Experimental overview on heavy-flavour measurements

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Universität Münster

International Workshop "QCD challenges from pp to AA collisions"

Track: *"Energy loss and transport in the medium and in small systems"*

Münster (Germany)
3rd September 2024

Heavy quarks: a unique probe for high-density QCD

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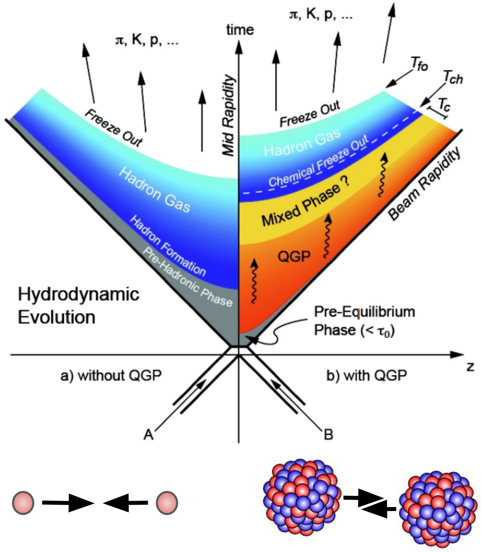


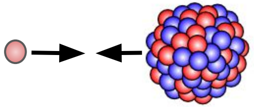
- **Charm** and **beauty** quarks: m_c~1.3 GeV/c^2, m_b~4.2 GeV/c^2
- **Produced** in **hard scattering** processes among partons

- **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**

pp collisions

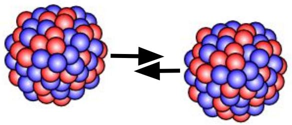
- Reference for Pb–Pb collisions
- Test of pQCD calculations



p–Pb collisions

Cold nuclear-matter effects

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



Pb–Pb collisions

Hot nuclear-matter effects

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

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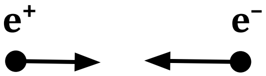
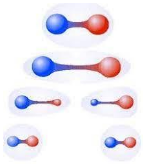
Hadronization: a key ingredient in all collision systems!

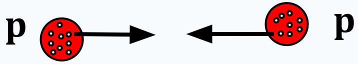


- "**Point-like**" object interaction
- **Fragmentation** in the vacuum



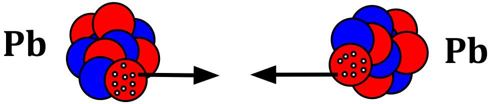
Fragmentation

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



What happens in pp collisions?

Track *"Hadronization of light and heavy flavour across collision systems"*

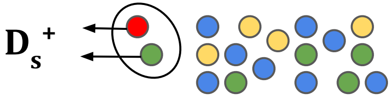


The focus of this talk

- **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

1 Production spectra and R_{AA}

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

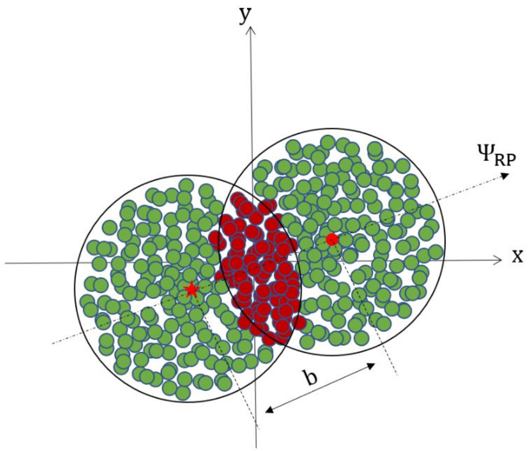
$\langle N_{coll} \rangle$: average number of binary nucleon-nucleon collisions

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

1 Production spectra and R_{AA}

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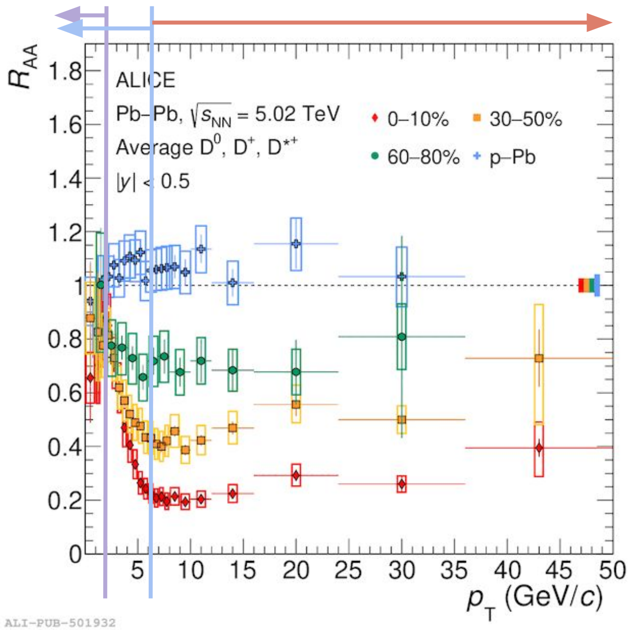
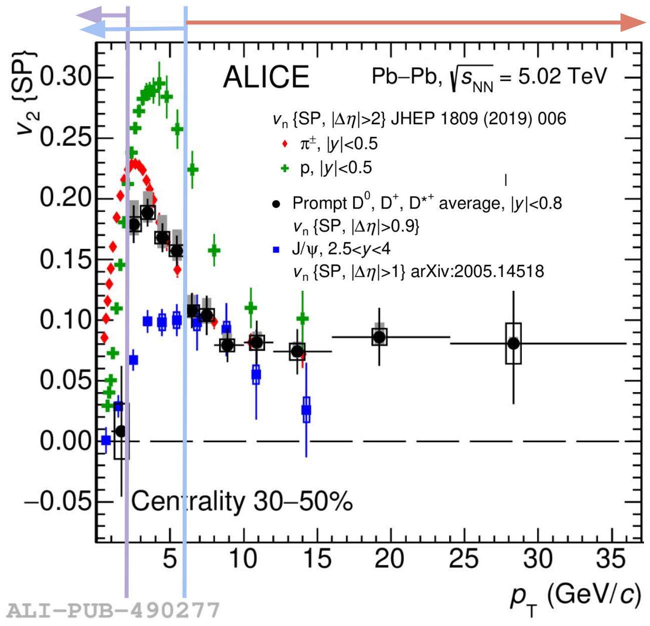


ALICE: JHEP 01 (2022) 174

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

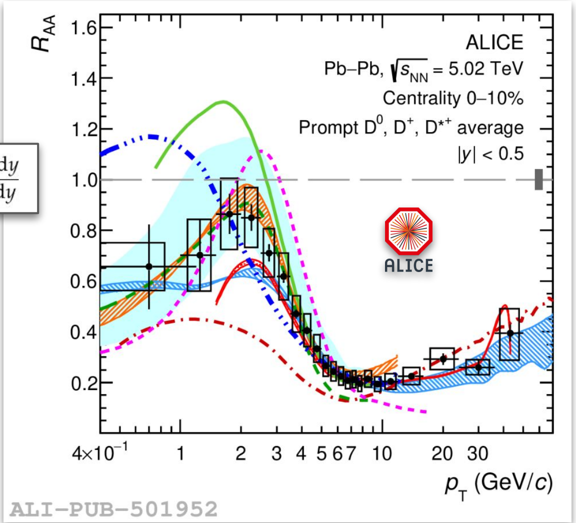
- Radiative E-loss
- Quark-mass and path length dependent E-loss

R_{AA} and v_2 compared to transport models

R_{AA}

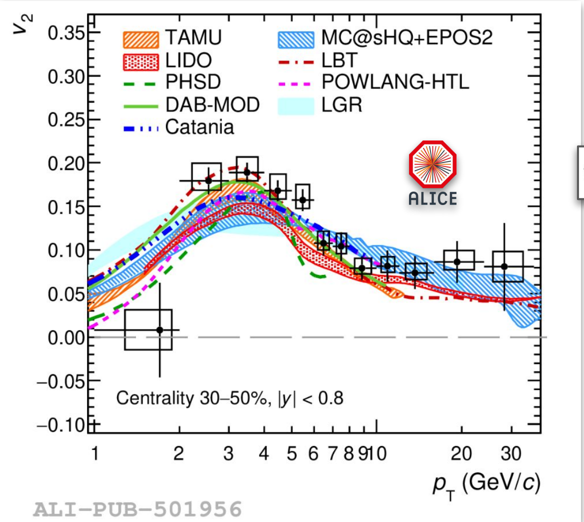
$$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

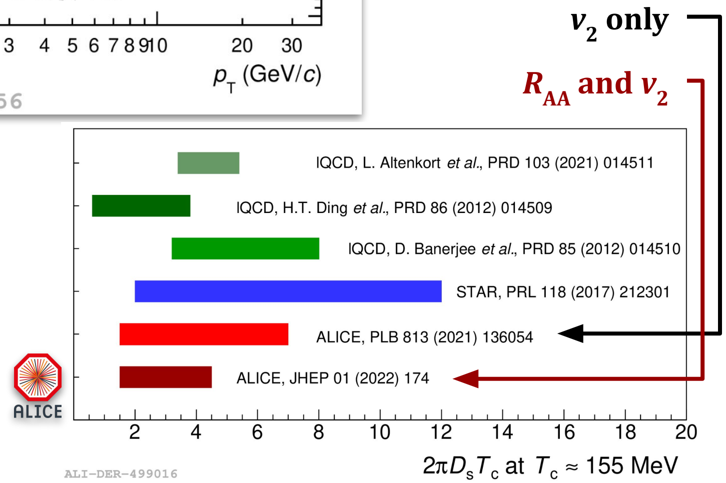
ALICE: JHEP 01 (2022) 174



v_2

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





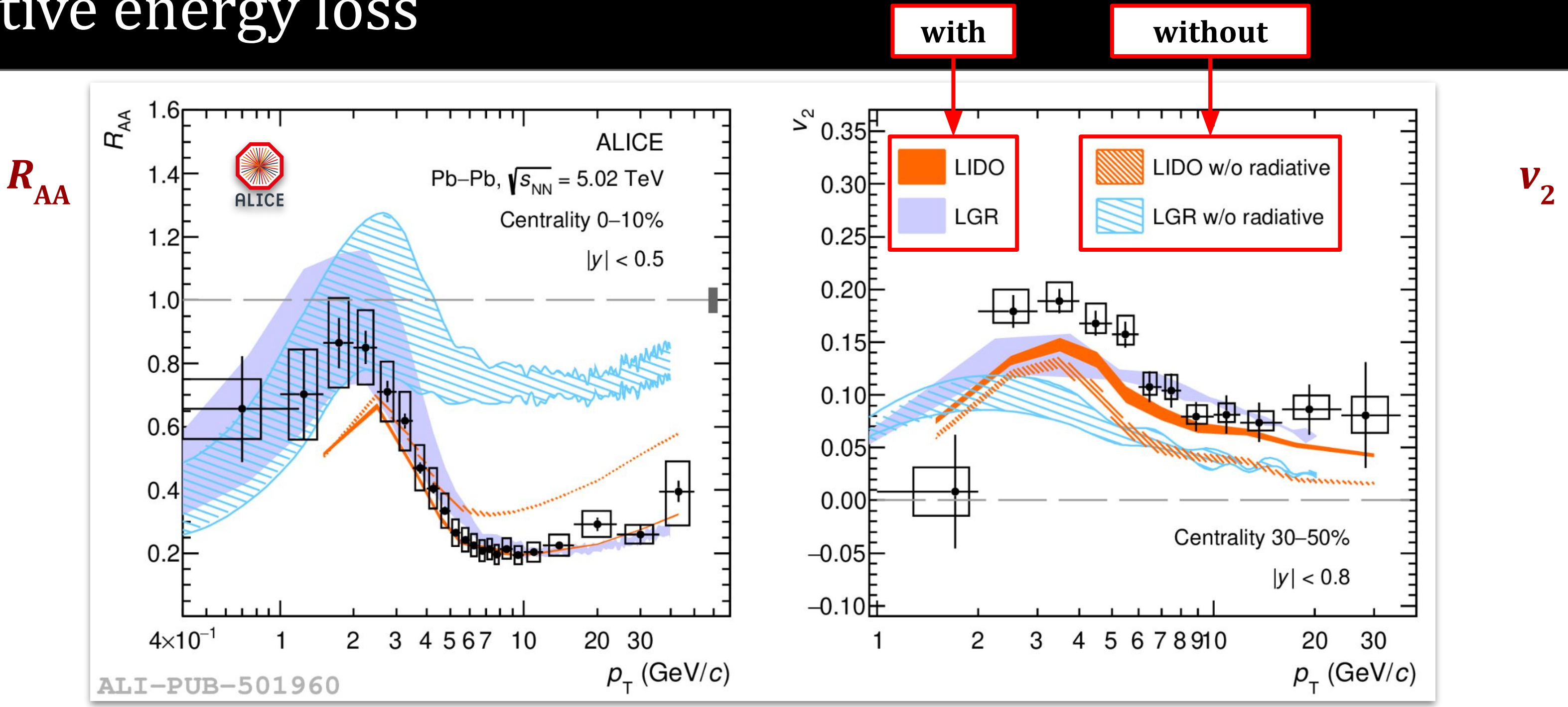
Measured R_{AA} **and** v_2 described by transport models

- **understanding** of **relevant effects** in different p_T intervals (next slides)
- 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**

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

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

Radiative energy loss



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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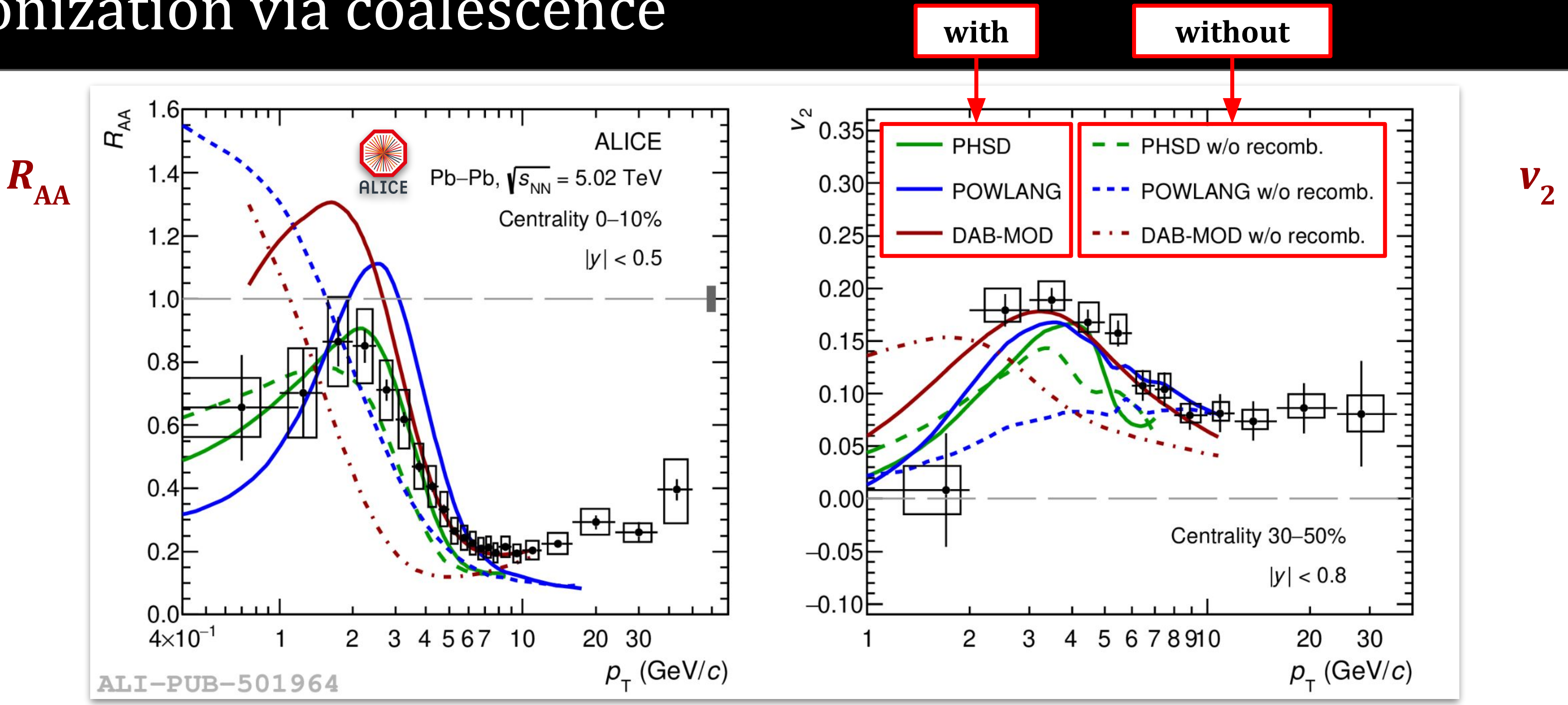
Hadronization via coalescence



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

TAMU: PRL 124, 042301 (2020)
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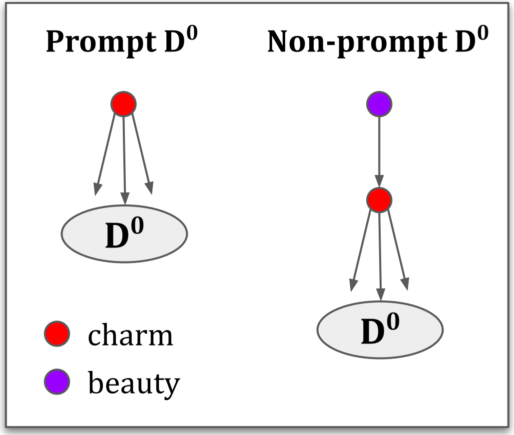
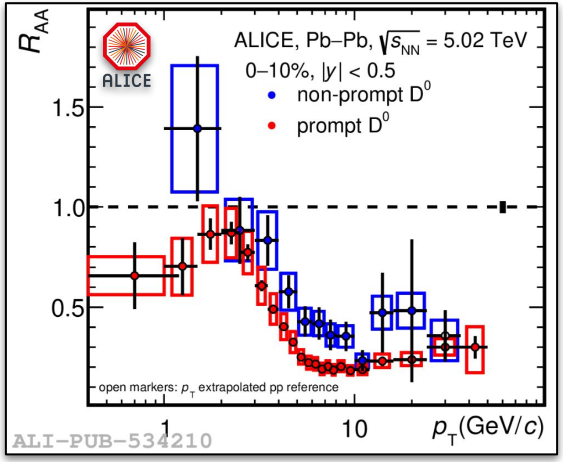
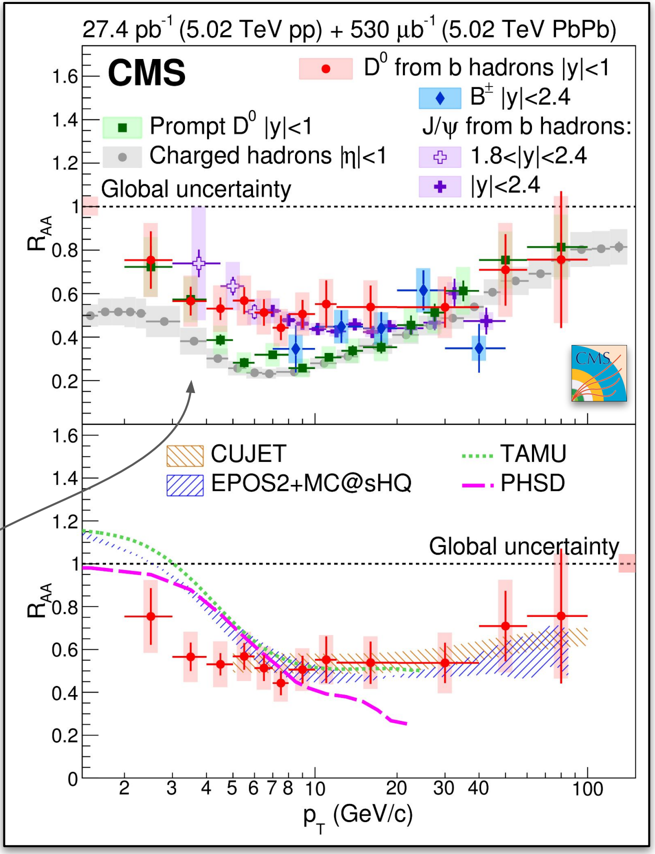
Beauty-quark dynamics from non-prompt D mesons



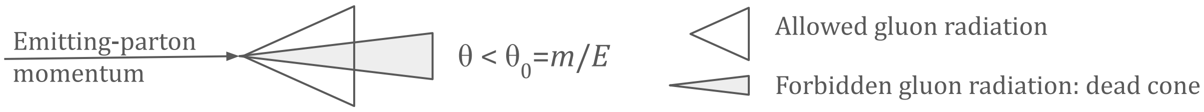




- R_{AA}(non-prompt D^0) described by models including radiative E-loss for $p_T > 5$ GeV/c
- The hierarchy

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

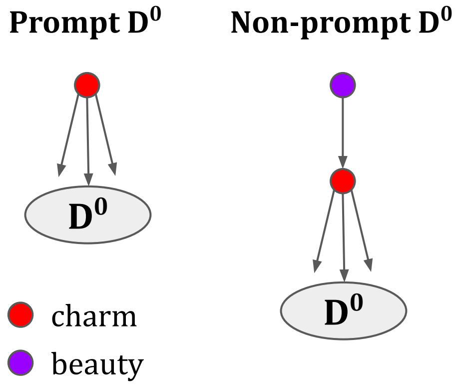
can be explained with the $\boldsymbol{m_b > m_c}$ hierarchy and the **dead-cone effect**

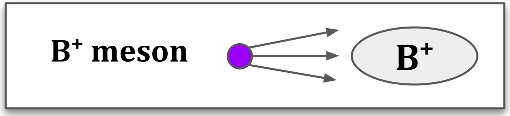


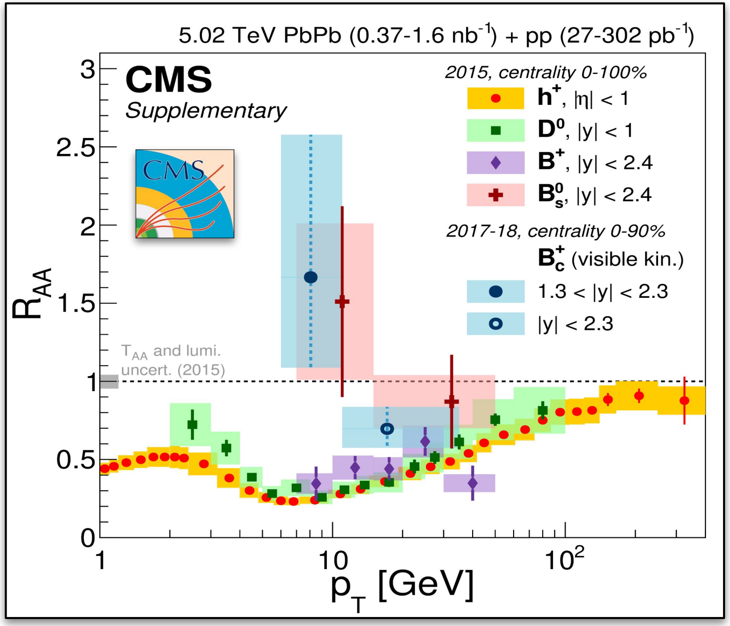
ALICE: JHEP 12 (2022) 126
CMS: PRL 123, 022001 (2019)

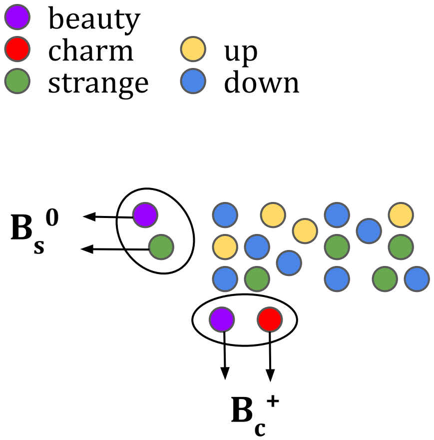
Beauty-quark hadronization from B mesons R_{AA}

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

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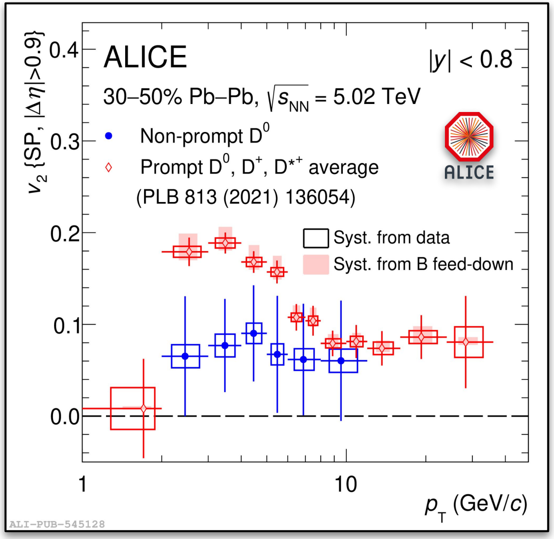

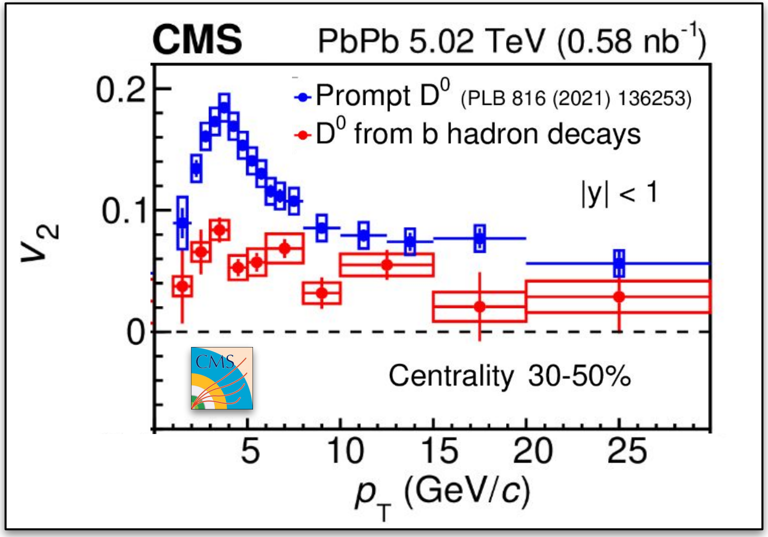

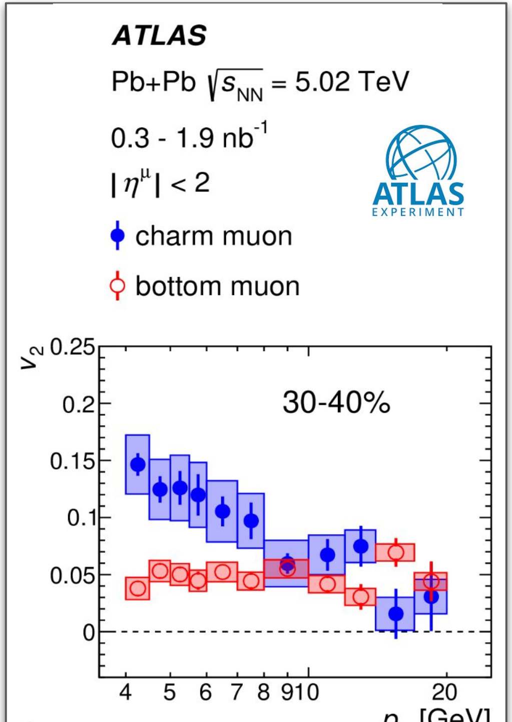

ALICE: arXiv:2307.14084 [nucl-ex]

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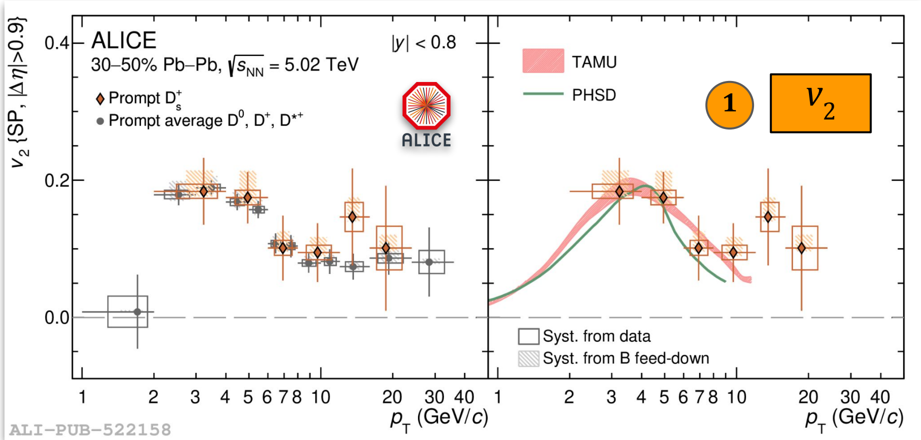
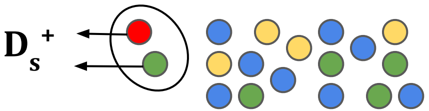
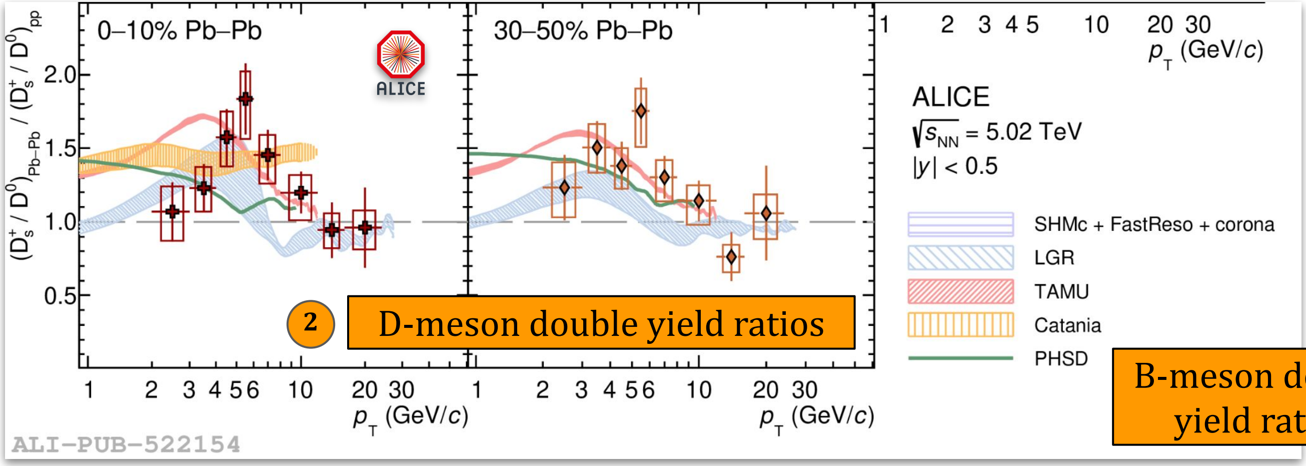
ALICE: PLB 827 (2022) 136986 CMS: PLB 829 (2022) 137062

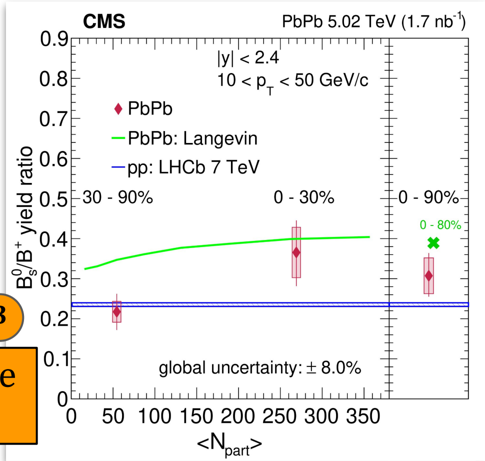


Sensitivity to **coalescence** and **strangeness enhancement**

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



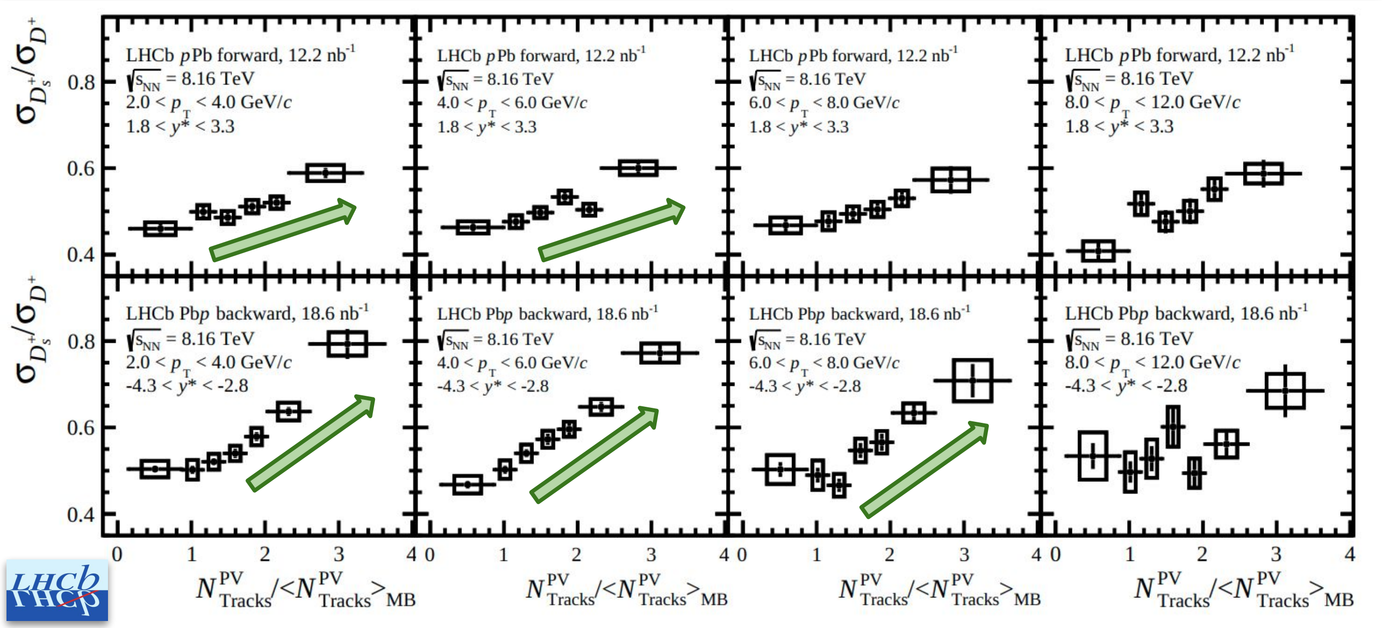




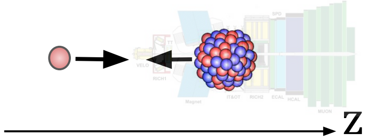
D_s^+ enhancement in high-multiplicity p–Pb collisions

LHCb: arXiv:2311.08490

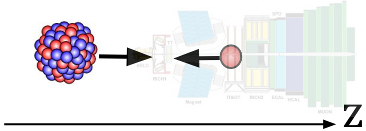
$2 < p_T < 4$ GeV/c^2 | **$4 < p_T < 6$ GeV/c^2** | **$6 < p_T < 8$ GeV/c^2** | **$8 < p_T < 12$ GeV/c^2**



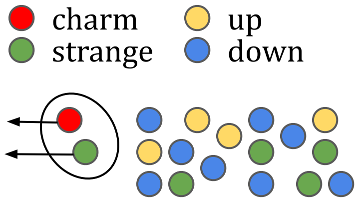
p–Pb (forward y*)



Pb–p (backward y*)

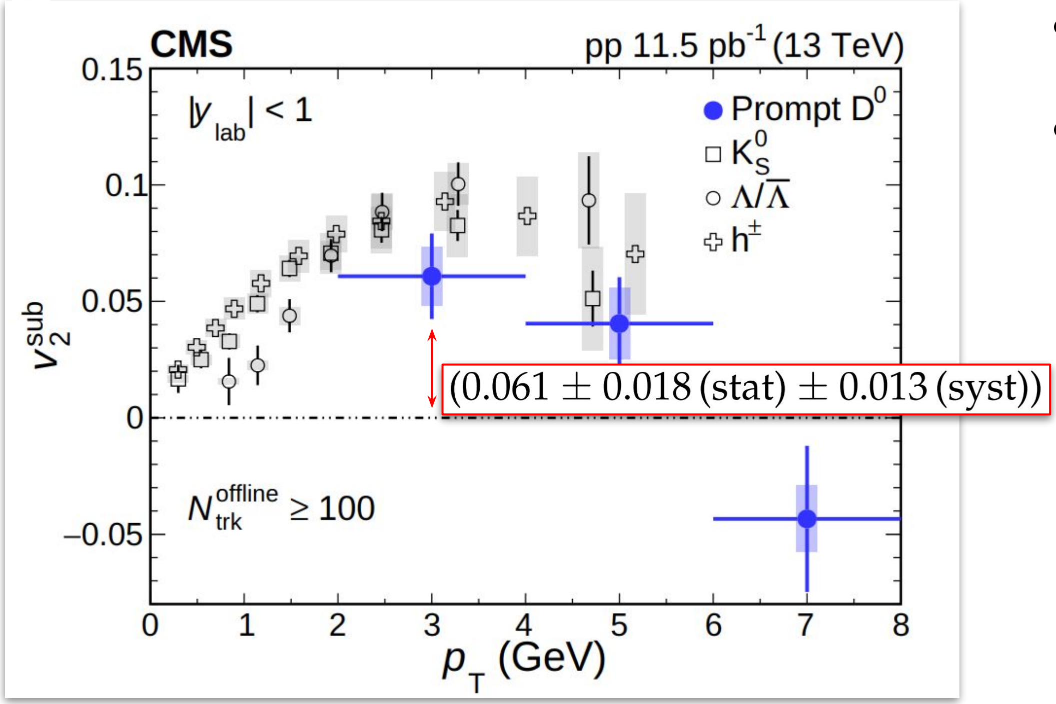


- Significant **increase vs. multiplicity** of prompt D_s^+/D^+ ratio in **p–Pb** collisions
  - **more pronounced** for **backward** collisions
- In line with a scenario including hadronization via **coalescence** and **strangeness enhancement** in **high-multiplicity p–Pb** collisions



Elliptic flow measurements in pp collisions

CMS: Phys. Lett. B 813 (2021) 136036



- Prompt D^0 v_2 in **pp collisions** at $\sqrt{s}$ = 13 TeV measured by the CMS Collaboration
- **Hint** of $\mathbf{v_2(D^0) > 0}$ in $2 < p_T < 4$ GeV/c (~2.7σ)

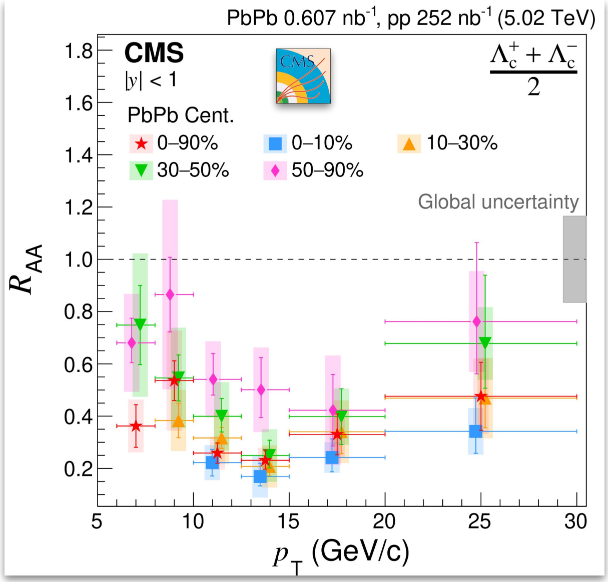
→ ***Collectivity in small systems***?

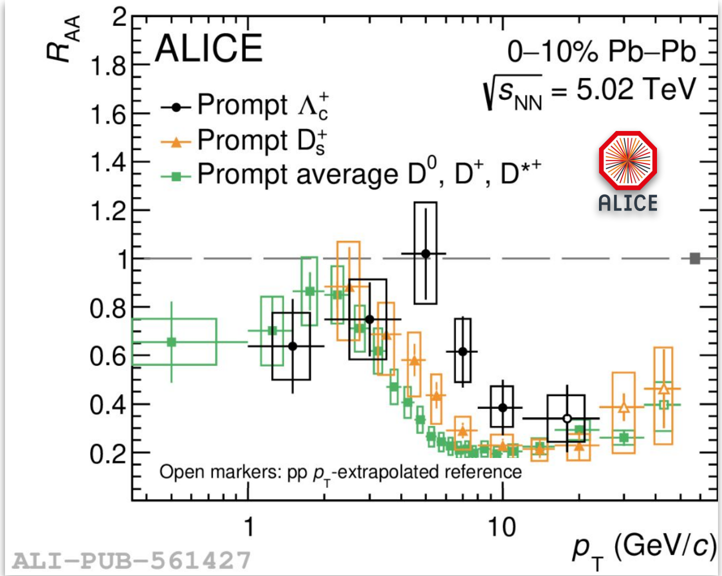
→ Influence of ***non-flow effects*** (initial-state effects, jets, resonance decays, ...) ?

Track *"Event properties and hydro in small and large systems"*

"Collectivity in high-energy pp collisions"
Y. Zhou, SQM 2024 (link)

Nuclear modification factor of Λ_c^+ baryon

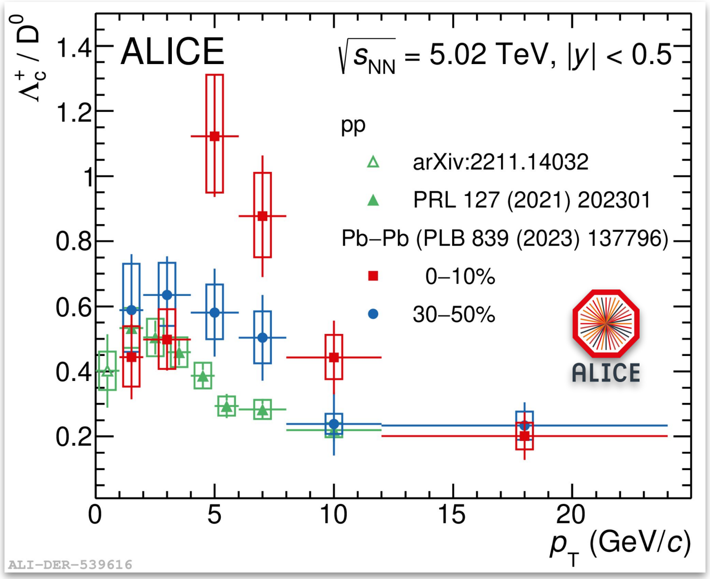


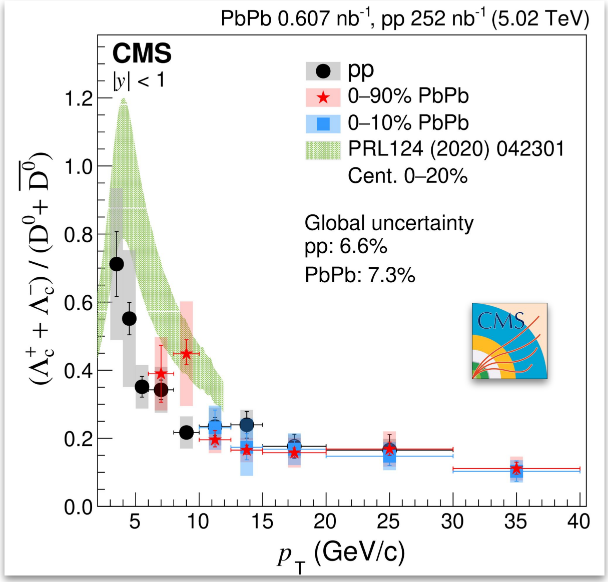


- Hint of $\boldsymbol{R_{AA}^{central}(\Lambda_c^+) < R_{AA}^{peripheral}(\Lambda_c^+)}$ → sensitivity to **different system size** and **energy density**
- Minimum value of $R_{AA}^{central}(D^0)$ at around p_T = 6-8 GeV/c, which is lower than that of $R_{AA}^{central}(\Lambda_c^+)$
- Hint of hierarchy $\boldsymbol{R_{AA}(\Lambda_c^+) > R_{AA}(D_s^+) > R_{AA}}$**(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]

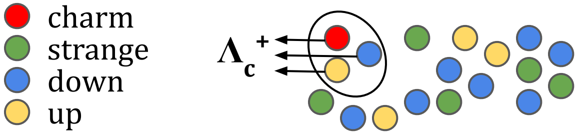
Λ_c^+/D^0 ratio in Pb–Pb collisions





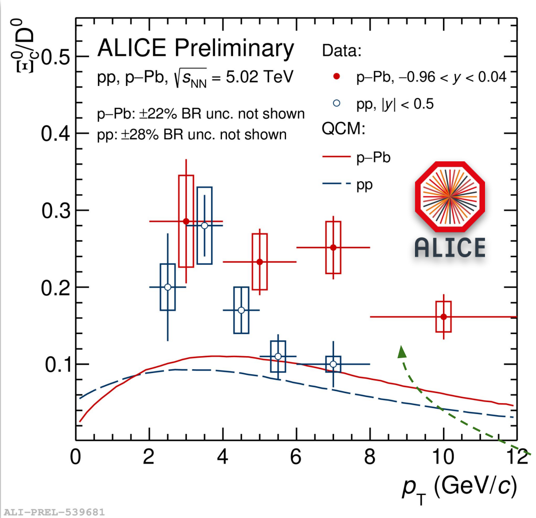
- **Λ_c^+/D^0** baryon-to-meson ratio ***at midrapidity*** significantly **higher** (ALICE: 3.7σ) in **central Pb-Pb** collisions than in **pp** collisions in the interval $4 < p_T < 8$ GeV/c
  - Measurement in central Pb-Pb collisions described by **transport models** with **recombination**

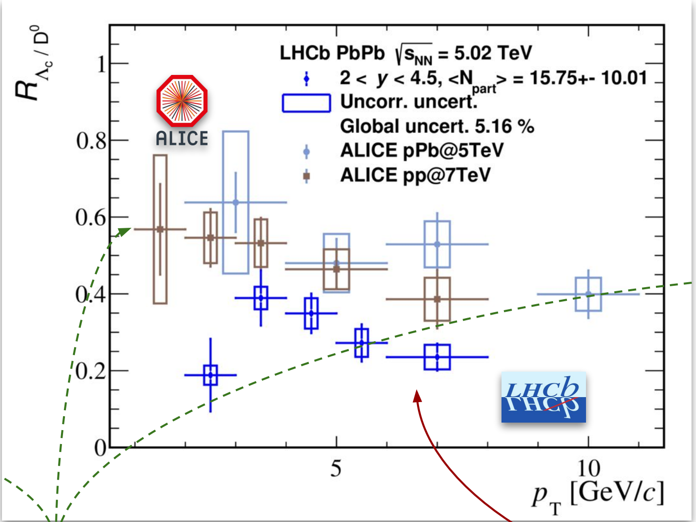
- No significant collision-system and centrality dependence for $p_T > 12$ GeV/c

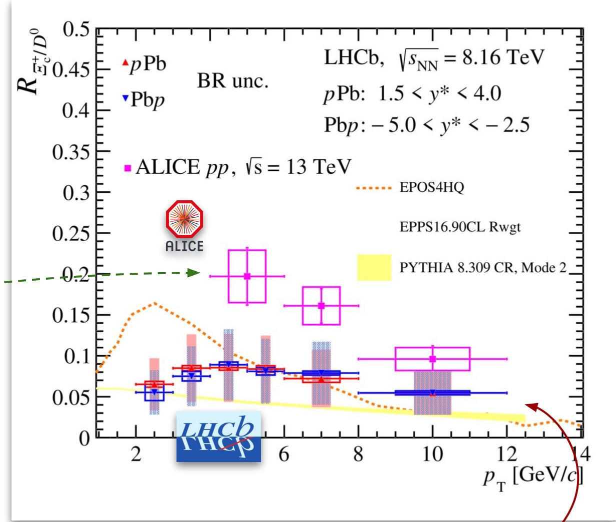


ALICE: PLB 839 (2023) 137796
CMS: arXiv:2307.11186 [nucl-ex]

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







Midrapidity ($|y| < 0.5$)

Forward rapidity

- Baryon-to-meson ratio at midrapidity compatible in pp and p–Pb collisions
  $\rightarrow$ 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?

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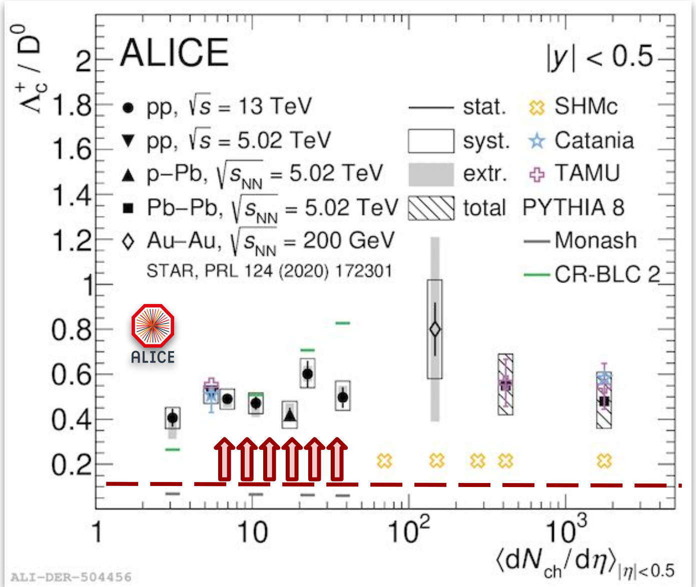
LEP: EPJC 75, 19 (2015)
ALICE: PLB 839 (2023) 137796



e^+e^-: **0.113 ± 0.013 ± 0.006**

Charm baryon-to-meson ratio

- **No** significant **dependence vs. multiplicity** of the $\boldsymbol{p_T}$**-integrated** $\boldsymbol{\Lambda_c^+/D^0}$ 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 $\boldsymbol{p_T}$**-differential** $\boldsymbol{\Lambda_c^+/D^0}$ **enhancement** just a consequence of **radial flow** and **recombination**?

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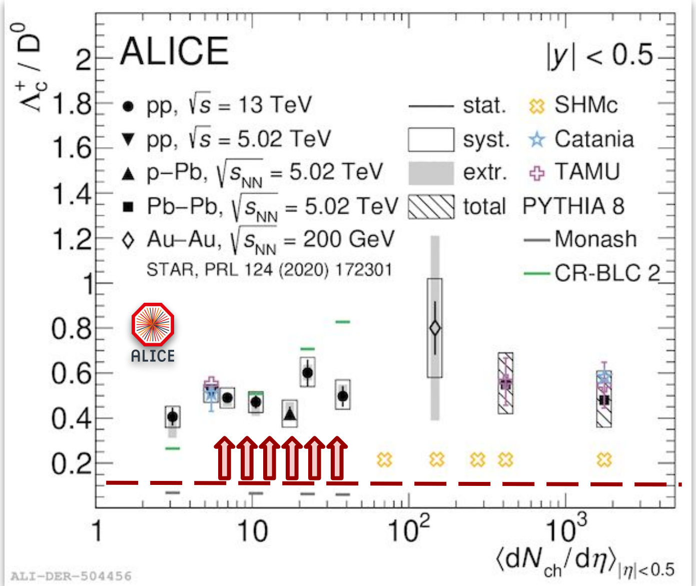
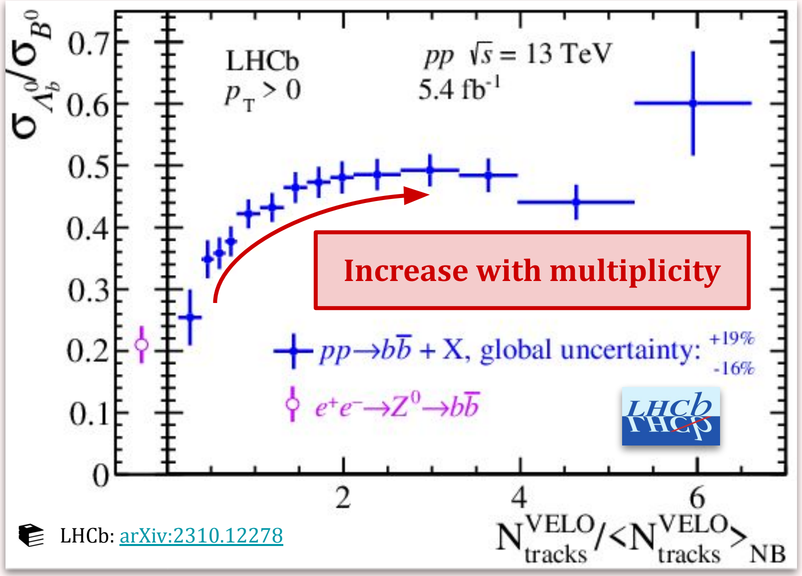


pp collisions

Beauty
baryon-to-meson
ratio



LHCb: arXiv:2310.12278

- 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

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

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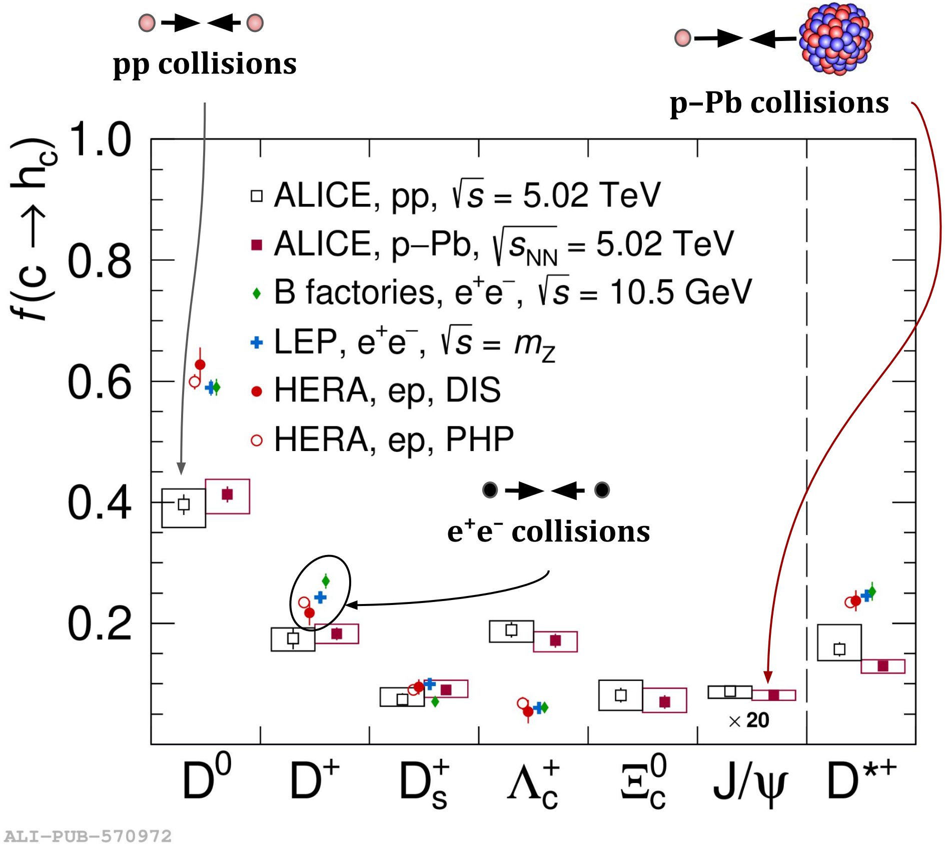
Baryon enhancement in all collision systems at the LHC compared to e^+e^-

- 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**?

Track *"Hadronization of light and heavy flavour across collision systems"*

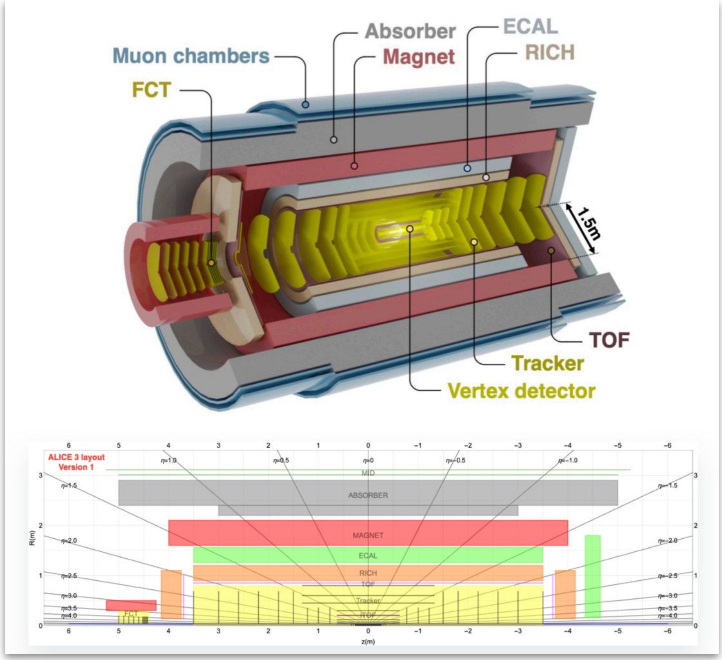


arXiv:2405.14571

Food for thinking …

… actually, just an unsatisfactory appetizer …

ALICE 3 LOI: CERN-LHCC-2022-009



Experiment vs. theory

1

- **Direct beauty** measurement **more challenging** that **non-prompt charm** (at least fro ALICE)
- **Do we really gain** in physics knowledge by measuring beauty hadrons rather than non-prompt charm?
  - decay kinematics non trivial? (e.g. polarization)

Future experiments

2

- Increase of statistics and acceptance (e.g. ALICE 3 up to $|\eta| < 4$)
- Possible measurements: D$\overline{\text{D}}$ correlation, … what else?!
- Can larger acceptance detectors be useful for other observables (e.g. hadronization vs. rapidity)?

2 3 4 …

The end


Thank you for listening
PSYCHIATRIC HELP 7¢
THE DOCTOR IS IN
SCHULZ
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Backup

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

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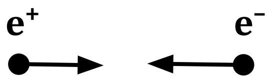
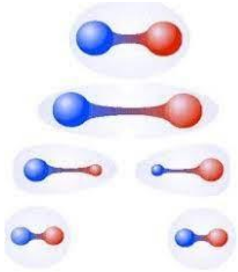
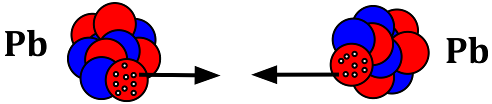


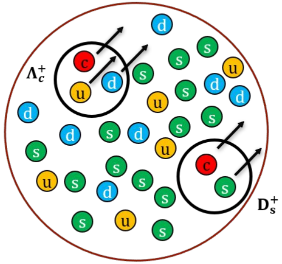
- "**Point-like**" object interaction
- **Fragmentation** in the vacuum



Hadronization: a key ingredient in all collision systems!

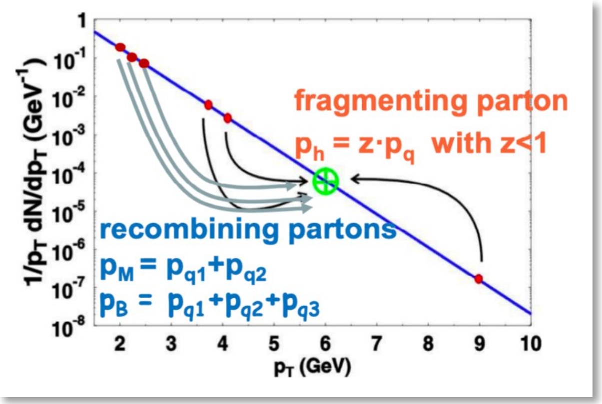


- **QGP**: complex system with **partonic d.o.f**
- Hadronization can be influenced by **coalescence** and **strangeness enhancement**



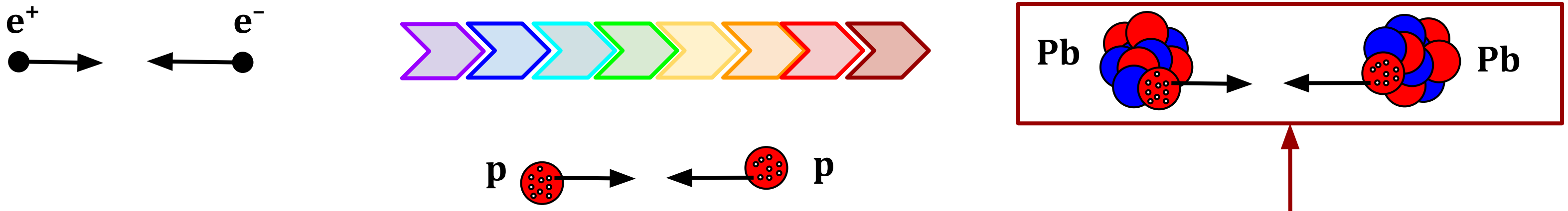
Fragmentation

- 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



- 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

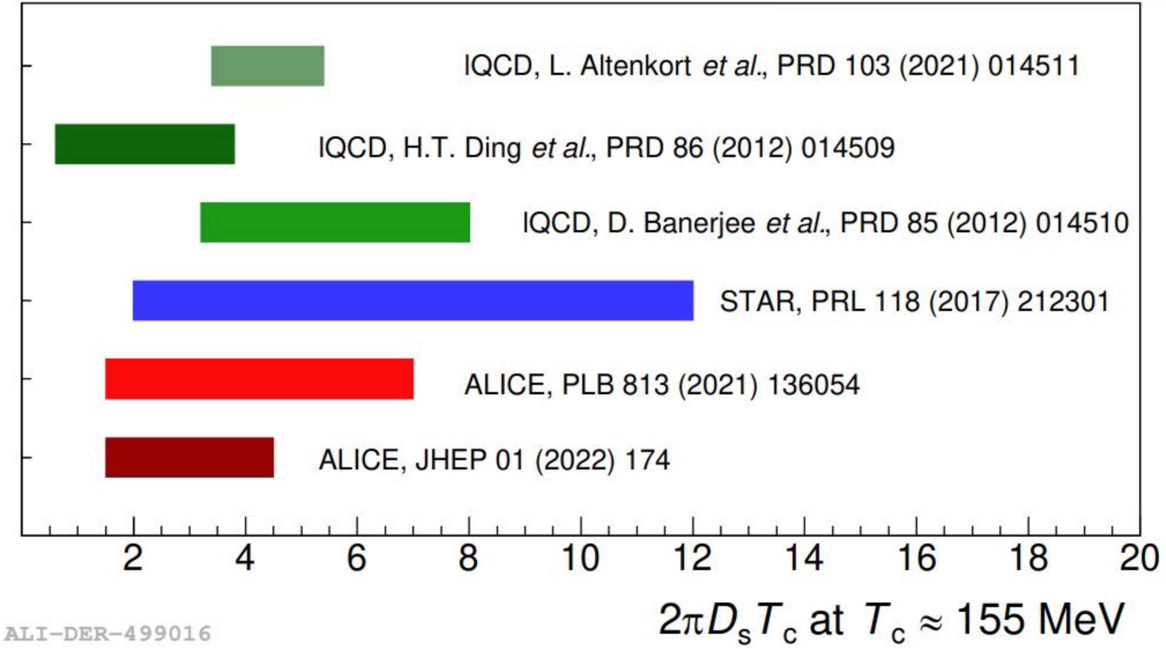
Constraining the spatial diffusion coefficient via the **data-to-model agreement**

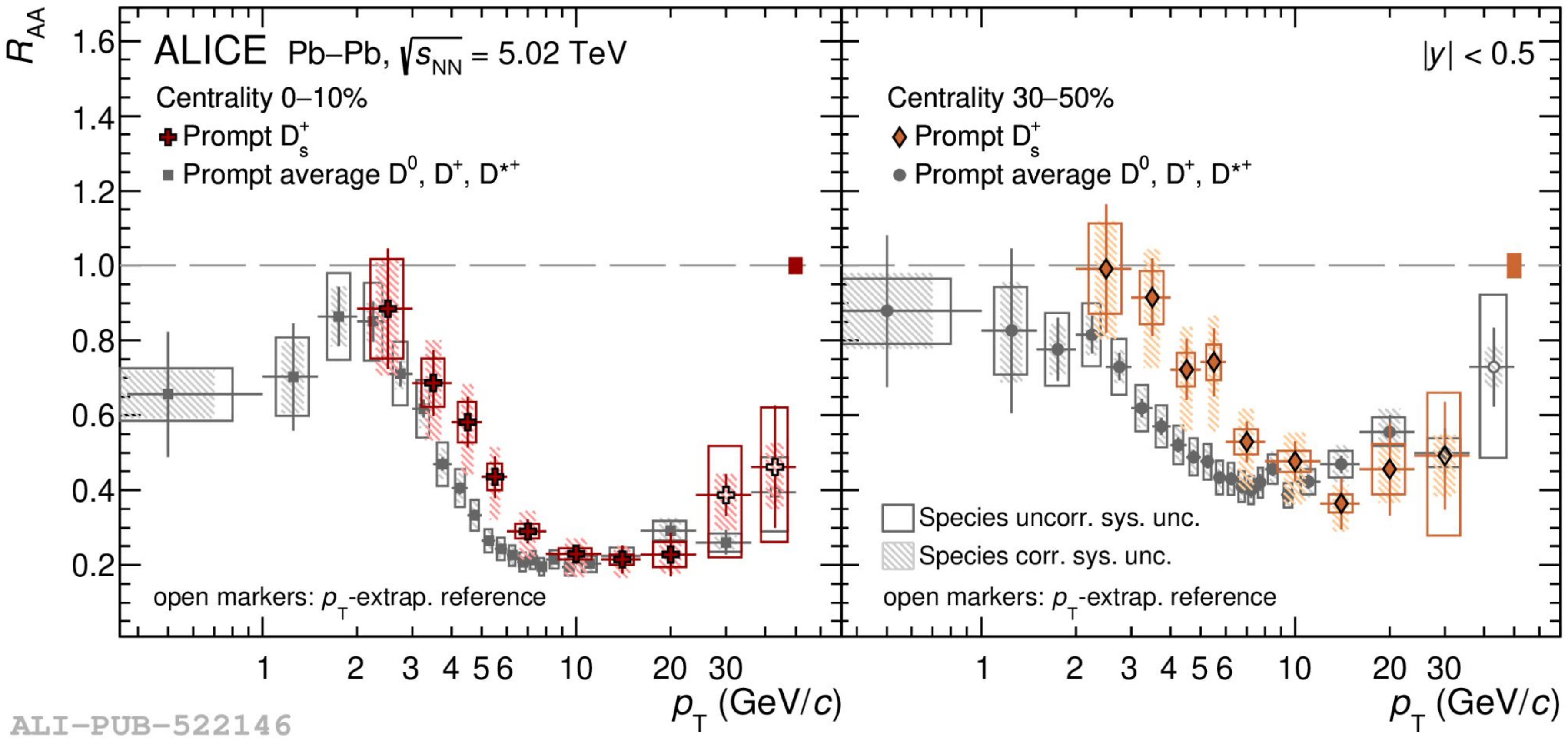
→ Using R_{AA} (with $\chi^2/\mathrm{ndf} < 5$) and v_2 (with $\chi^2/\mathrm{ndf} < 2$) non-strange D measurements

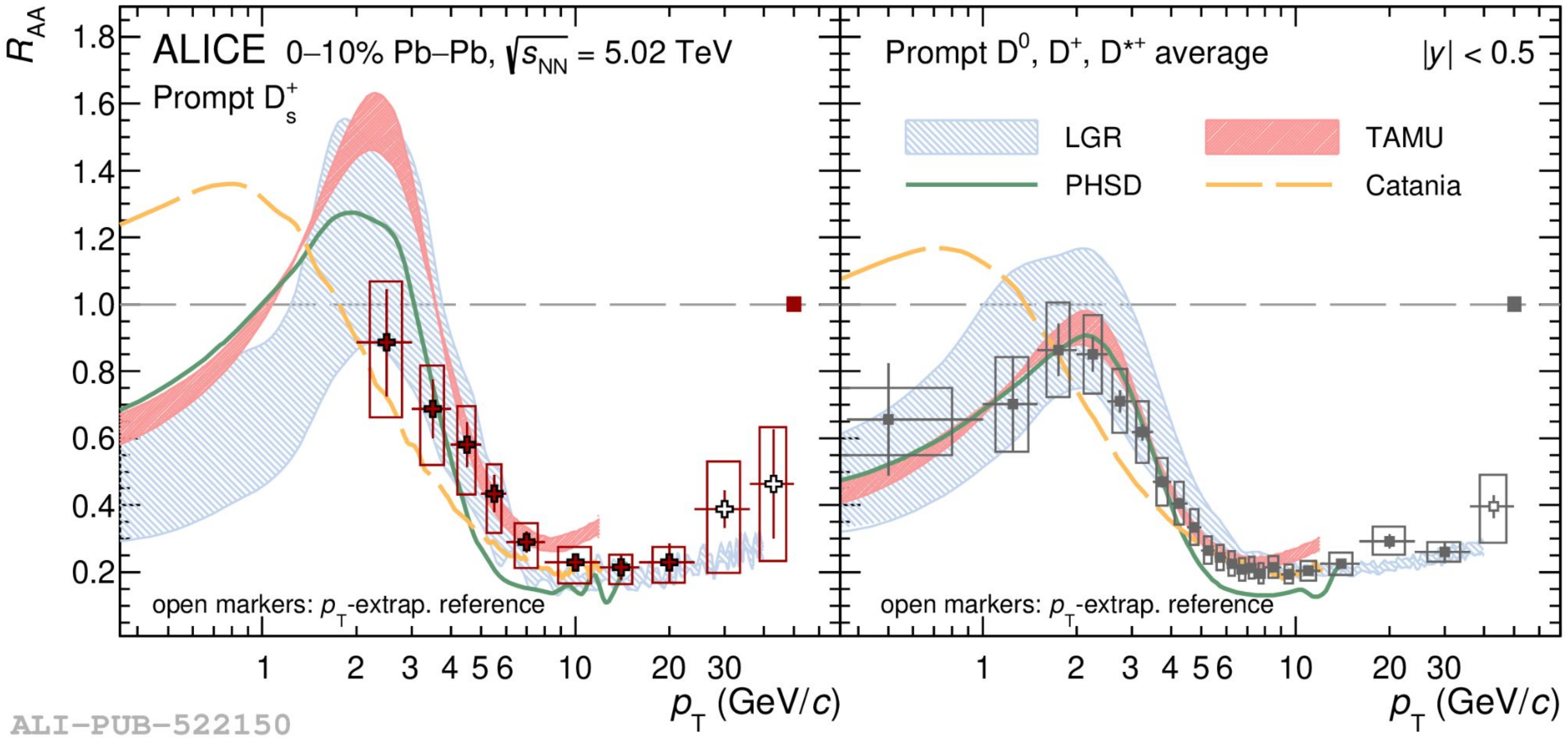
→ TAMU, MC@sHQ, LIDO, LGR, and Catania "selected"

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

New




ALICE Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
|y| < 0.5
Centrality 0–10%
Prompt D_s^+
Prompt average D^0, D^+, D^{*+}
Centrality 30–50%
Prompt D_s^+
Prompt average D^0, D^+, D^{*+}
Species uncorr. sys. unc.
Species corr. sys. unc.
open markers: p_T-extrap. reference
open markers: p_T-extrap. reference
R_{AA}
p_T (GeV/c)
p_T (GeV/c)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
1 2 3 4 5 6 10 20 30
1 2 3 4 5 6 10 20 30
ALI-PUB-522146


ALICE 0–10% Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Prompt D_s^+
Prompt D^0, D^+, D^{*+} average
$|y|$ < 0.5
LGR
TAMU
PHSD
Catania
R_{AA}
open markers: p_T-extrap. reference
p_T (GeV/c)
ALI-PUB-522150

Prompt Ds+

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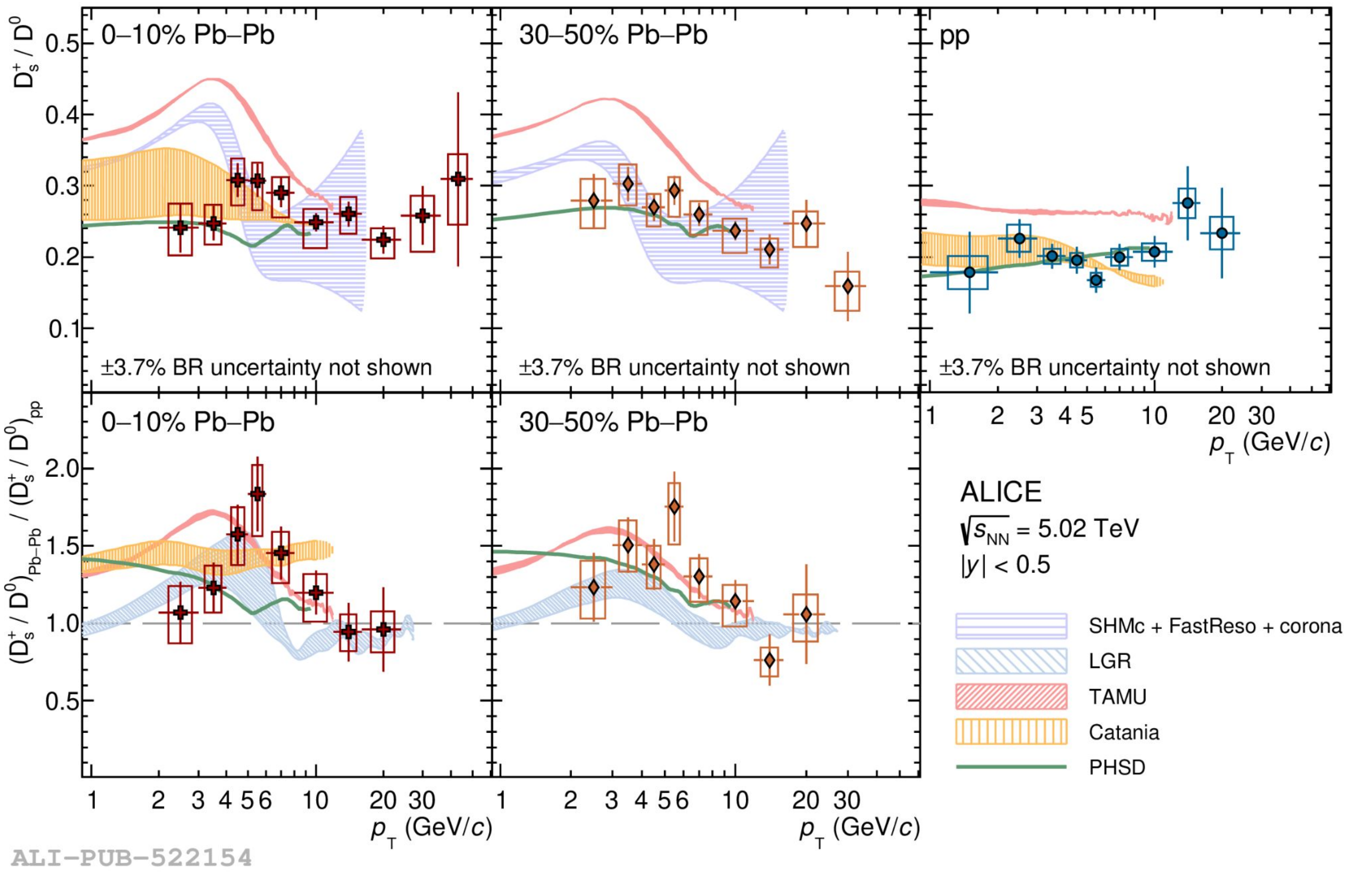
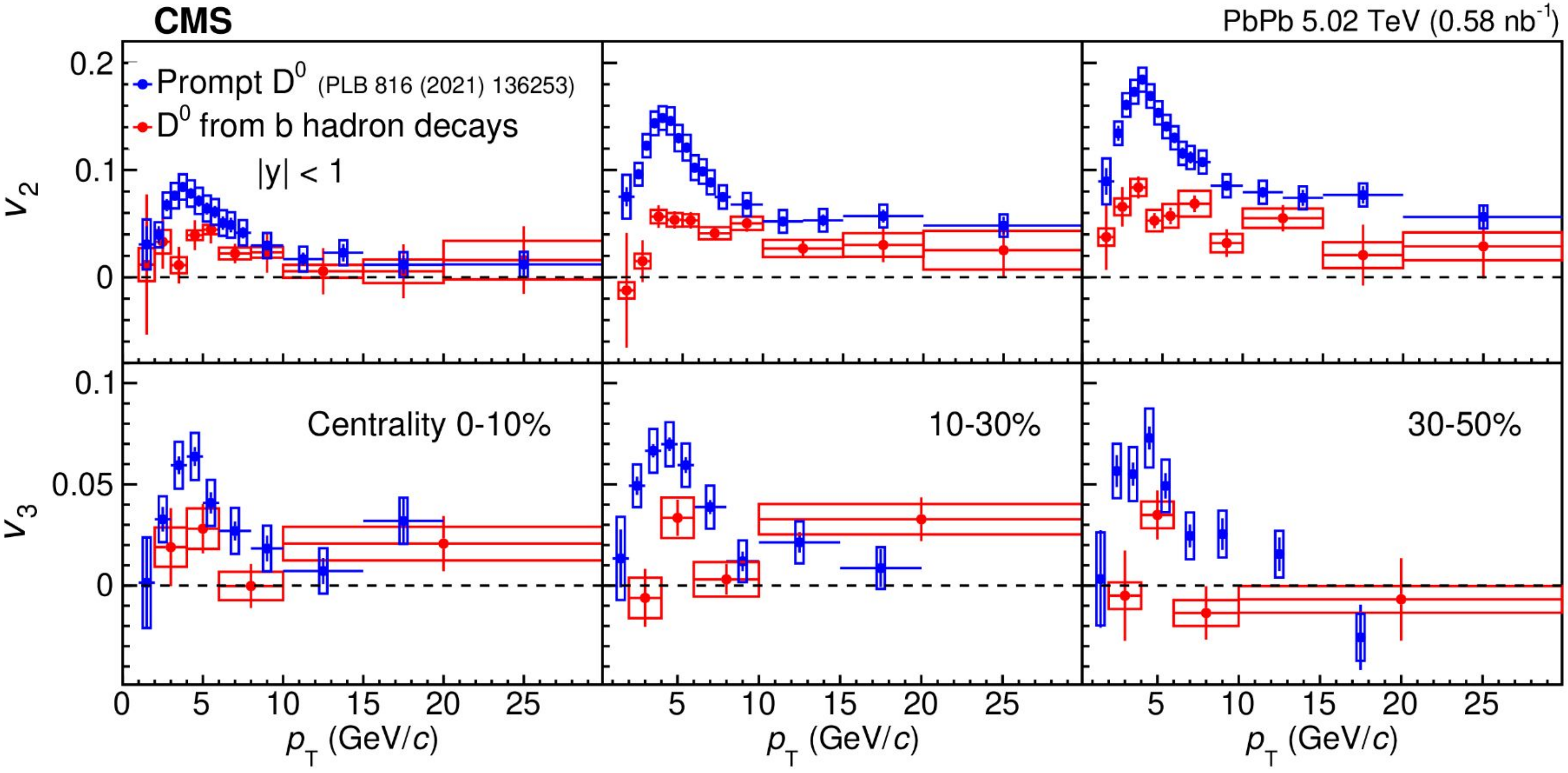
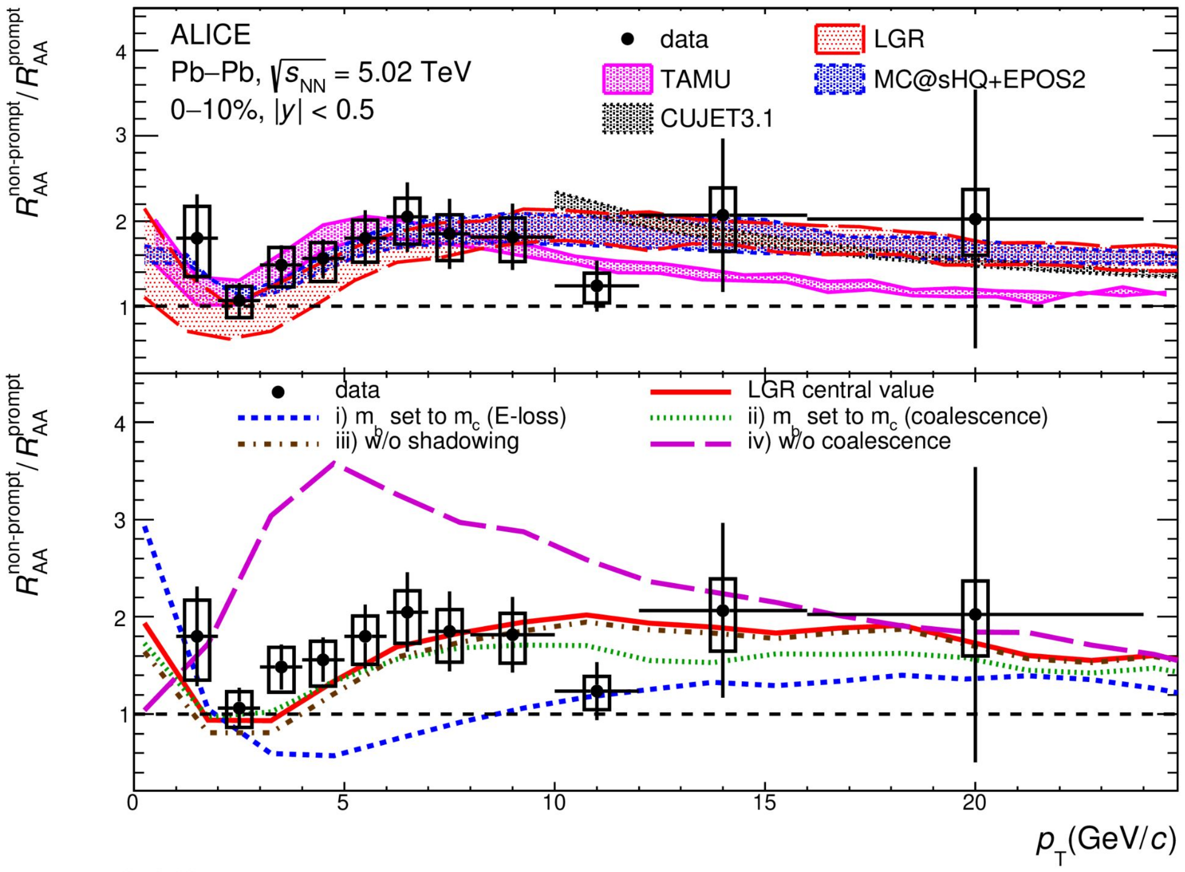
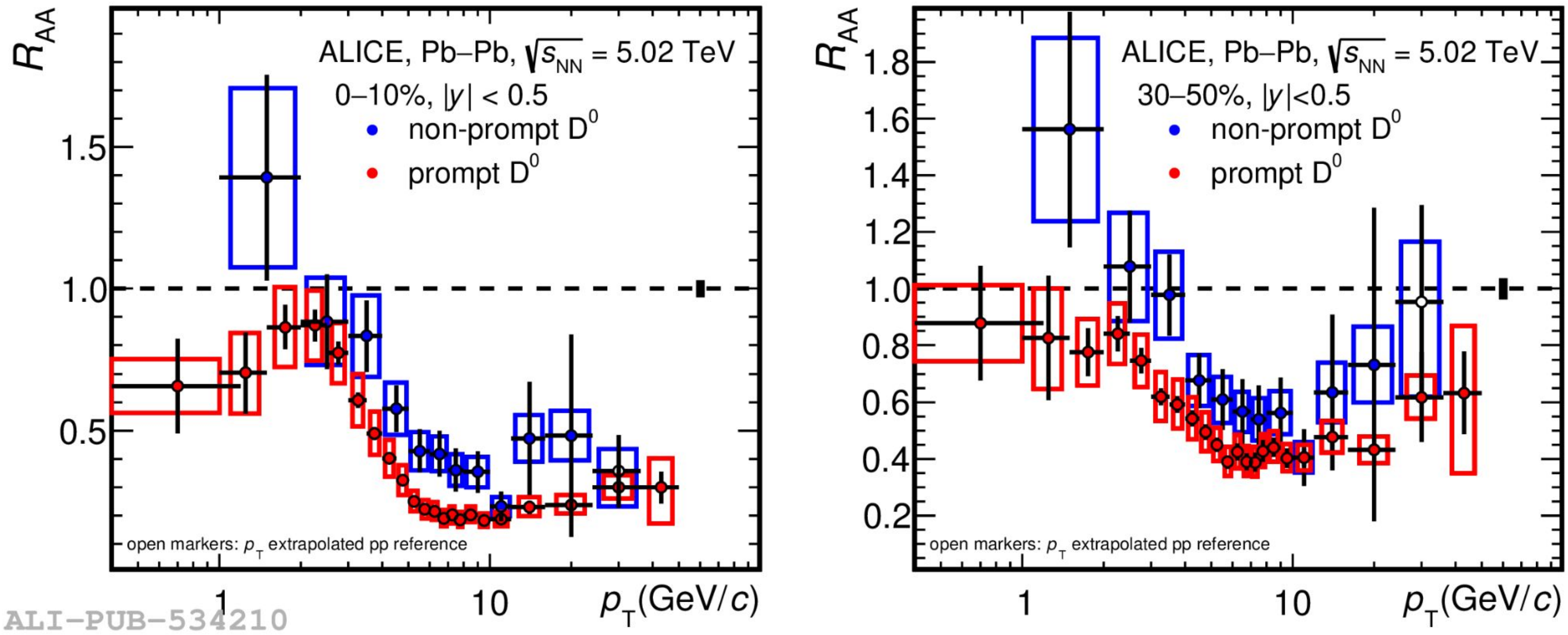
ALICE: https://arxiv.org/pdf/2210.10006.pdf

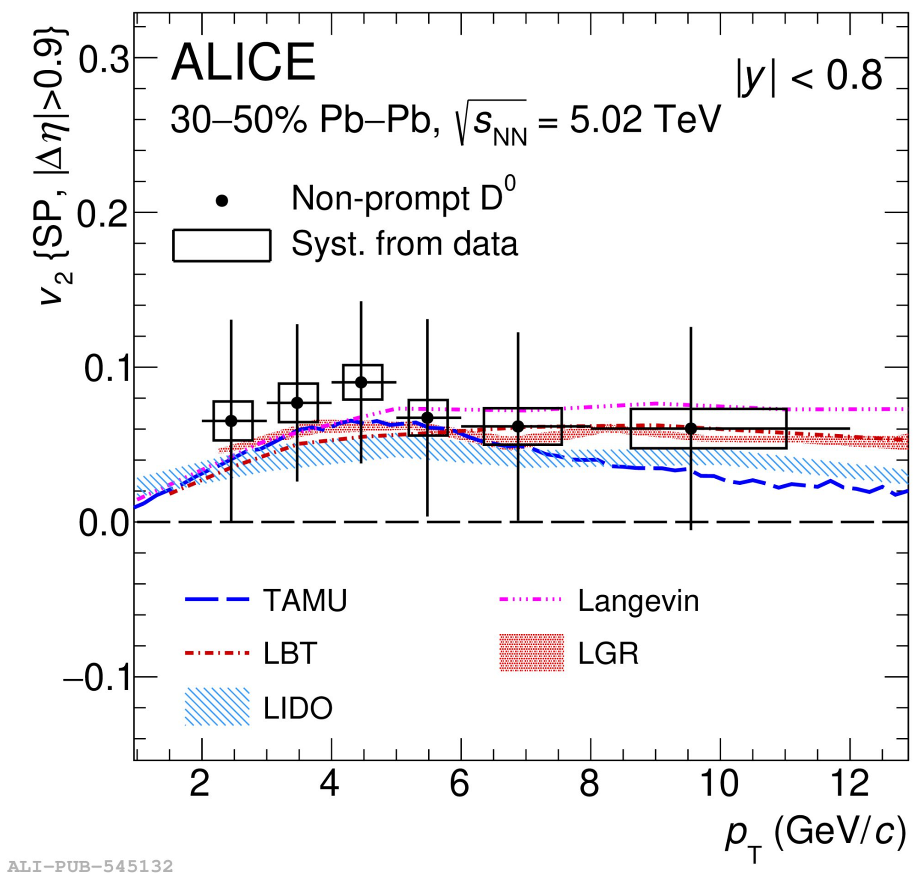


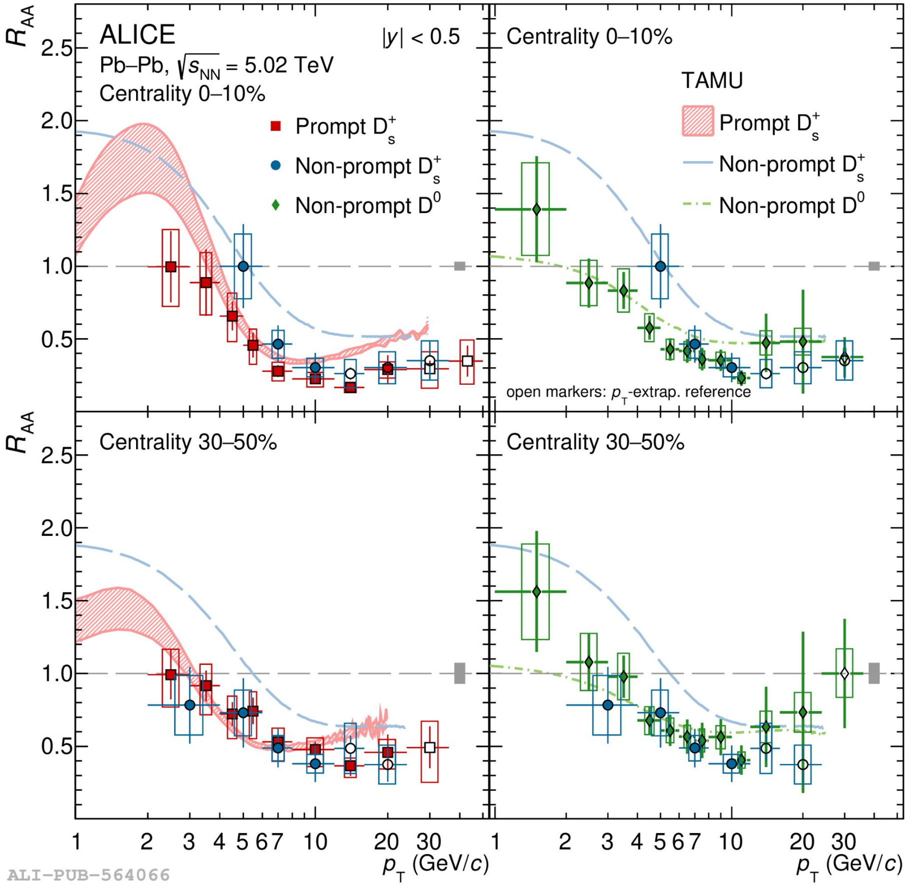

CMS
PbPb 5.02 TeV (0.58 nb^{-1})
Prompt D^0 (PLB 816 (2021) 136253)
D^0 from b hadron decays
|y| < 1
v_2
v_3
Centrality 0-10%
10-30%
30-50%
p_T (GeV/c)

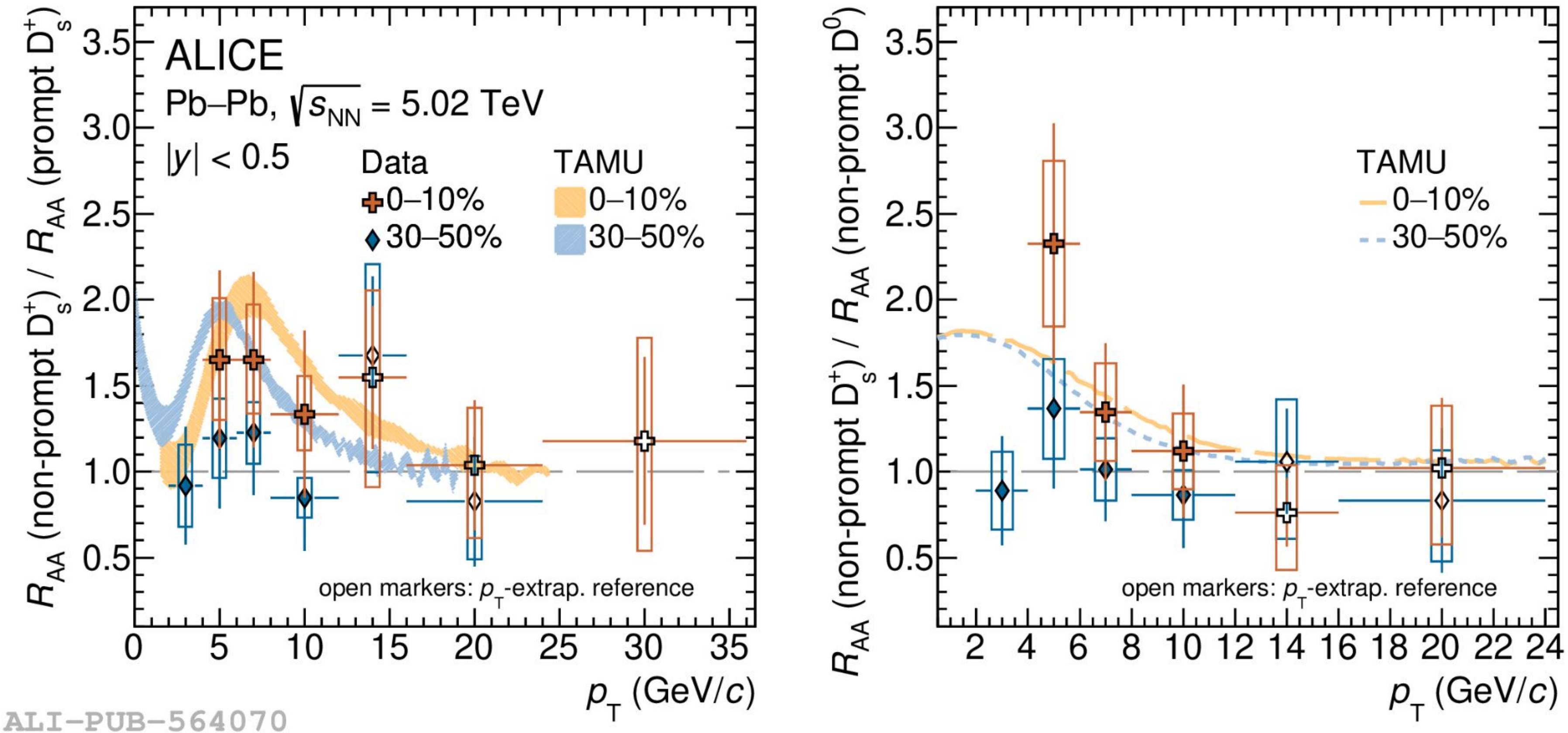


ALI−PUB−534213

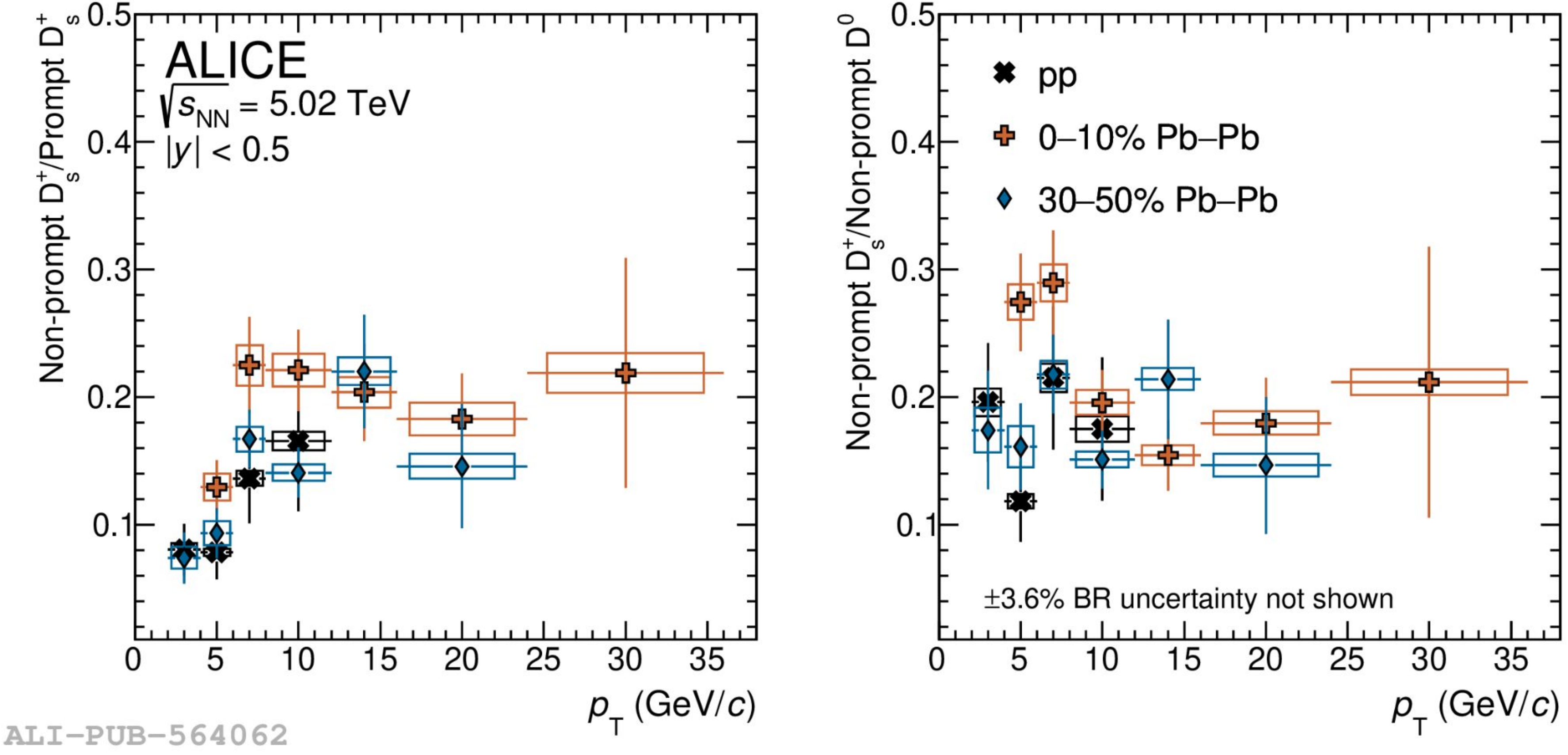

ALICE, Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
0–10%, |y| < 0.5
non-prompt D^0
prompt D^0
open markers: p_T extrapolated pp reference
R_{AA}
p_T(GeV/c)
ALI-PUB-534210
ALICE, Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
30–50%, |y|<0.5
non-prompt D^0
prompt D^0
open markers: p_T extrapolated pp reference
R_{AA}
p_T(GeV/c)


ALICE
30–50% Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
|y| < 0.8
Non-prompt D^0
Syst. from data
TAMU
LBT
LIDO
Langevin
LGR
v_2 {SP, |Δη|>0.9}
0.3
0.2
0.1
0.0
–0.1
2
4
6
8
10
12
p_T (GeV/c)
ALI-PUB-545132


ALICE
|y| < 0.5
Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Centrality 0–10%
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


ALICE
√s_NN = 5.02 TeV
|y| < 0.5
Non-prompt D_s^+/Prompt D_s^+
Non-prompt D_s^+/Non-prompt D^0
pp
0–10% Pb–Pb
30–50% Pb–Pb
±3.6% BR uncertainty not shown
p_T (GeV/c)
ALI-PUB-564062

E-loss and transport models

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	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}

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

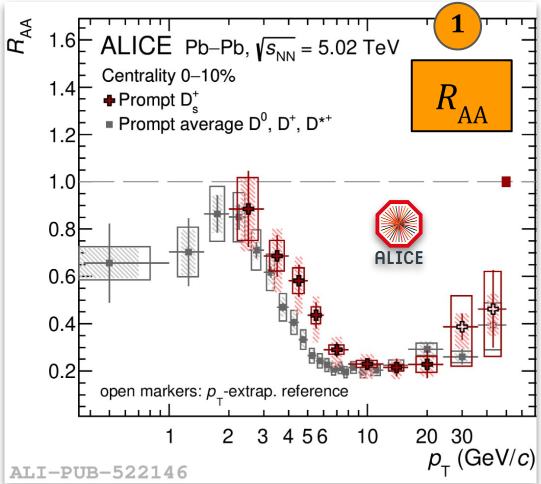
$$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

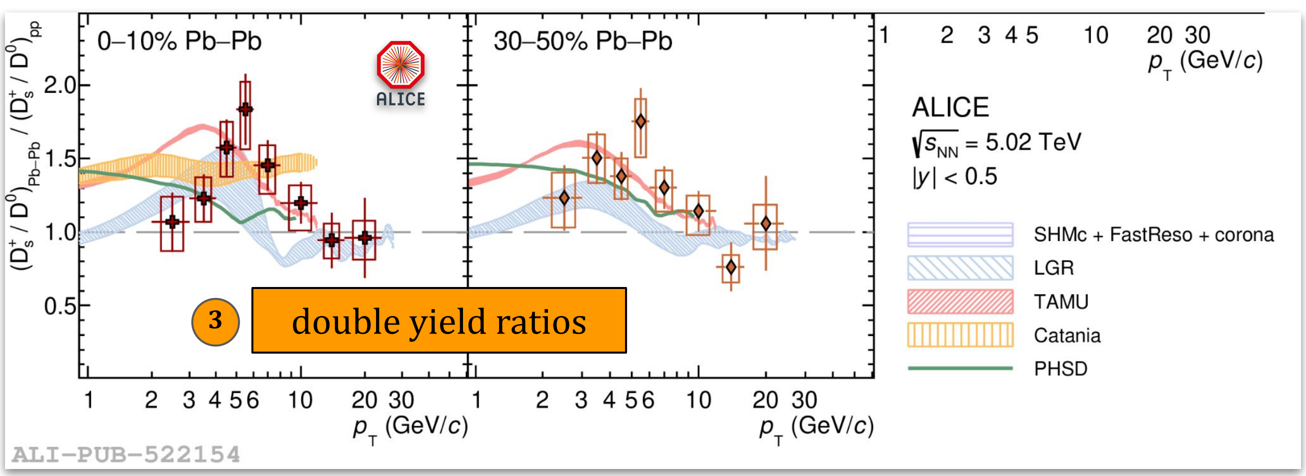
2 Anisotropic flow

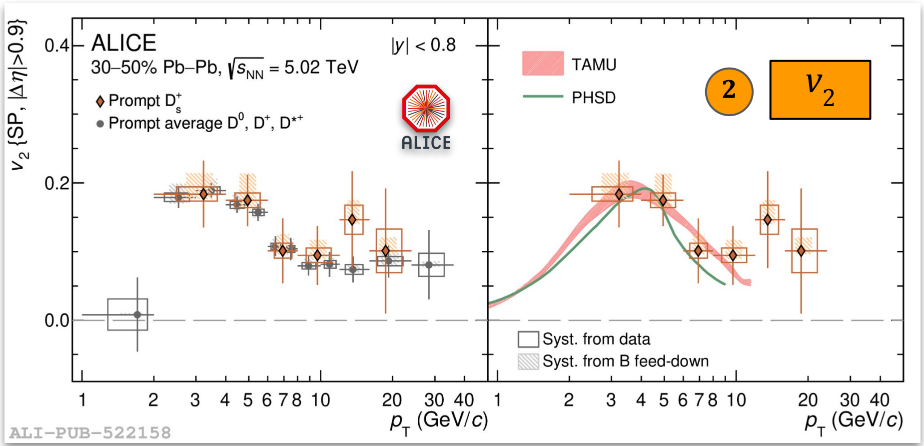
$$v_n(p_T) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

3 … and particle ratios!

Heavy-strange-meson production

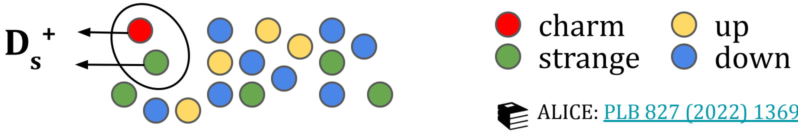






Sensitivity to **coalescence** and **strangeness enhancement**

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



ALICE: PLB 827 (2022) 136986

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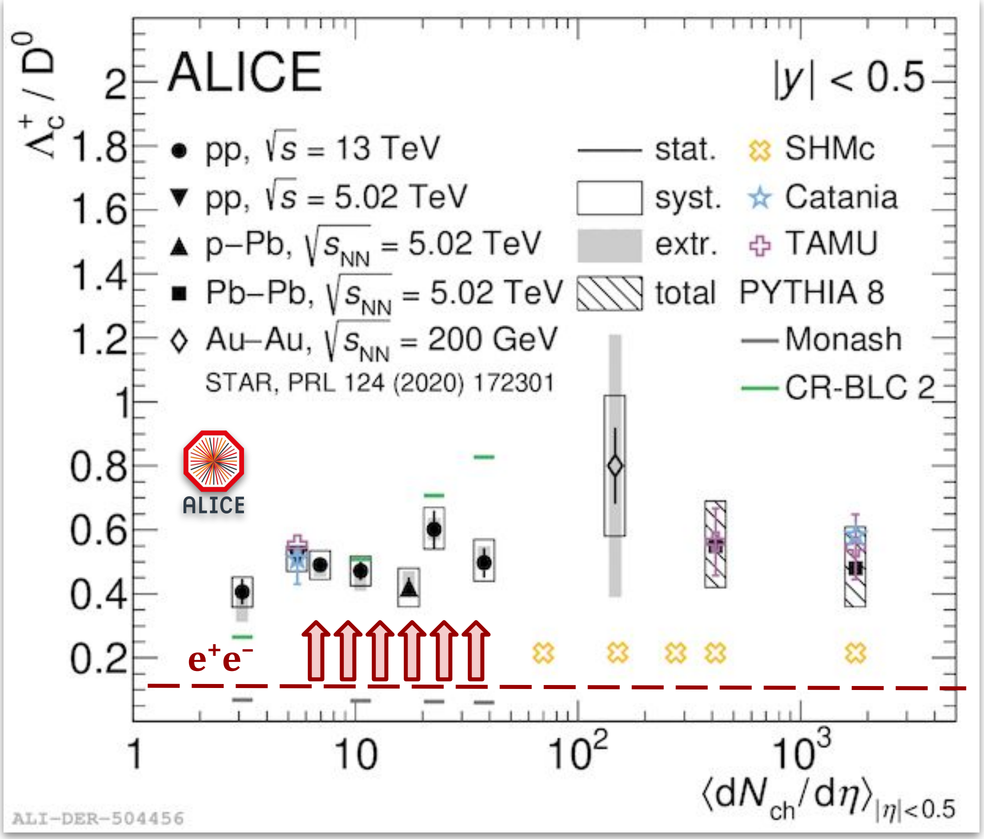
Baryon enhancement in all collision systems at the LHC compared to e^+e^-

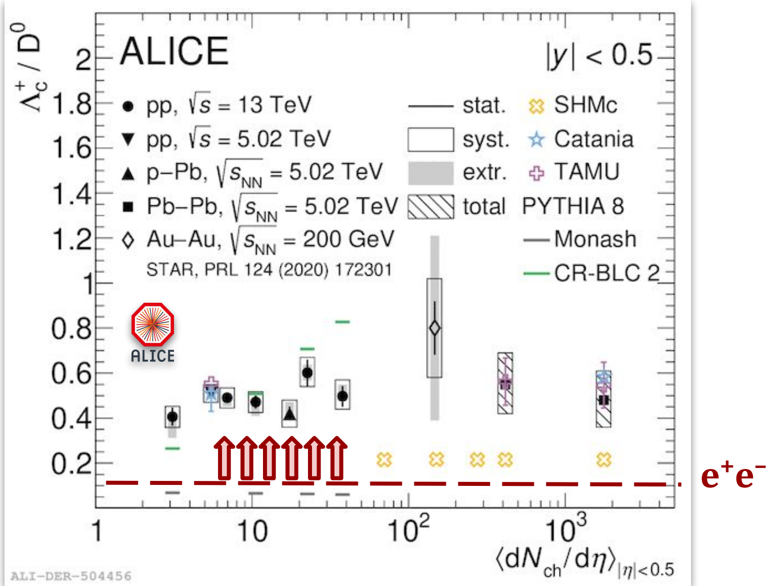
LEP: EPJC 75, 19 (2015)
ALICE: PLB 839 (2023) 137796

- **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

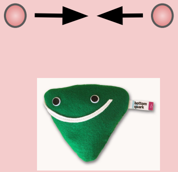
→ Is the **p_T-differential Λ_c^+/D^0 enhancement** just a consequence of **radial flow** and **recombination**?



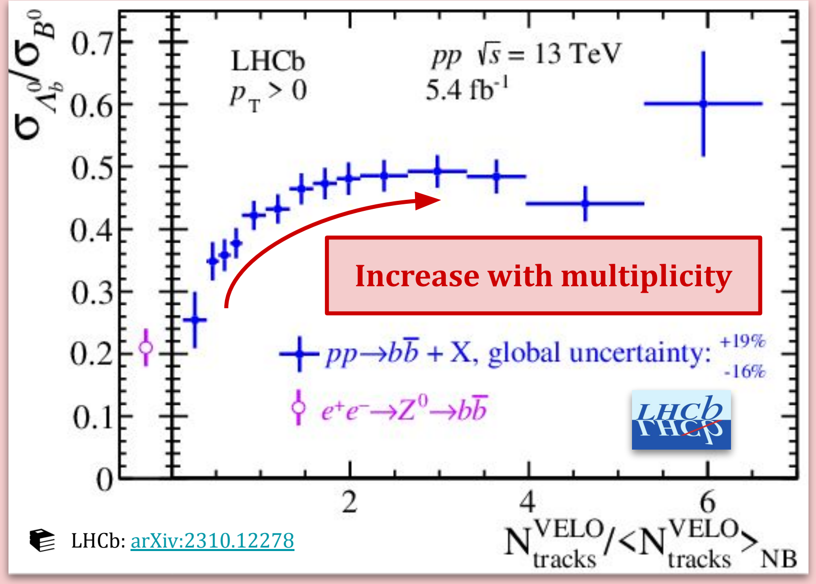
Charm-baryon production at the LHC - open points (2/2)



pp collisions



Beauty
baryon-to-meson
ratio



LHCb: arXiv:2310.12278

- **No** significant **dependence** versus multiplicity of the $\boldsymbol{p_T}$**-integrated** $\boldsymbol{\Lambda_c^+/D^0}$ ratio **across collision systems**
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→ Is the $\boldsymbol{p_T}$**-differential** $\boldsymbol{\Lambda_c^+/D^0}$ **enhancement** just a consequence of **radial flow** and **recombination**?