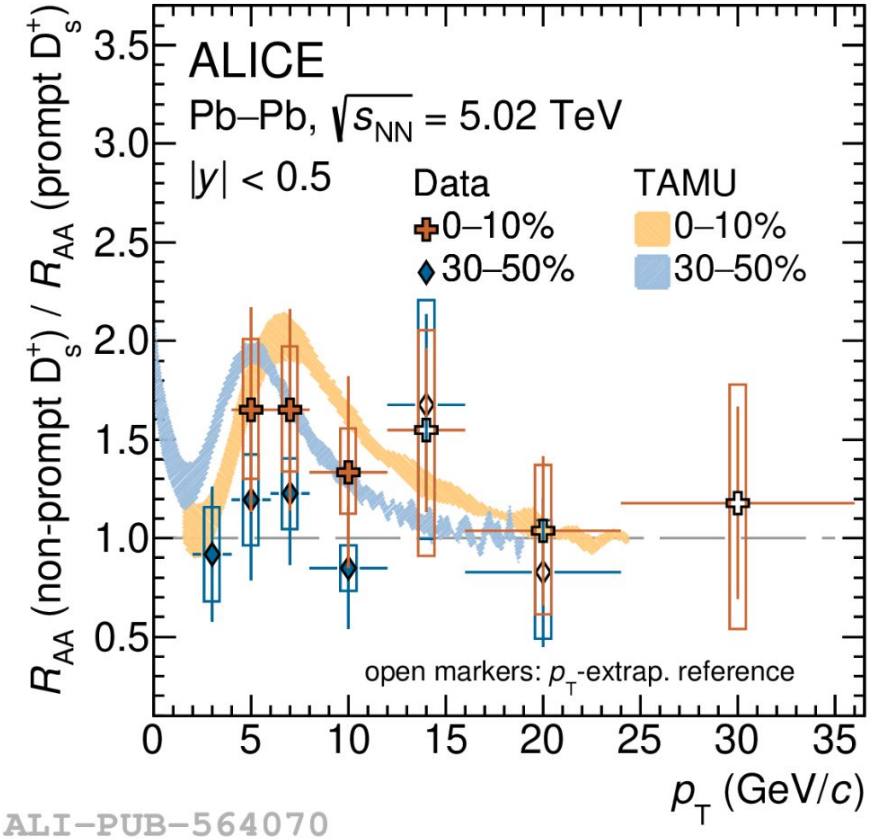


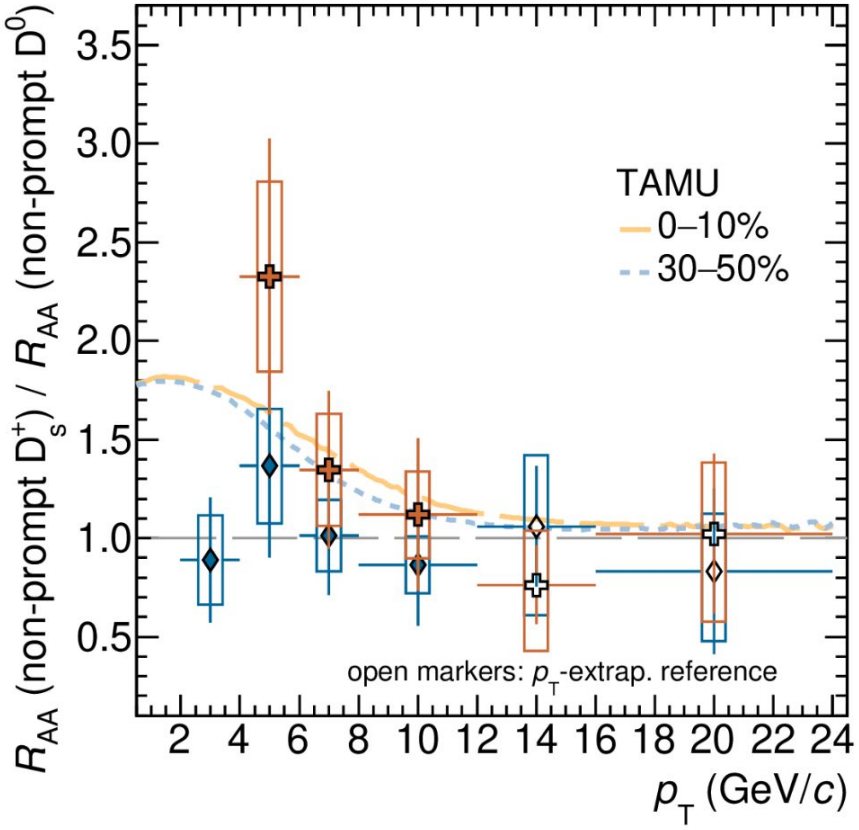
ALI-PUB-534210



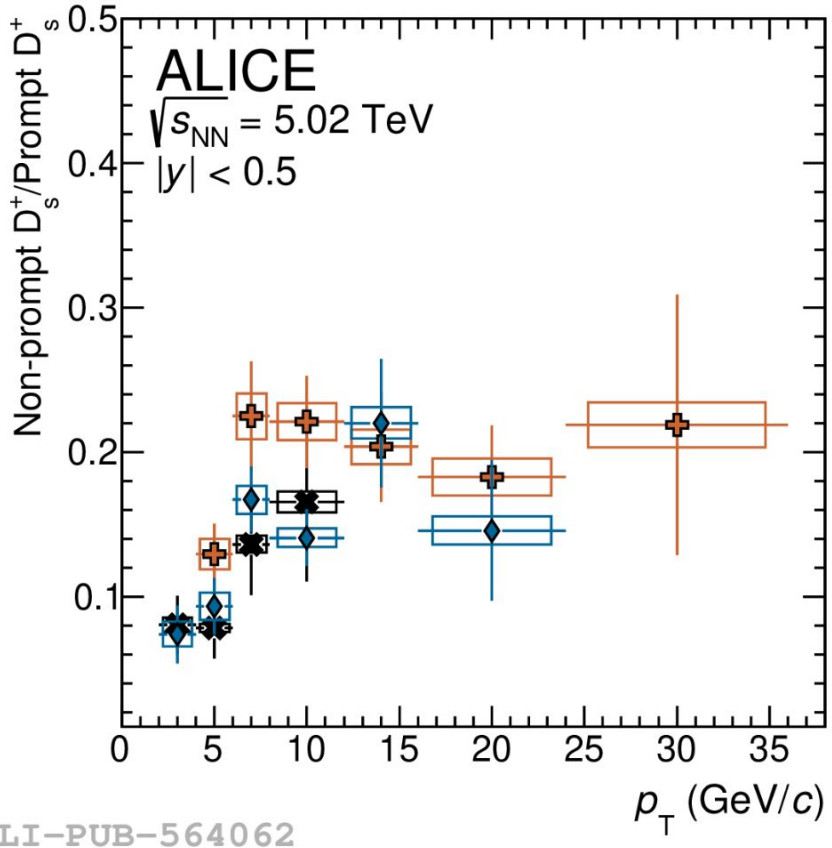
ALI-PUB-545132

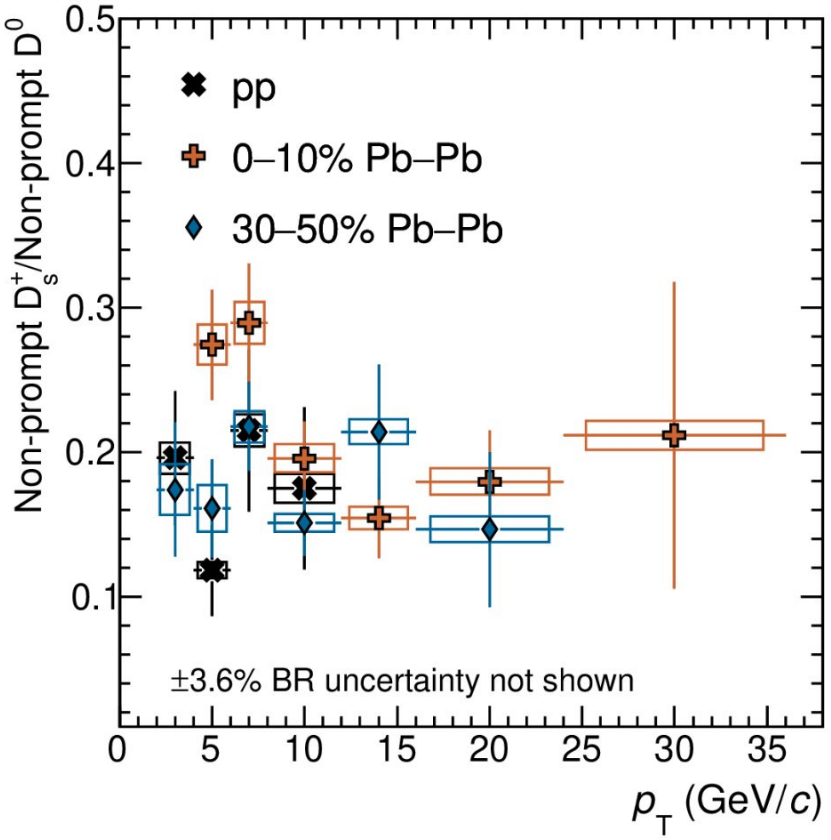

ALICE
Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Centrality 0–10%
|y| < 0.5
Prompt D_s^+
Non-prompt D_s^+
Non-prompt D^0
Centrality 0–10%
TAMU
Prompt D_s^+
Non-prompt D_s^+
Non-prompt D^0
open markers: p_T-extrap. reference
Centrality 30–50%
Centrality 30–50%
R_{AA}
p_T (GeV/c)
ALI-PUB-564066





ALI-PUB-564070





ALI-PUB-564062

E-loss and transport models

	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
CUJET 3.1	✅	✅	❌	✅	✅
DREENA-A	✅	✅	❌	✅	❌
$SCET_{M,G}$	✅	✅	❌	❌	✅

	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
TAMU	✅	❌	✅	✅	✅
LIDO	✅	✅	✅	✅	✅
PHSD	✅	❌	✅	✅	✅
DAB-MOD	✅	✅	✅	✅	❌
Catania	✅	❌	✅	✅	✅
MC@sHQ+EPOS	✅	✅	✅	✅	✅
LBT	✅	✅	✅	✅	✅
POWLANG+HTL	✅	❌	✅	✅	✅
LGR	✅	✅	✅	✅	✅

But more importantly: different **implementations** and **input parameters**.

The observables in Pb-Pb collisions

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1. **Production spectra and R_{AA}**

$$R_{AA}(p_T, y) = \frac{1}{\langle T_{AA} \rangle} \frac{d^2N_{AA}/dp_T dy}{d^2\sigma_{pp}/dp_T dy}$$

$$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

2. **Anisotropic flow**

$$v_n(p_T) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

3. **… and particle ratios!**

Heavy-strange-meson production

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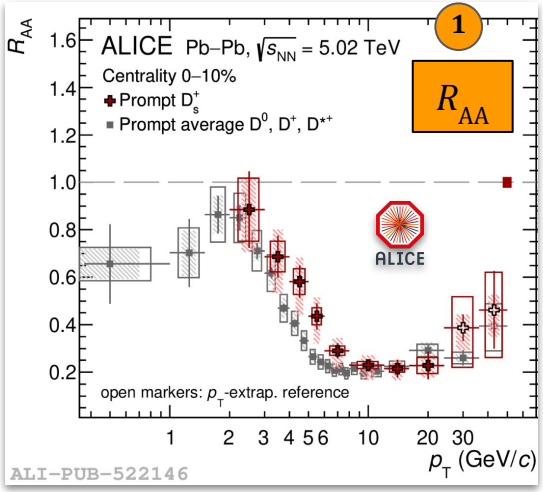
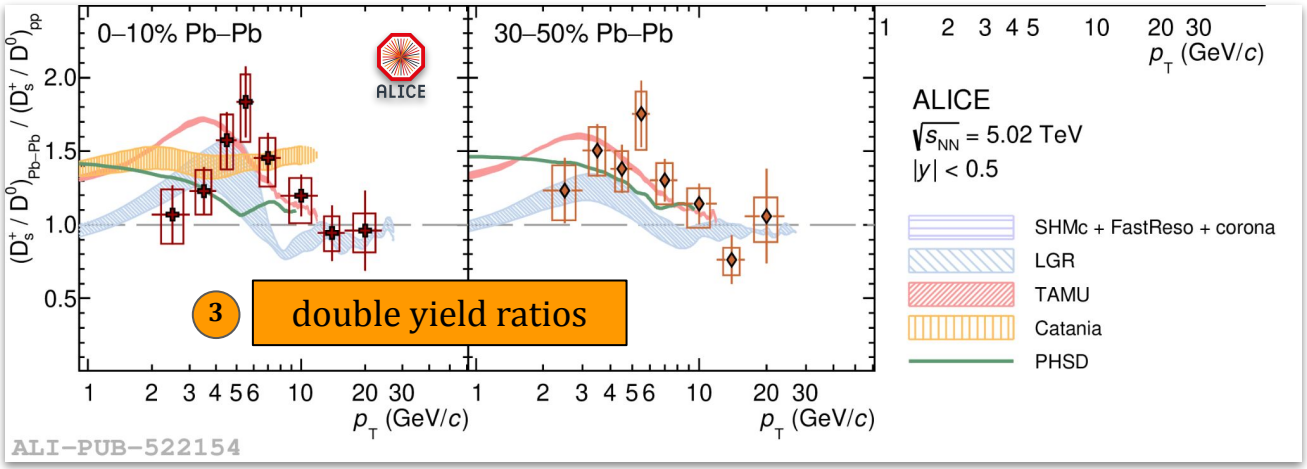
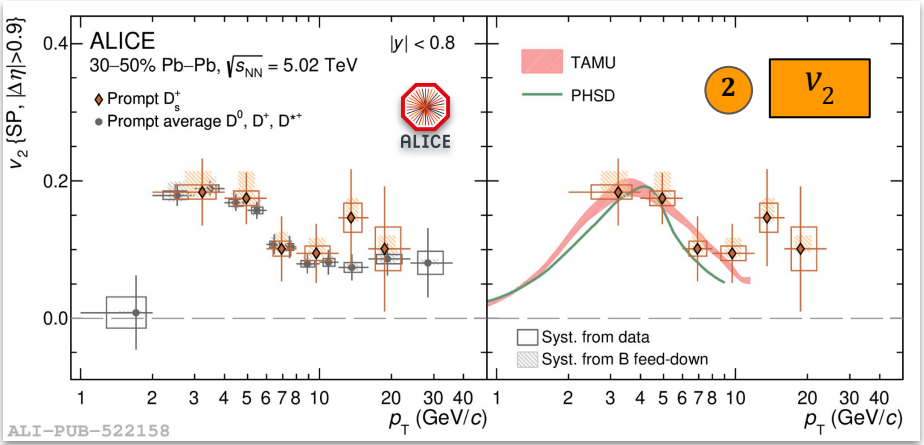
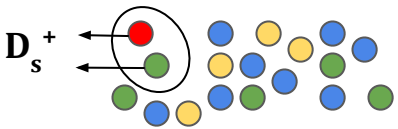






Sensitivity to **coalescence** and **strangeness enhancement**

1. hint of $R_{AA}(D_s^+) > R_{AA}$(non-strange D) at intermediate p_T
2. v_2 described by models including charm-quark coalescence with strange quarks flowing in the QGP
3. D_s^+/D^0 ratio in Pb-Pb collisions higher than that in pp collisions of about 2.3-2.4σ at intermediate p_T



charm up
strange down

ALICE: PLB 827 (2022) 136986

Charm-baryon production at the LHC - open points (2/2)

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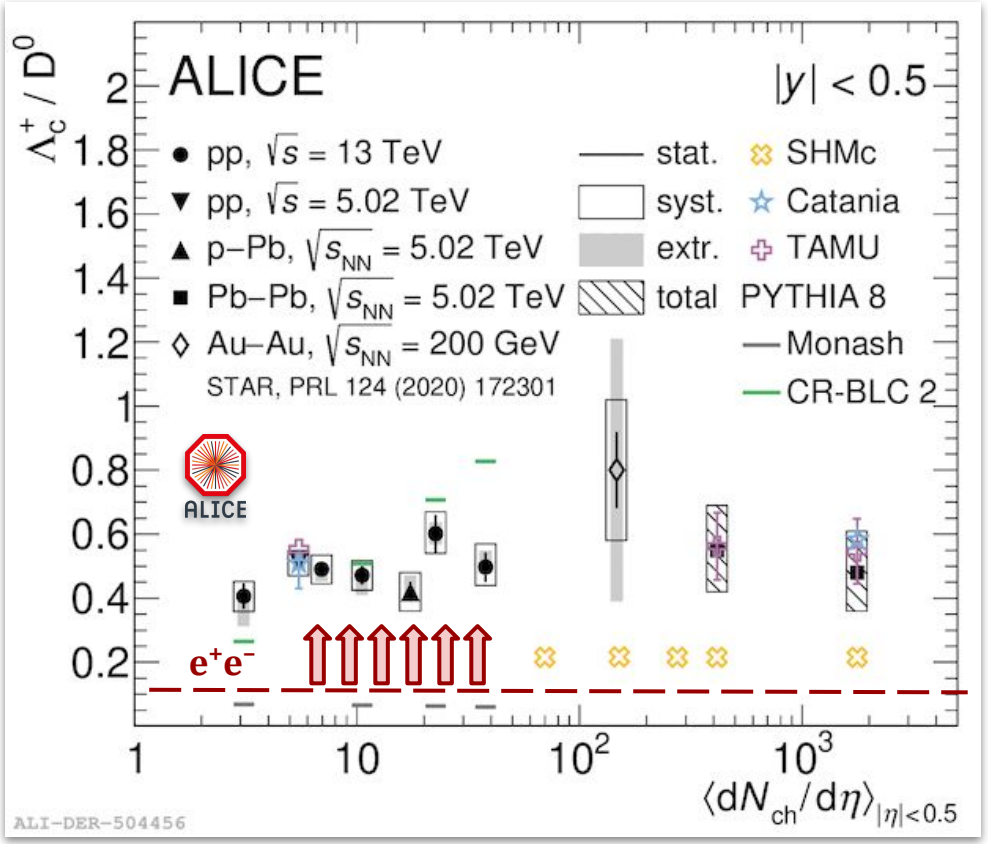
LEP: EPJC 75, 19 (2015)
ALICE: PLB 839 (2023) 137796

Baryon enhancement in all collision systems at the LHC compared to e^+e^-

- **No** significant **dependence** versus multiplicity of the **p_T-integrated Λ_c^+/D^0** ratio **across collision systems**
- Ratio described by Catania (fragmentation + coalescence) and TAMU (SHM+RQM + 4-momentum conserving coalescence in Pb-Pb)
- PYTHIA CR-BLC prediction does not reproduce the trend vs. multiplicity in pp collisions

→ Is the **p_T-differential Λ_c^+/D^0 enhancement** just a consequence of **radial flow** and **recombination**?



Charm-baryon production at the LHC - open points (2/2)

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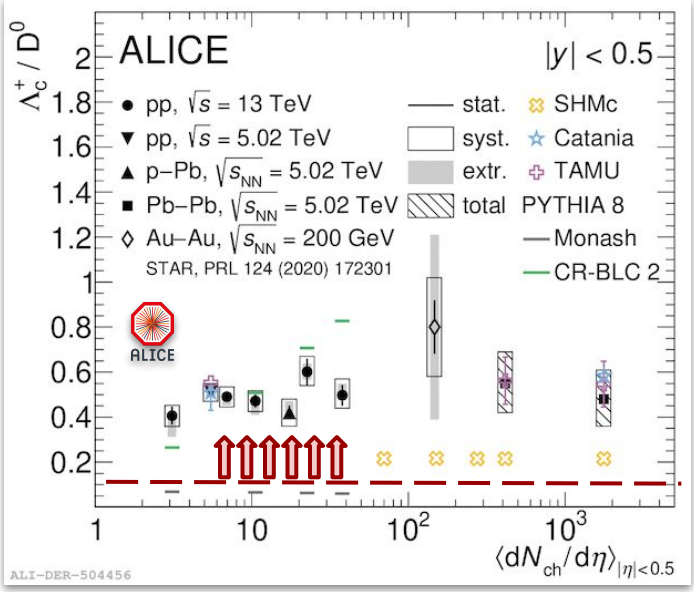
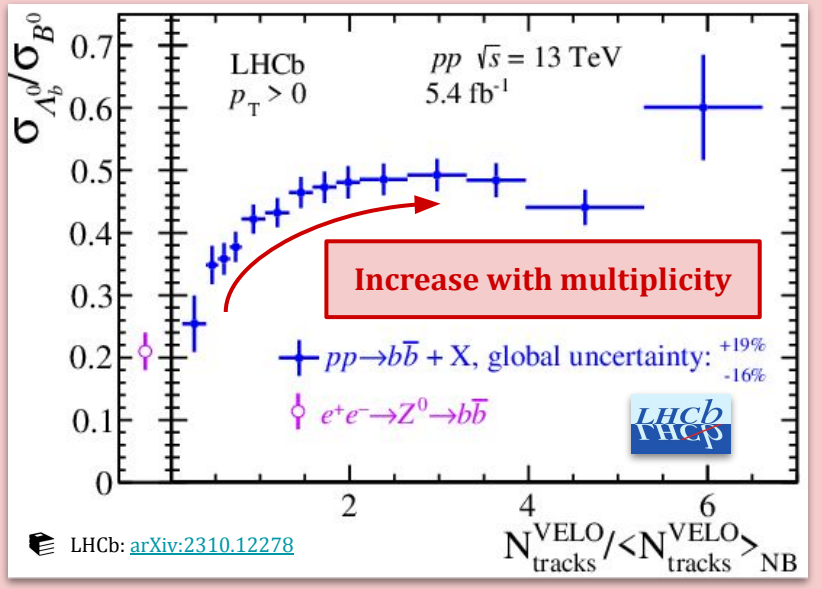


e⁺e⁻

pp collisions

Beauty
baryon-to-meson ratio



- **No** significant **dependence** versus multiplicity of the p_T**-integrated** Λ_c^+/D^0 ratio **across collision systems**
- Ratio described by Catania (fragmentation + coalescence) and TAMU (SHM+RQM + 4-momentum conserving coalescence in Pb–Pb)
- PYTHIA 8 CR-BLC prediction does not reproduce the trend vs. multiplicity in pp collisions

→ Is the p_T**-differential** Λ_c^+/D^0 **enhancement** just a consequence of **radial flow** and **recombination**?

Observables:

- production yield and RAA
- flow
- ccbar cross section in p-Pb (?)

Topics:

- ratio Lc/D0 from pp to Pb-Pb → confronto anche con LHCb in 60-80% e con CMS a mid-rapidity
- Lc Pb-Pb mid-rapidity (https://indico.cern.ch/event/1139644/contributions/5539868/attachments/2708392/4702520/Soumik_Chandra_Measurement_of_charm_quark_QM2023.pdf)
- **RAA prompt** e non prompt **D mesons** → anche da CMS (https://indico.cern.ch/event/1139644/contributions/5542698/attachments/2709279/4704316/MilanStojanovic_D0_CMS_QM2023.pdf)
- **Prompt** and **non-prompt Ds** da pp a Pb-Pb
  - RAA ratio Ds here https://indico.uni-muenster.de/event/1409/contributions/2013/attachments/924/1867/VoelklHPnonPrompt.pdf
- **RAA mesoni B CMS** (https://indico.cern.ch/event/1139644/contributions/5539863/attachments/2708556/4702825/qm2023_ta.pdf)
  - **bS, bC cms**: https://indico.uni-muenster.de/event/1409/contributions/2022/attachments/988/2067/hp2023_qm.pdf
- **RAA vs. v2 e spatial diffusion coefficient**. Flow D0 di CMS
- ccbar e FF in p-Pb
- D0, Lc, Xic in p-Pb → vedi talk Moriond e anche risultati Xic di LHCb
  - https://indico.cern.ch/event/1139644/contributions/5539922/attachments/2708428/4703445/QM2023_ChenxiGu.pdf)
  - per D0 p-Pb ALICE: https://indico.uni-muenster.de/event/1409/contributions/2001/
- Performance Xic in Pb-Pb(Jianhui)