Experimental results on open and hidden heavy-flavour measurements

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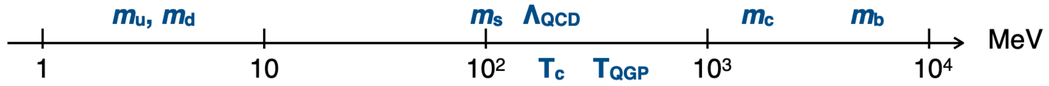
9 April 2022 Kraków, Poland

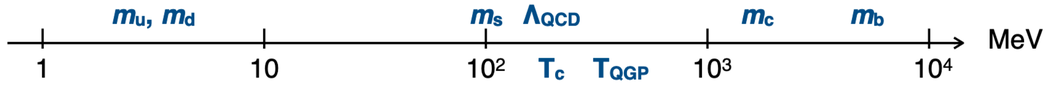
Heavy quarks as tools for precise QGP characterization



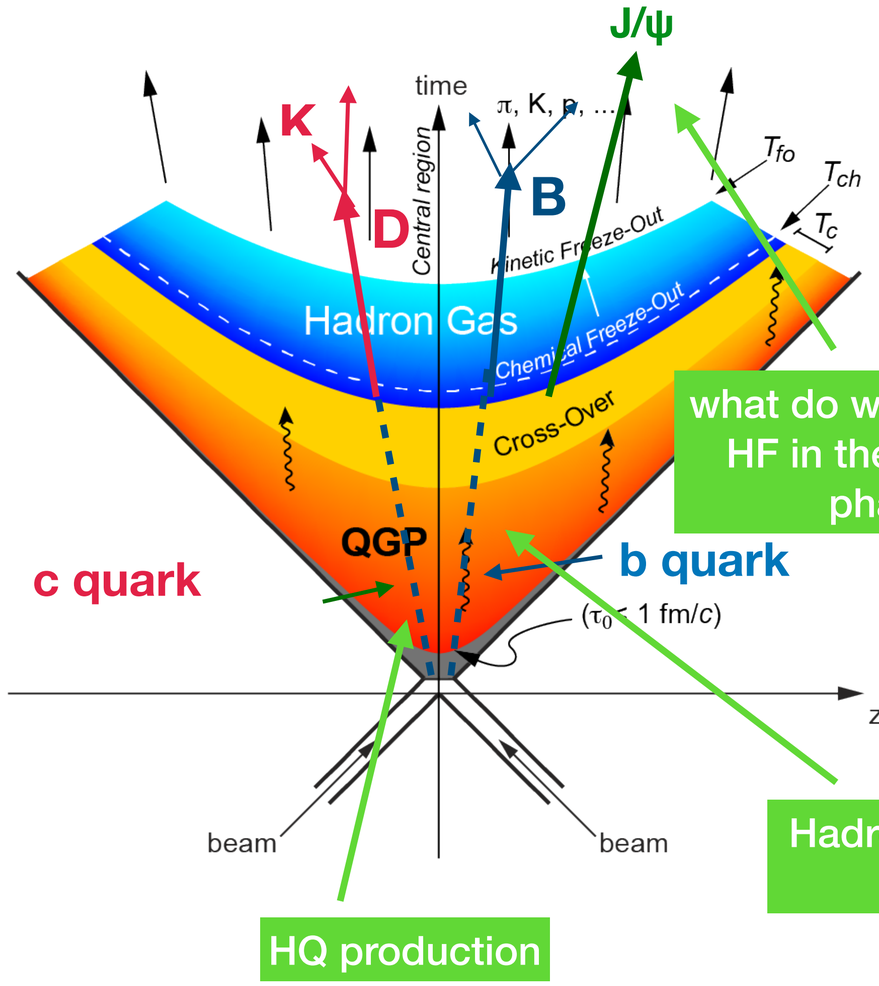
Investigating QGP features:

- **how do HQ interact with medium constituents?**
  - energy loss, quarkonia suppression/recombination, HQ diffusion and thermalization

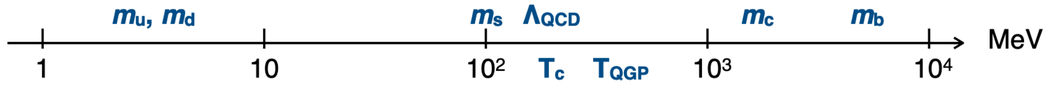
Heavy quarks as tools for precise QGP characterization



- What are the **hadron formation mechanisms in QGP?**
  - do they differ from small systems?
- **what is the origin of the observed collective effects** in high-multiplicity pp and p-Pb collisions?
- is there an **interaction of charm hadrons with charged particles** in the **hadronic phase**?



Heavy quarks as tools for precise QGP characterization

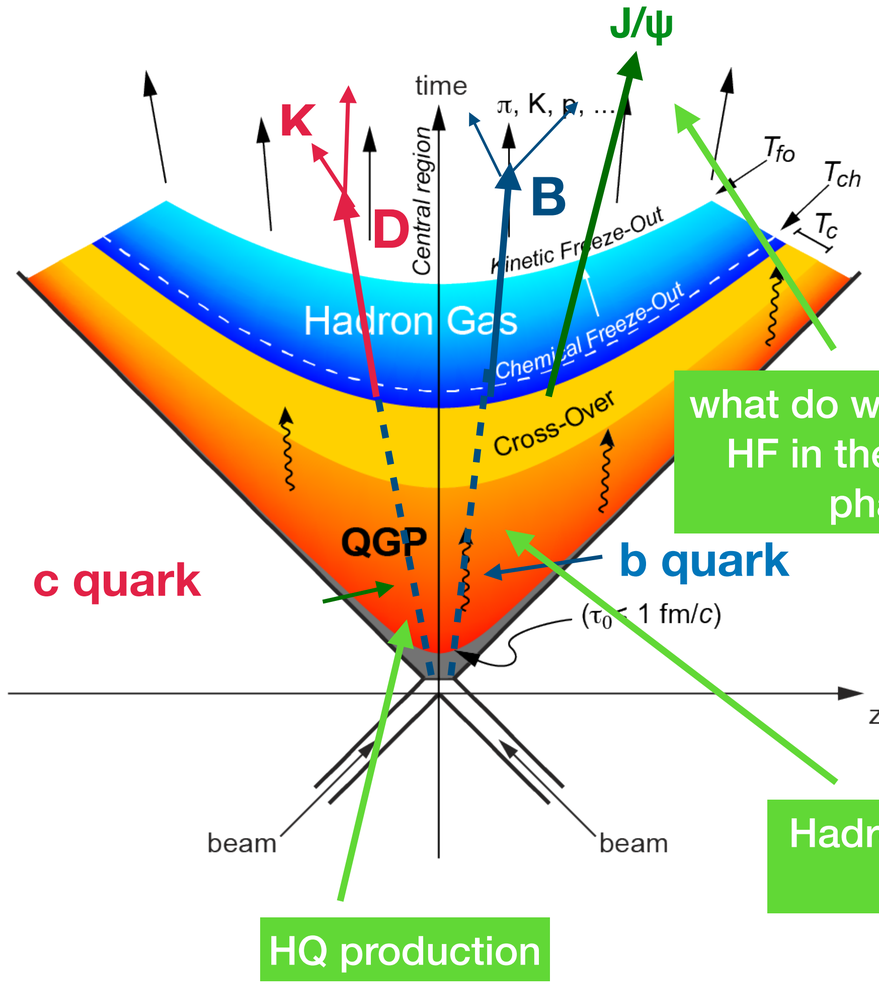


Huge amount of results since the last QM 2019:

✓ final and more precise measurements

✓ extended p_T and *y* coverage, differential studies

✓ addressing new observables and new particles



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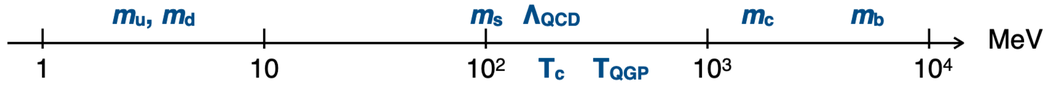

Selection of topics and results

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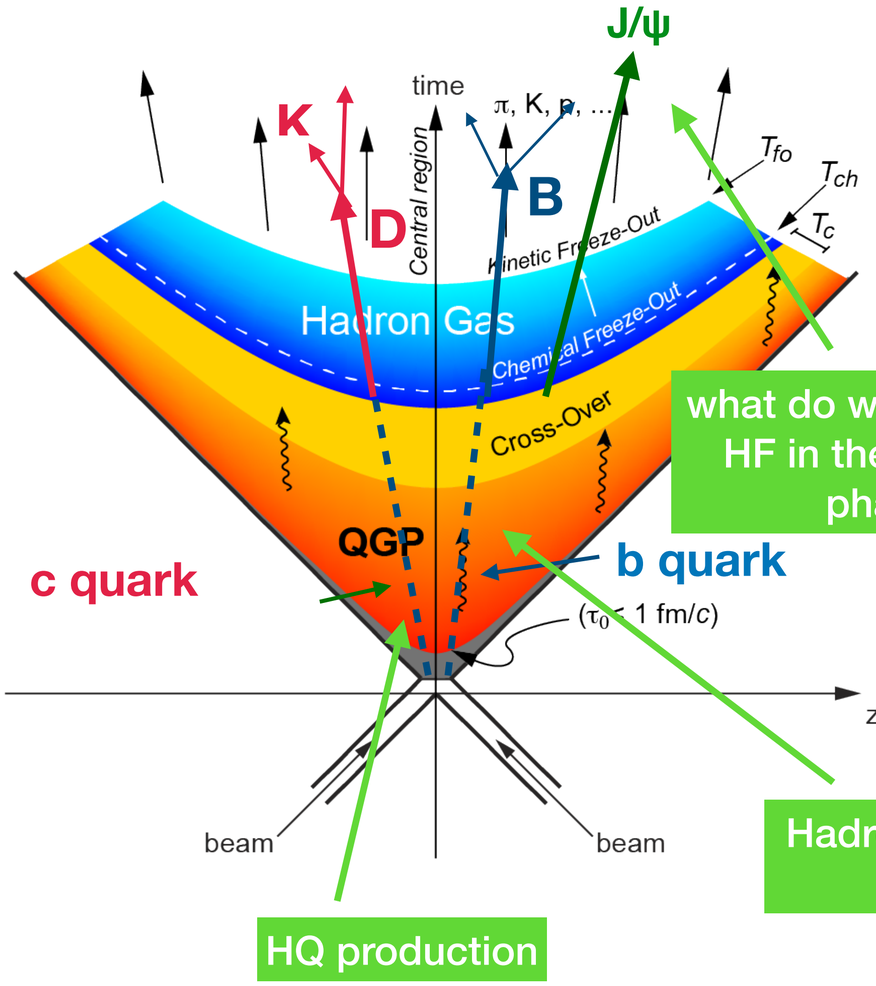
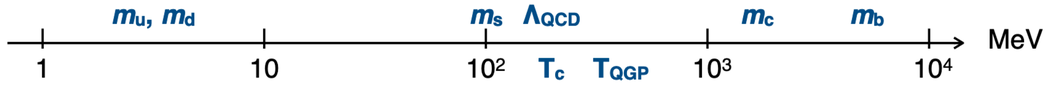


Heavy quarks as tools for precise QGP characterization



Selection of topics and results

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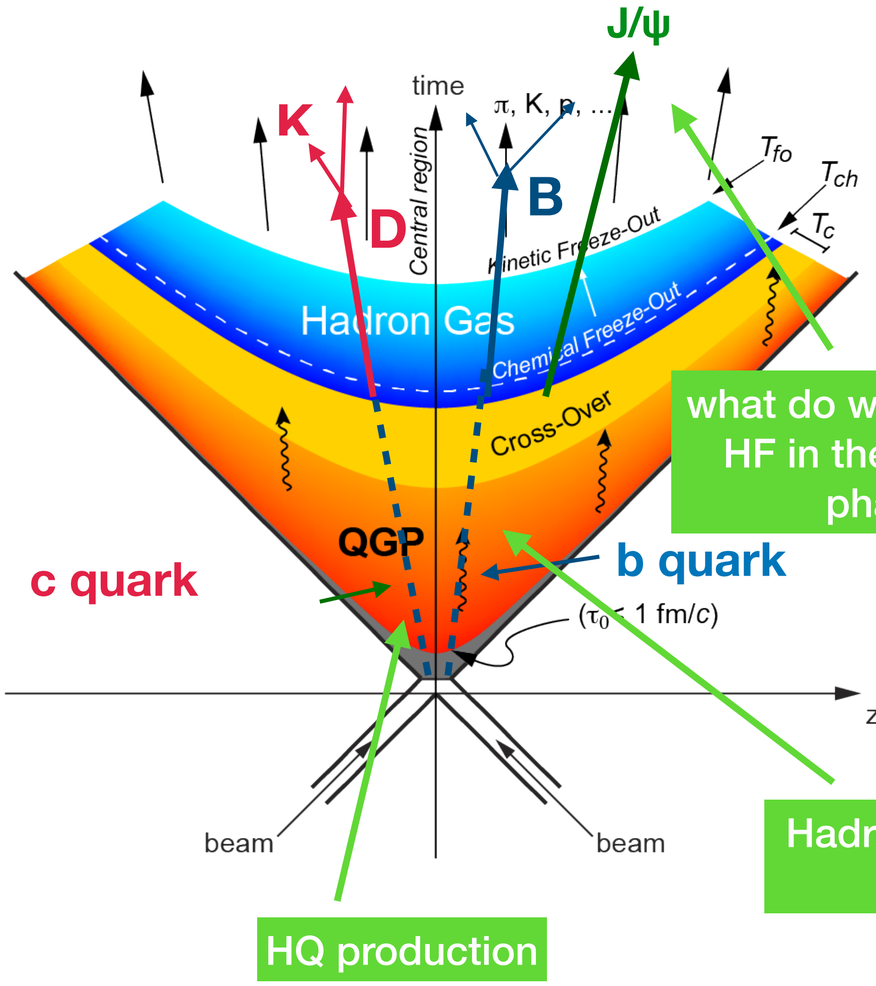
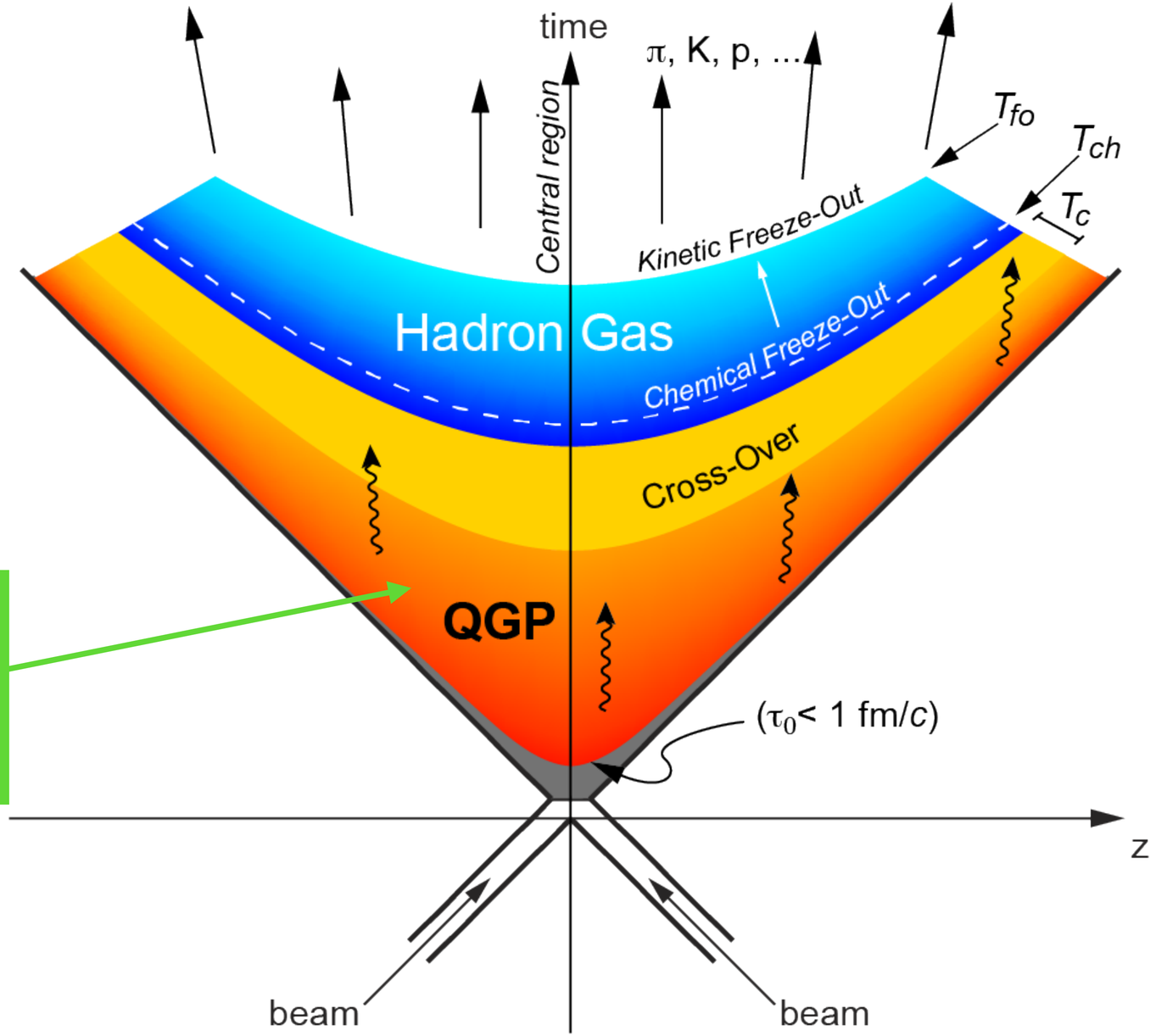
not shown: production measurements in pp collisions (input for models to describe spectra modification in QGP) and p-N measurements



Interaction of heavy quarks with the QGP



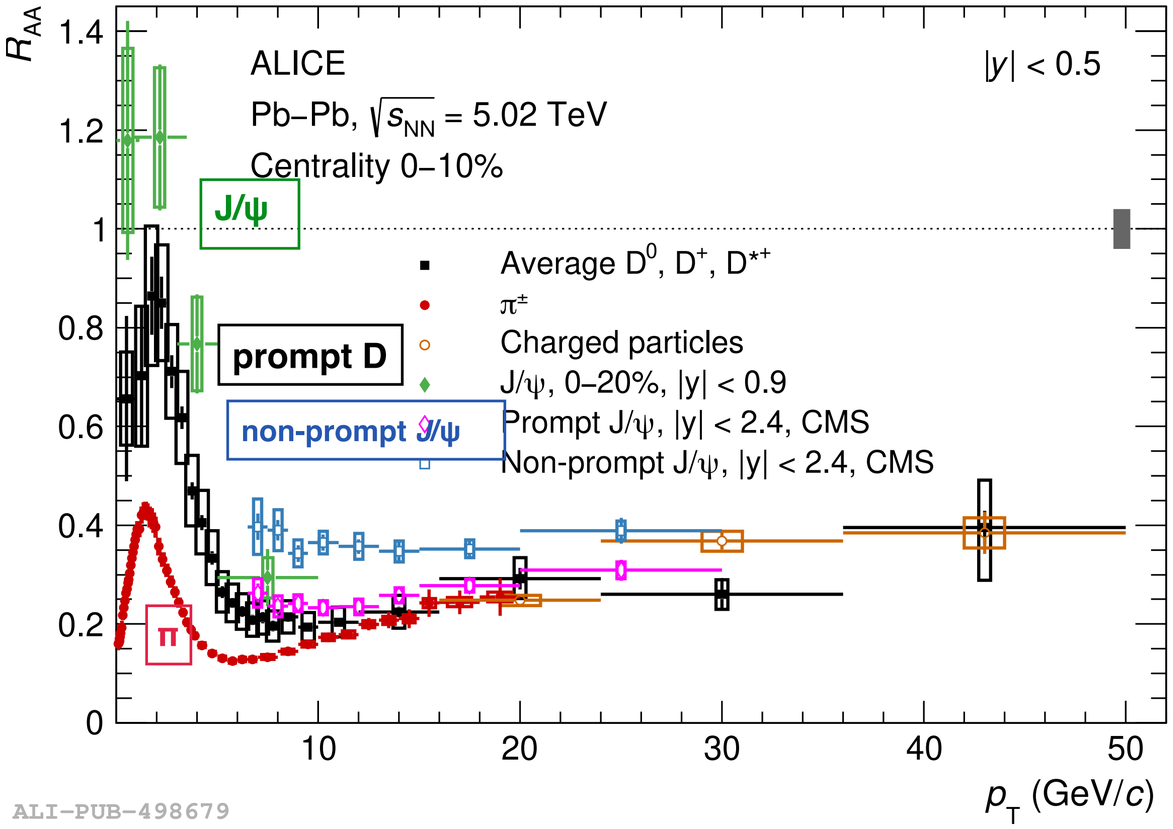
HQ interaction with QGP constituents

Open heavy flavour energy loss: colour-charge and quark-mass dependence

u d s c b c $\bar{c}$

JHEP 01 (2022) 174

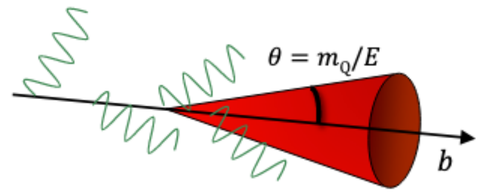
L. Vermunt 7Apr



$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

R_{AA} (π) < R_{AA} (D) < R_{AA} (non-prompt J/ψ)

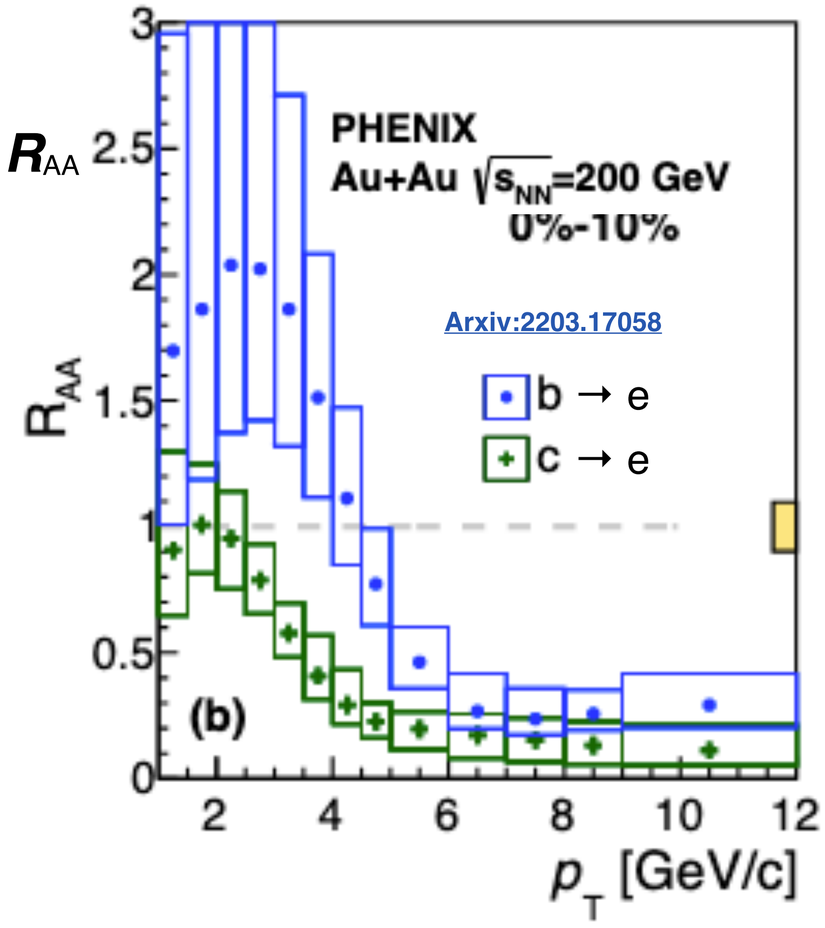


Access to the low-p_T region for charm and beauty hadron R_{AA} through the measurement of prompt D and non-prompt, D^0, J/ψ and leptons from beauty hadron decays.

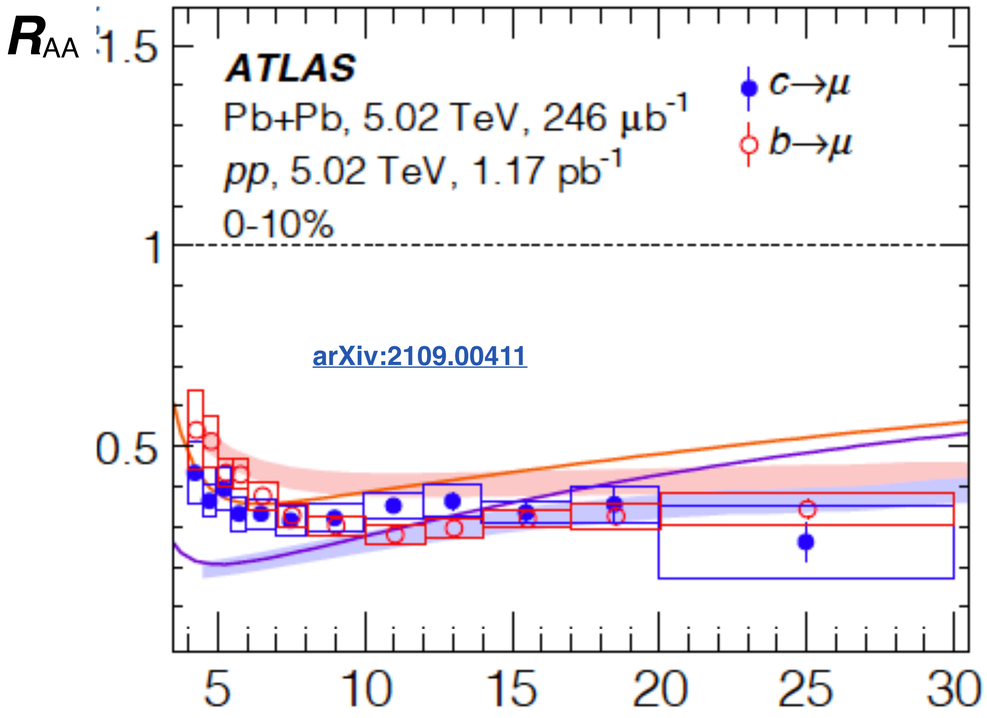
➡ caveat: different kinematics —> different B p_T investigated

Open heavy flavour energy loss: colour-charge and quark-mass dependence

b



T. Hachiya, Apr 6
Q. Hu, Apr 7



precise measurements of full decay topology of beauty hadrons

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Open heavy flavour energy loss: colour-charge and quark-mass dependence

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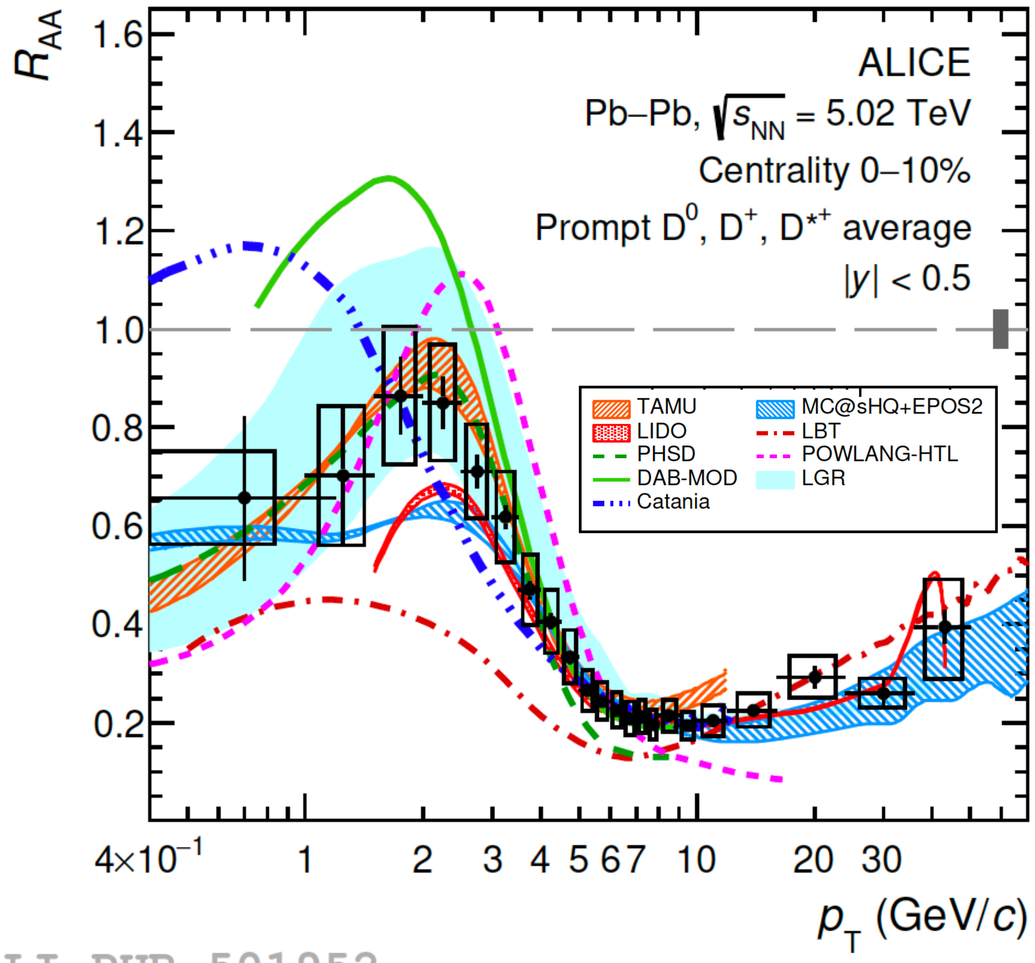
L. Vermunt 7Apr

JHEP 01 (2022) 174



ALI-PUB-501952

not only energy loss:

Interpretation of R_{AA} p_T shape

➡several mechanisms that contribute in different p_T range

R_{AA} shape: interplay of parton energy loss, shadowing, radial flow, hadronization mechanisms

TAMU: PRL 124, 042301 (2020)
PHSD: PRC 93, 034906 (2016)
POWLANG: EPJC 75, 121 (2015)
CATANIA: PRC 96, 044905 (2017)

MC@sHQ+EPOS: PRC 91, 014904 (2015)
LIDO: PRC 98 064901 (2018)
LBT: PLB 777 (2018) 255-259
LGR: EPJC, 80 7 (2020) 671
DAB-MOD M&T: PRC 96 064903 (2017)

Total charm production cross section in heavy-ion collisions

D^0 measured down to p_T=0: investigating if there is a modification of total yields in different systems

Collision System	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0 [1]	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3*
	D_s [2]	15 ± 2 ± 4
	Λ_c [3]	40 ± 6 ± 27**
	Total	112 ± 6 ± 27
p+p at 200 GeV [4]	**Total**	130 ± 30 ± 26

STAR: D^0, D^+ measured down to p_T=0 in Au-Au collisions
PhysRevC.99.034908

Total charm production cross section per nucleon-nucleon in Au+Au consistent with that measured in pp collisions: follows ~ N_{coll} scaling from p+p to Au+Au

- Contribution from other charm baryon states? Phys. Rev. D 105, L011103

Z. Zhang, 7 Apr
M. Faggin, 7Apr

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crucial to measure all HF charm hadron ground states!

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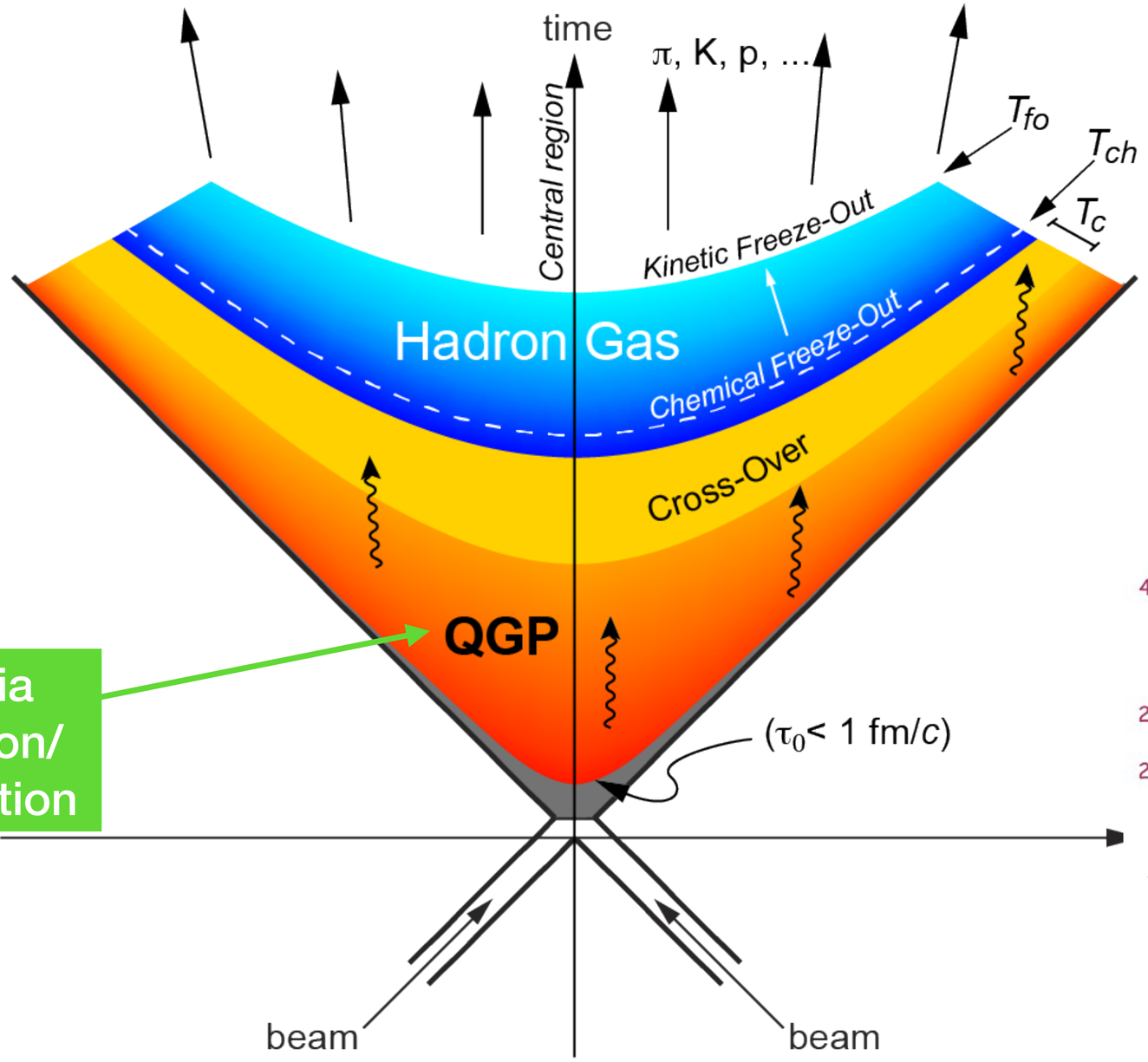
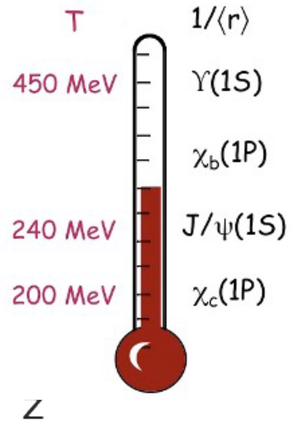
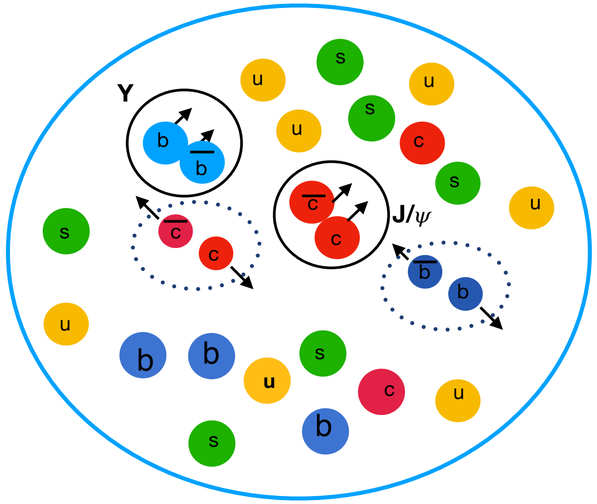
Interaction of heavy quarks with the QGP



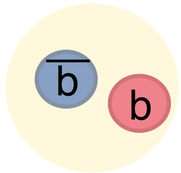
Quarkonia suppression/ recombination

quarkonia: **sequential melting** depending on their binding energy; quarkonia **regeneration** at low p_T





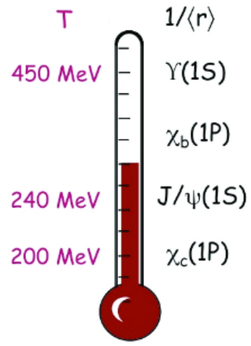
Quarkonia suppression in the QGP: R_{AA}

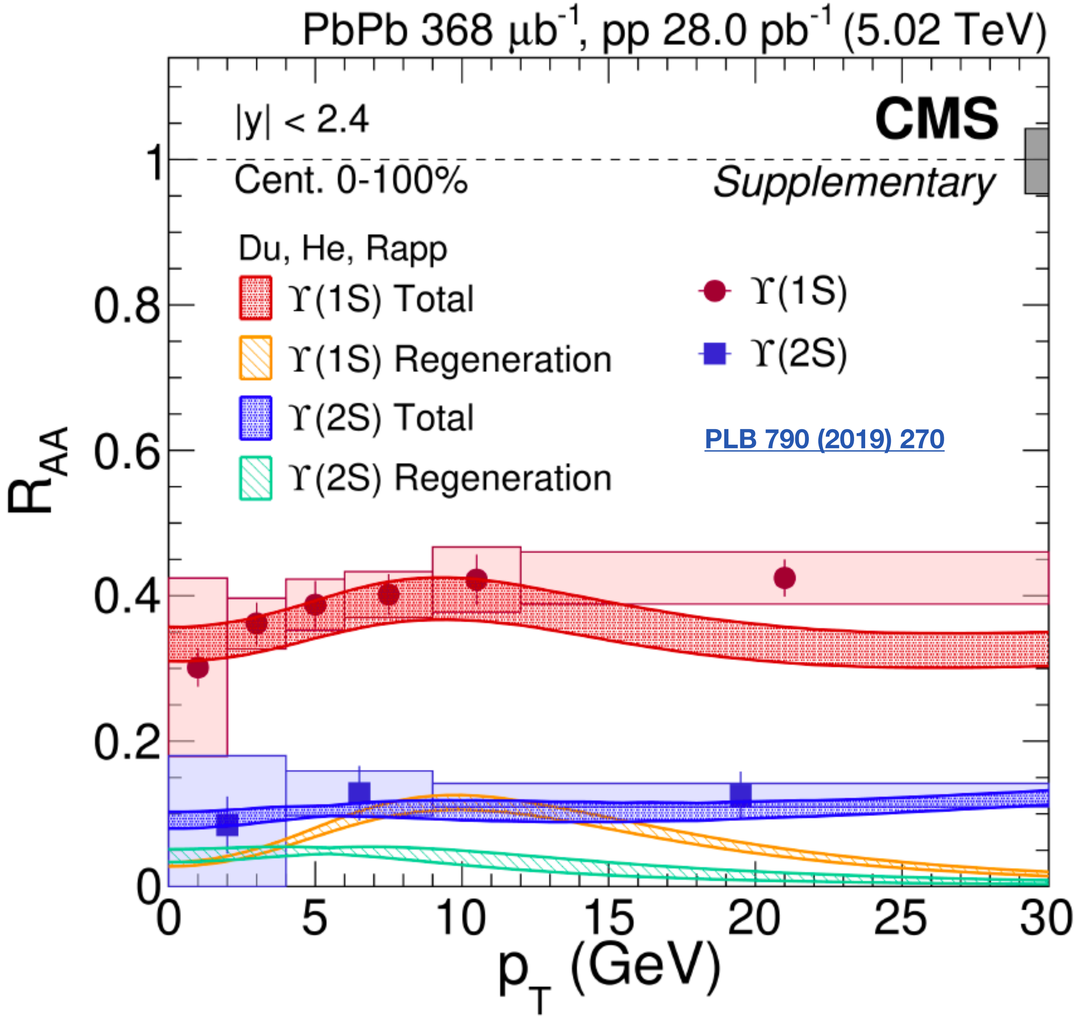


$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

Probing the sequential suppression

S. Lee 7Apr

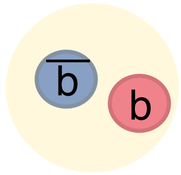




Bottomonium: very clear ordering of R_{AA} as in the sequential melting picture

- transport calculation describe measurements
  - small contribution from regeneration
- **Suppression is the dominant process**

Quarkonia suppression in the QGP: R_{AA}



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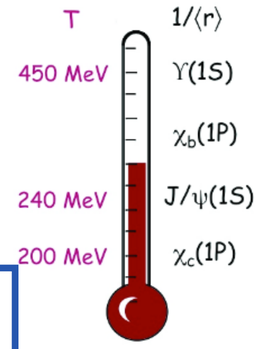
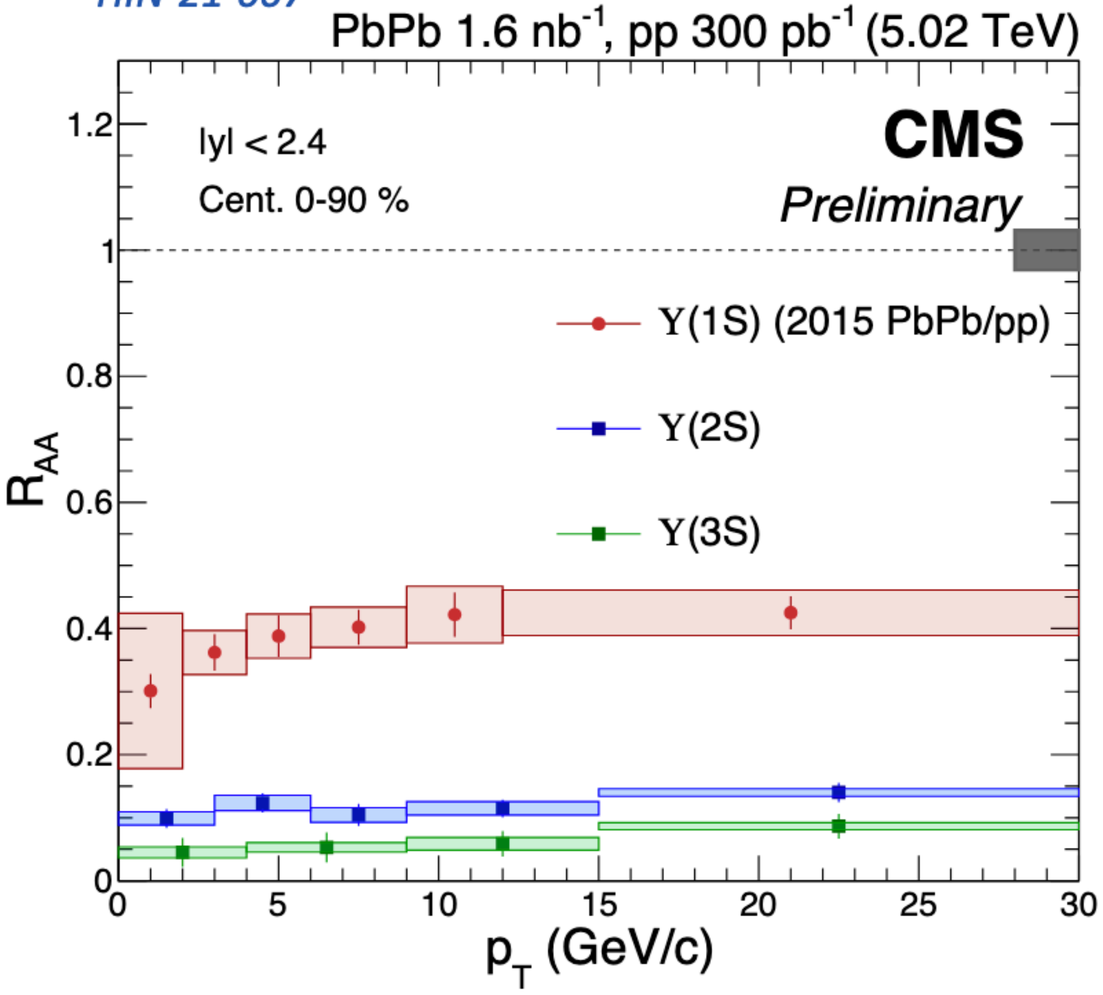


HIN-21-007

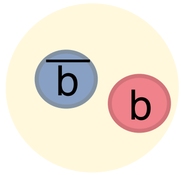


Bottomonium: First Y(3S) measurement in Pb-Pb

- no significant p_T dependence of R_{AA}

- $$\frac{R_{AA}^{(3S)}}{R_{AA}^{(2S)}} \approx 0.5$$

Quarkonia suppression in the QGP: R_{AA}



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Probing the sequential suppression

S. Lee 7Apr
A. Lebedev 7 Apr

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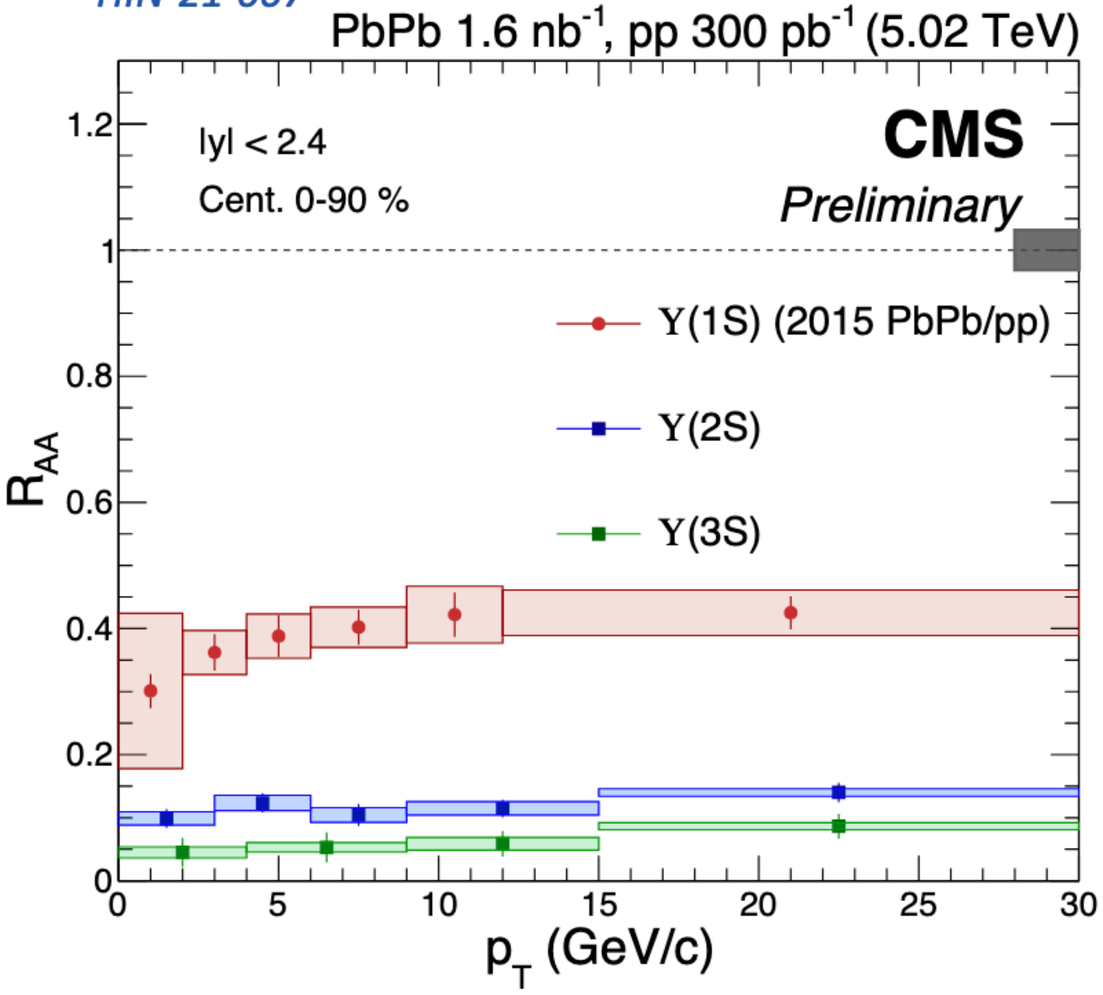
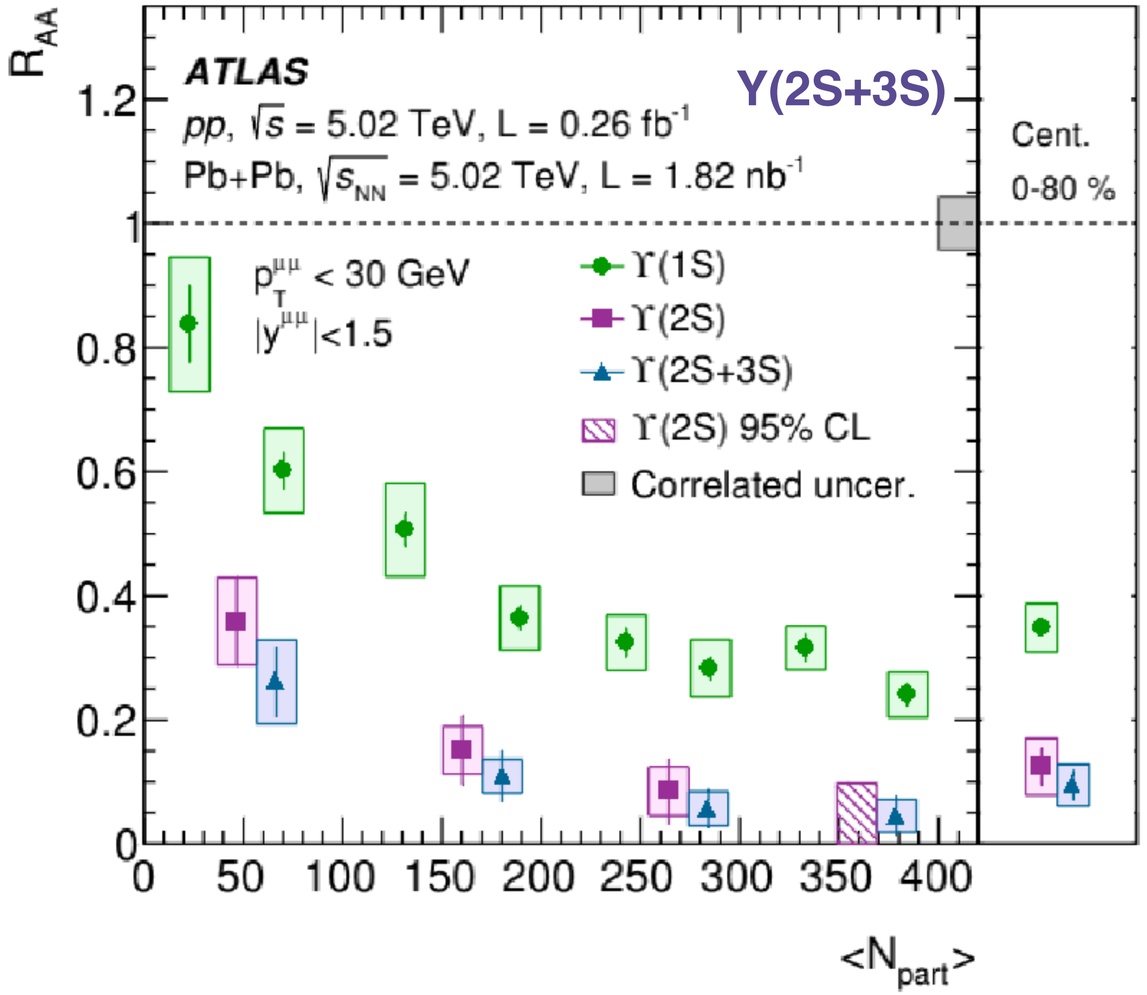
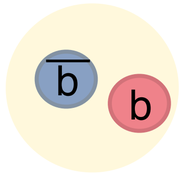




Quarkonia suppression in the QGP: R_{AA}



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Probing the sequential suppression

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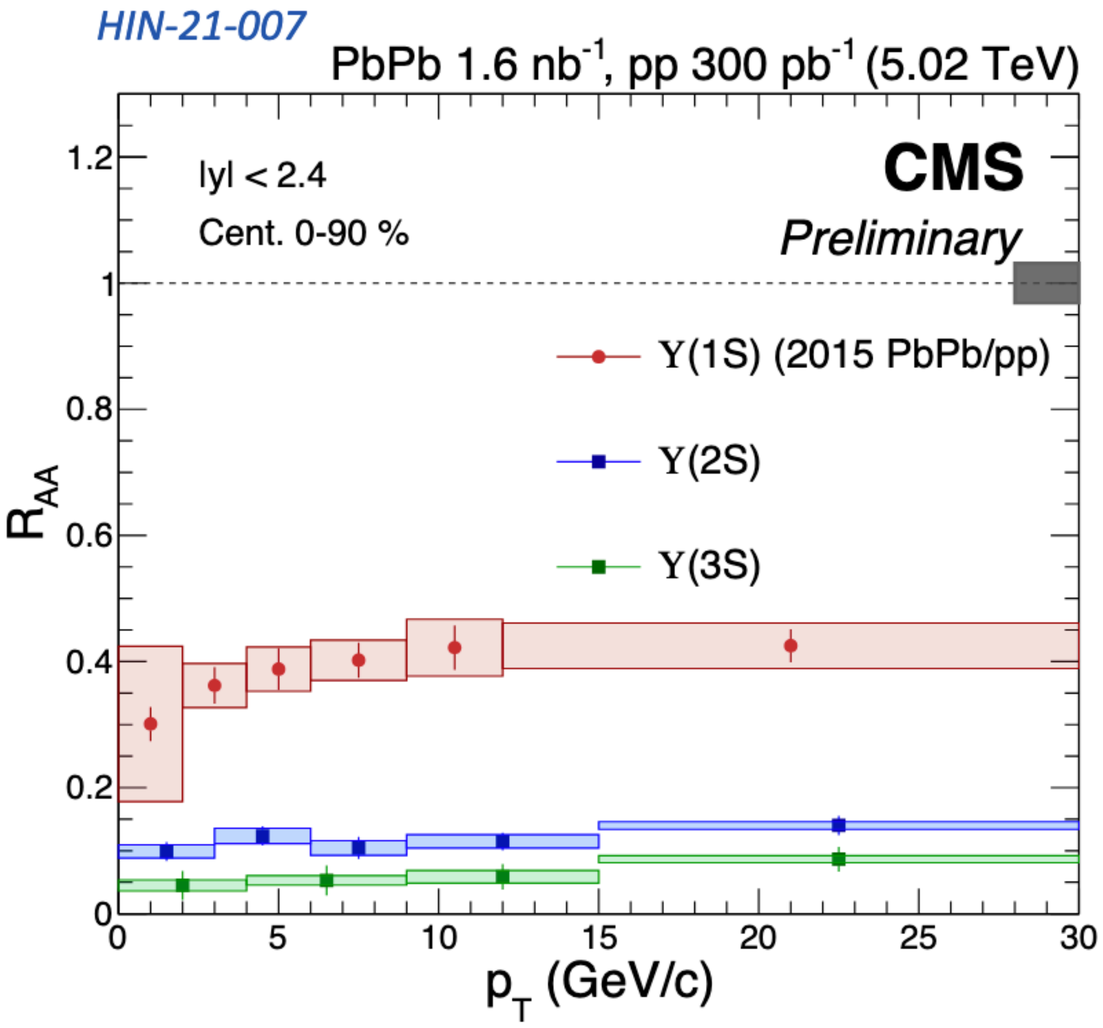
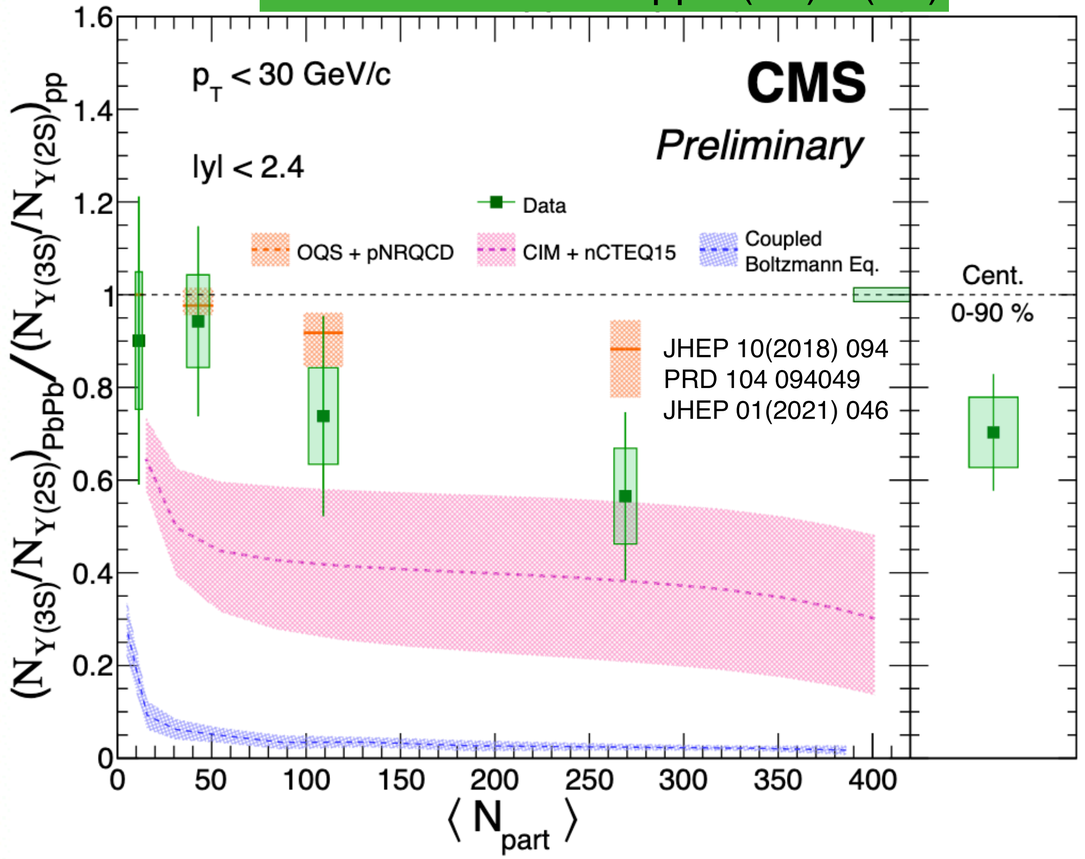
A. Lebedev 7 Apr

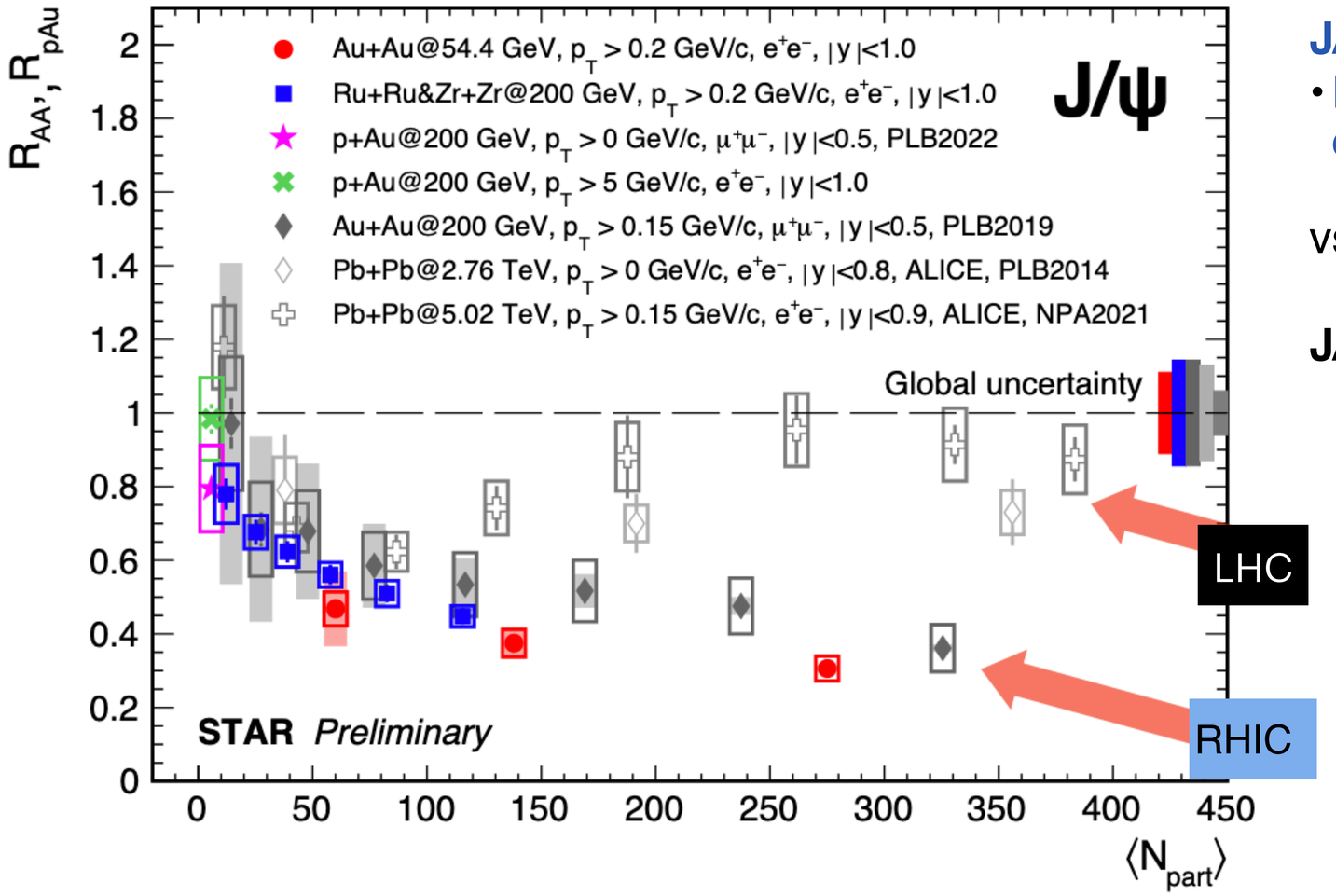


Double ratio Pb-Pb/pp Υ(3S)/Υ(2S)



could provide more constraints to theoretical models

Quarkonia suppression and recombination in the QGP: RHIC vs LHC R_{AA}



J/ψ R_{AA} in Ru+Ru&Zr+Zr and Au+Au 54.4 GeV

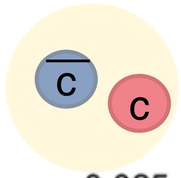
- No significant energy and nuclei species dependence of the R_{AA}

vs

J/ψ R_{AA} in Pb-Pb at 2.76, 5.02 TeV

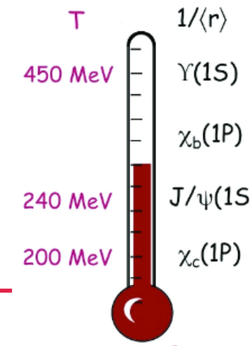
- Larger contribution from recombination at LHC than at RHIC

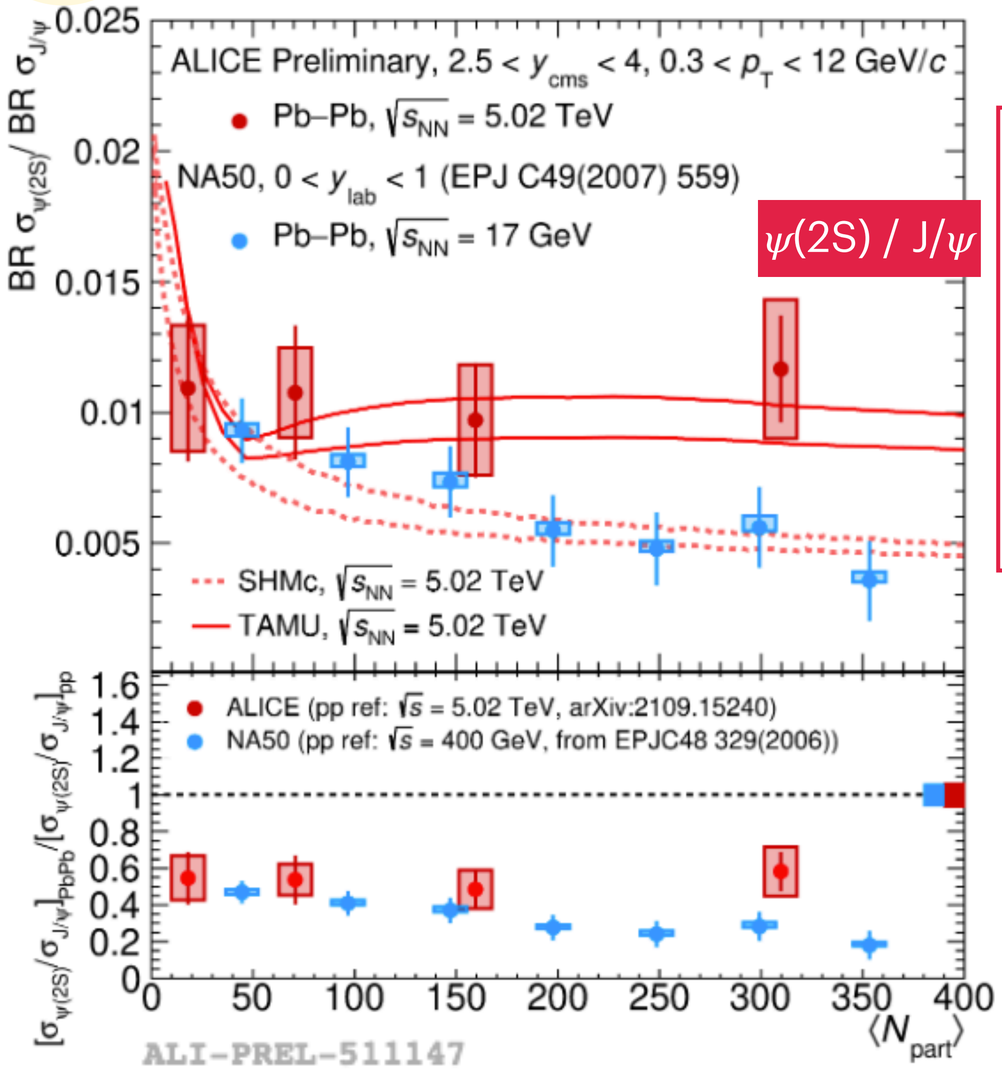
Quarkonia suppression and recombination in the QGP: R_{AA}



$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

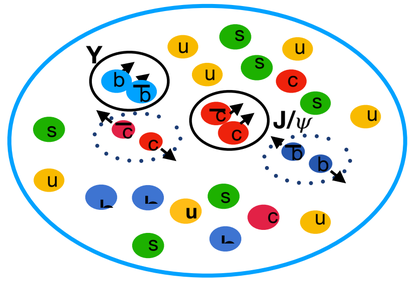
Probing the sequential suppression and **possible recombination**





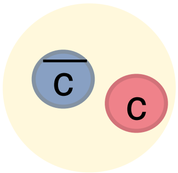
Charmonium: First ψ(2S) measurement down to 0 p_T

- ψ(2S) strongly suppressed wrt to J/ψ
- TAMU and SHMc models:
  - initial state effects (shadowing) and charm cross section uncertainty cancel in the ratio
  - smaller theoretical uncertainties
- Hint of larger ψ(2S)/J/ψ in central collisions at **LHC** wrt **SPS**



J.A.Saetre 7Apr
A.Andronic 6Apr

Quarkonia suppression and recombination in the QGP: R_{AA}



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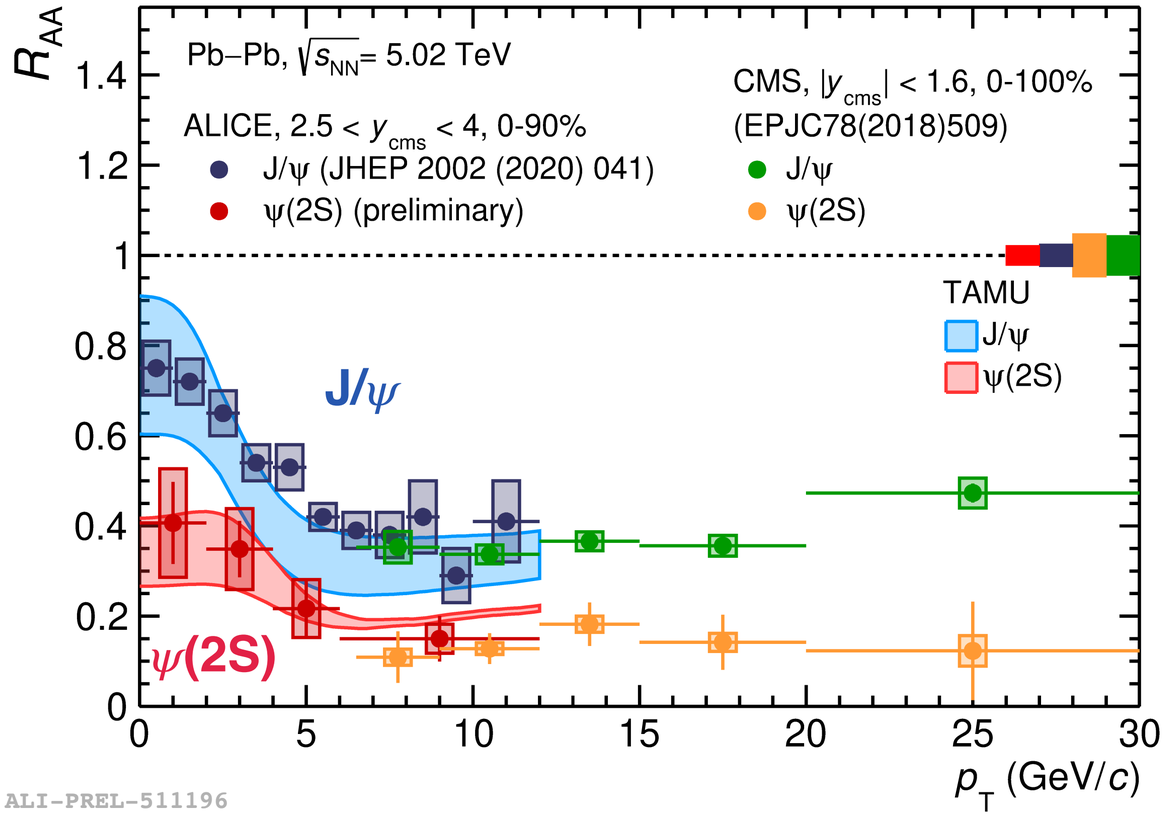
Probing the sequential suppression and **possible recombination**



TAMU: Nucl.Phys.A 943 (2015) 147-15

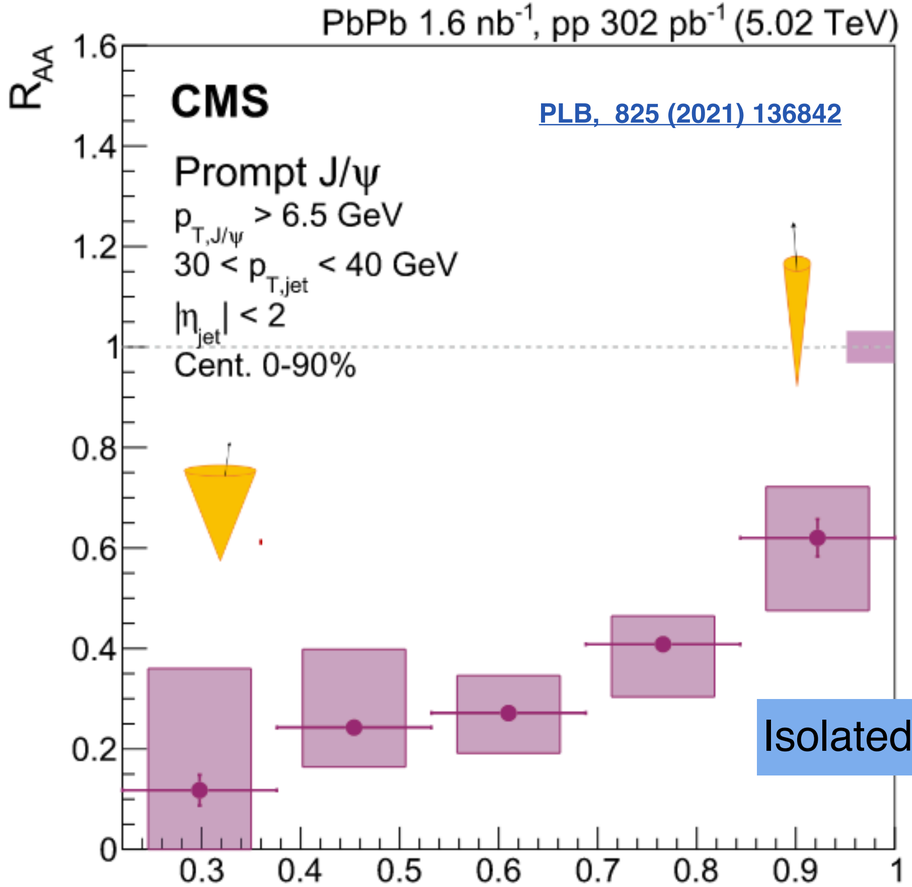
Charmonium: larger suppression of ψ(2S) wrt J/ψ in a wide p_T range

- agreement among **ALICE** and **CMS** in the overlapping p_T region
- **increasing R_{AA} at low p_T**: regeneration of charmonium, described by models, for J/ψ and ψ(2S)

recombination: at which temperature? up to which p_T?

J.A.Saetre 7Apr

J/ψ-jets in Pb-Pb collisions



jet fragmentation z

$$z = \frac{p_T\,(J/\psi)}{p_T\,(\mathrm{Jet})}$$

S. Lee 7Apr

More on HFjet: L.C.Mendez 8 Apr

- J/ψ produced with a large amount of surrounding jet activity more suppressed than those produced in isolation
  - J/ψ with lower z are produced later in the parton shower —> interact more with QGP
  - **jet quenching important mechanism to model J/ψ suppression**

J/ψ-jets in Pb-Pb collisions

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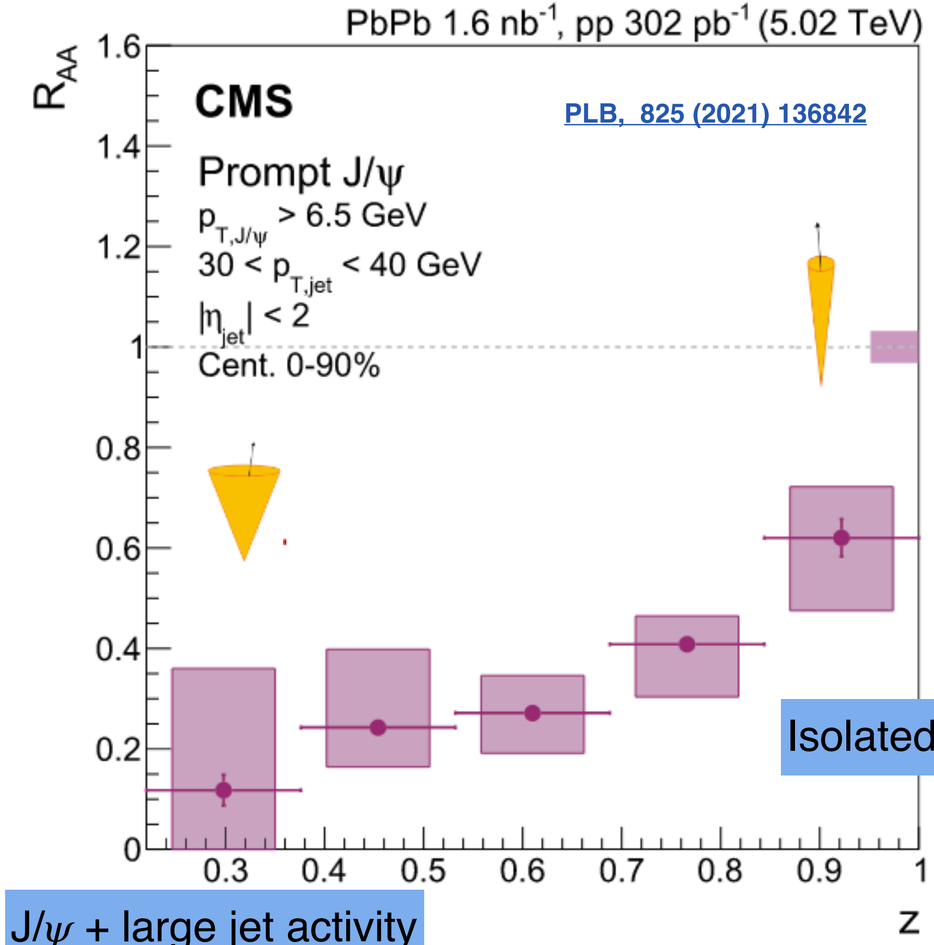

Isolated J/ψ

J/ψ + large jet activity

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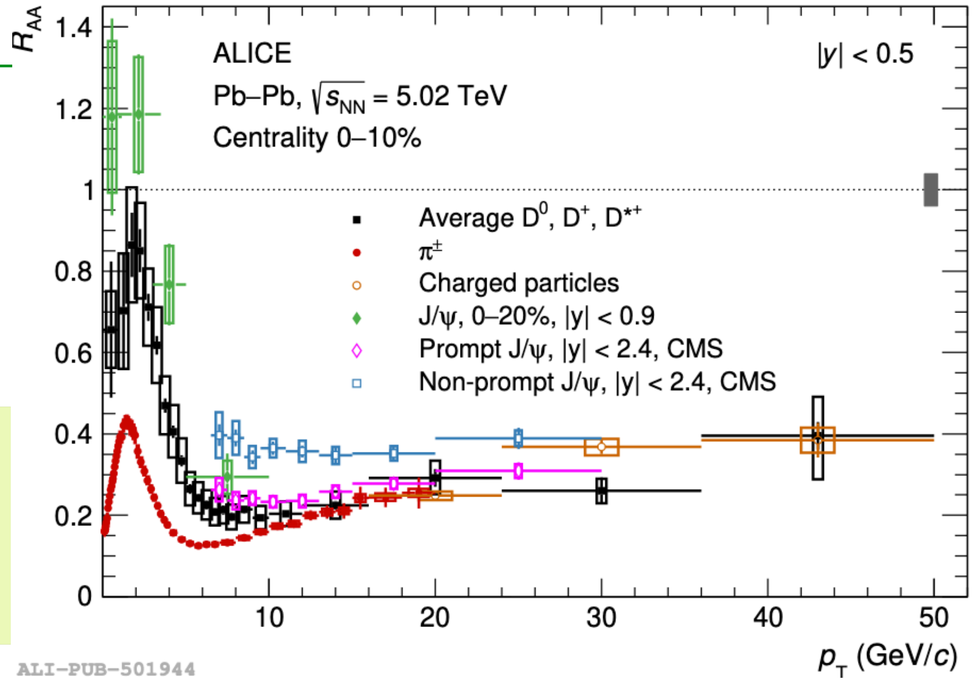
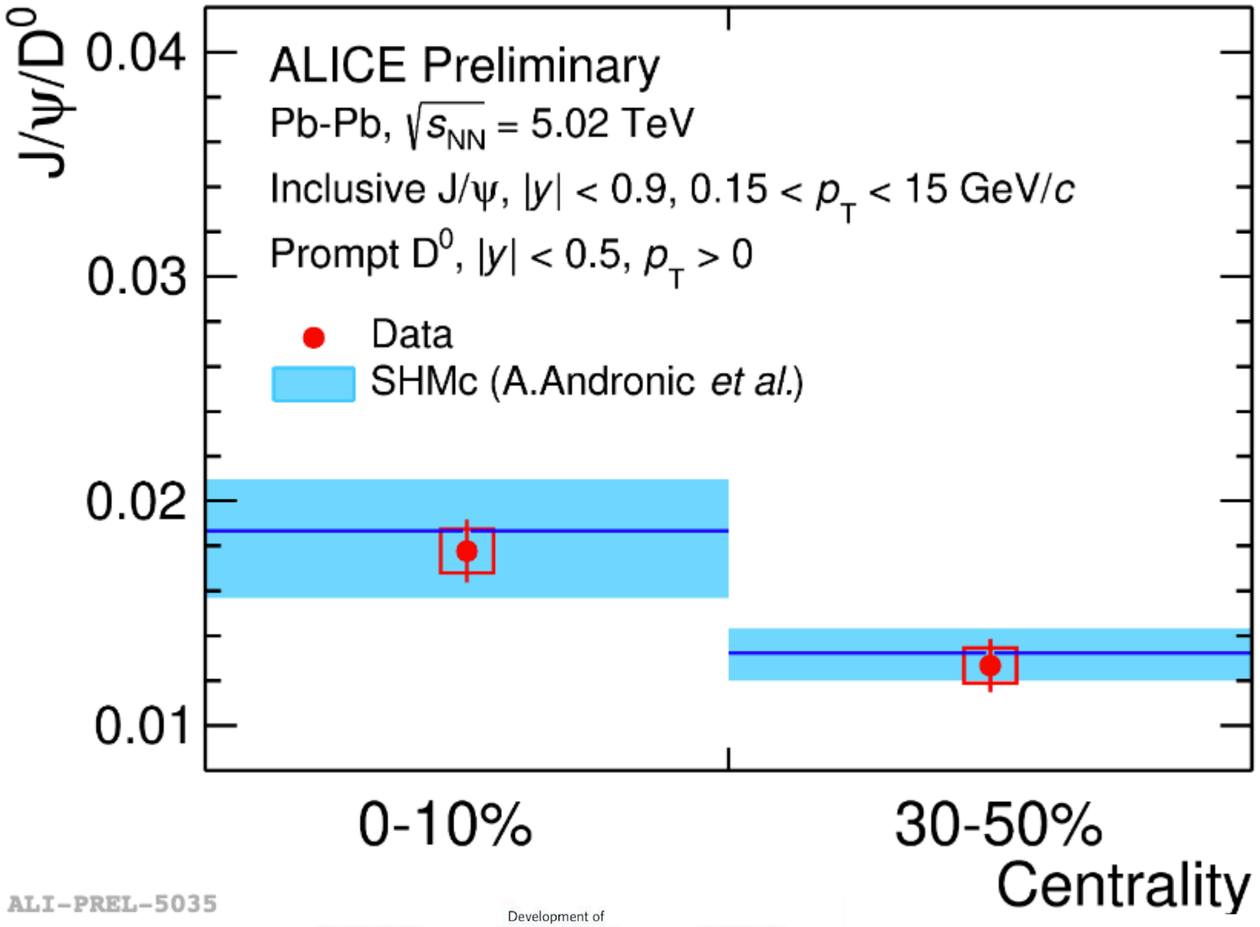


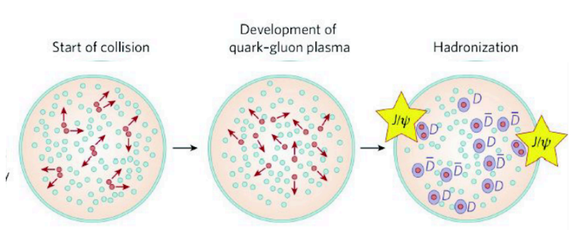
jet fragmentation z

$$z = \frac{p_T\,(J/\psi)}{p_T\,(\mathrm{Jet})}$$

Similar **prompt D** and **prompt J/ψ** at intermediate/high p_T: contribution from production with parton shower from the splitting of a hard-scattered gluon

J/ψ and D^0 relative contribution in the QGP





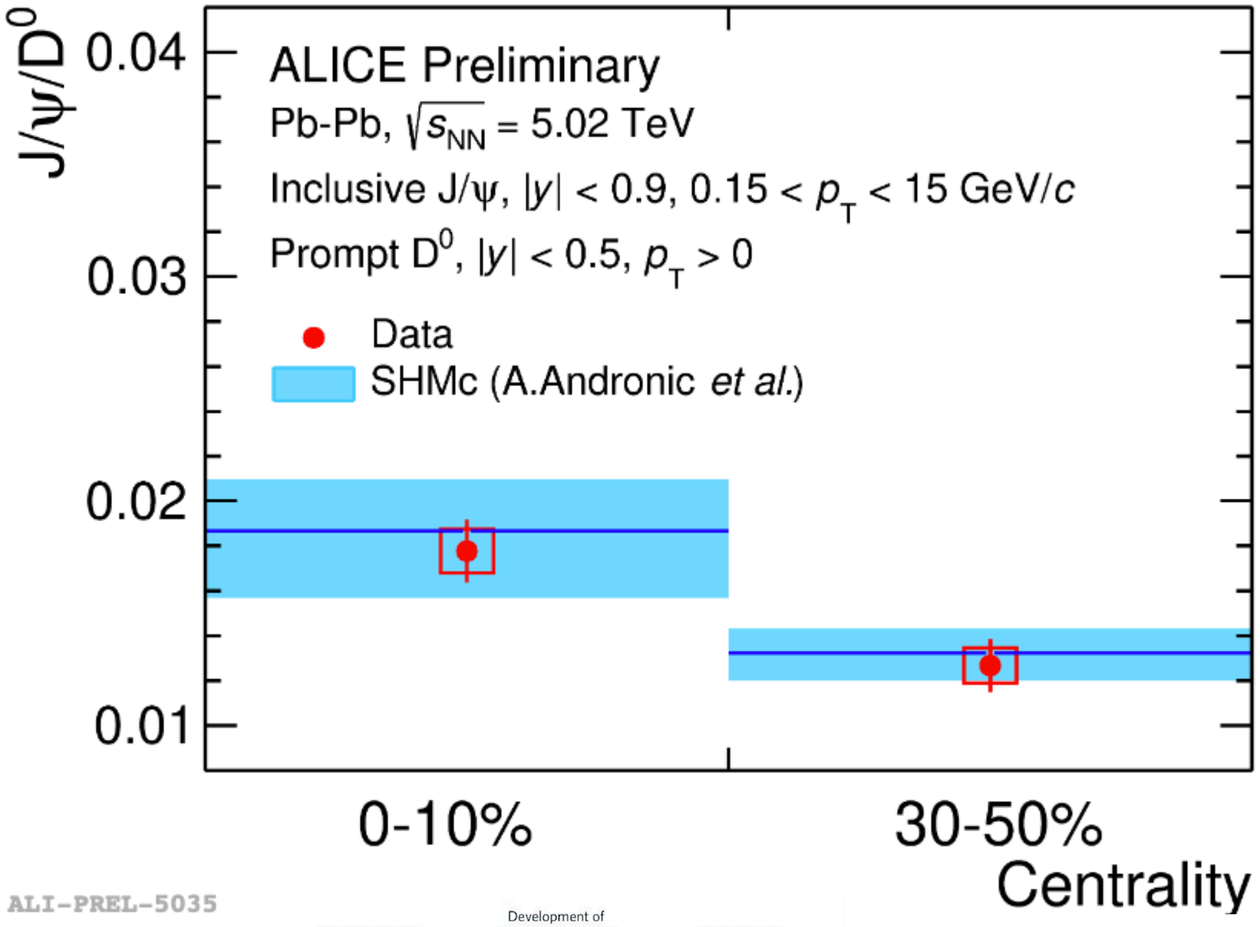
[Nature 448 (2007) 302-309]

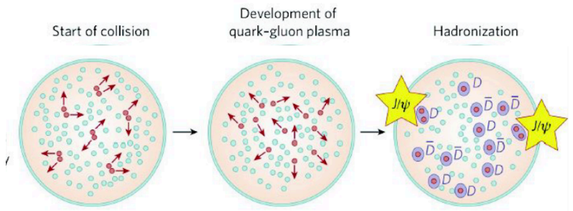
- **Similar p_T-integrated D^0/N$_{coll}$ in 0-10% and 30-50% PbPb:**
- **Larger J/ψ/D^0 in 0-10%:**

➡ due to larger J/ψ contribution from the recombination in most central events?

➡ caveat: inclusive J/ψ; possible centrality dependence of f(c→D^0)

J/ψ and D^0 relative contribution in the QGP





[Nature 448 (2007) 302-309]

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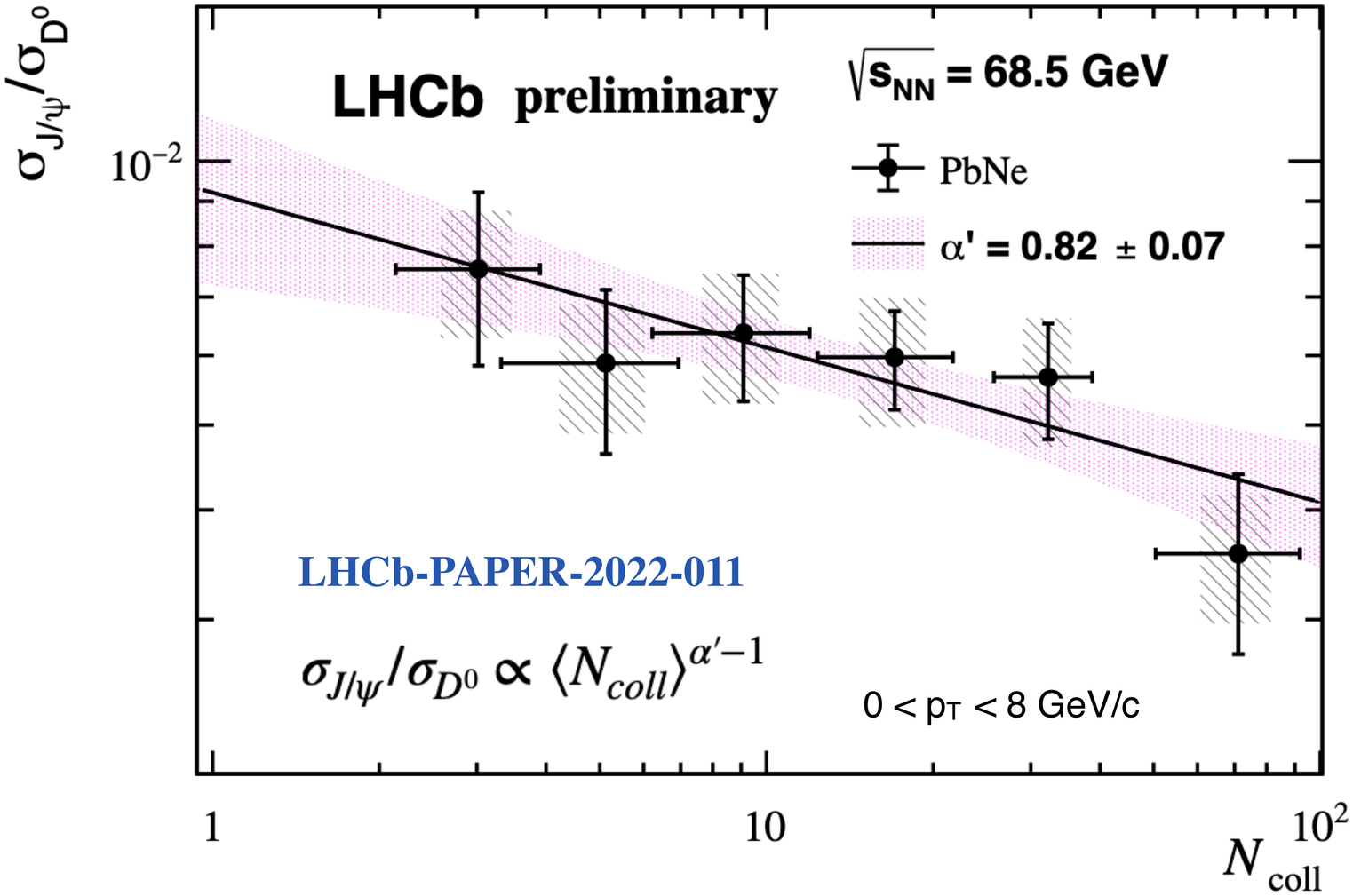
  - ➡ due to larger J/ψ contribution from the recombination in most central events?
    - ➡ caveat: inclusive J/ψ; possible centrality dependence of f(c—>D^0)
- **Comparison with SHMc:** JHEP07 (2021) 035
- most of the thermodynamic parameters cancel out:
  - ➡ sensitive to charm fugacity: increase of charm fugacity in most central according to SHMc

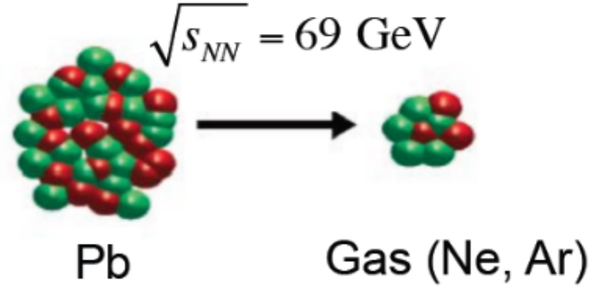
Precise measurement of total charm cross section needed

J/ψ and D^0 in PbNe collisions at 68.5 GeV

First measurement in fixed-target nucleus-nucleus collisions at the LHC: QGP in PbNe?

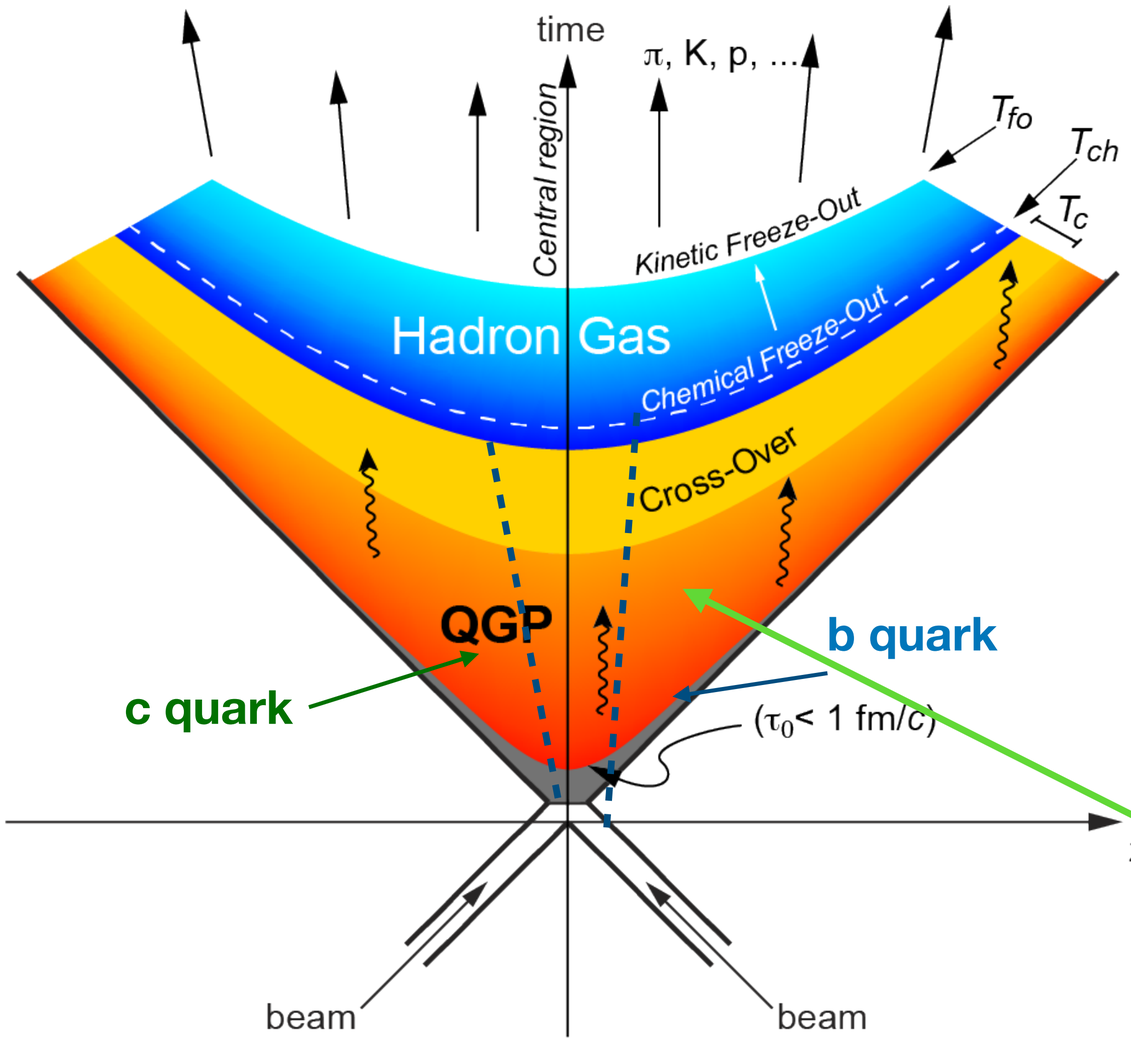
Look for the onset of the transition from ordinary hadronic matter to the QGP

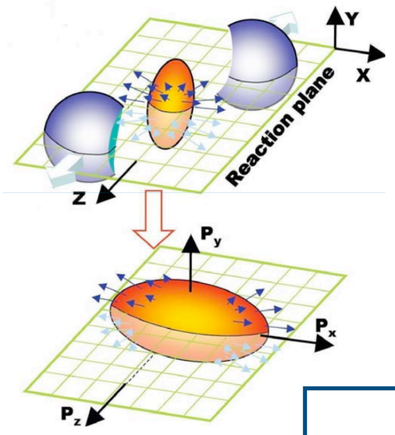




- similar trend as results at pA fixed target experiment at NA50 (Phys.Lett. B 410 (1997) 337)
- no anomalous J/ψ suppression is observed that could indicate the formation of QGP
- decreasing trend due to additional nuclear effects for J/ψ

J. Sun, 7 Apr



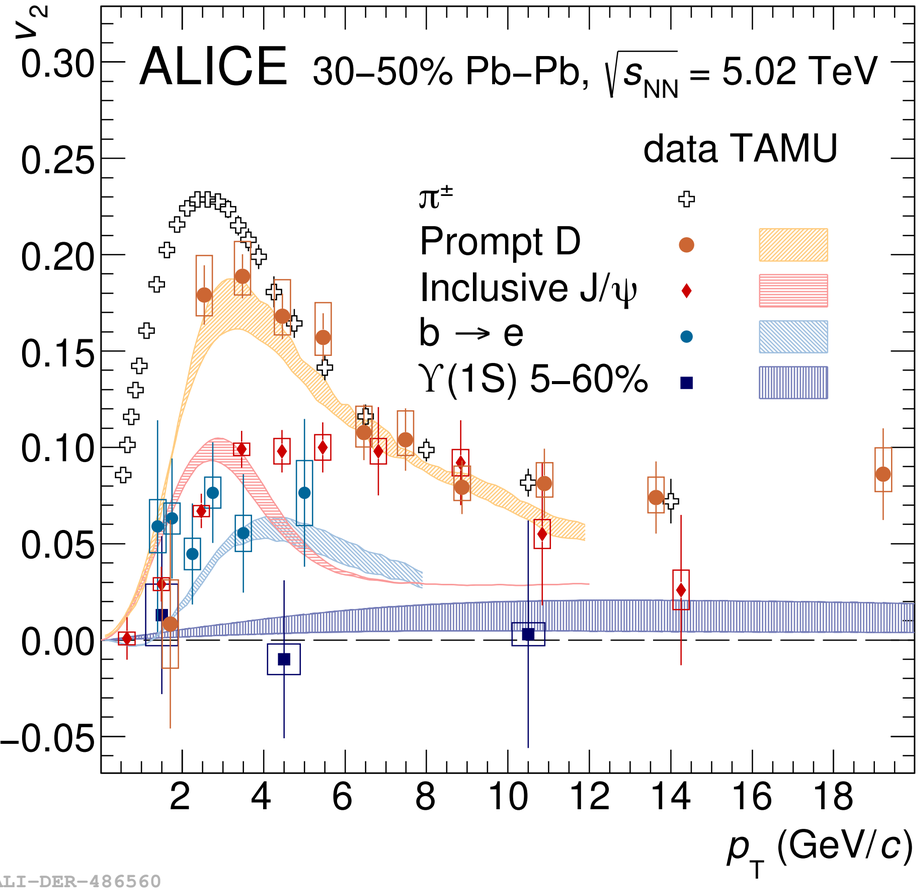


Thermalization
as a consequence of HQ coupling with medium

Which is the degree of thermalization of HQs in the medium?

Overview of charm, beauty and charmonium, bottomonium v_2

➡Positive v_2 of hadrons with charm observed at RHIC and LHC
- **charm quarks largely thermalize in QGP until hadronization**
- **smaller v_2 of open-beauty hadrons**



- **beauty** v_2 measured via electrons and muons from HF hadron decays and non-prompt J/Ψ, and quarkonia: Υ

$0 \sim v_2^{\Upsilon(1S)} < v_2^{(b->e)} \sim v_2^{(incl\ J/\Psi)} < v_2^{(D)} < v_2^{h}$ at low p_T

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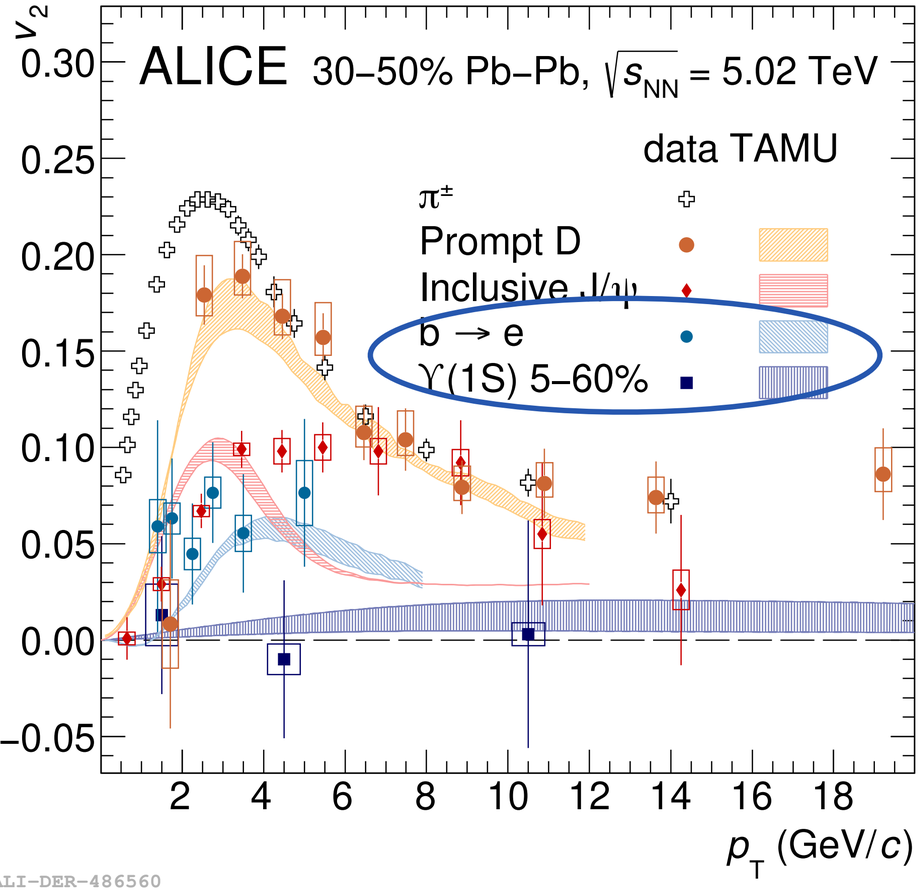

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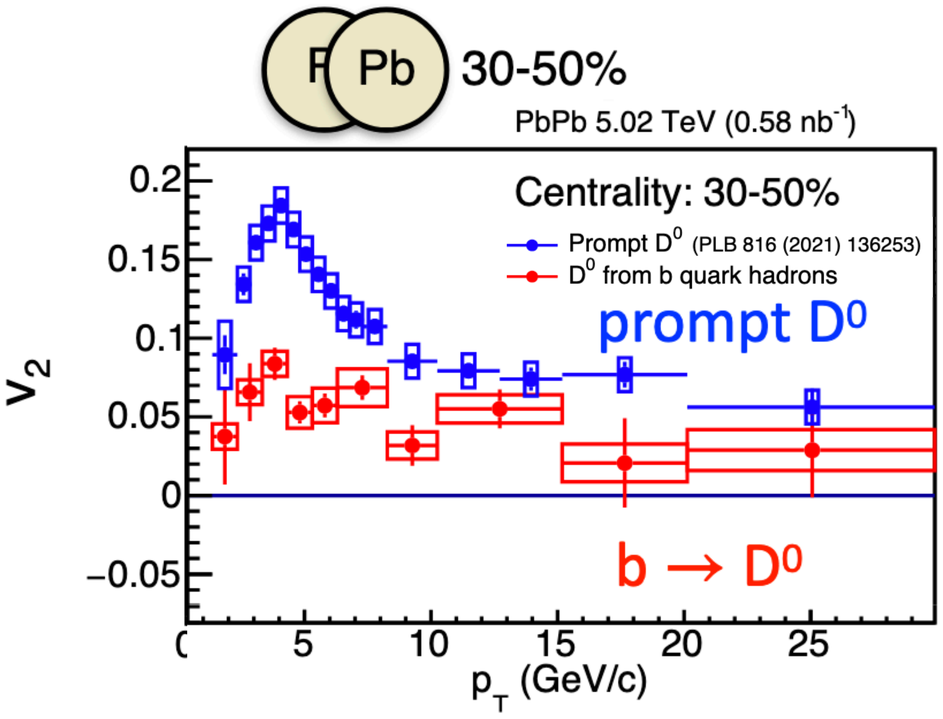
- **Open beauty-hadrons $v_2 > 0$: for** from recombination with light quarks?
- **Bottomonia: $v_2^{\Upsilon(1S)} = 0$:** negligible recombination. Does beauty flow?

beauty v_2

M. Stojanovic 7Apr
X. Peng 7 Apr
G. Oh 7 Apr

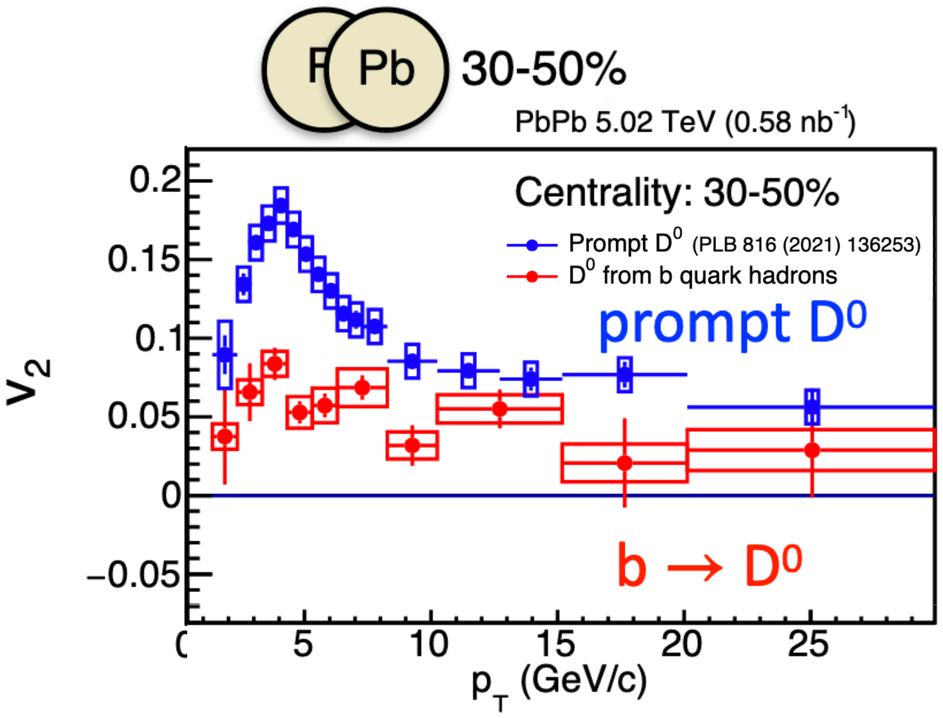


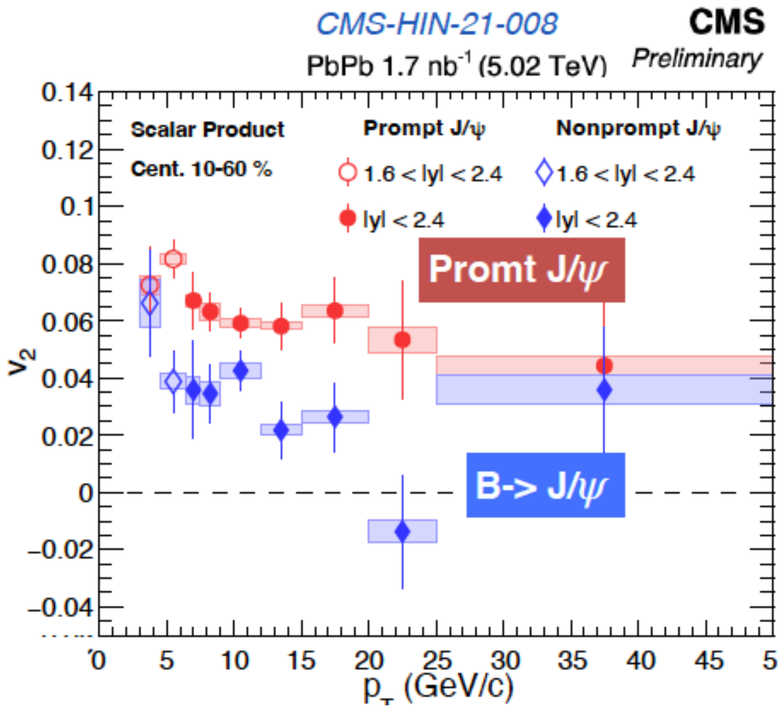
First measurement of non-prompt D^0 v_2

- Prompt D^0 v_2 > non-prompt D^0 v_2

beauty v_2

M. Stojanovic 7Apr
X. Peng 7 Apr
G. Oh 7 Apr





First measurement of non-prompt D^0 v_2

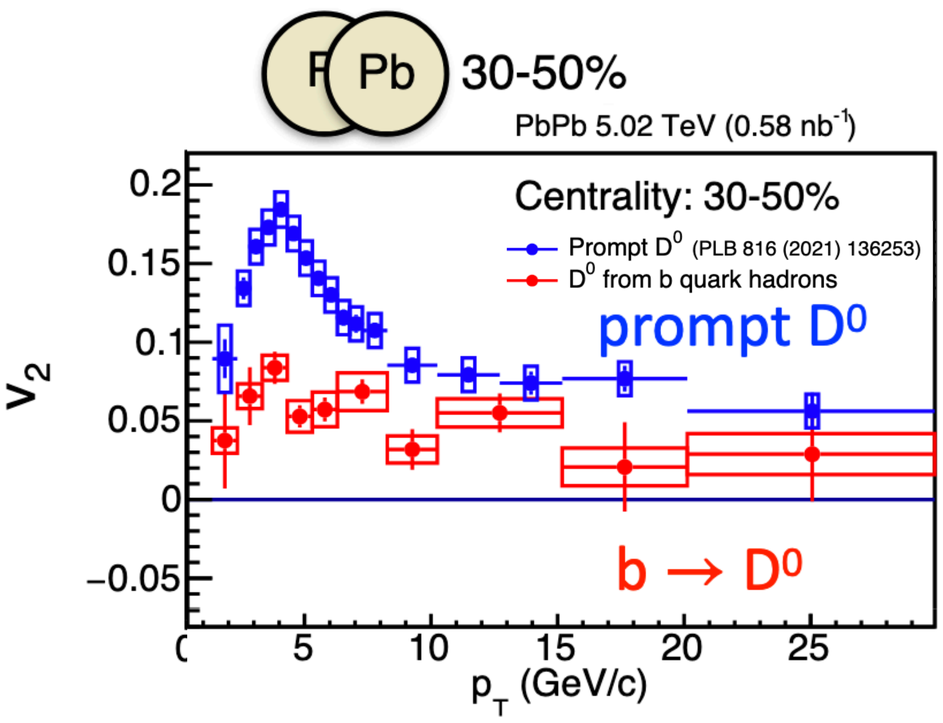
non-prompt J/ψ v_2

- Prompt D^0 v_2 > non-prompt D^0 v_2

- **Prompt J/ψ v_2 > non-prompt J/ψ v_2**

beauty v_2

M. Stojanovic 7Apr
X. Peng 7 Apr
G. Oh 7 Apr
Q. Hu, Apr 7



First measurement of non-prompt D^0 v_2

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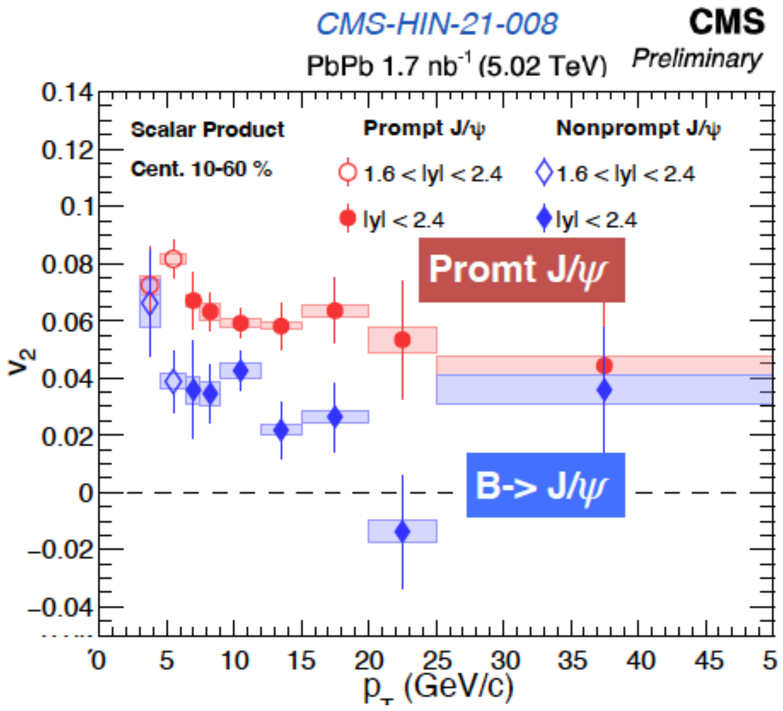
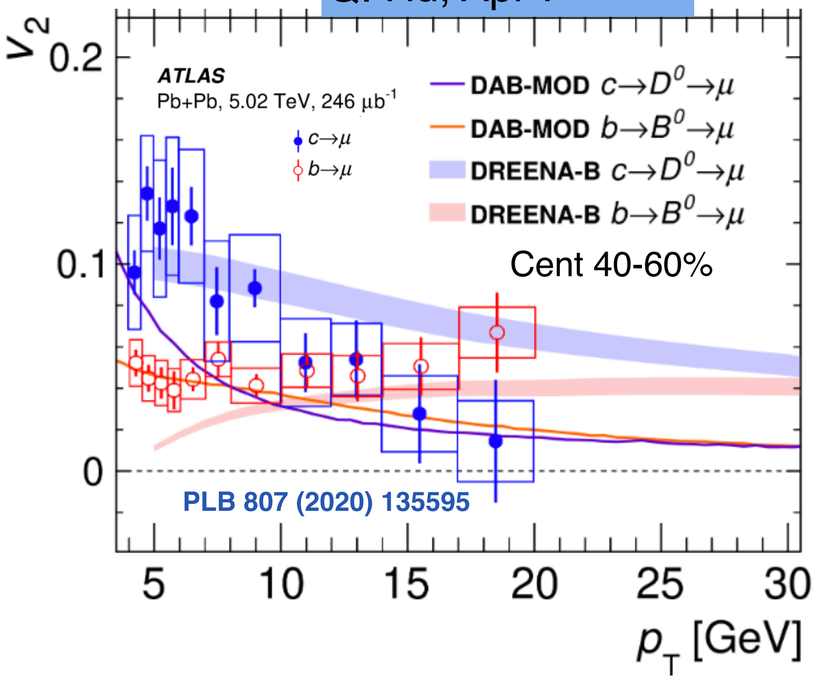


non-prompt J/ψ v_2

- **Prompt J/ψ v_2 > non-prompt J/ψ v_2**



v_2 of muons from HF hadron decays

Mass splitting of **charm** and **bottom** at low p_T in v_2.

Positive beauty hadron v_2 both at low and high p_T
➡ Indication of participation in the collective motions of the system

Overview of charm, beauty and charmonium, bottomonium v_2

➡Positive v_2 of hadrons with charm observed at RHIC and LHC
- **charm quarks largely thermalize in QGP until hadronization**
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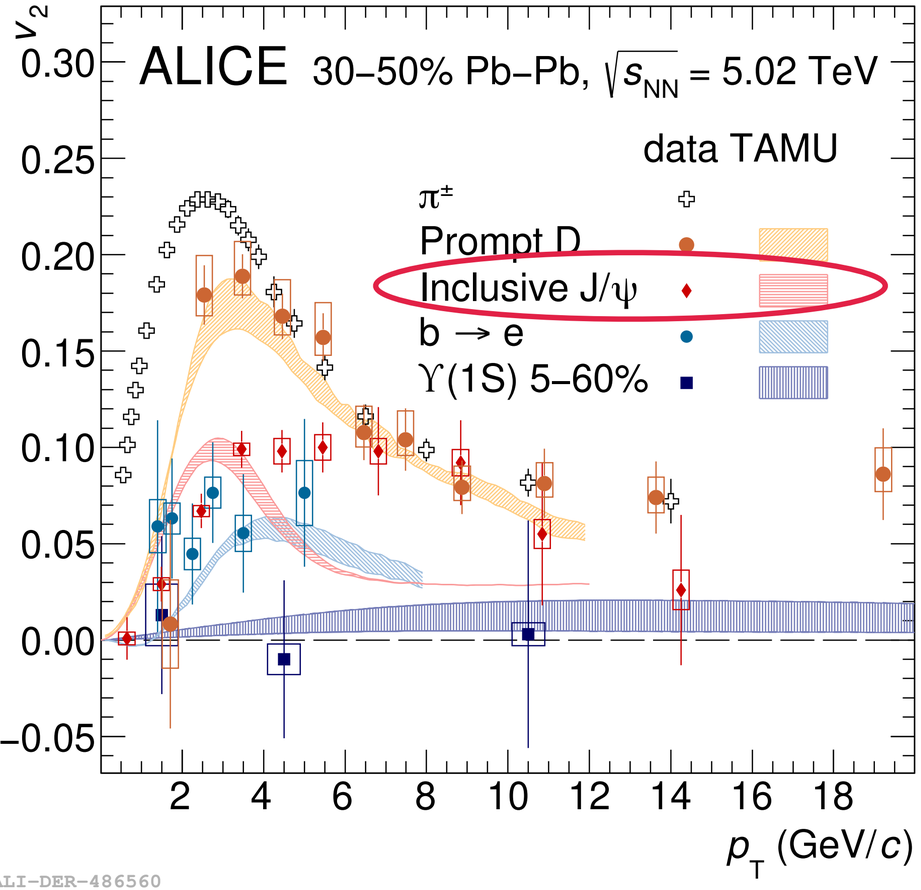

charmonia: recombining charm quarks, inherit thermalized charm flow
- described by models that implement suppression+recombination

Arxiv:2111.13528

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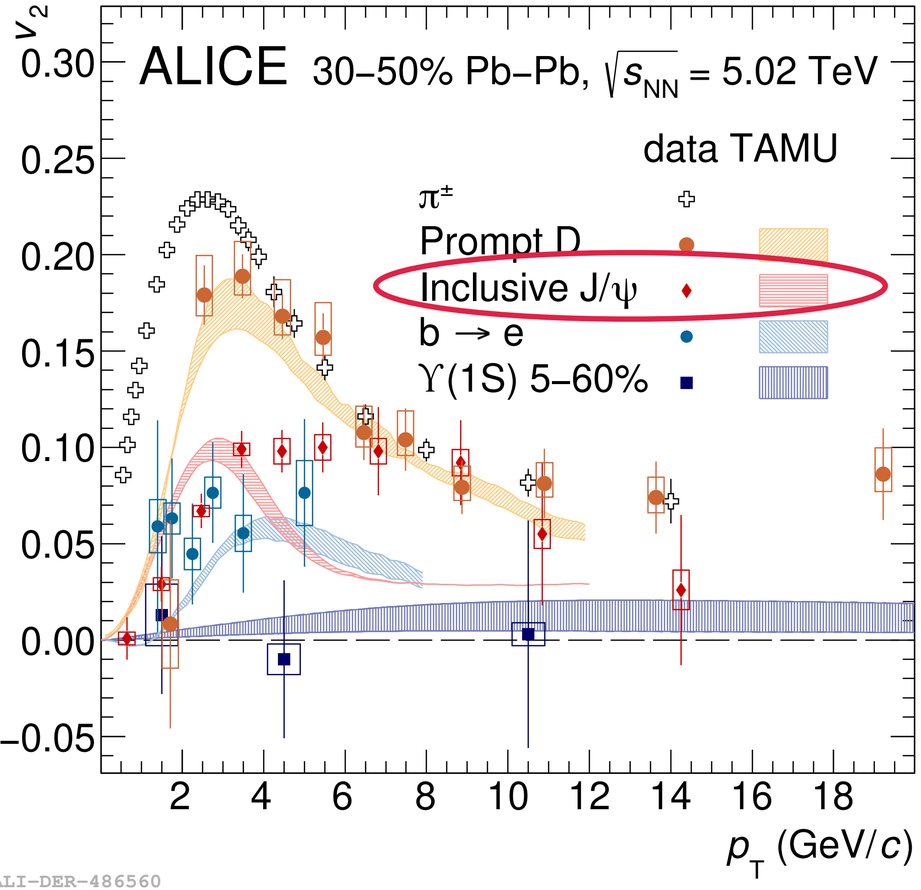
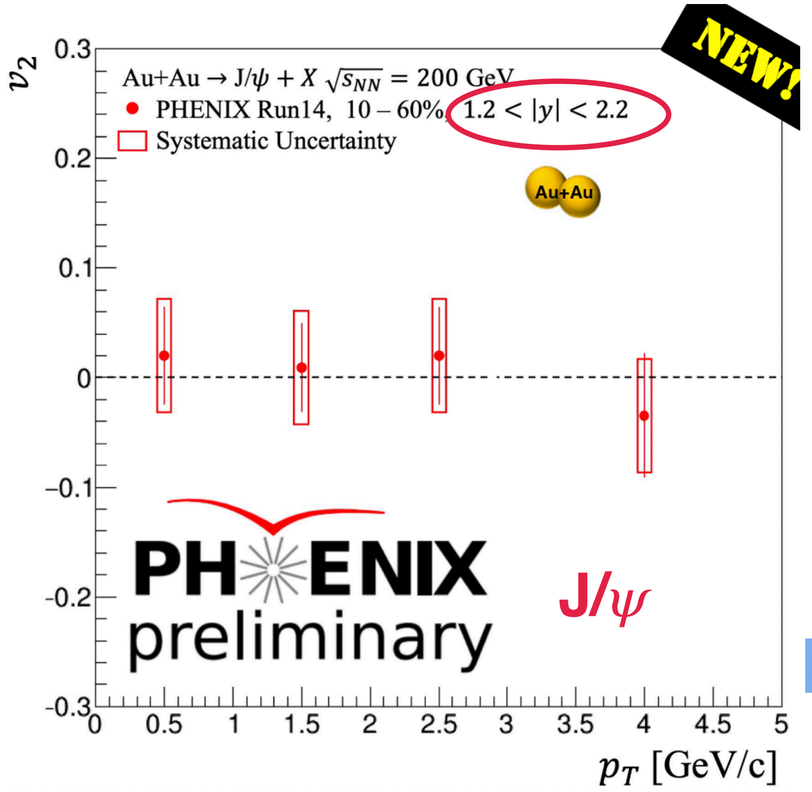


charmonia: recombining charm quarks, inherit thermalized charm flow
- described by models that implement suppression+recombination
  - RHIC: less recombination that at LHC —> v_2(J/ψ,Au-Au) ~ 0

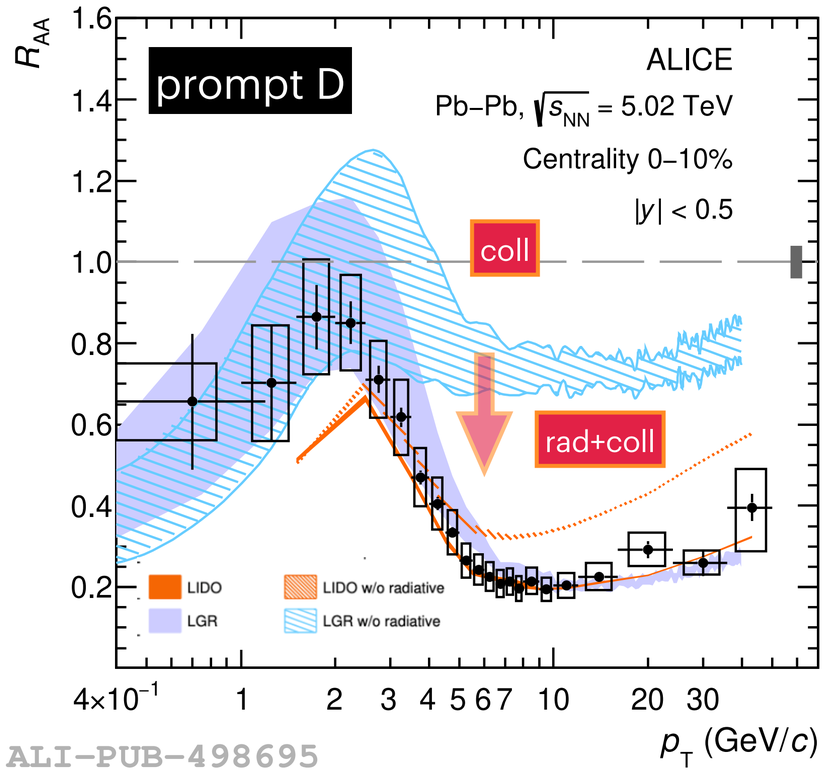


L. Bichon, Apr 7

R_{AA} and v_2 vs models: systematic comparison

JHEP 01 (2022) 174

Radiative vs w/o radiative

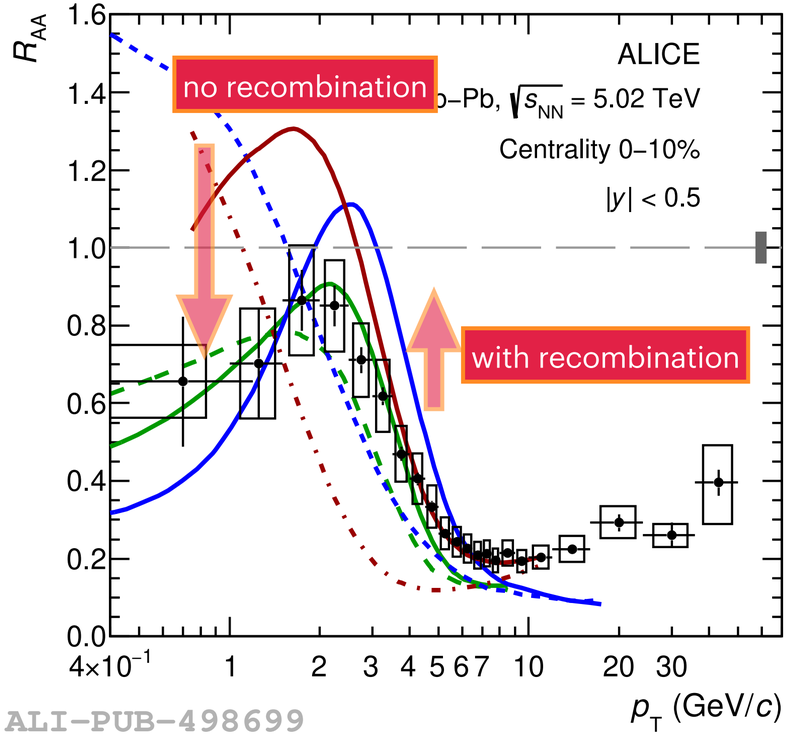


ALI-PUB-498695

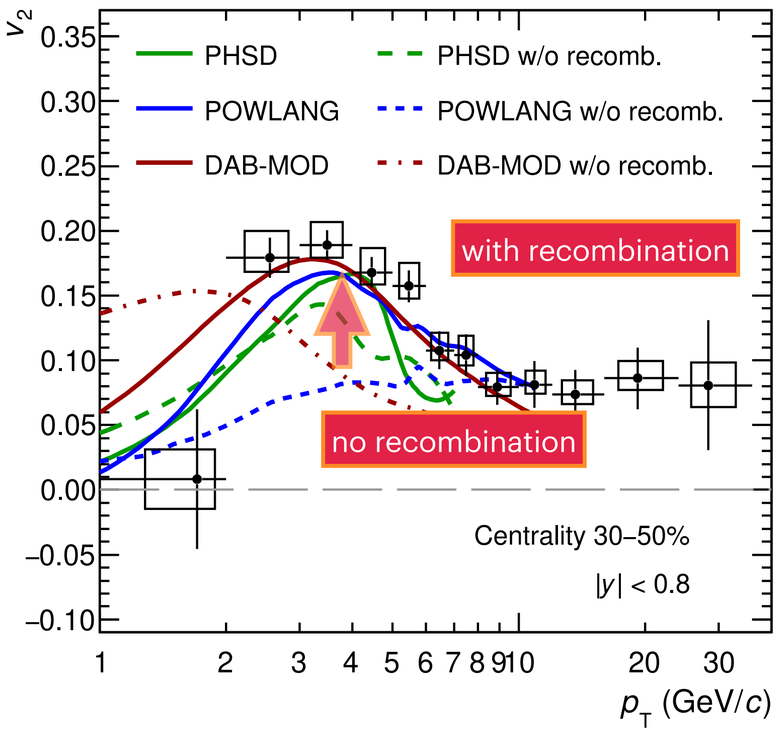
JHEP 01 (2022) 174

recombination w/o recombination

L. Vermunt 7Apr



ALI-PUB-498699

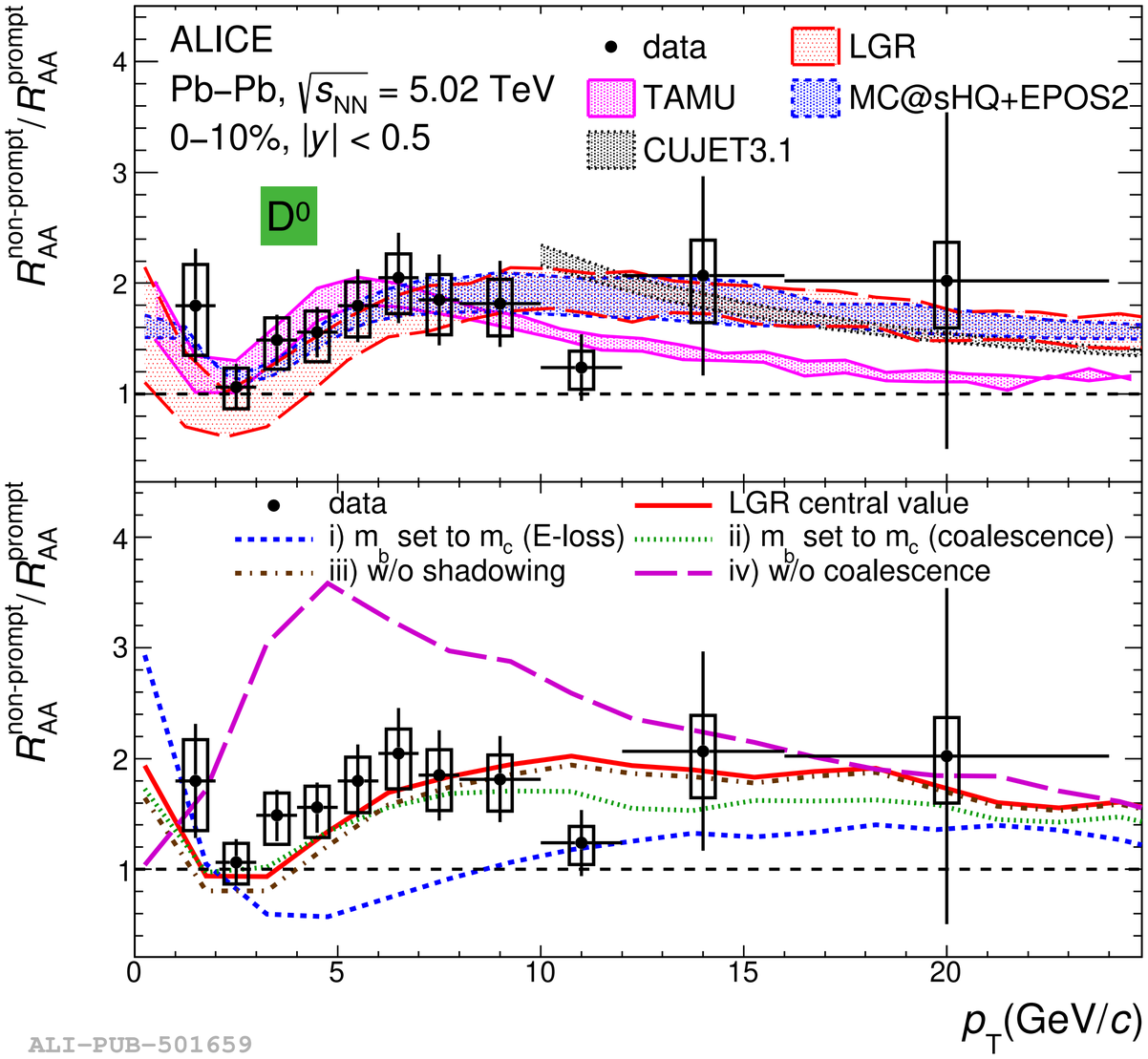


recombination, collisional and radiative energy loss: systematic study to disentangle contributions in the models and constraint theory

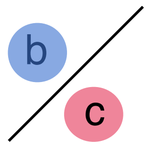
- Recombination with light quarks enhances R_{AA} and v_2 at low and intermediate p_T
- Both Radiative and Collisional energy loss needed to describe measurements at high p_T

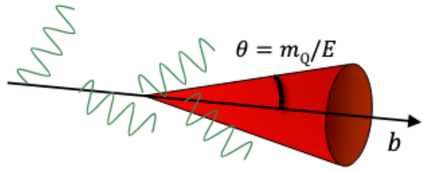
beauty vs charm quark in QGP: model comparison

arXiv:2202.00815



X. Peng, 6 Apr





beauty/charm R_{AA} ratio: via non-prompt/prompt D:

Smaller beauty suppression: for $p_T > 5$ GeV/c

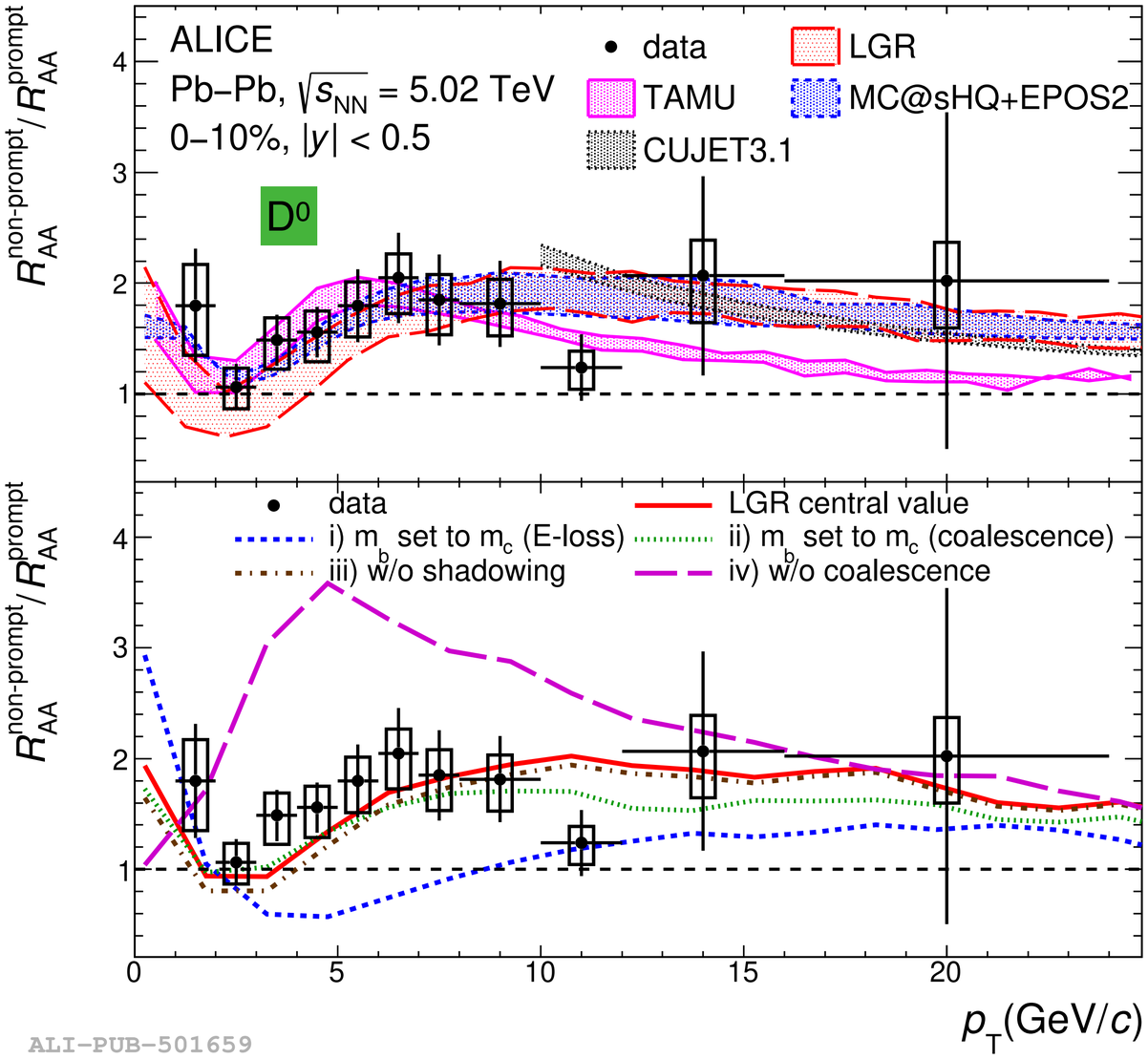
- described by **models that include both collisional and radiative processes, recombination plus fragmentations**
  - **if charm-quark mass in b-energy loss —> underestimate data**
  - **excluding charm and beauty coalescence —> overestimate data**

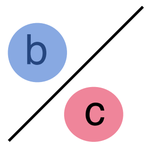
MC@sHQ+EPOS: PRC 89, 014905 (2014) TAMU: PLB 735 (2014) 445-450

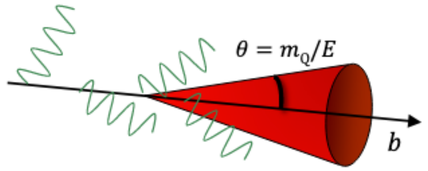
CUTJET 3.1: Chin. Phys. C 43 (2019) 044101 LGR: EPJC, 80 7 (2020) 671

beauty vs charm quark in QGP: model comparison

arXiv:2202.00815







Mass dependence of energy loss and need of coalescence for both beauty and charm

- described by **models that include both collisional and radiative processes, recombination plus fragmentations**
  - **if charm-quark mass in b-energy loss —> underestimate data**
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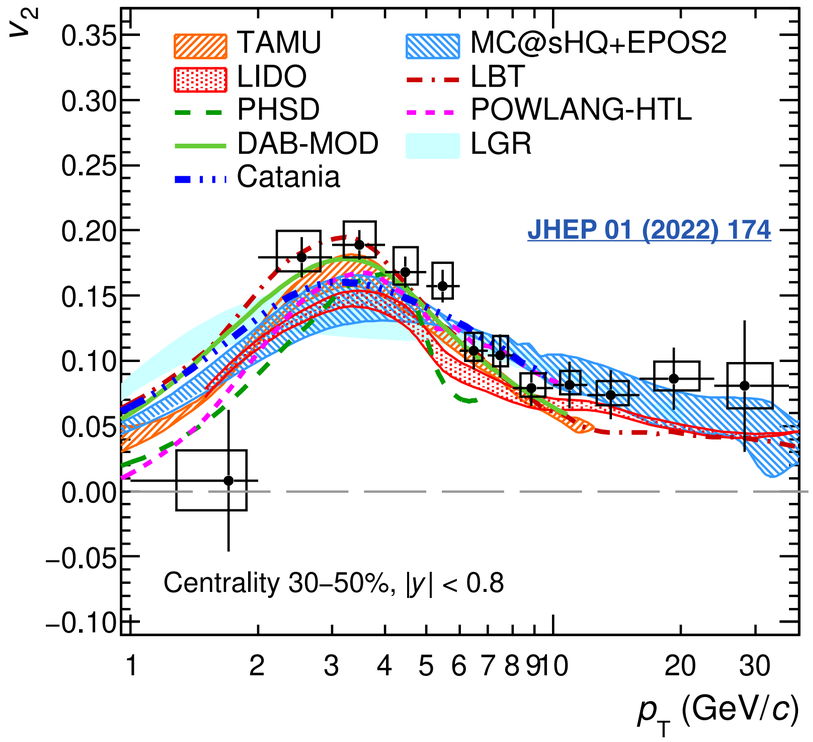
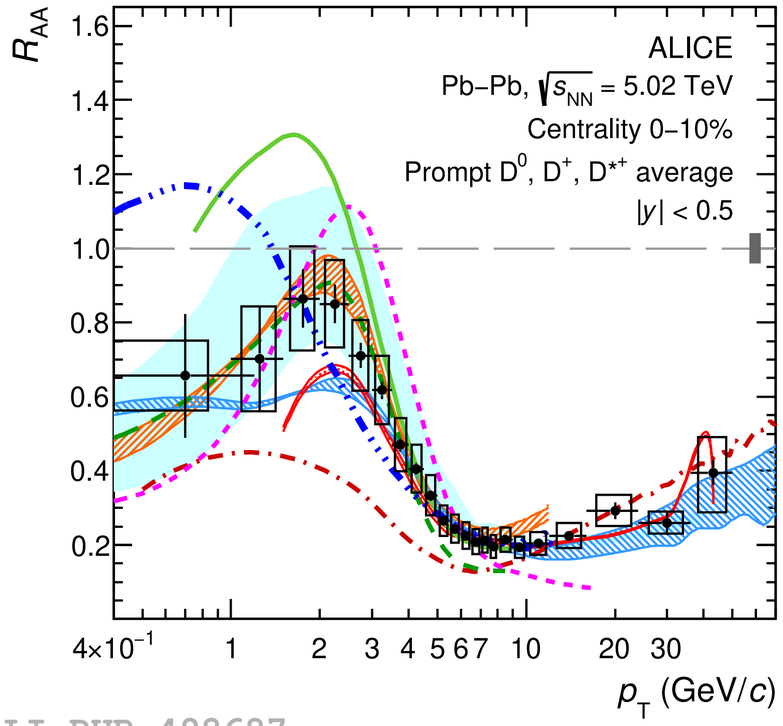
MC@sHQ+EPOS: PRC 89, 014905 (2014) TAMU: PLB 735 (2014) 445-450

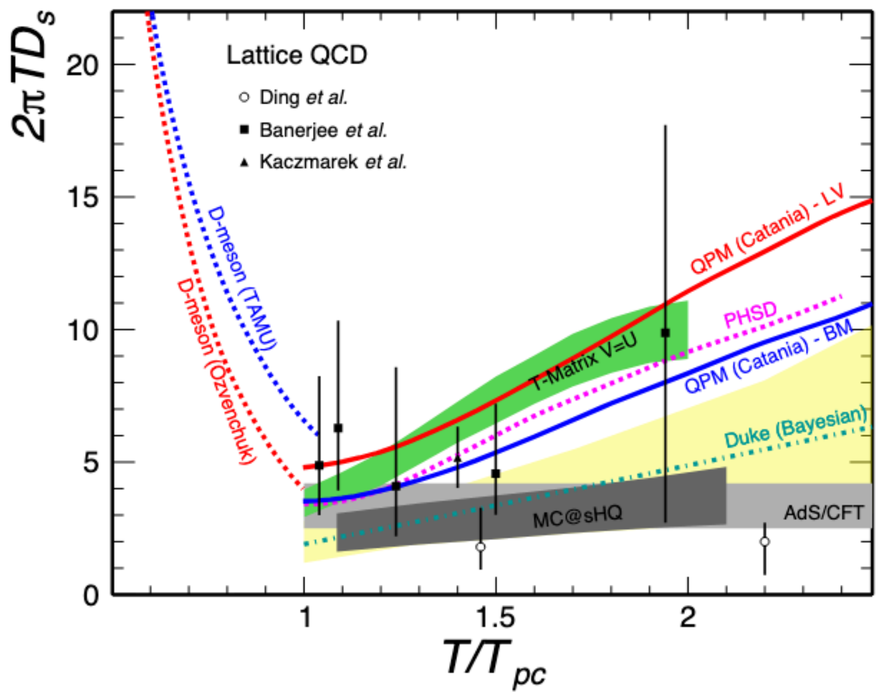
CUTJET 3.1: Chin. Phys. C 43 (2019) 044101 LGR: EPJC, 80 7 (2020) 671

Constraint to QGP: diffusion coefficient

measurements down to low-p_T: production yields and angular distributions sensitive to the diffusion and possible thermalization of charm quark in medium.







XD, Y-J Lee & R. Rapp, Ann. Rev. Nucl & Part. Sci. 69 (2019) 417

R_{AA}, v_2: simultaneous description

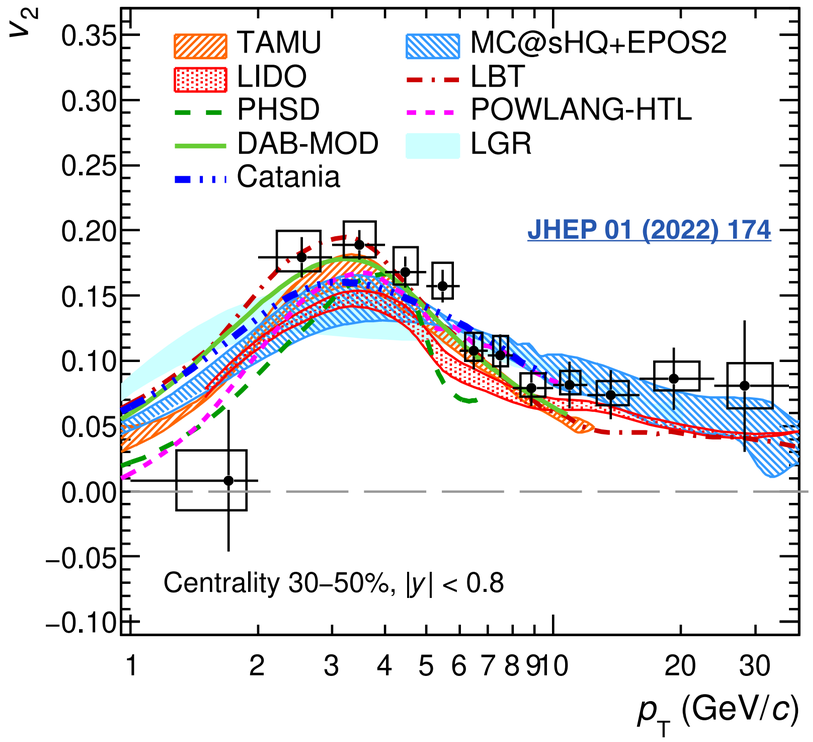
➡provide constrain by computing data-to-model agreement:

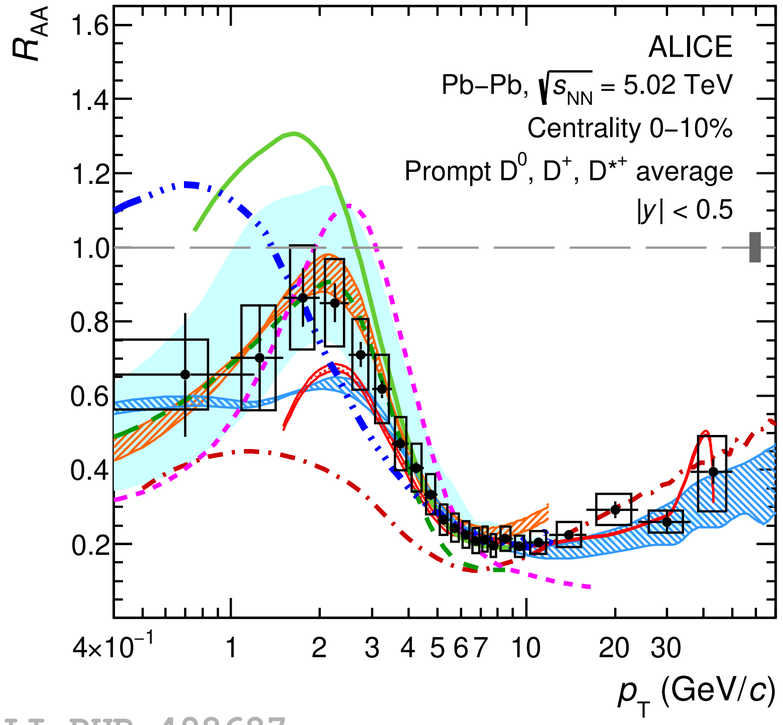
L. Vermunt 7 Apr
L. Altenkort 6 Apr

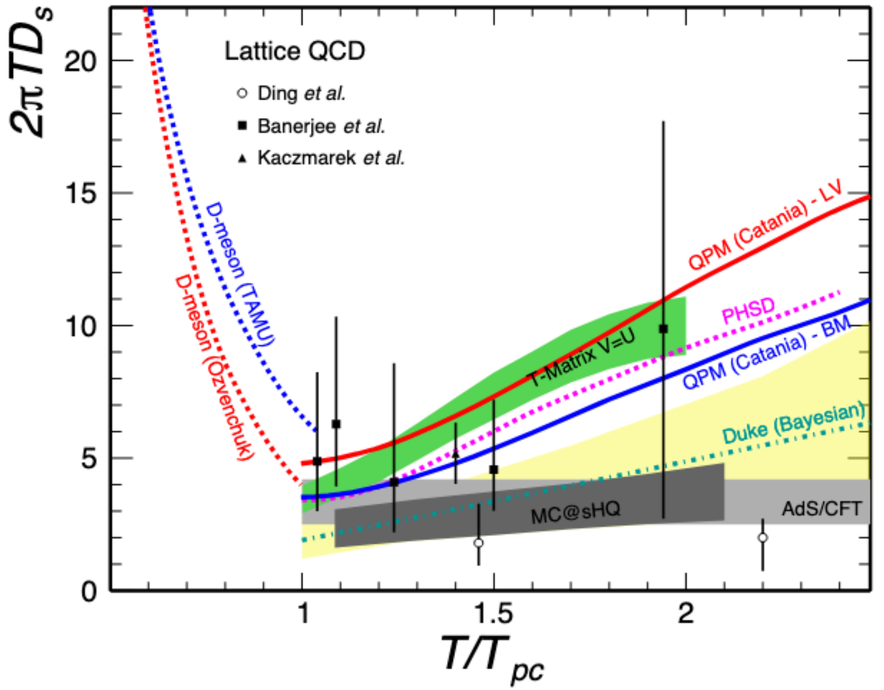
➡ **Recent estimate considering** R_{AA}, v_2, v_3 in different centrality ranges**: $1.5 < 2\pi D_s T_c < 4.5$** at the critical temperature for the QGP phase transition, $T_c = 155$ (τ_c = 3-8 fm/c), in agreement with **lQCD calculations**

Constraint to QGP: diffusion coefficient

measurements down to low-p_T: production yields and angular distributions sensitive to the diffusion and possible thermalization of charm quark in medium.

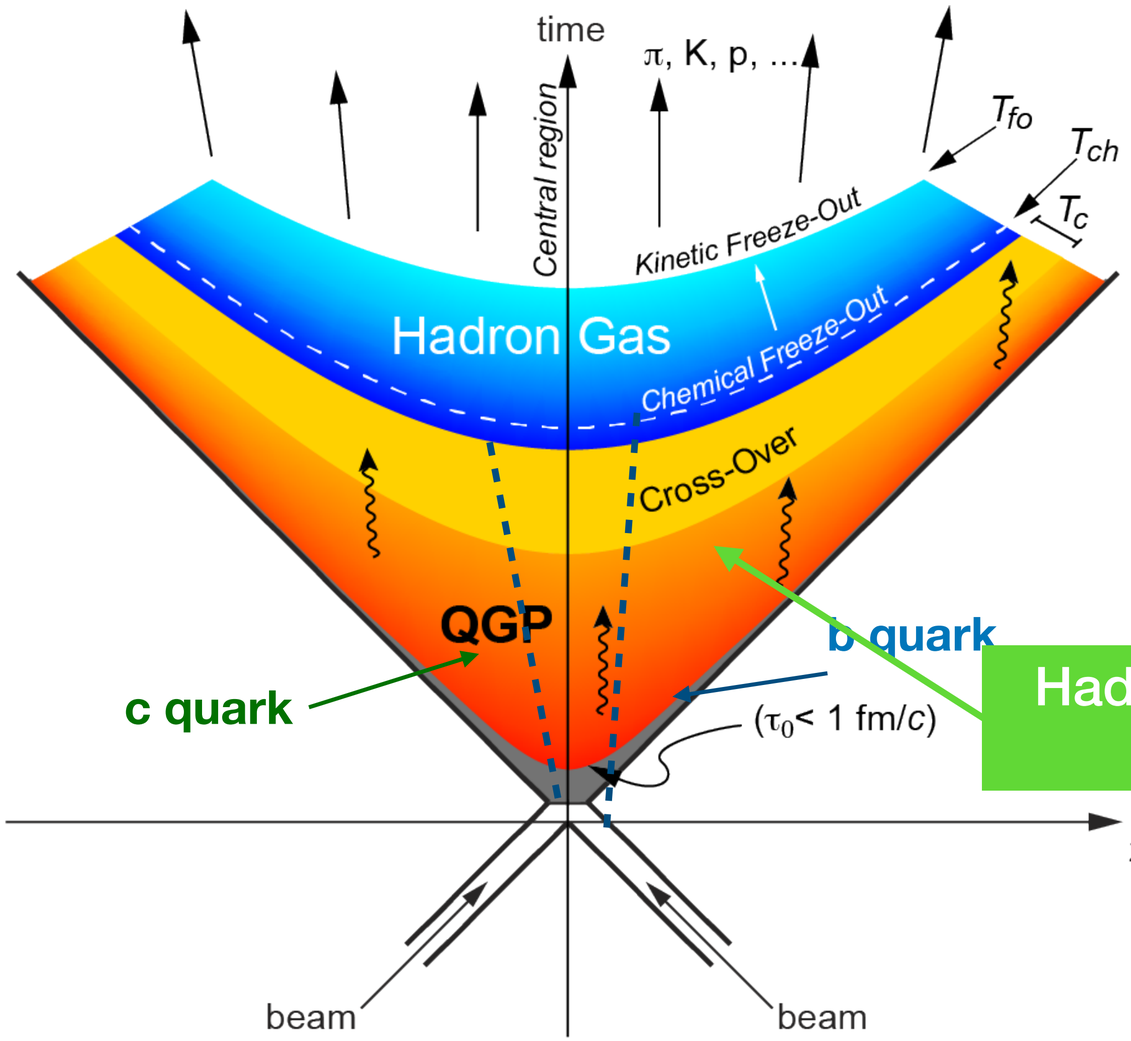




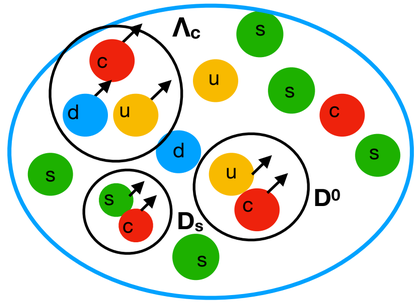


XD, Y-J Lee & R. Rapp, Ann. Rev. Nucl & Part. Sci. 69 (2019) 417

More precise data measurements will provide important constraint to beauty spatial diffusion coefficient

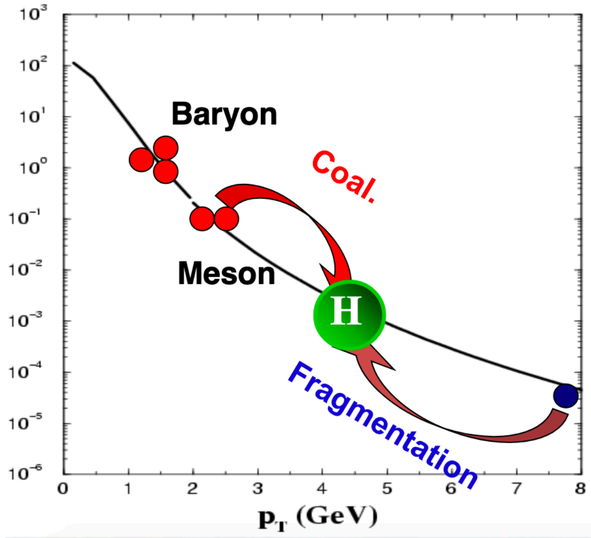


Hadronization in QGP

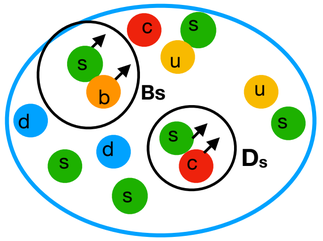


Hadronization in QGP:

- **Recombination** at low-intermediate p_T of c and b with light quark in the medium

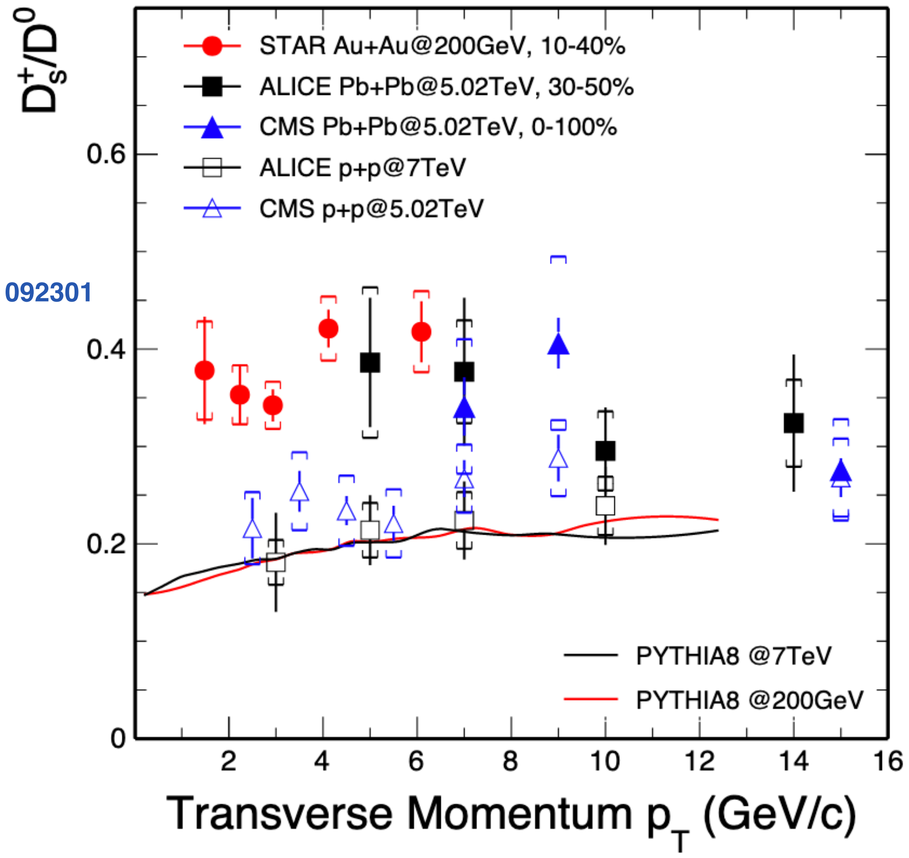


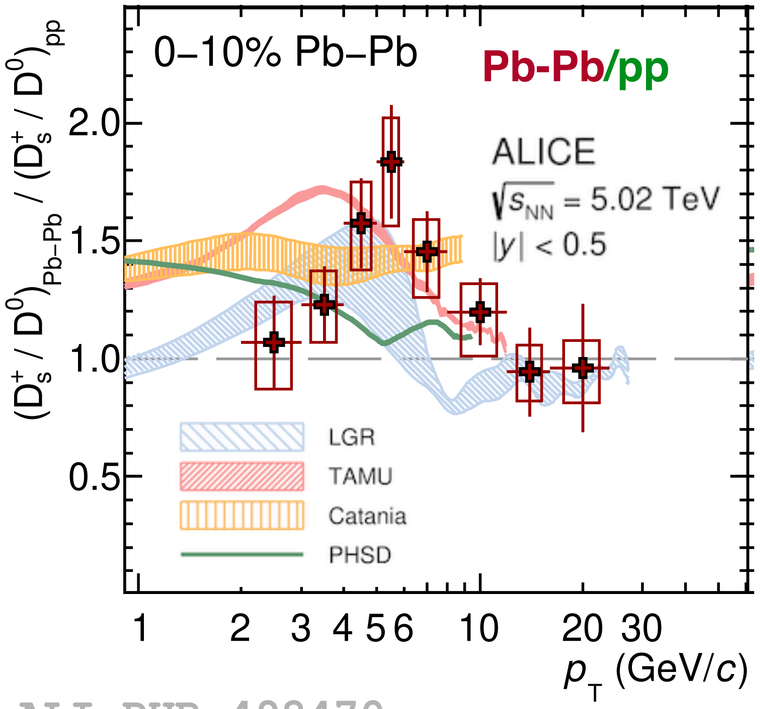
Hadronisation: charm non-strange and strange D meson



Recombination + **Strangeness enhancement** in the A-A **wrt to pp** collisions —> enhancement of strange heavy mesons in A-A w.r.t. pp?

Phys. Rev. Lett. 127, 092301





PLB 827 (2022) 136986

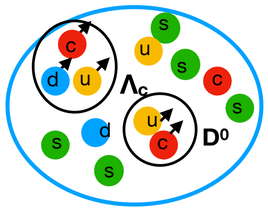
ALI-PUB-498470

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

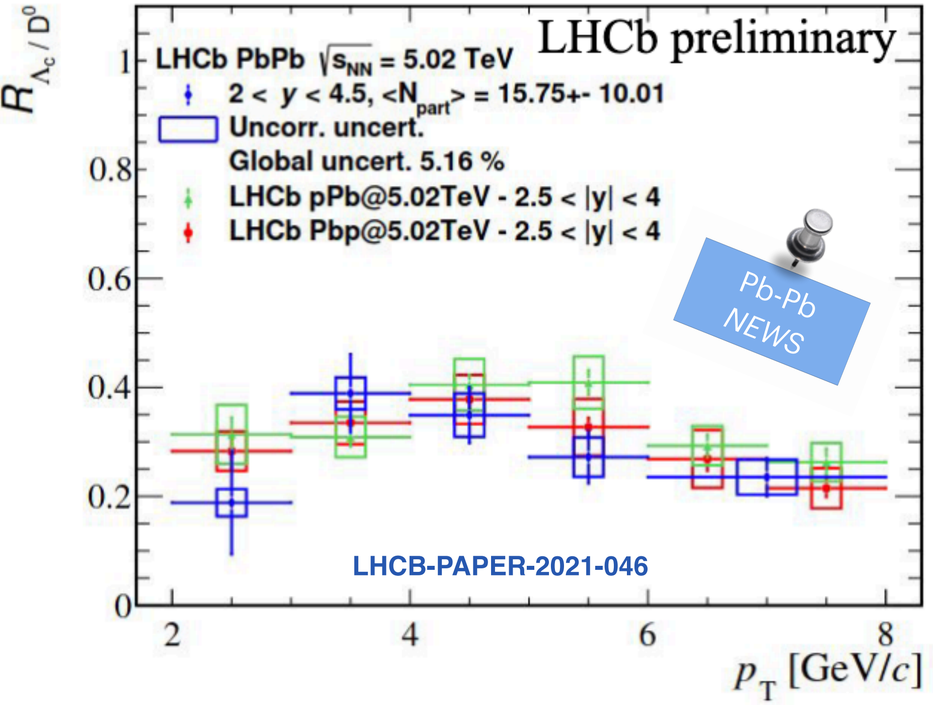
Compatible results at low-intermediate p_T: $D_s/D^0 \sim 0.4$

Agreement with models that include strangeness enhancement, frag + reco in QGP

Hadronisation: baryon-to-meson yield ratios



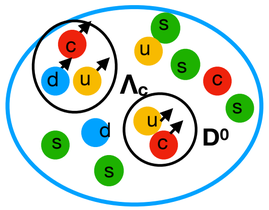
B. Audurier, 7 Apr



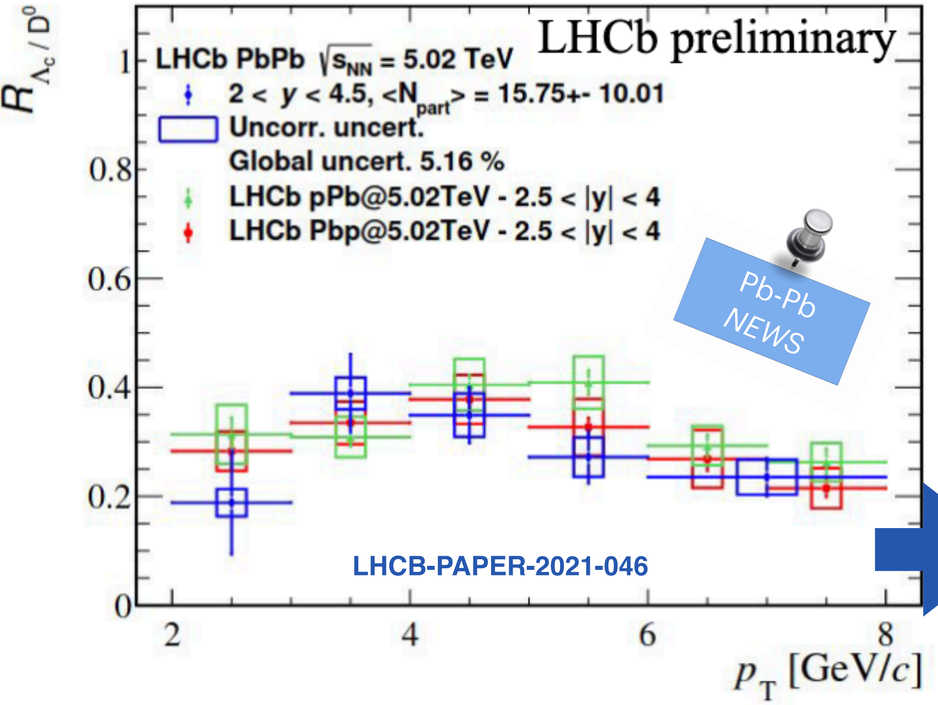
LHCb: enter the games with Pb-Pb measurements!

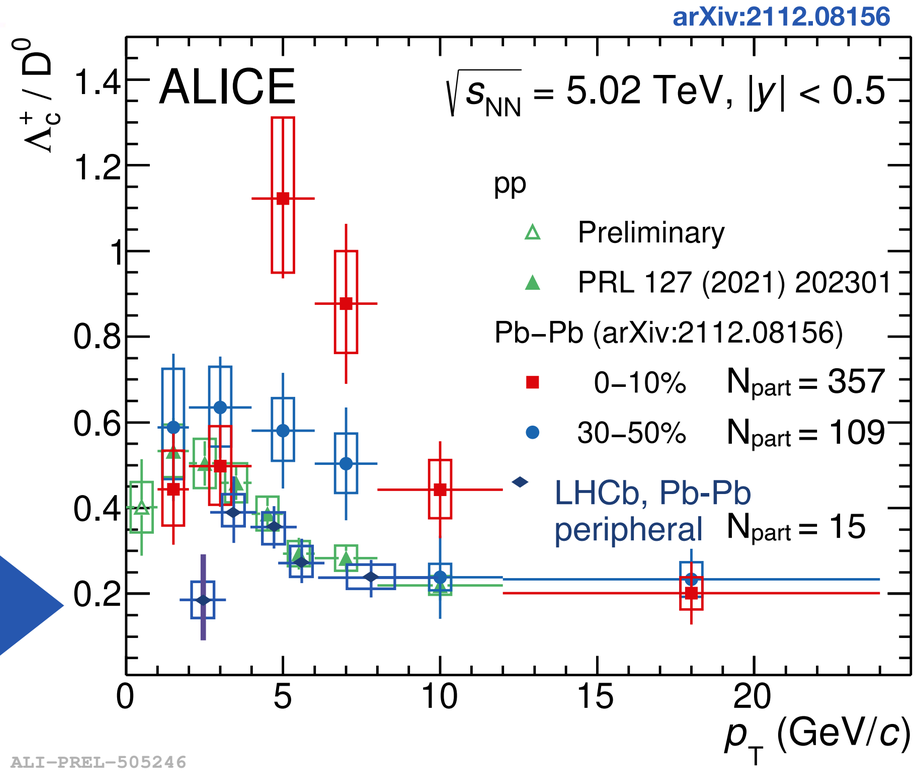
centrality 65-80% Pb-Pb

Hadronisation: baryon-to-meson yield ratios



B. Audurier, 7 Apr
L. Vermunt, 7 Apr
J. Wang, 7 Apr





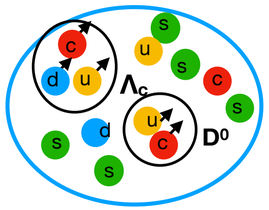
increasing trend of the Λ^+_c/D^0 at intermediate p_T from **pp**, to **semi-central** and **most central** Pb-Pb events

LHCb: enter the games with Pb-Pb measurements!

centrality 65-80% Pb-Pb

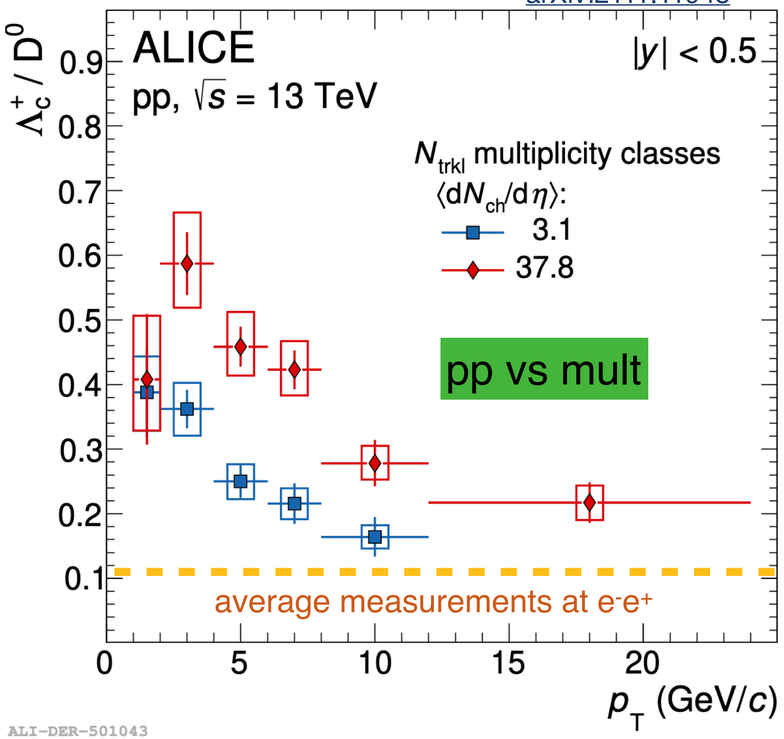
LHCb: peripheral Pb-Pb collisions at forward rapidity in line with measurements by ALICE in **pp collisions** at mid rapidity from $p_T > 3$ GeV/c

Hadronisation: baryon-to-meson yield ratios

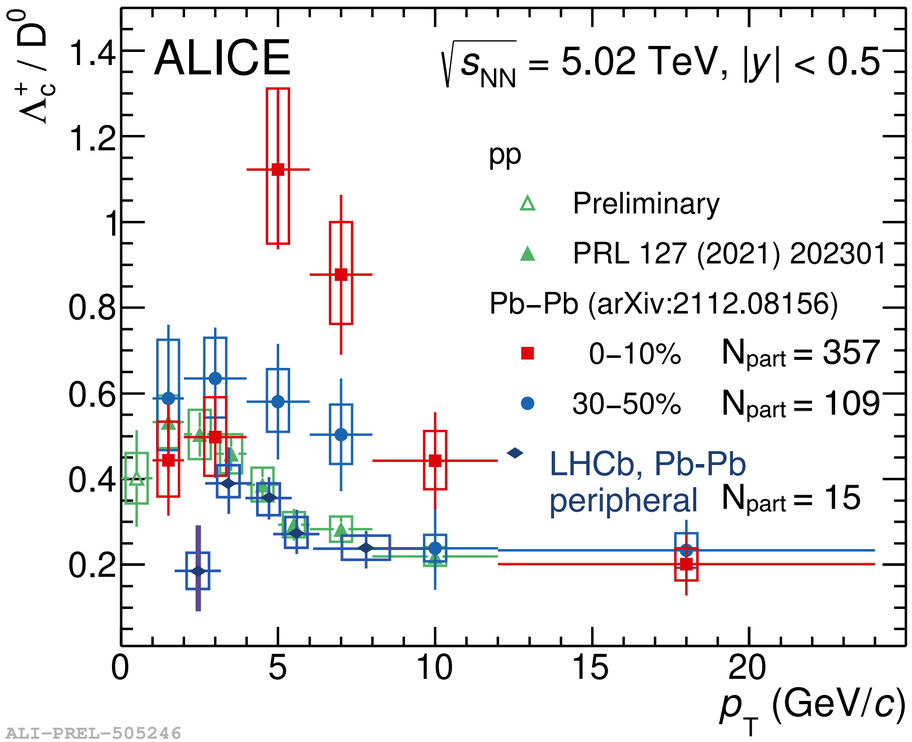


B. Audurier, 7 Apr
L. Vermunt, 7 Apr
L. Dello Stritto 7 Apr
M. Faggin 7 Apr

arXiv:2111.11948



arXiv:2112.08156

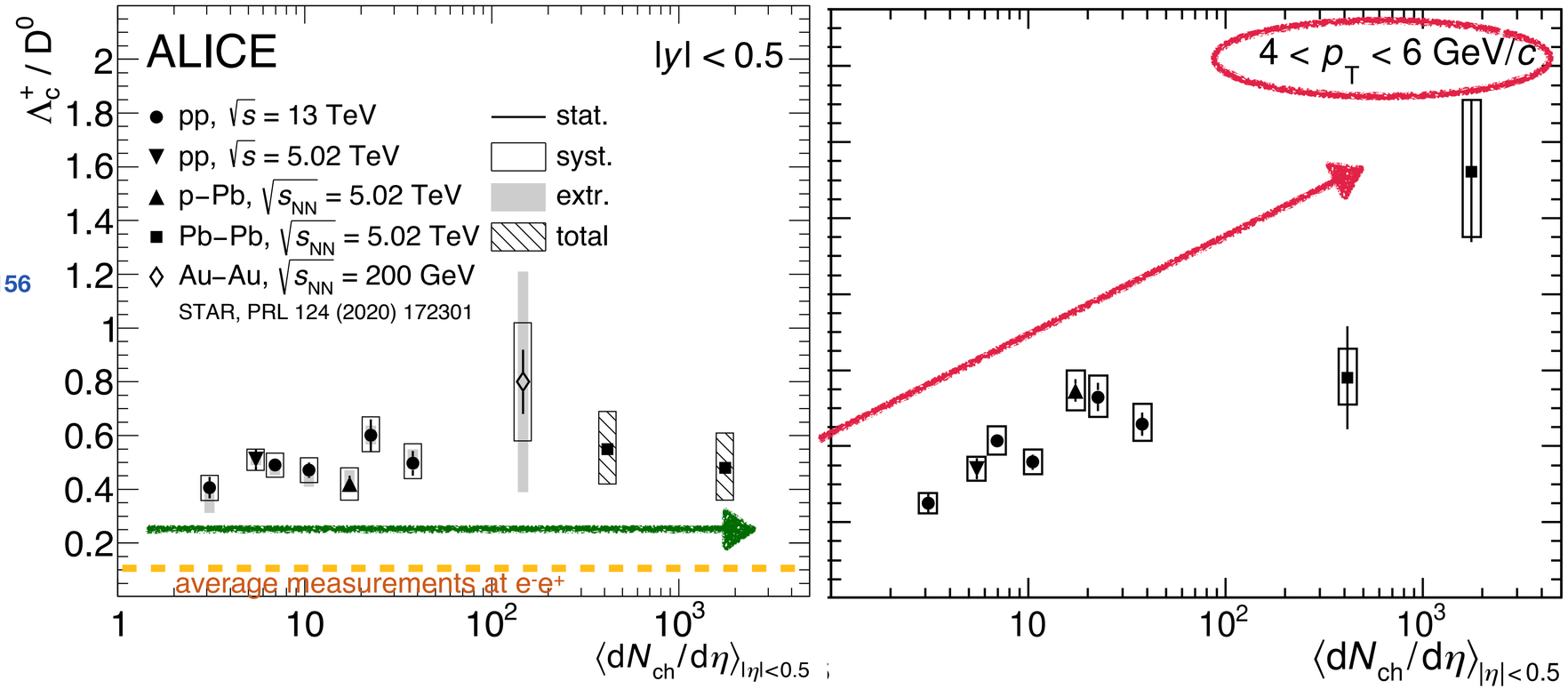


LHCb: peripheral Pb-Pb collisions at forward rapidity in line with measurements by ALICE in **pp collisions** at mid rapidity from $p_T > 3$ GeV/c

Is there a **transition of the hadronization mechanisms with multiplicity across different systems?** the same formalisms describe results from small to large systems?

Charm baryon/meson: from small to large systems

pp: arXiv:2111.11948
Pb-Pb: arXiv:2112.08156



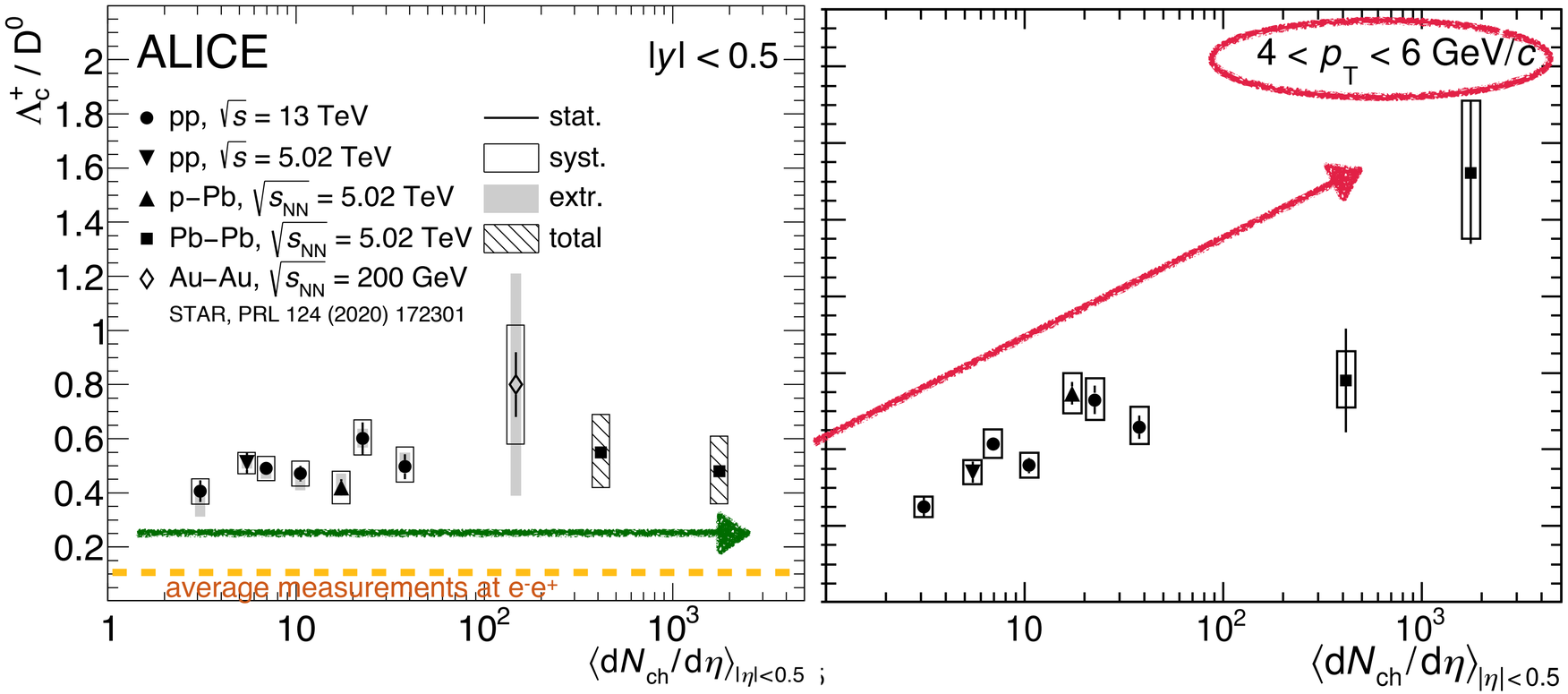
L. Vermunt, 7 Apr
L. Dello Stritto, 7Apr

p_T -integrated for $p_T > 0$: no evident multiplicity dependence from very low (pp) to very high (most central Pb-Pb) multiplicity

➡ no enhancement of total yield of Λ^+_c wrt D^0 in Pb-Pb wrt to pp collisions

- a **dense particle environment** in pp: act as proxy for "collectivity"?
- different hadronization mechanisms for baryons and mesons act in different momentum ranges? effect of radial flow?

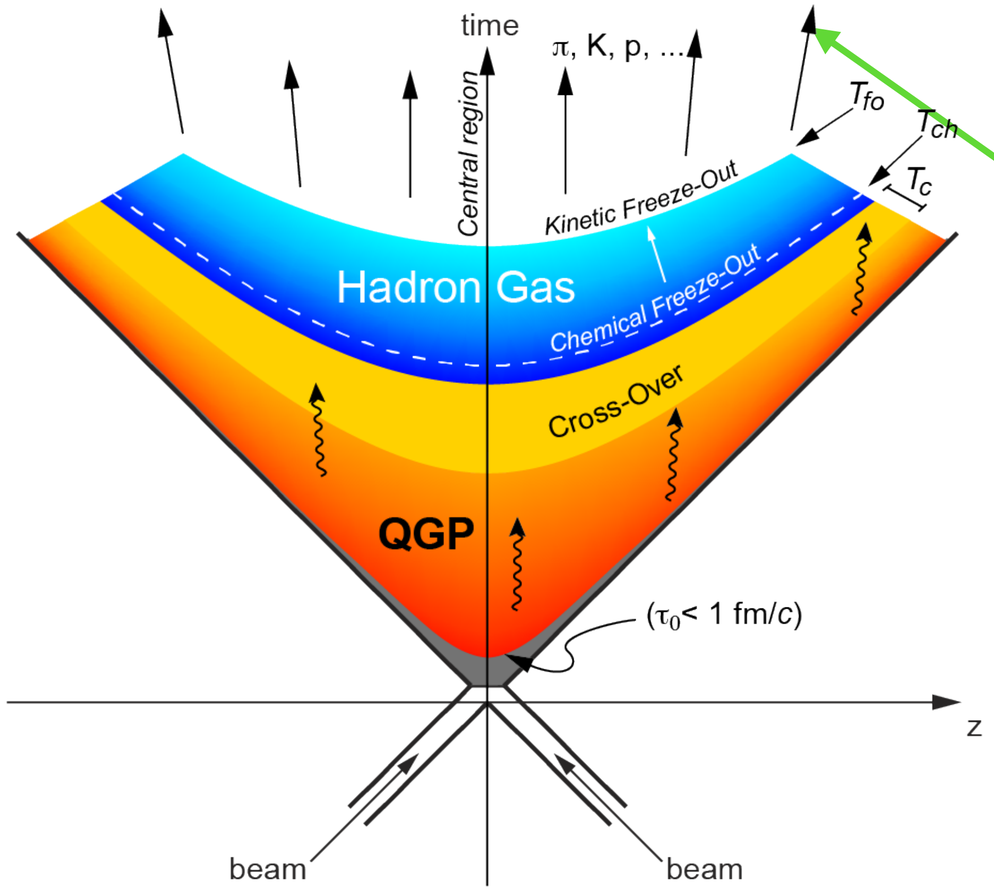
Charm baryon/meson: from small to large systems



L. Vermunt, 7 Apr
L. Dello Stritto, 7Apr

Few models available in small systems to investigate HF production/hadronisation vs multiplicity: **further theoretical developments also required**

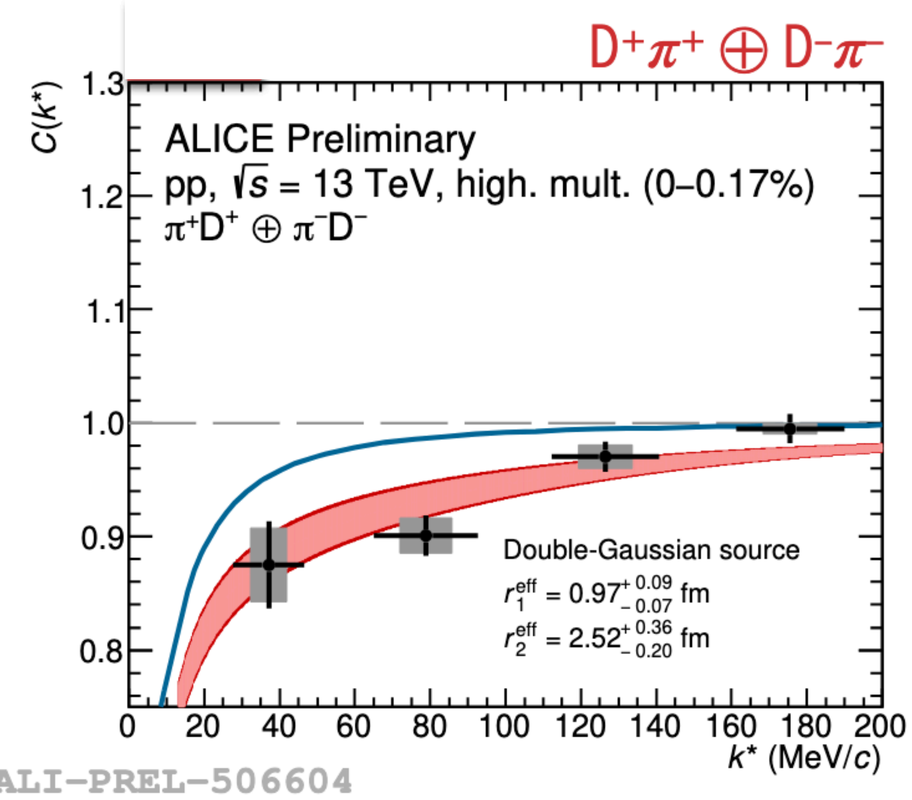
—> p_T -integrated yields for $p_T > 0$ crucial measurements

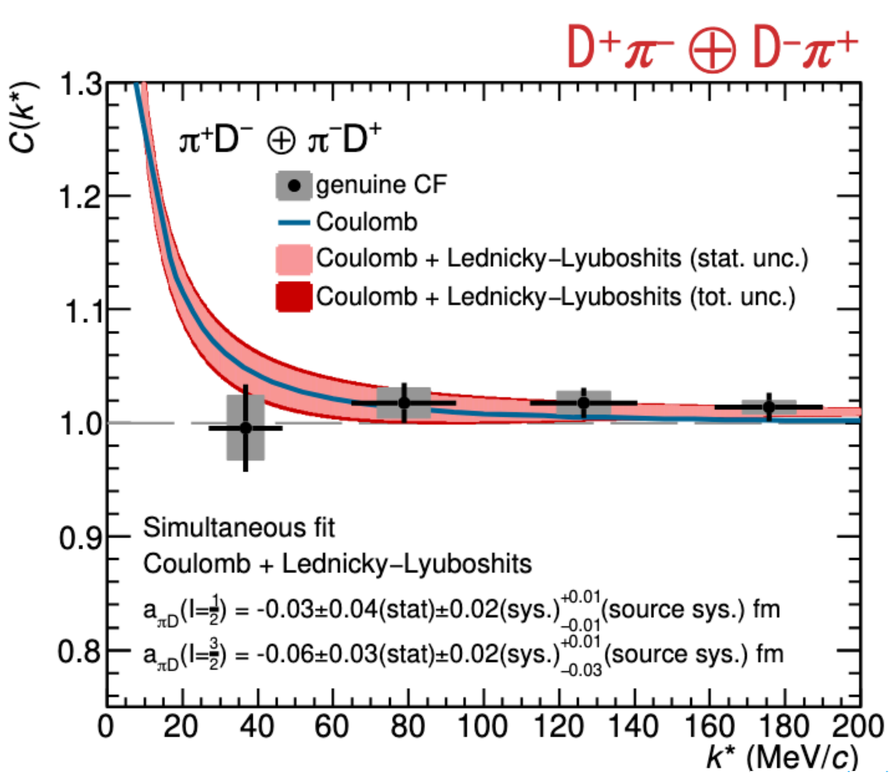


what do we learn from HF in the hadronic phase?

investigating hadronic phase with charm hadrons

how much hadronic rescattering influence our observables after the hadronization?



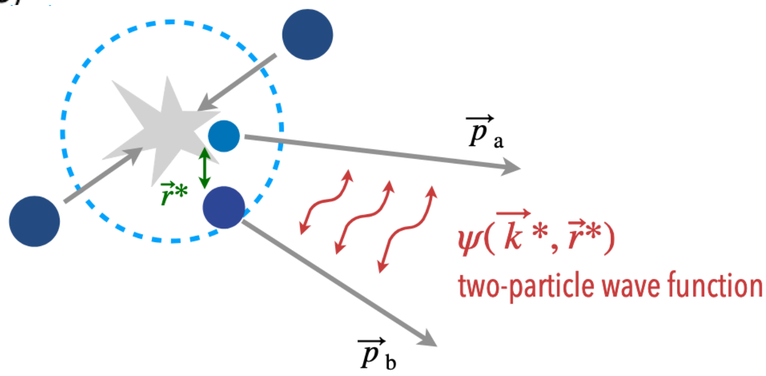


First measurements of interaction of D mesons with light-flavour hadrons: **scattering parameters governing elastic and inelastic D-π,K,p collisions**

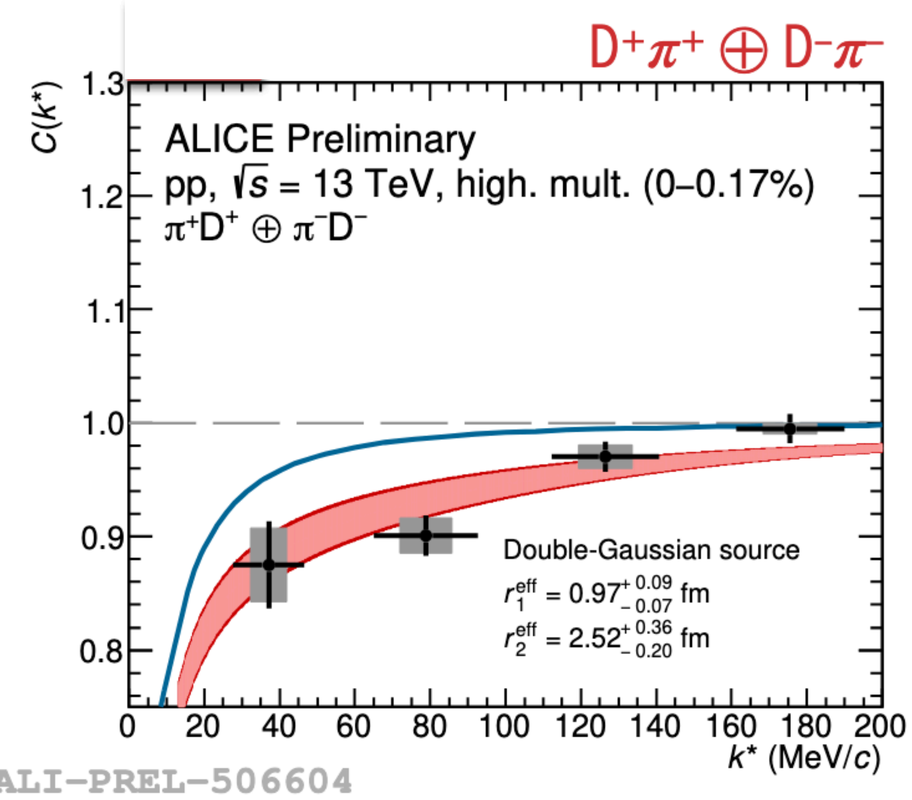
crucial ingredient for models based on charm-hadron transport in hadronic phase

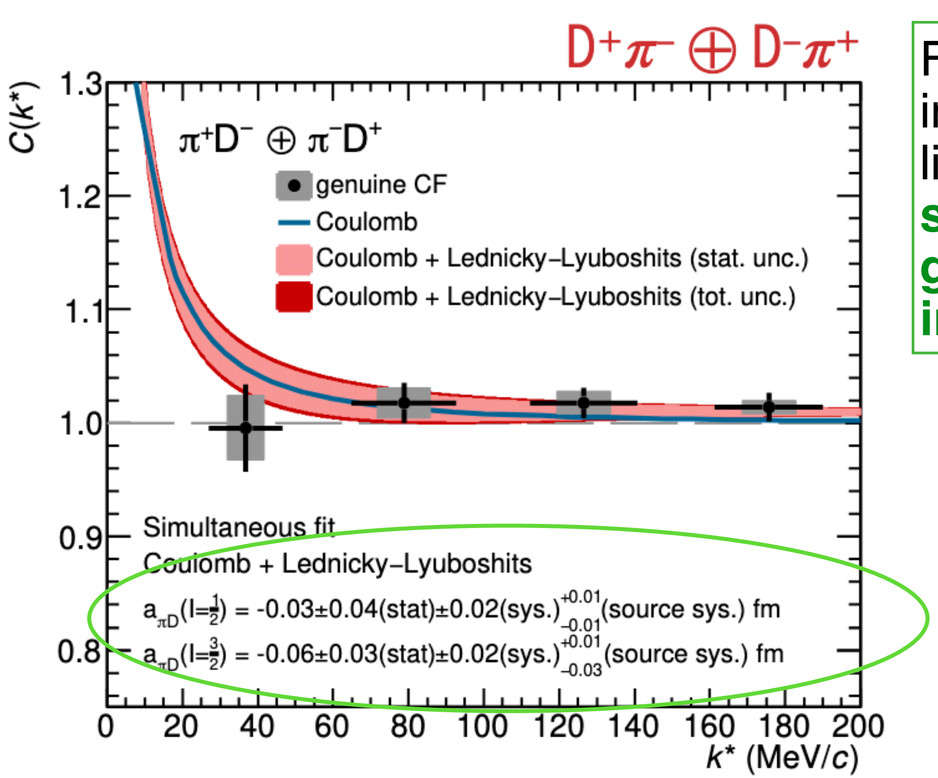
First constraint to models.

- The strong interaction is studied by means of correlation in momentum space among D-π, D-K and D-p combinations.



investigating hadronic phase with charm hadrons





First measurements of interaction of D mesons with light-flavour hadrons: **scattering parameters governing elastic and inelastic D-π,K,p collisions**

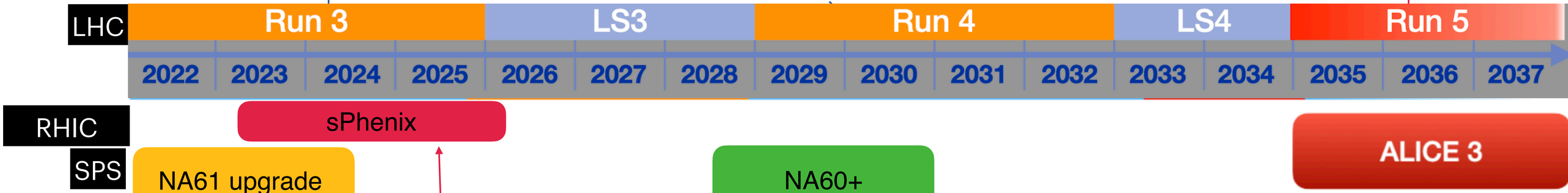
crucial ingredient for models based on charm-hadron transport in hadronic phase

measurement indicates a small rescattering of D mesons in the hadronic phase

The Future is now

- charm and beauty mesons and baryons: v_2, R_{AA}
- low p_T regime, wider η range
- D_s constraint with beauty

- Systematic measurements of multi-heavy-flavour hadrons
- $D\overline{D}$ correlations
- p-wave charmonium



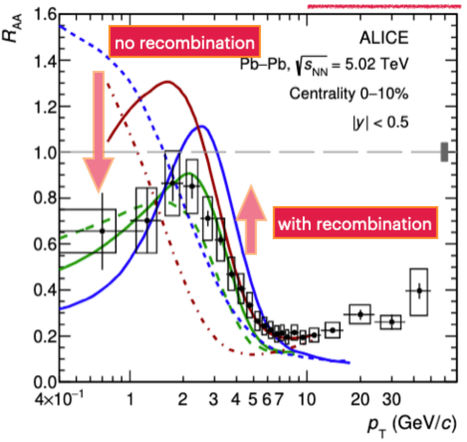
- Y spectroscopy
- open heavy flavor over full kinematic range: v_2, R_{AA}

- Onset of J/ψ suppression
- Hadronic decays of charmed mesons/baryons

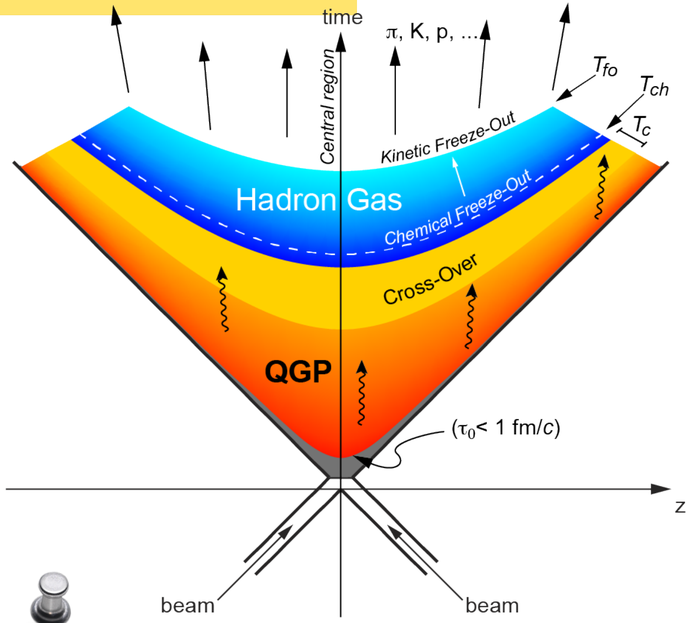
- open charm production at SPS

Improved measurements: expected to offer new constraints to models; further insights into the hot and dense medium, origin of collectivity in small systems

Conclusions

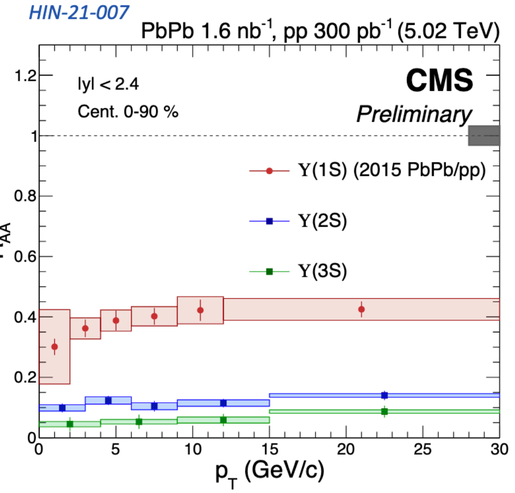


Systematic studies ongoing to disentangle **different mechanisms in the theory models to explain R_{AA}** and **v_2 shape**: good knowledge of **charm.**
More baryons to be measured in different systems

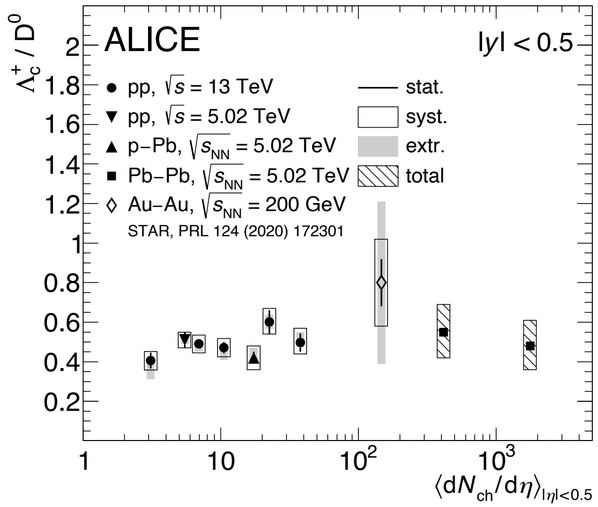


New channels accessible in the **beauty** sector in different collision systems: **less interaction with medium than charm**
Towards more constraints to D_s with beauty

studies of **baryon-to-meson ratios** as a function of multiplicity in pp: evolution of the p_T-spectra, but indication of **no enhancement of baryon-to-meson from small to large systems**



Quarkonia: interplay of recombination, energy loss and suppression in the QGP.
New measurements and comparison with models to better clarify momentum range for different contributions

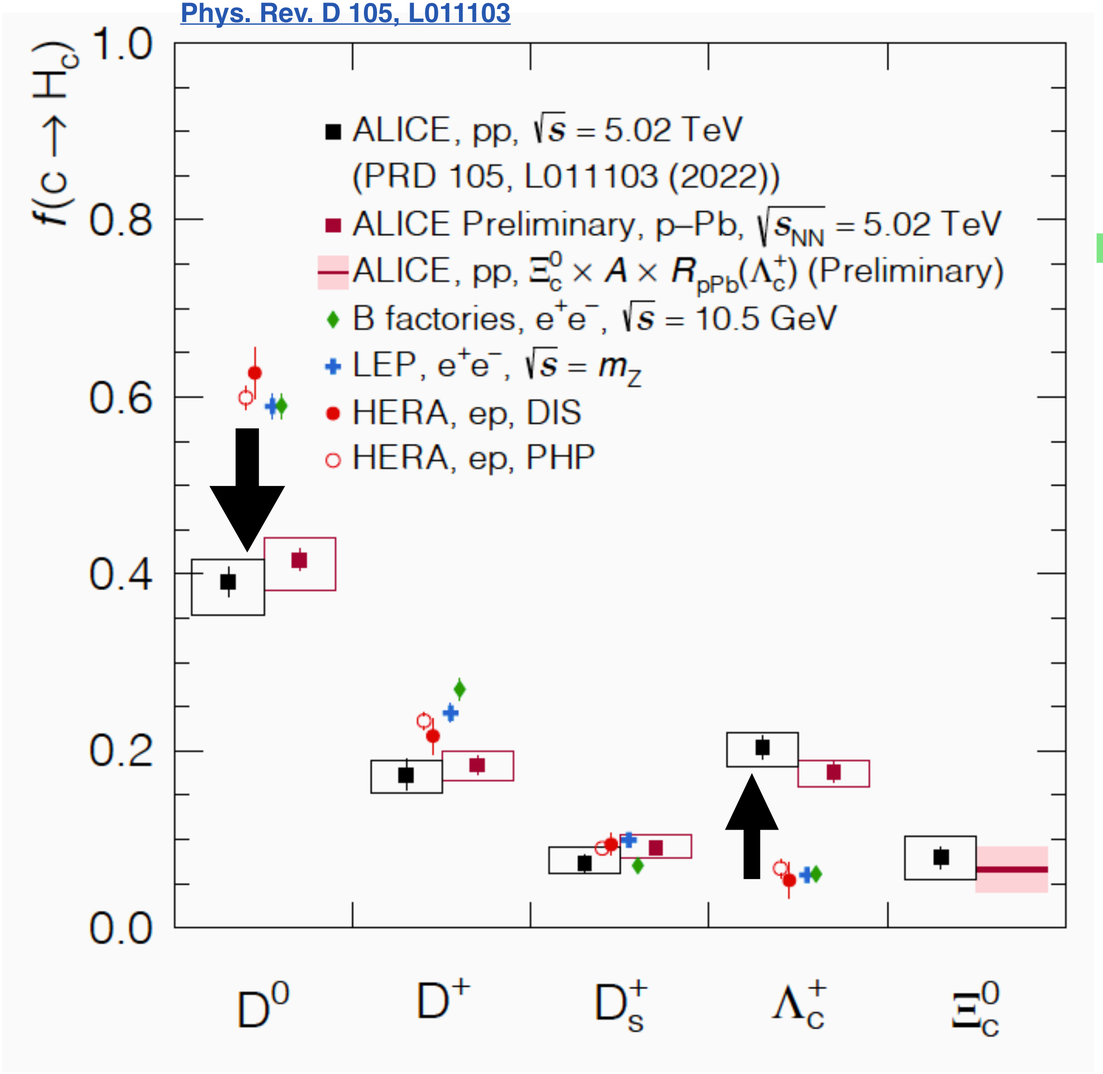


THANKS!

In particular, for the discussions and inputs to: A. Dainese, R.Arnaldi, F. Prino, E. Scomparin, A.Dubla, A.Rossi, F. Grosa, L.Bianchi, L.Micheletti, B. Trzeciak, B. Audurier, M. Fontana, D. Mitzel, M. Morello, J.Sun, M.Durham, L. An, Y. Kim, A. Stahl, S.Polikarpov, L.Gladilin, D. Perepelitsa

charm fragmentation fractions in pp, p-Pb

Phys. Rev. D 105, L011103



- New charm baryon and meson measurements down to very low pT
  - all ground states of charm hadrons measured with high precision

First measurement of charm fragmentation fractions in pp collisions

A significance deviation from e^+e^-, ep f_c—>H_c measurements observed in pp collisions

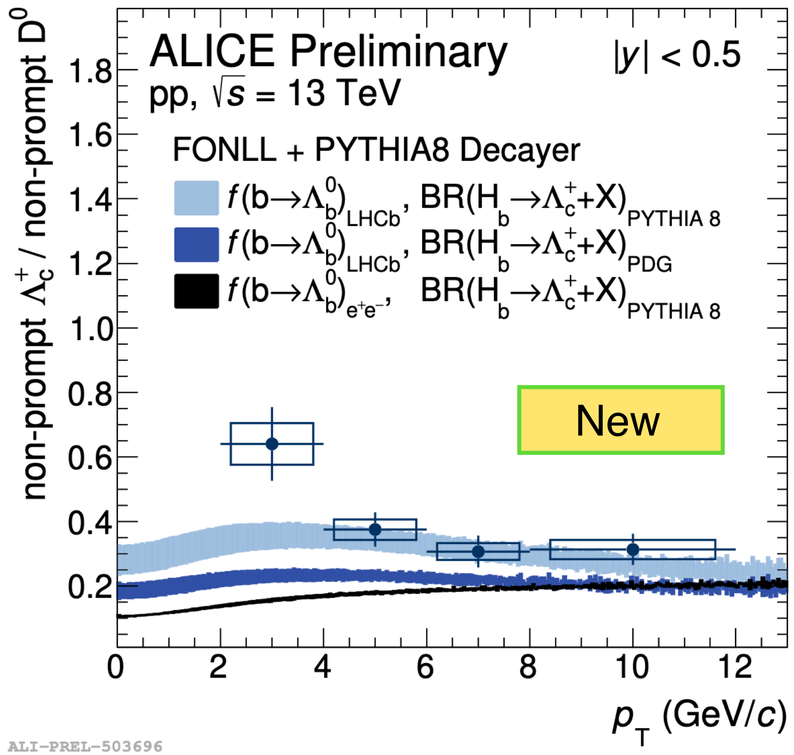
✓larger baryon-to-meson ratios wrt to pp at low momenta
✓strong pt dependence
✓different fragmentation fractions

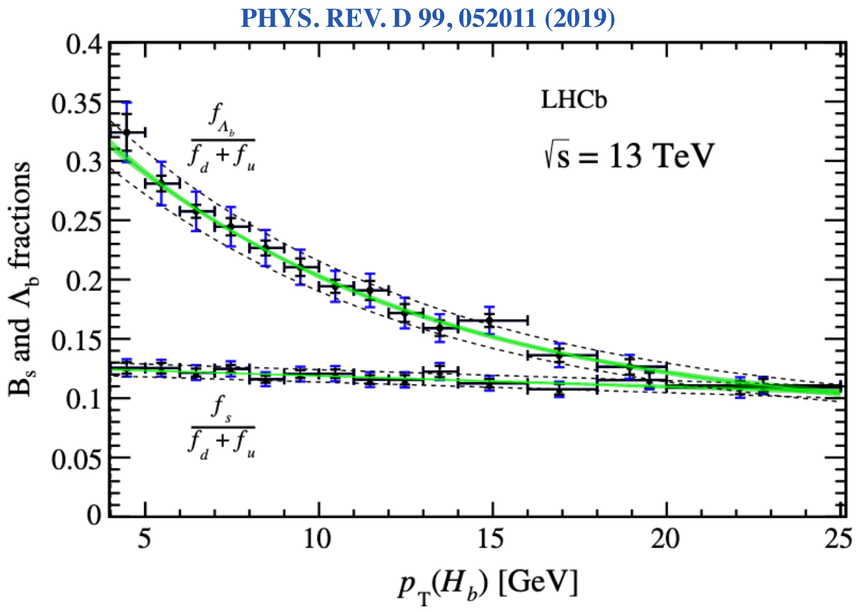
Fragmentation of charm quark is not a universal process among different collision systems:
➡ hadronic environment in pp collisions plays a role!

Fragmentation functions universality violated already in pp collisions
Multiple parton interactions in pp build a system rich of quarks or gluons, dense enough to alter hadronisation w.r.t. e_+e

Hadronisation: beauty baryons/meson in small systems

(B. Audurier 7Apr)



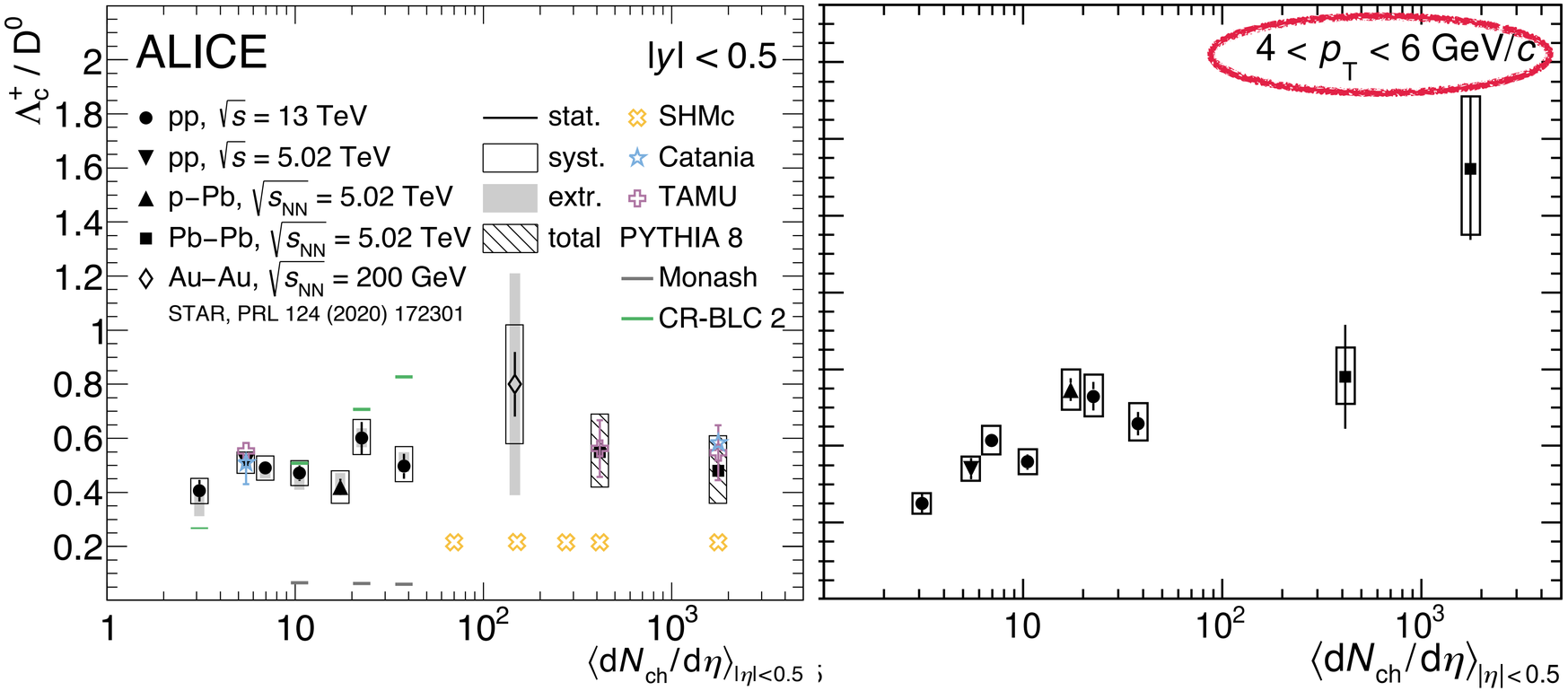


Fragmentation of beauty: first measurements of non-prompt Λ_c over non-prompt D^0 in pp and p-Pb collisions:

- FONLL + Pythia 8 and fragmentation fraction f_c—>Λ_b measured by LHCb (Phys. Rev. D 100, 031102(R))
  - **predictions with f_c—>Λ_b measured at e^+e^- underestimate data**
- suggest similar trend vs p_T as for prompt Λ_c/D^0: hint of larger enhancement at low p_T
- similar p_T shape as measured by LHCb for Λ_b/B
  - caveats: different p_T for non-prompt Λ_c and Λ_b

beauty fragmentation fractions for baryons different wrt to e^+e^- measurements

Charm baryon/meson: from small to large systems



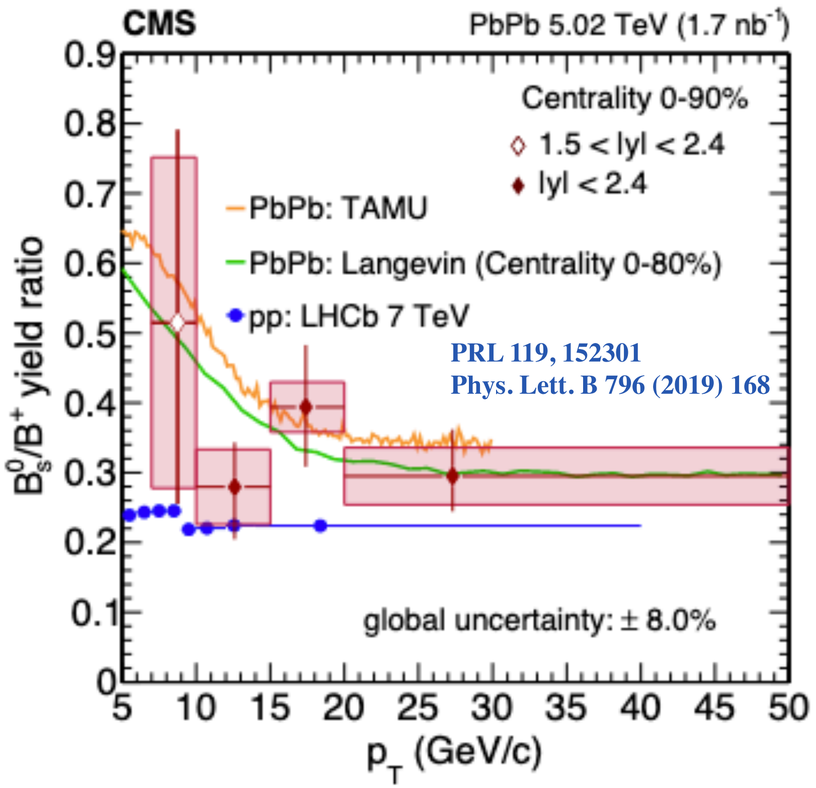
L. Vermunt, 7 Apr
L. Dello Stritto, 7Apr

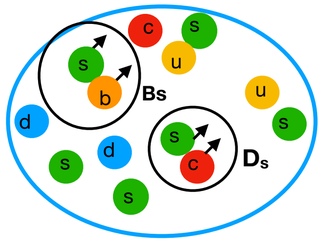
Reproduced by fragm+recomb and SHM predictions (including new charm-baryon states for the latter)

Few models available in small systems to investigate HF production/hadronisation vs multiplicity: **further theoretical developments also required**

—> p_T -integrated yields for $p_T > 0$ crucial measurements

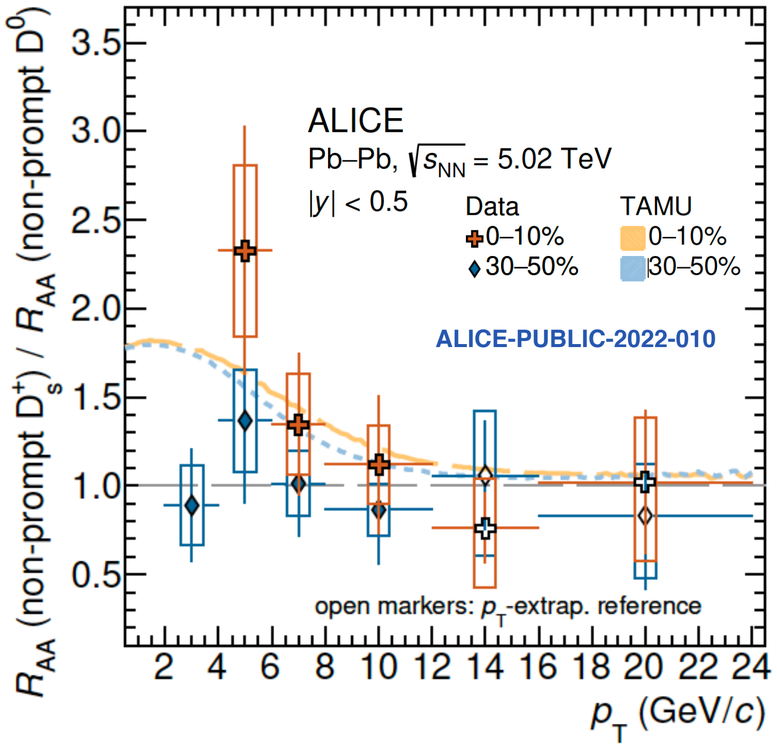
Hadronisation: beauty non-strange and strange mesons





hadronization of **beauty quarks** in pp and Pb-Pb: need precise measurements

T. Sheng, 7 Apr
X.Peng 7Apr



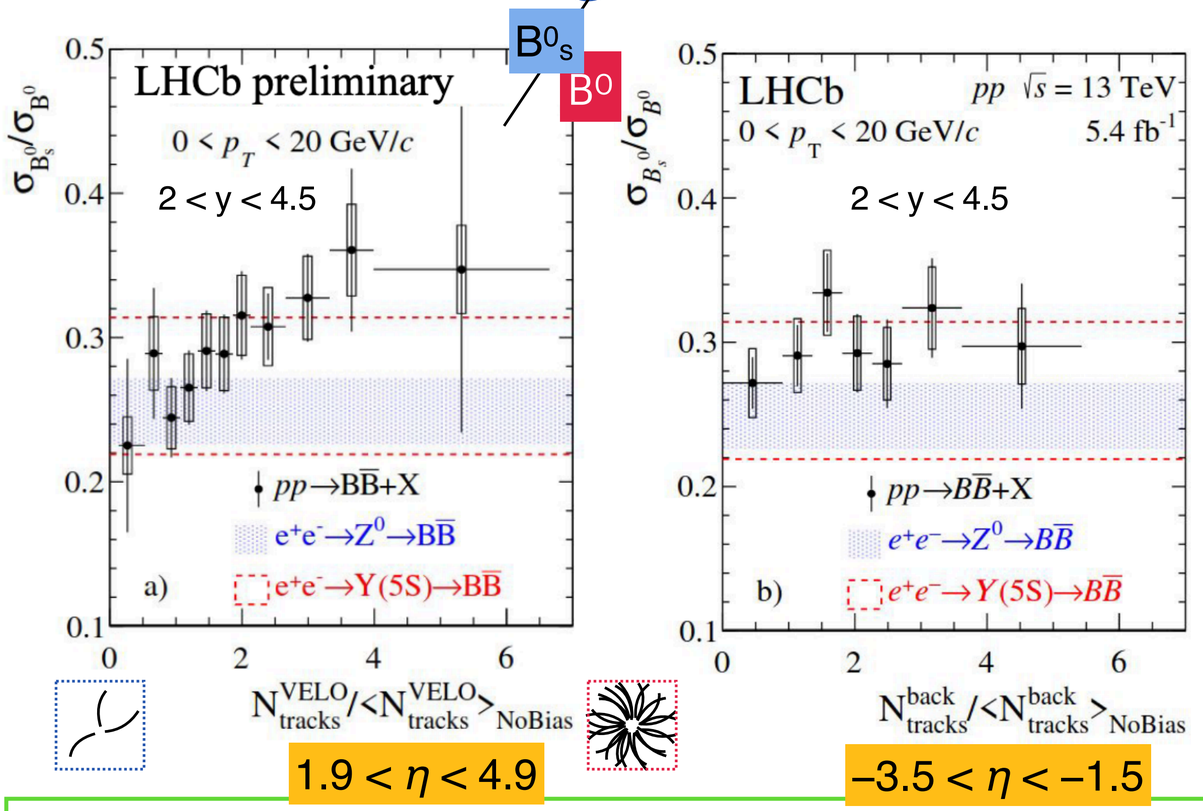
B^0_s/B^+: suggestion for increased B_s yield relative to B^+

Non-prompt D^0 and non-prompt D_s in Pb-Pb collisions

- Hint for increased non-prompt D_s yield relative to non-prompt D^0
- **Non-prompt D_s originating 50% from B_s decays and 50% from B^0 and B^+ decays**

models that include parton recombination predict an enhancement of yield ratios at low momentum

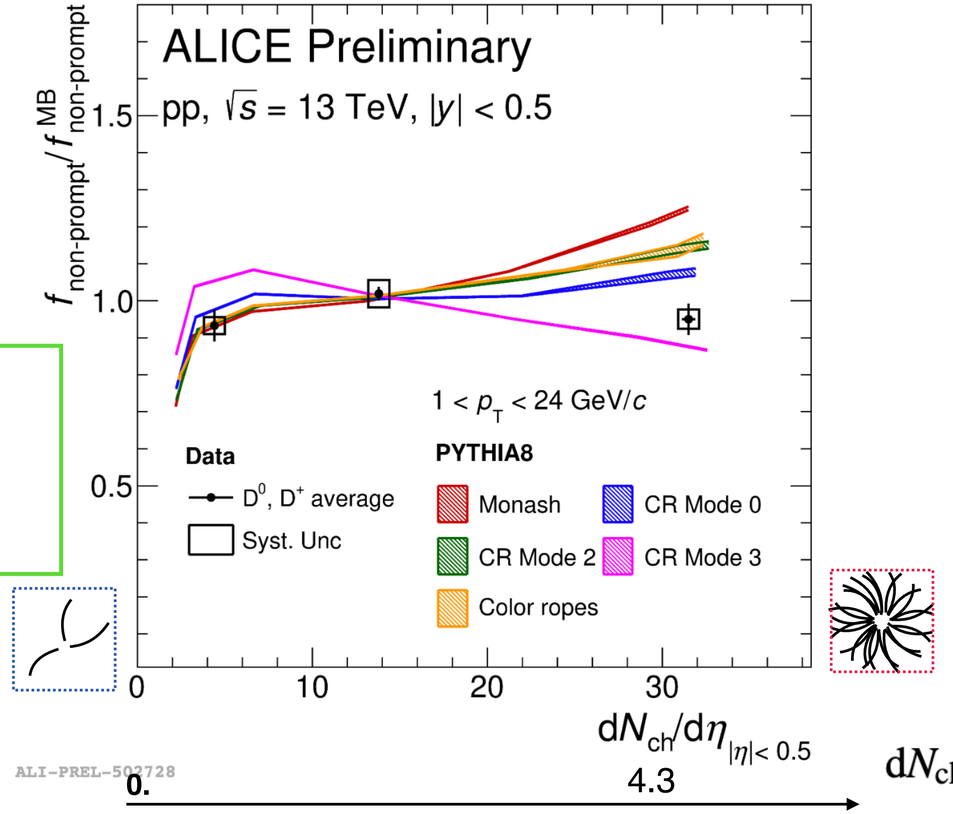
Strange charm and beauty mesons vs multiplicity



Hint of B_s/B^0 increase with increasing multiplicity

for $0 < p_T < 20$ GeV/c: no significant increase when different multiplicity estimator is used.

local effect? does depend on the particle density measured in the same rapidity interval as the B?

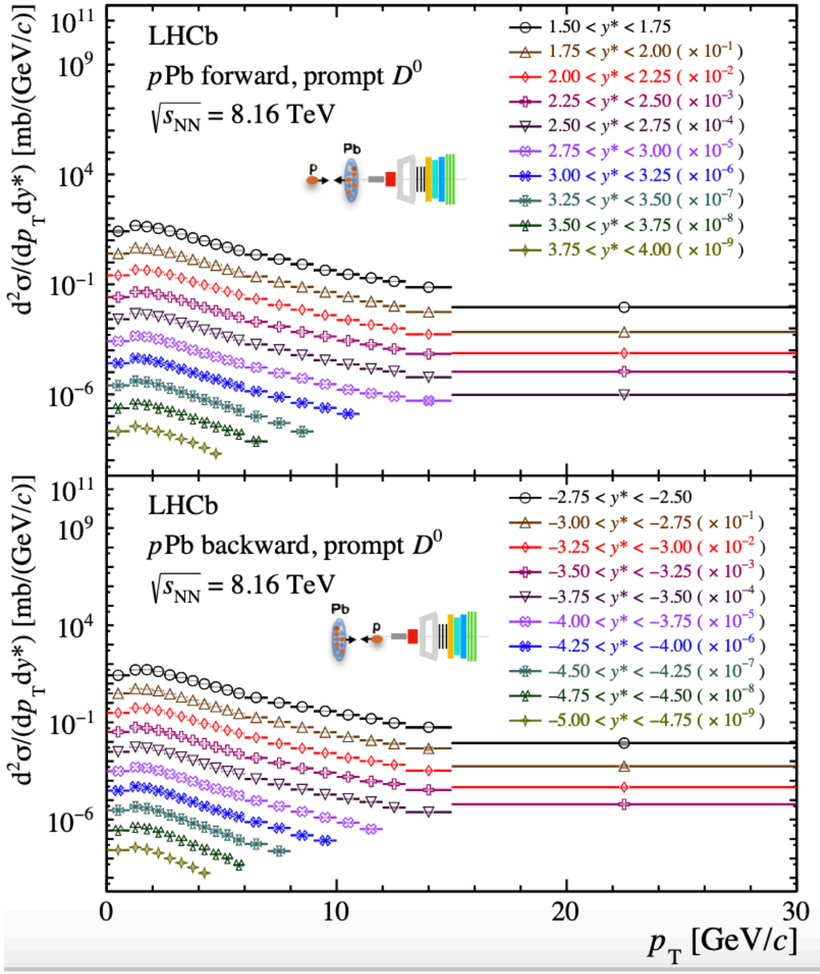


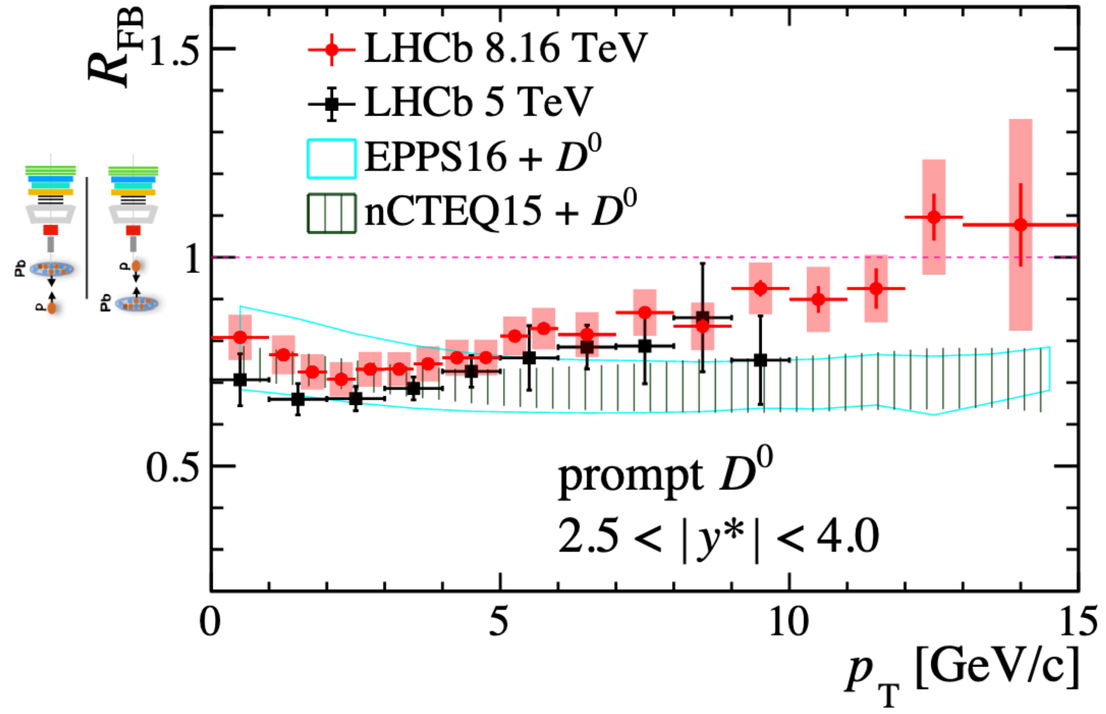
- **D^+_s/D^0 (backup) and non-prompt D meson fractions do not show dependence on multiplicity**
  - similar multiplicity ranges as measured by LHCb
  - described by Pythia predictions

B. Audurier 7Apr
L. Dello Stritto 7Apr
S. Perrin 6Apr

New Open-charm production in pPb collisions

LHCb-PAPER-2022-007





- Tension between data and theory predictions at high p_T.
- Additional effect required?

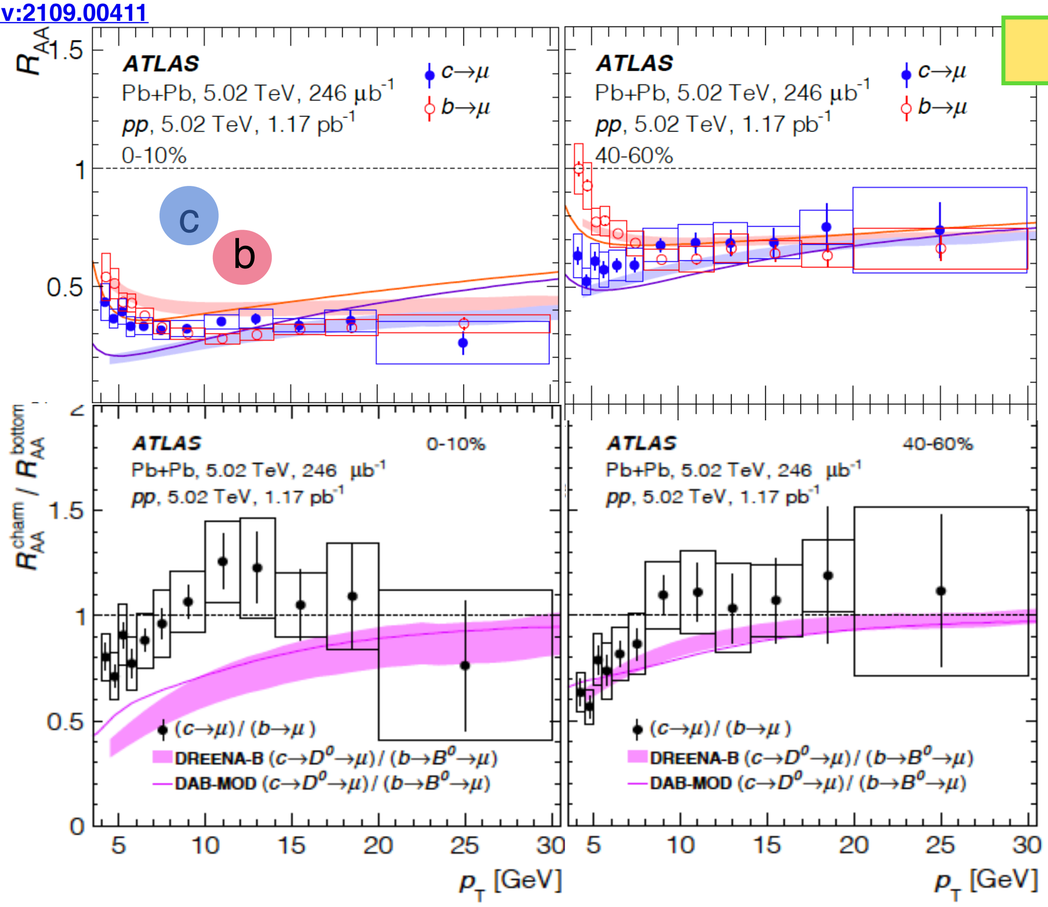
B. Audurier 7Apr

8

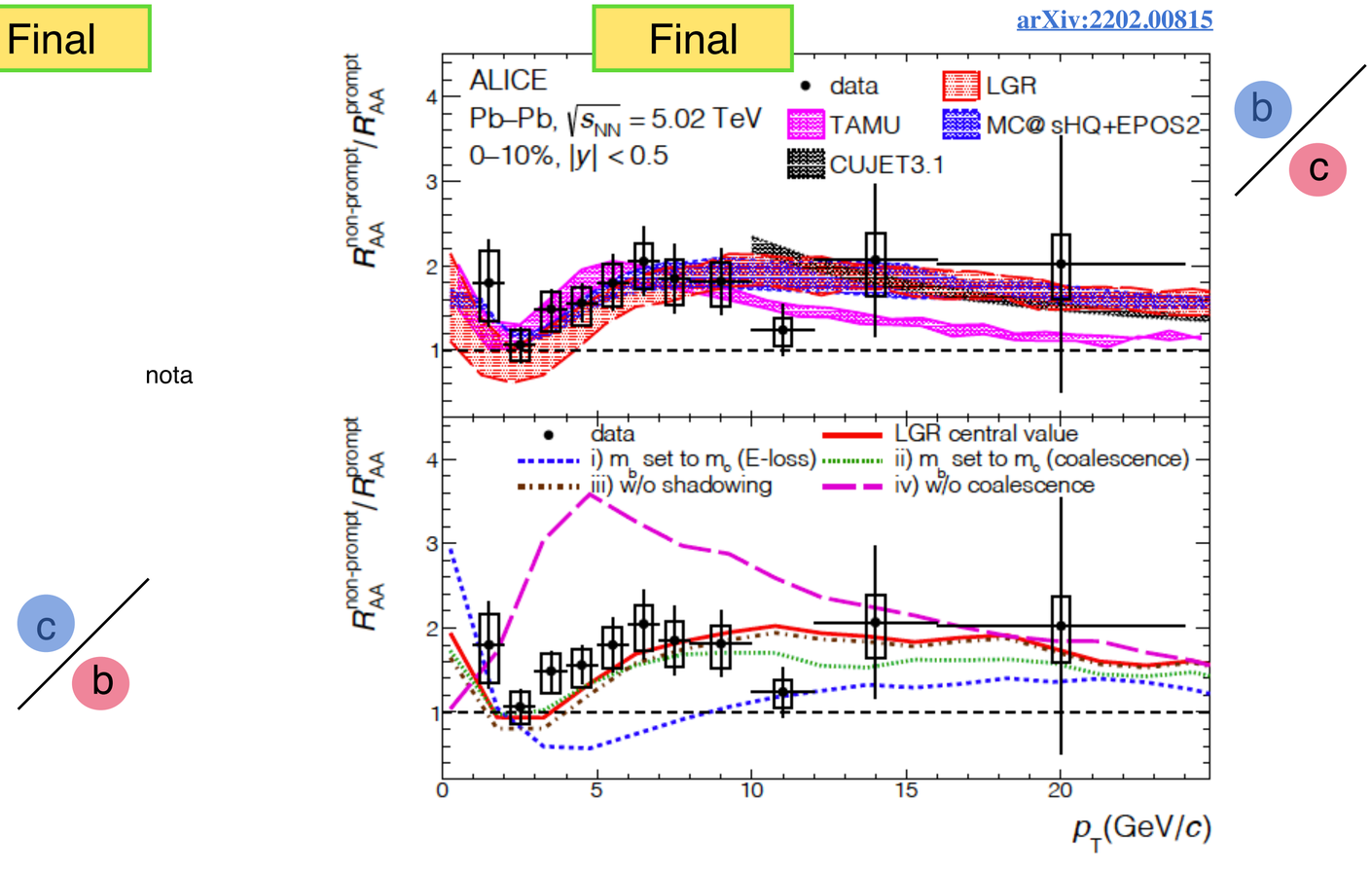
ATLAS: See Q.Hu 7Apr

beauty vs charm quark in QGP

arXiv:2109.00411



nota



beauty/**charm** R_{AA} ratio: via non-prompt/prompt D or leptons from semi-leptonic decays of charm and beauty:

- **Smaller beauty suppression:** for $p_T > 4$ GeV/c (D mesons) and $p_T > 10$ GeV/c (HF leptons): **beauty quark lose less energy than charm quark in the QGP due to the large mass**

Heavy flavor v_2 from CMS

Charged hadrons
Phys. Lett. B 776 (2017) 195

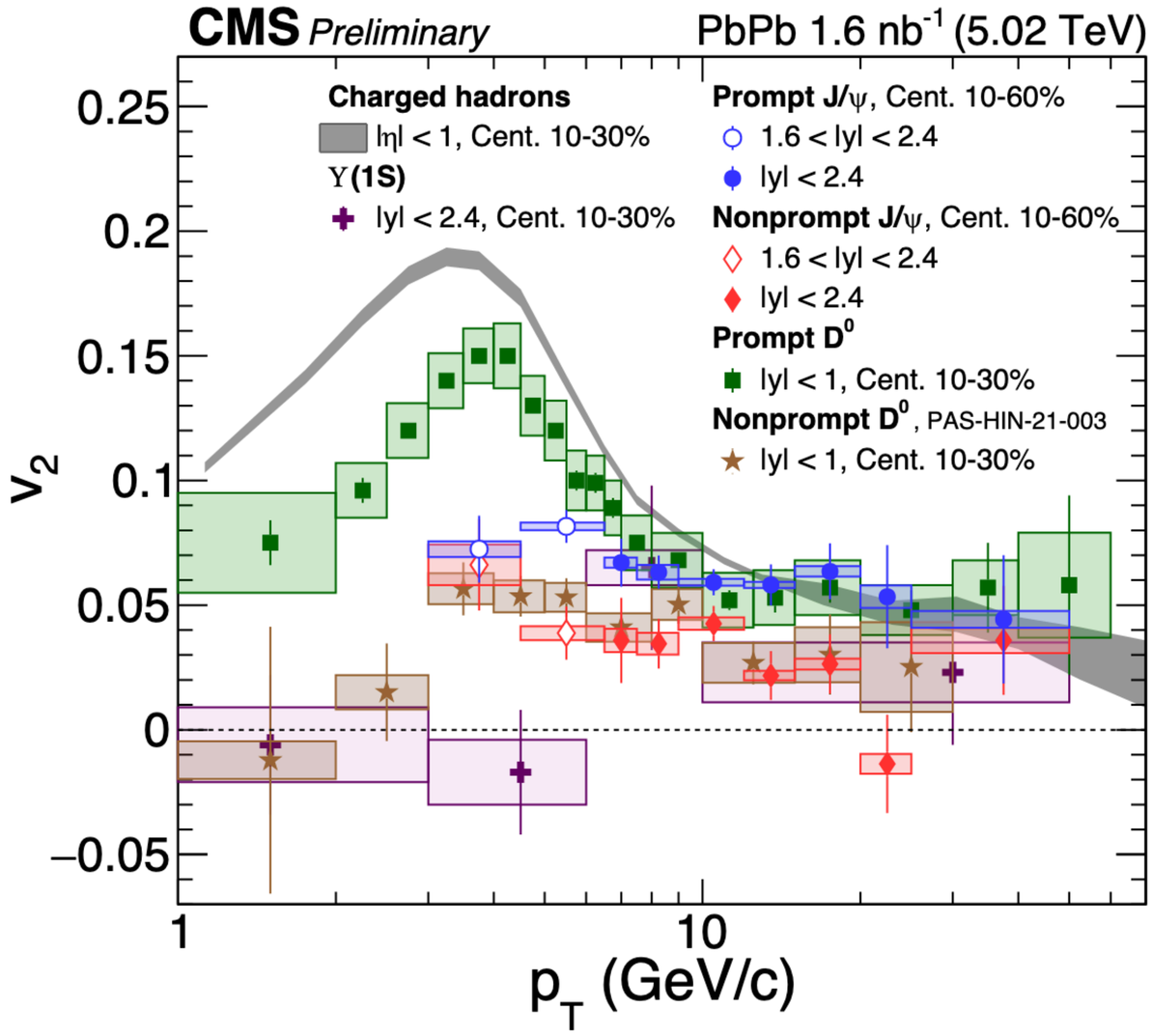
Prompt D^0
Phys. Lett. B 816 (2021) 136253

Nonprompt D^0
CMS–PAS–HIN–21–003

Prompt J/ψ
CMS–PAS–HIN–21–008

Nonprompt J/ψ
CMS–PAS–HIN–21–008

Υ(1S)
CMS–PAS–HIN–21–008



Statistical hadronisation of charm

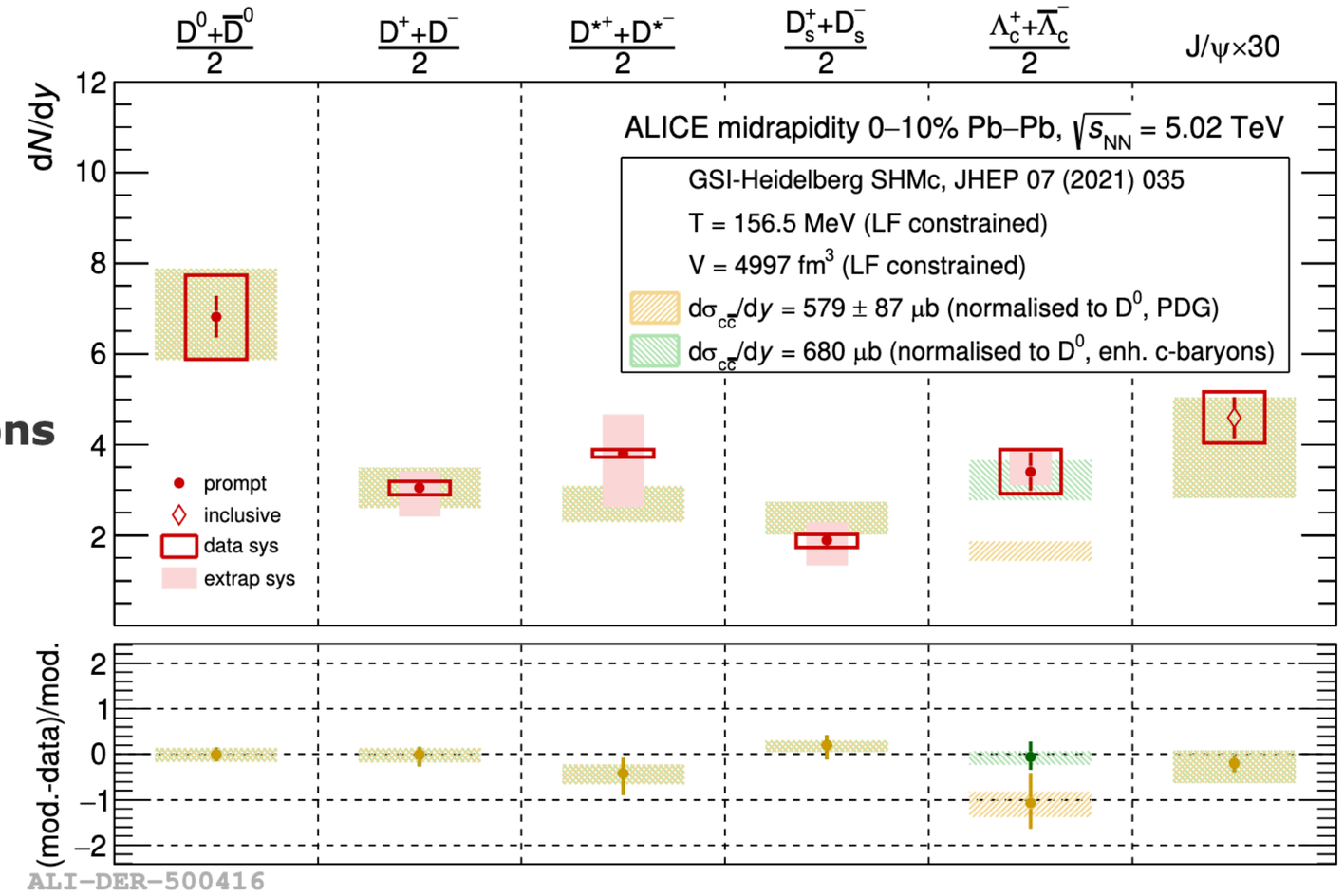
SHMc (charm quarks fully thermalised in the QGP)

→ Distributed into hadrons at phase boundary according to **thermal weights**

Measured yields of **open-charm mesons compatible** with SHMc

Measured yield of Λ_c^+ **underestimated**

→ Described in case of an enhanced charm-baryon resonance spectrum

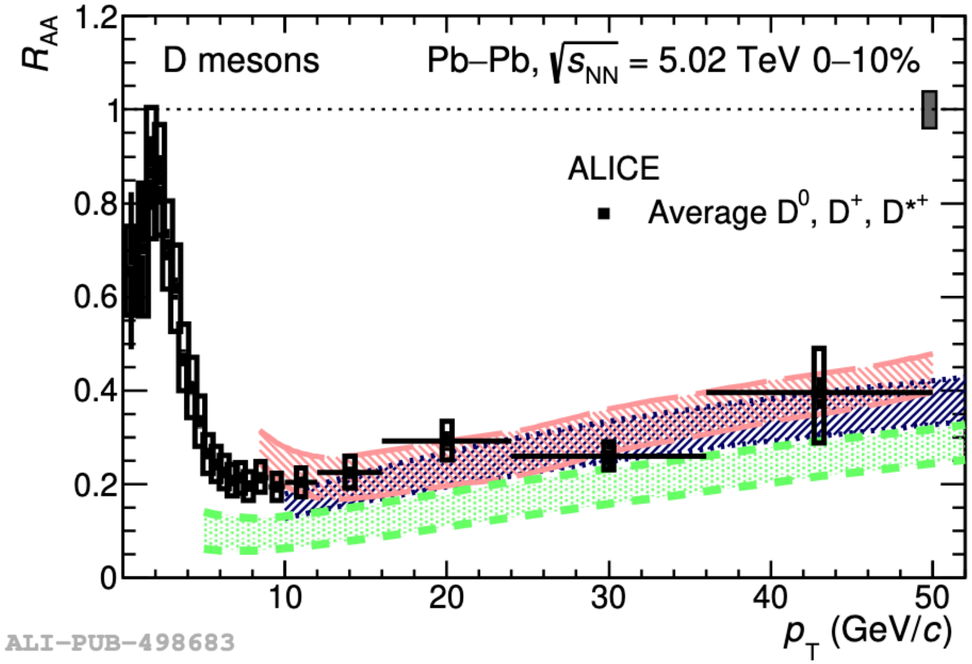


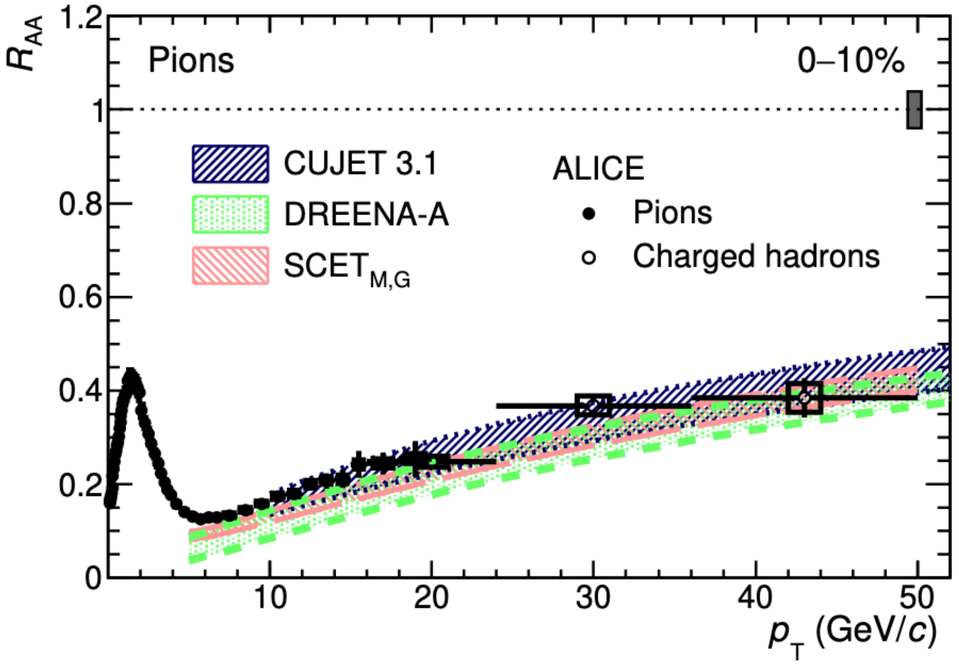
SHMc: JHEP 07 (2021) 035

Charm-quark transport models: ingredients

	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**.





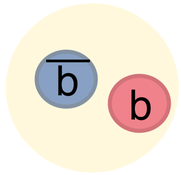
Perturbative QCD calculations describe reasonably well the measured R_{AA}, "confirming"

- the **quadratic path length dependence** of radiative energy loss;
- the expected mass dependence due to the **dead-cone effect**.

	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF	
CUJET 3.1	✅	✅	❌	✅	✅	opacity expansion model
DREENA-A	✅	✅	❌	✅	❌	
$SCET_{M,G}$	✅	✅	❌	❌	✅	soft-collinear effective theory

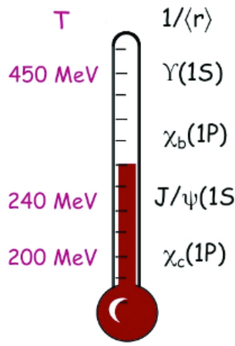
JHEP 01 (2022) 174

Quarkonia suppression in the QGP: R_{AA}

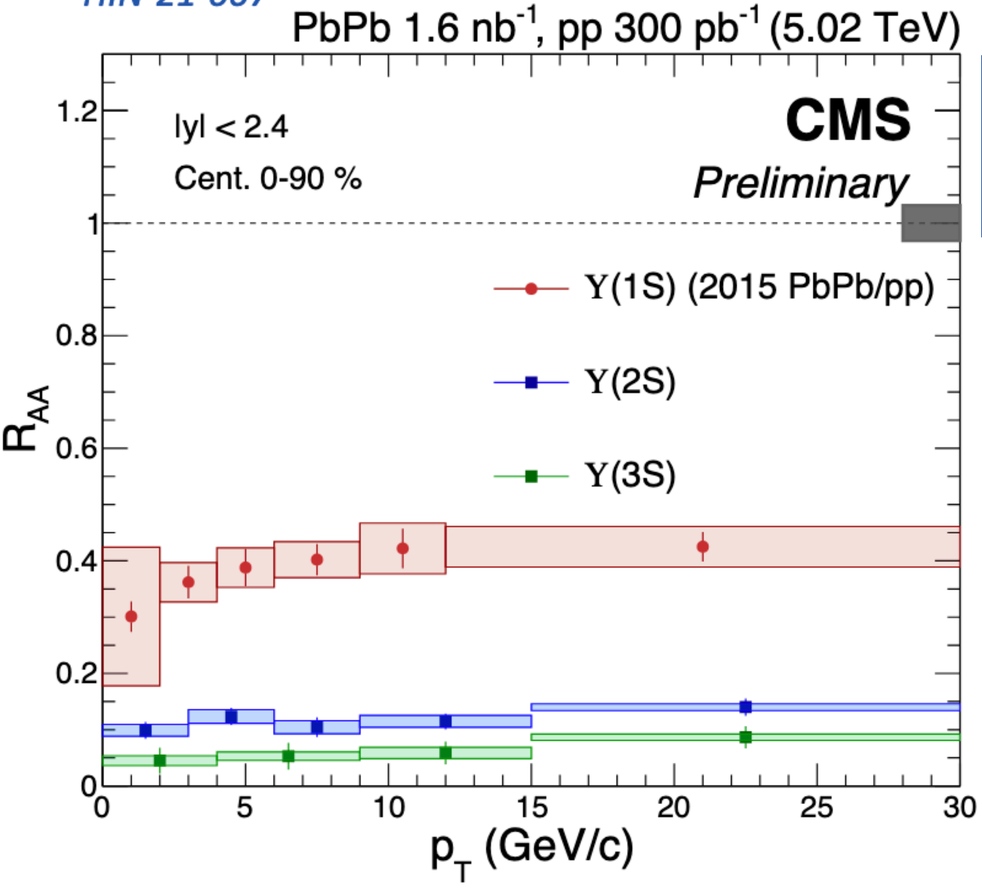


$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

Probing the sequential suppression



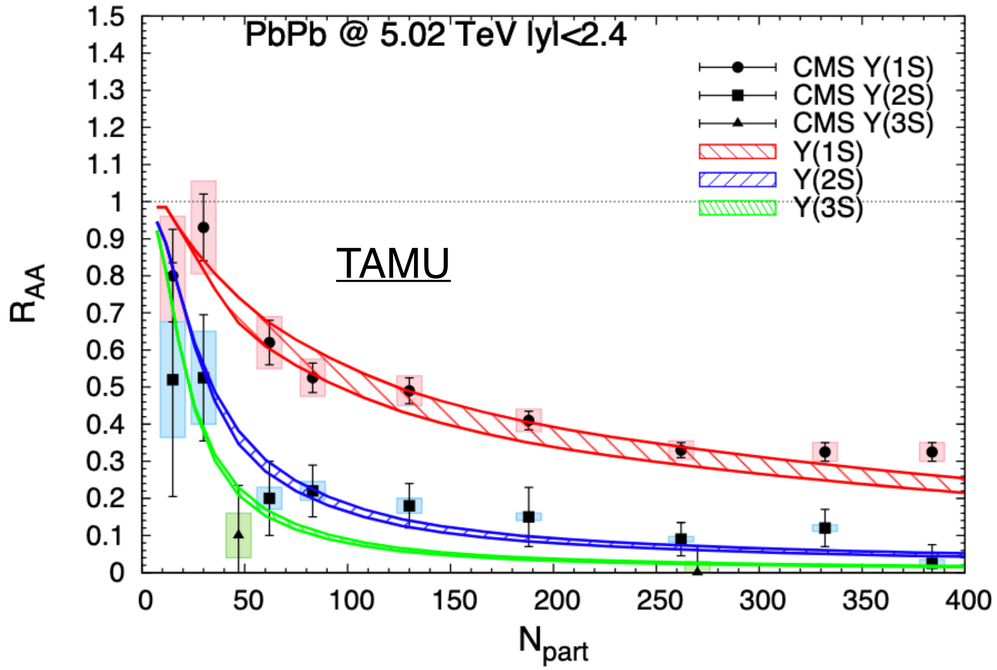
HIN-21-007



Bottomonium: First Υ(3S) measurement in Pb-Pb

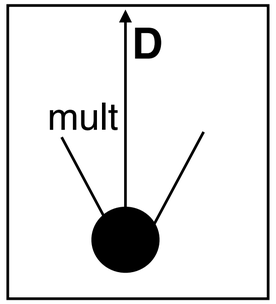
- very clear ordering of R_{AA}: ordering like sequential melting picture
- no significant p_T dependence of R_{AA}

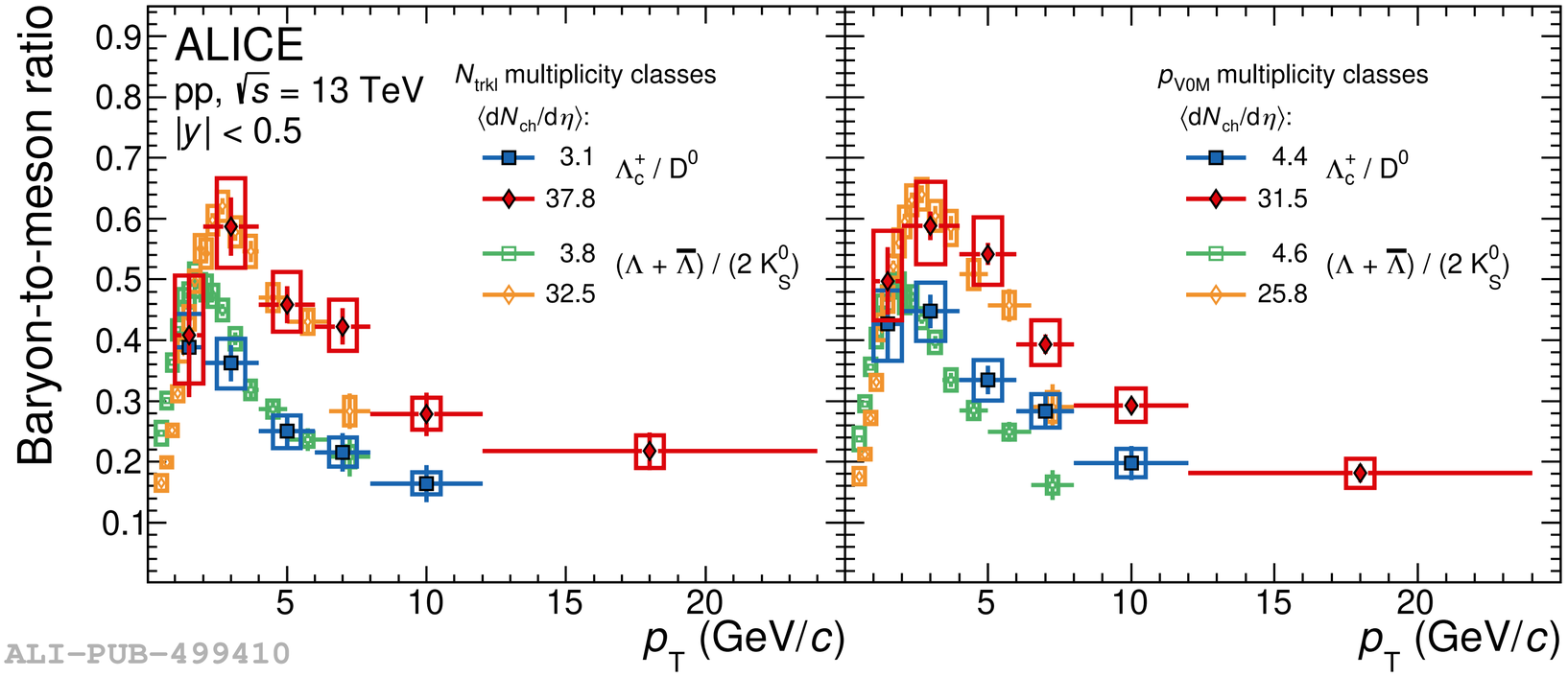
- $\frac{R_{AA}^{(3S)}}{R_{AA}^{(2S)}} \approx 0.5$



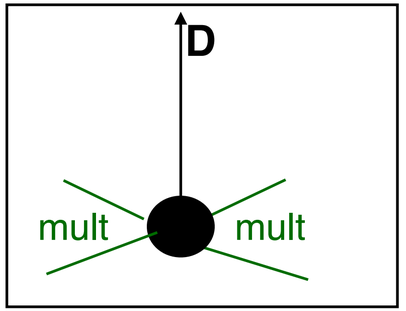
Thur 9:40 AM S. Lee

Λ^+_c/D^0 vs Λ/K^0_S: heavy-flavour vs light-flavour yield ratios





ALI-PUB-499410

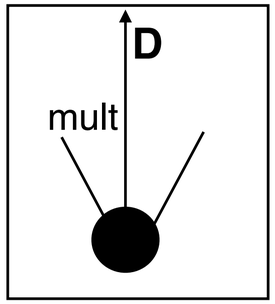


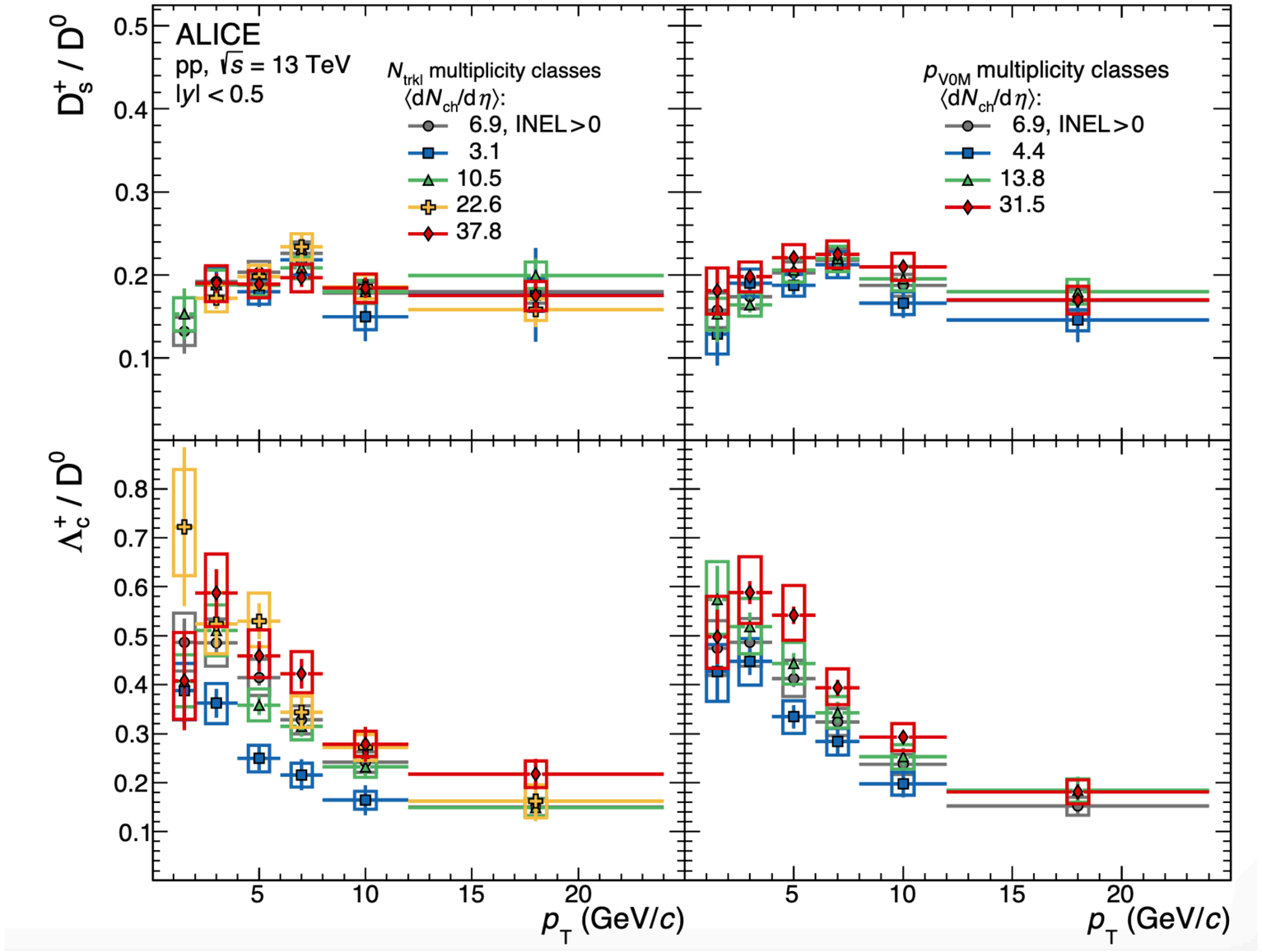
−3.7 < η < −1.7 and 2.8 < η < 5.1

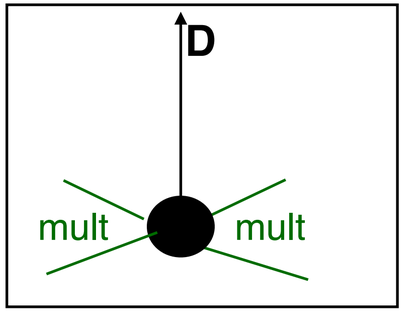
Similar trend of baryon-to-meson yield ratios as in the heavy-flavour and light-flavour sector, both in MB pp collisions and in different charged-particle multiplicity intervals:

- Similar shift of the peak toward higher momentum, with increasing multiplicty? —> potential common mechanisms for LF and HF baryons formation

D_{+s}/D^0 vs multiplicity

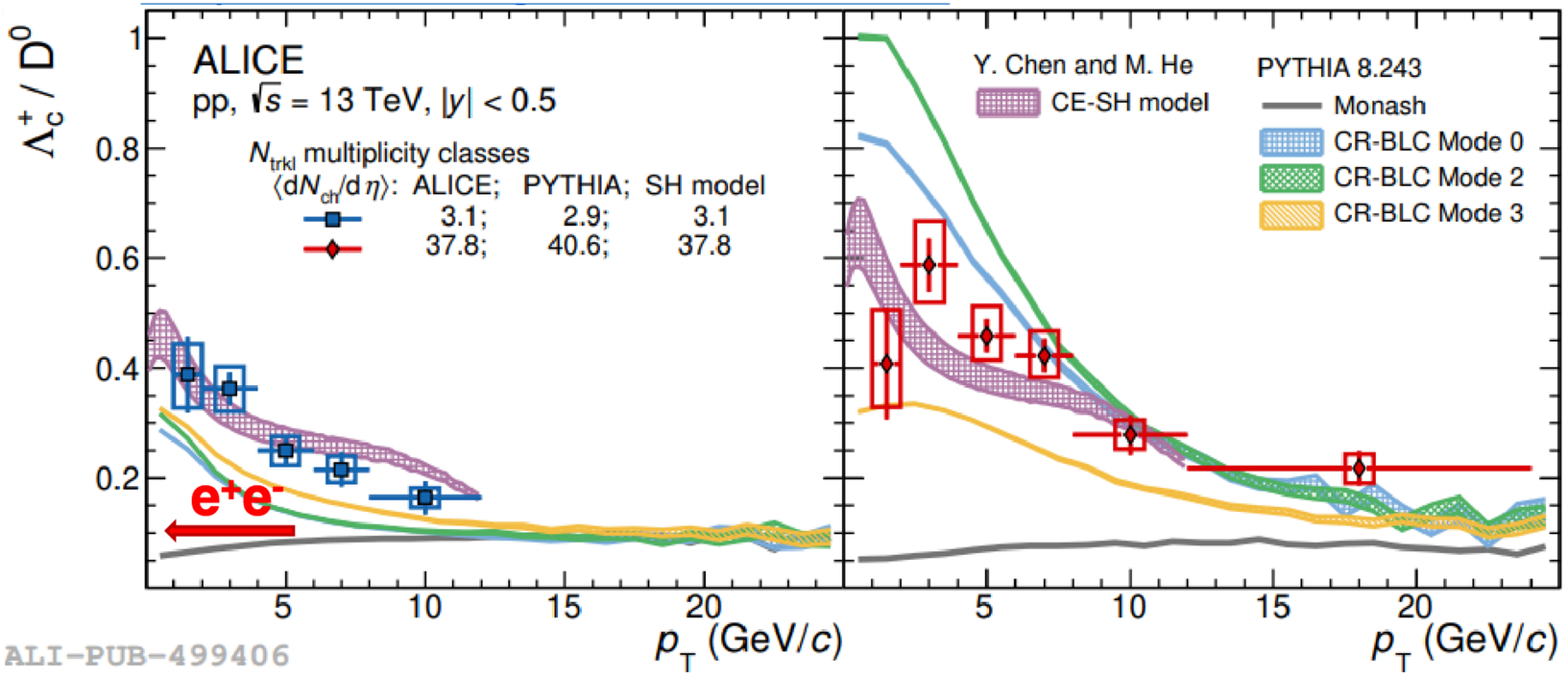






$-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$

Charm baryon/meson: from small to large systems



Described by:

- Pythia with CR Beyond Leading Color (junctions to enhance baryon formation) JHEP 08 (2015) 003
- SH model with **Multiplicity dependence** derived from **reduced volume size towards smaller multiplicity.**

Phys.Lett.B 815(2021) 136144

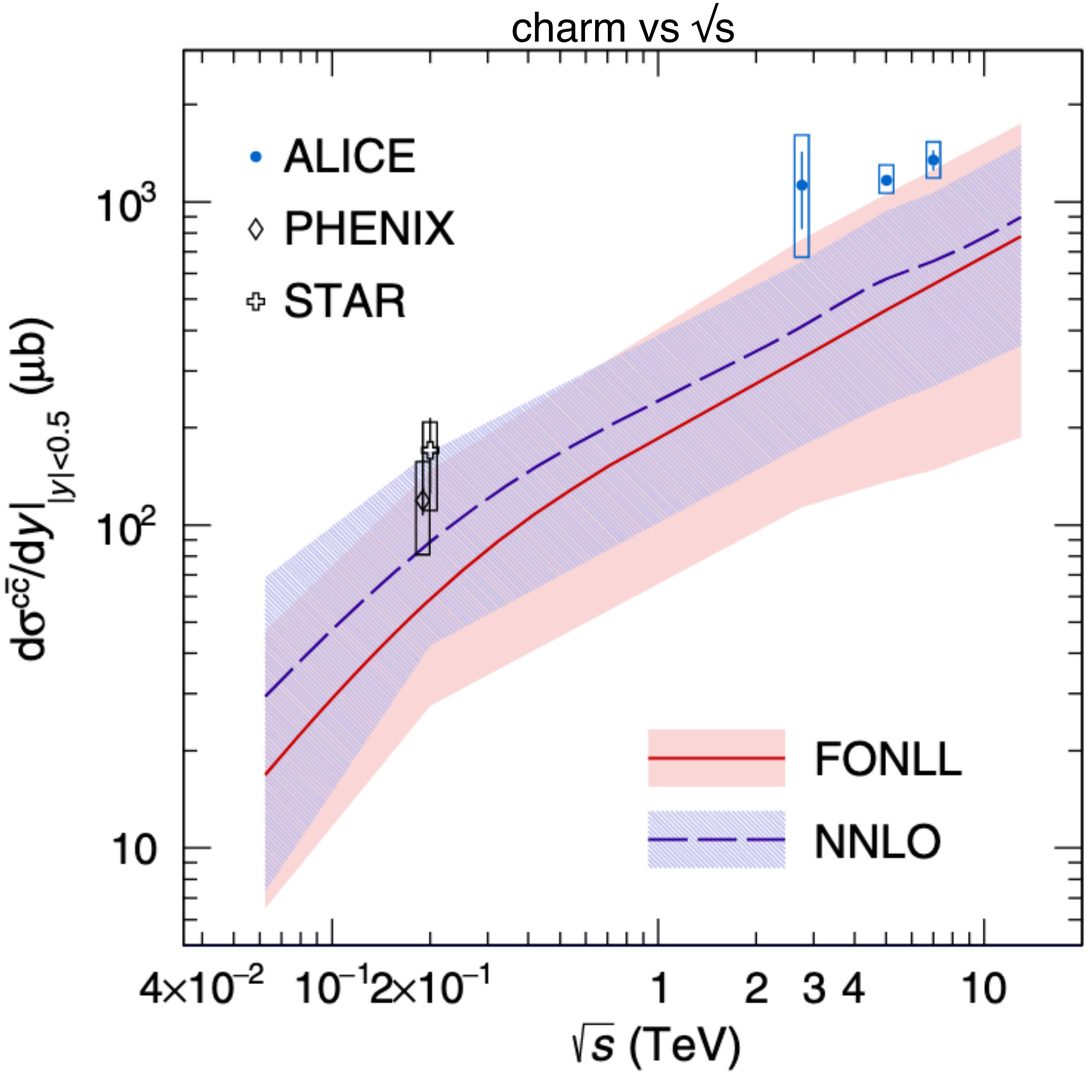
Collective effects in high-multiplicity pp and pPb collisions, significant spectra modification in high-multiplicity pp collisions!

What is the origin of these observations in high-multiplicity small system?

Total charm production cross section: pp, Pb-Pb

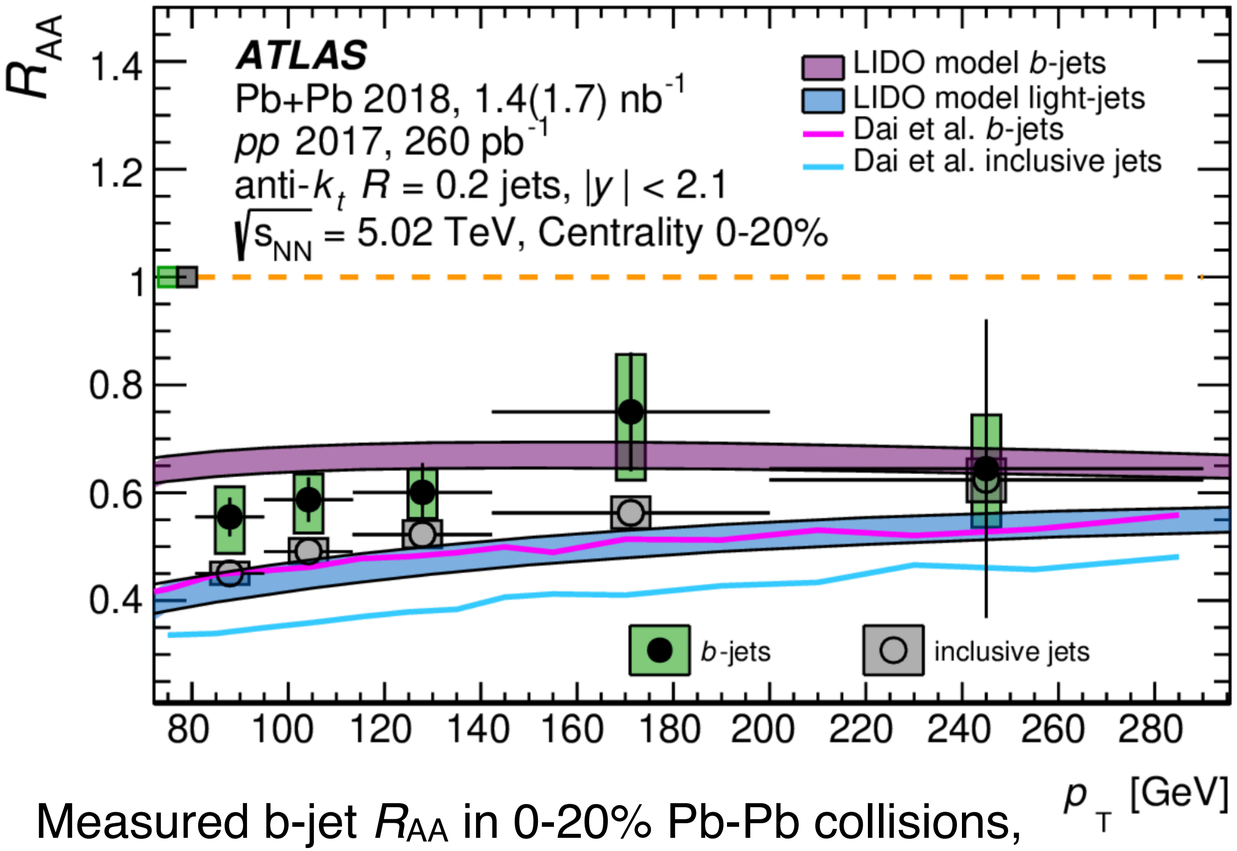
- New charm baryon and meson measurements down to very low pT
  - all ground states of charm hadrons measured with high precision

total charm cross section including all measured charm hadron ground states
• 40% higher including charm-baryon measurements



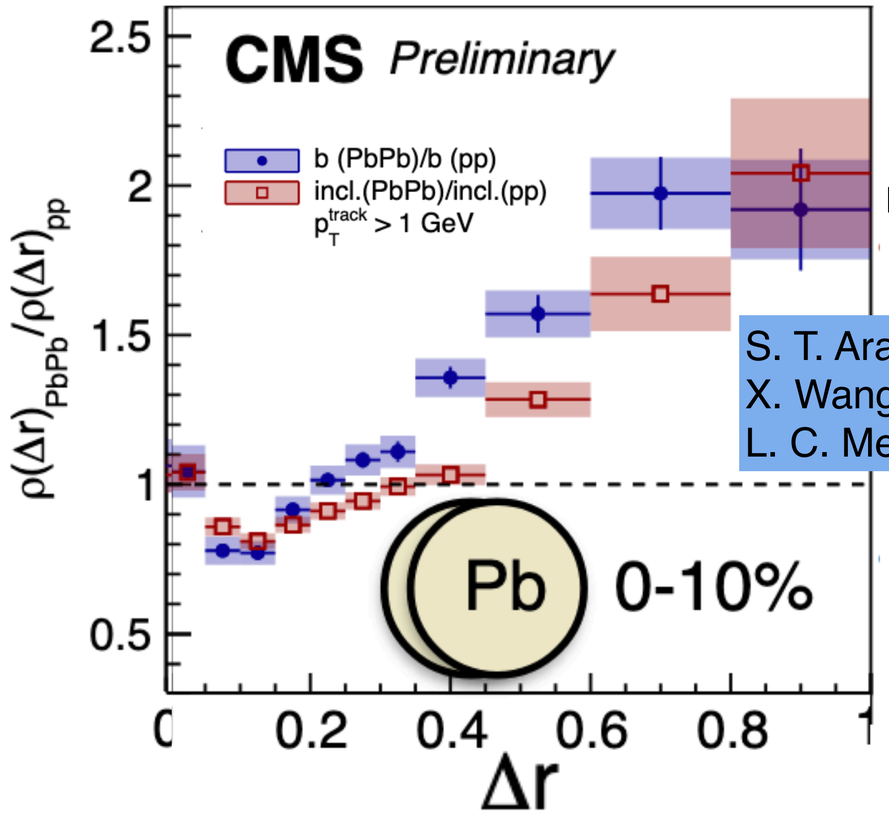
b-jet R_{AA}

Study in-medium color/mass dependent energy loss and modification of internal jet sub-structure with heavy-flavour jets



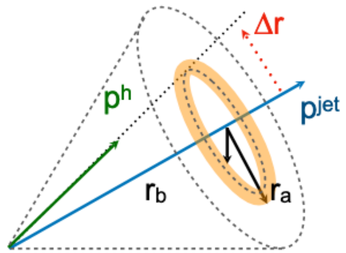
Measured b-jet R_{AA} in 0-20% Pb-Pb collisions, compared to inclusive jets

in central Pb+Pb, b-jets are less suppressed than inclusive jets



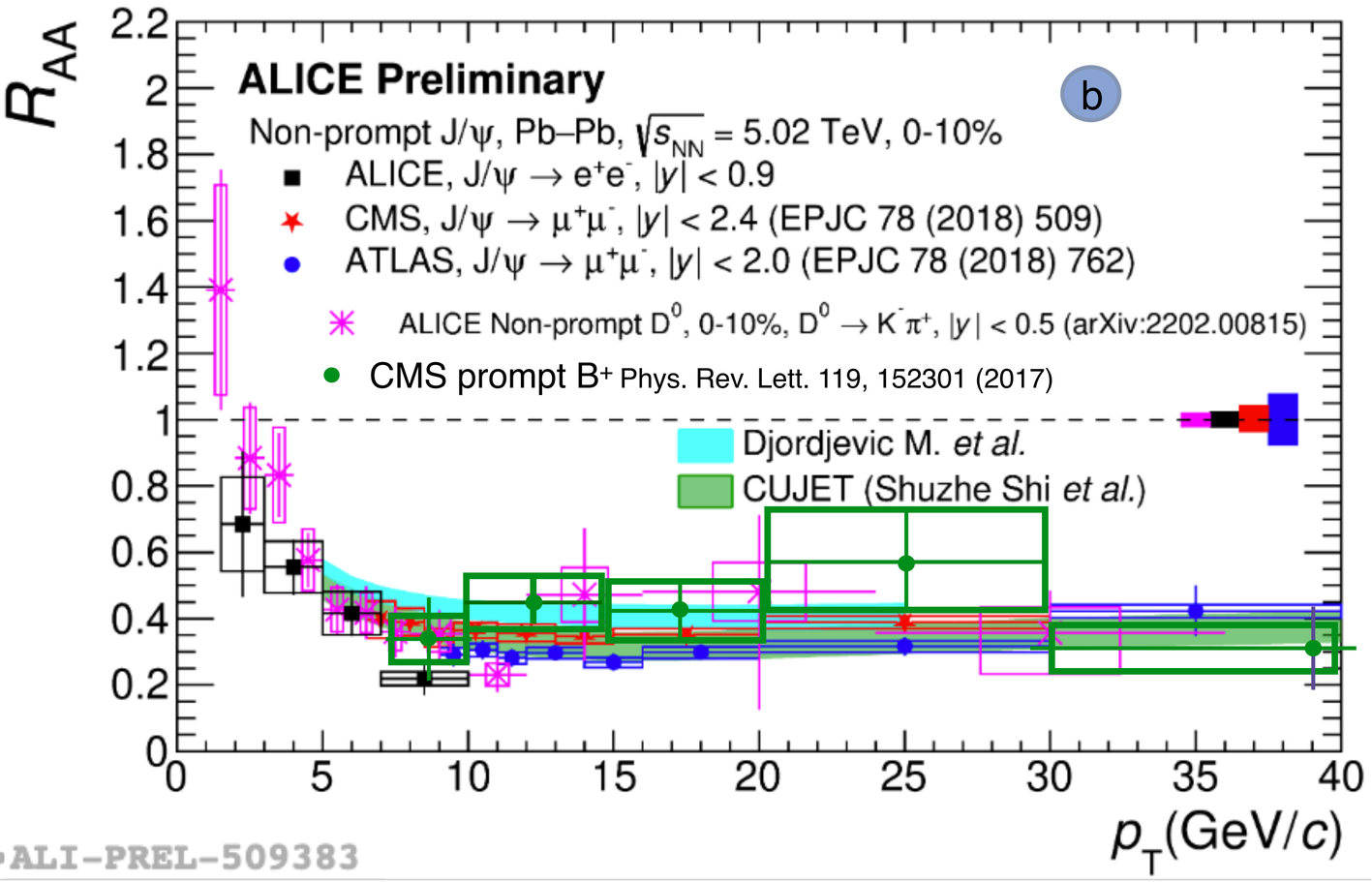
PAS-HIN-20-003

S. T. Araya (7Apr, 16:50)
X. Wang (6Apr 3:20)
L. C. Mendez 8 Apr



Enhancement/depletion of constituent hadrons of jets as a function of the distance. b-jet: broader in Pb-Pb than in pp. **Relative modification of b jets is slightly stronger than that of inclusive jets** (redistribution of the beauty mesons with respect to the jet axis)

Open heavy flavour energy loss: colour-charge and quark-mass dependence



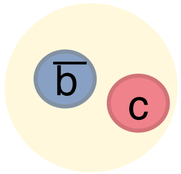
T. Sheng., 7Apr
J.A.Saetre 7Apr
L. Vermunt 7Apr

precise measurements of full decay topology of beauty hadrons

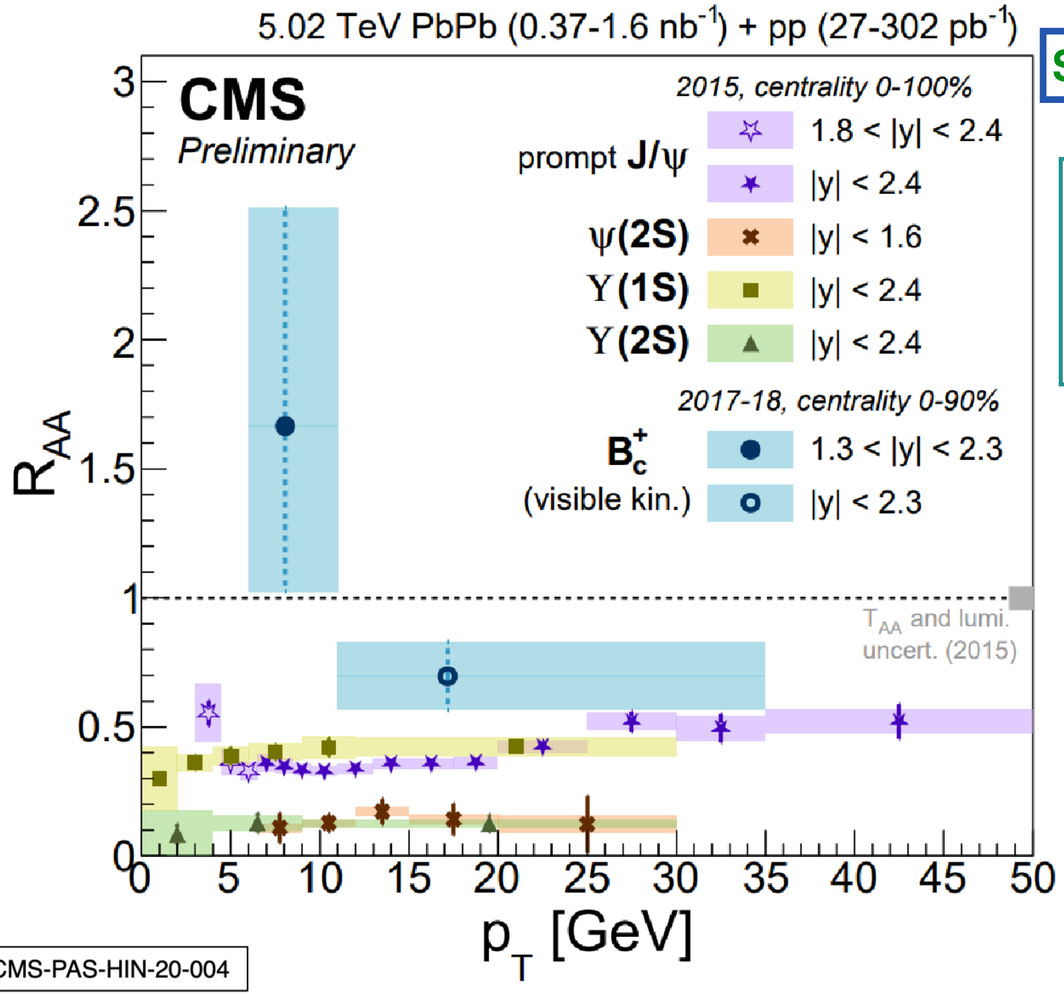
Access to the low-p_T region for charm and beauty hadron R_{AA} through the measurement of prompt D and non-prompt, D^0, J/ψ and leptons from beauty hadron decays. **B^+ measured for $p_T > 7$ GeV/c**

➡ caveat: different kinematics —> different B p_T investigated

B^+_c Nuclear Modification Factor



See T. Sheng 7Apr



arxiv.2201.02659

Special "onium" state : First B^+_c measurement in Pb-Pb

State	J/ψ	Ψ(2S)	B_c^+	Υ(1S)	Υ(2S)	Υ(3S)
Mass (GeV)	3.10	3.68	6.27	9.46	10.02	10.36
Δ E (GeV)	0.64	0.05	0.87	1.10	0.54	0.20

B_c binding energy between J/ψ and Υ(1S):

bridges the gap between charmonia and bottomonia.

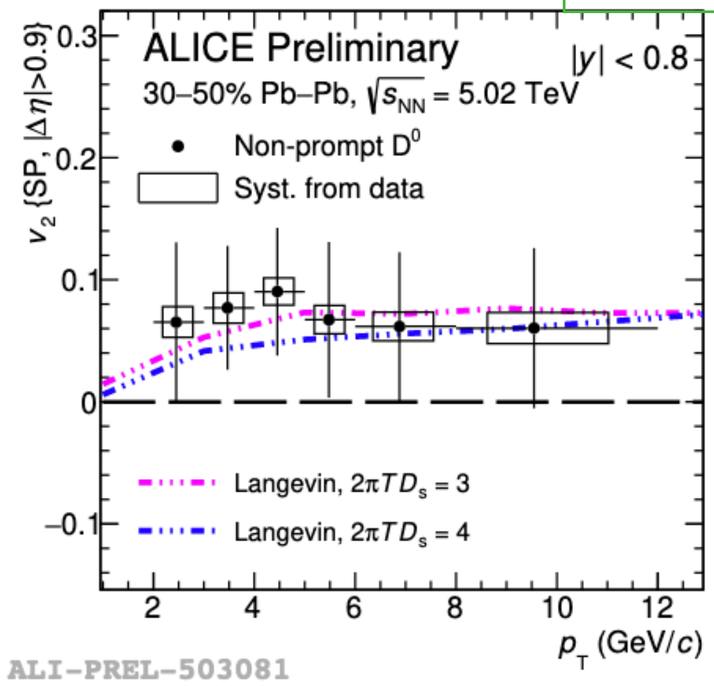
- Production in single hard scattering: strongly disfavoured
  - B_c production in pp smaller than other quarkonia states
- Could be enhanced by the **combination** of **beauty** quarks with the **charm** quarks

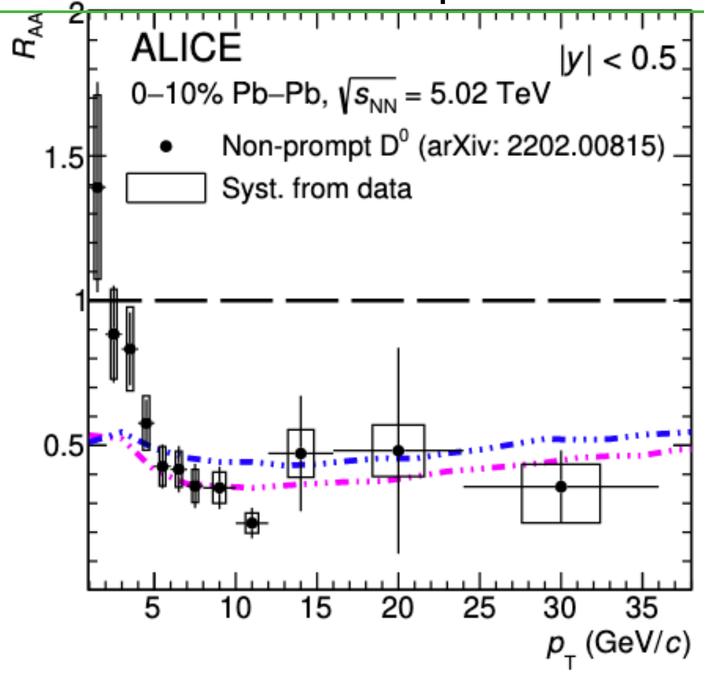
  ➡ additional insights into the recombination mechanism.

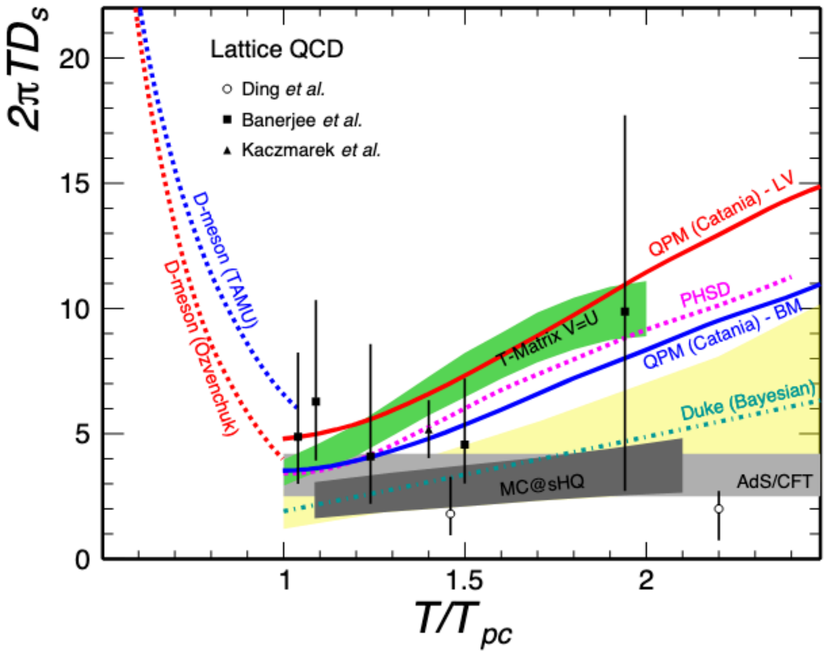
Investigating **effects on QGP on heavy-quark bound states: more precision data with Run3+4**

Constraint to QGP: diffusion coefficient

measurements down to low-p_T: production yields and angular distributions sensitive to the diffusion and possible thermalization of charm quark in medium.







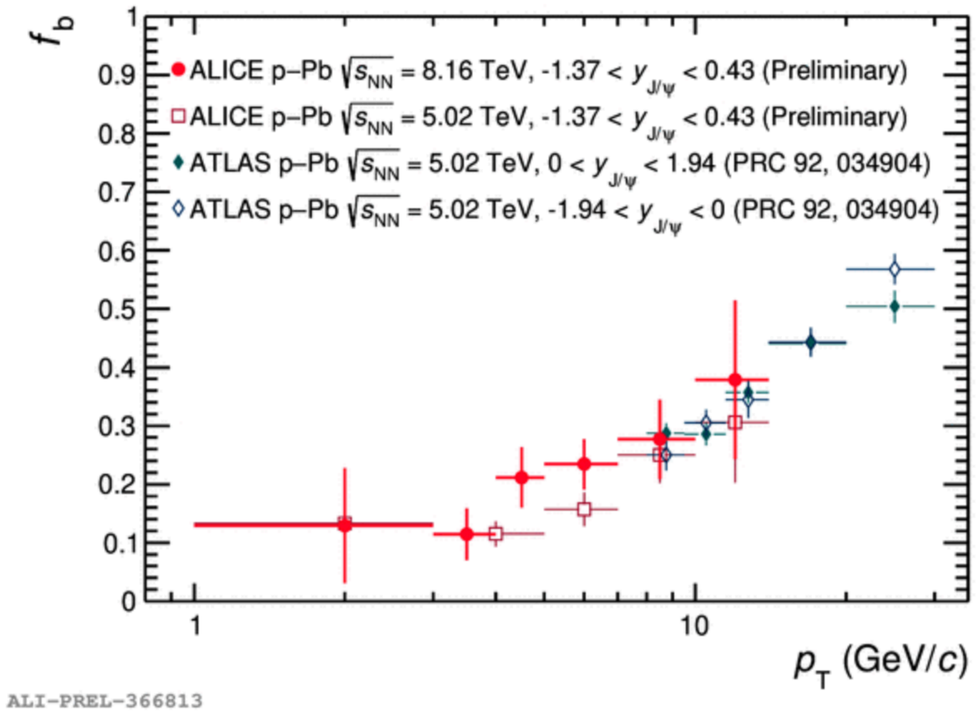
XD, Y-J Lee & R. Rapp, Ann. Rev. Nucl & Part. Sci. 69 (2019) 417

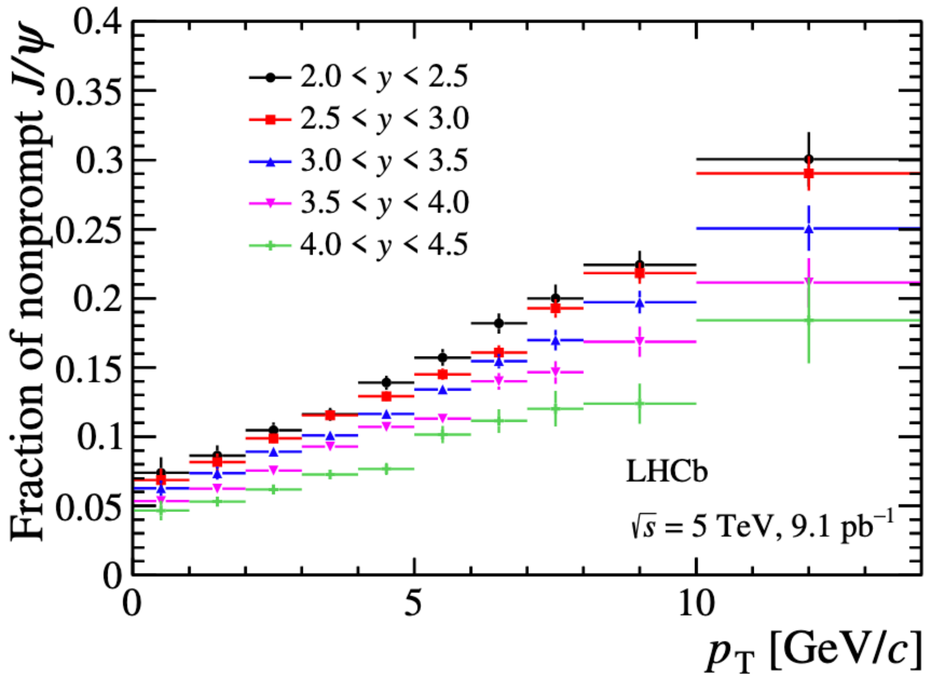
Non-prompt D^0 R_{AA} and v_2 simultaneously compared with different Langevin configurations for $2\pi TD_s$

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

More precise data measurements will provide important constraint to beauty spatial diffusion coefficient

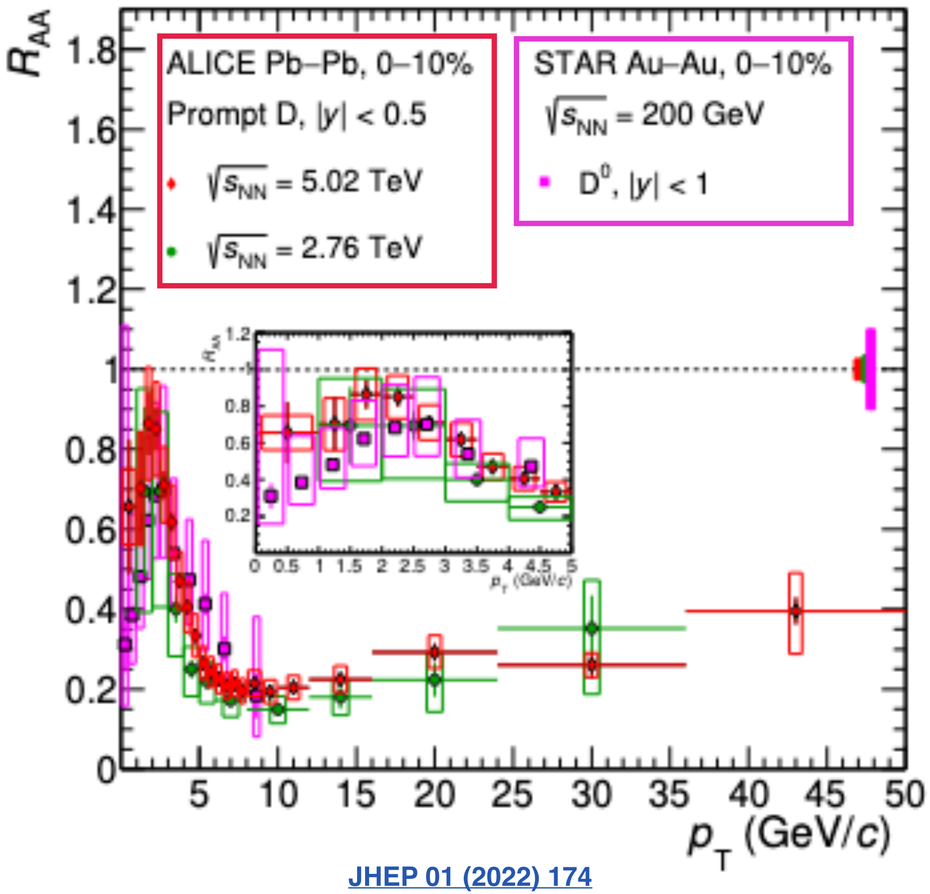
fraction of J/psi from beauty hadron decays in pPb collisions at 8.16 TeV in pPb collisions





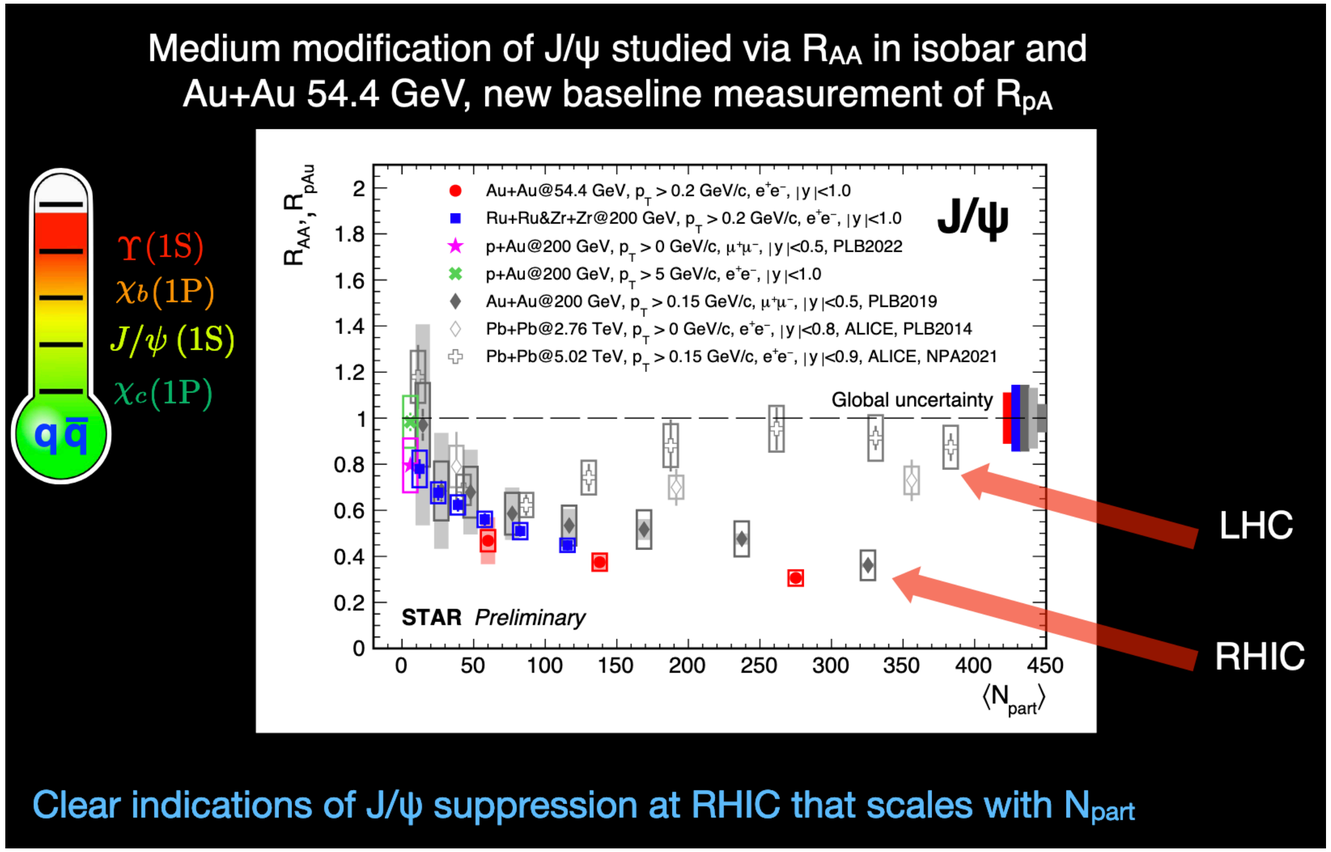
Energy loss in the QGP: Open HF R_{AA}

See T. Sheng 7Apr



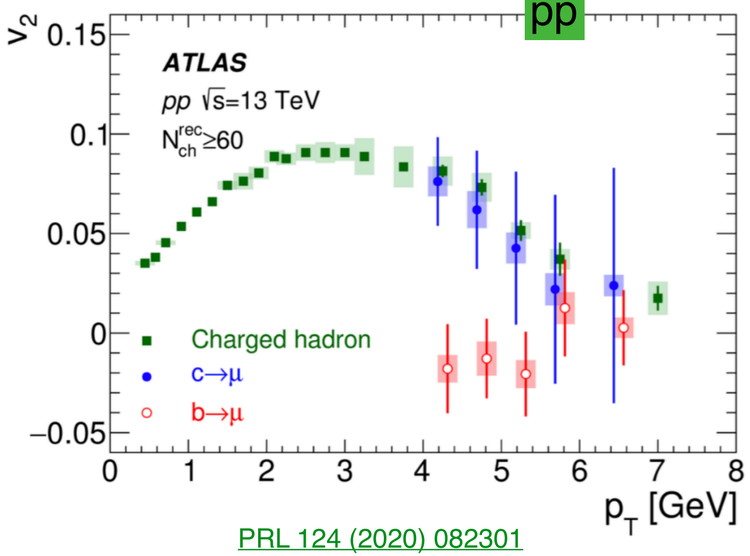
JHEP 01 (2022) 174

Different QGP density/size/lifetime with energy? hint of smaller R_{AA} from **STAR** for p_T<2 GeV/c and larger for p_T> 4 GeV/c dependence with collision energy of the p_T distribution of charm, initial/final state effects and medium properties → more precision neede to draw conclusions



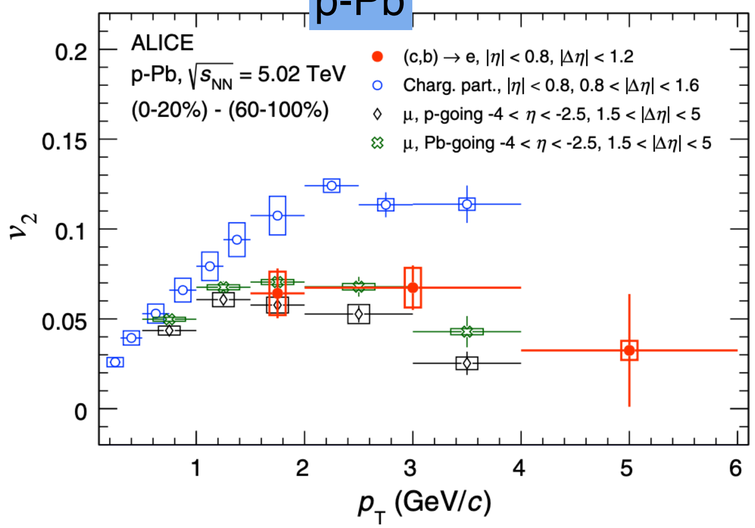
Collectivity in small systems? v_2 in high multiplicity collisions

pp



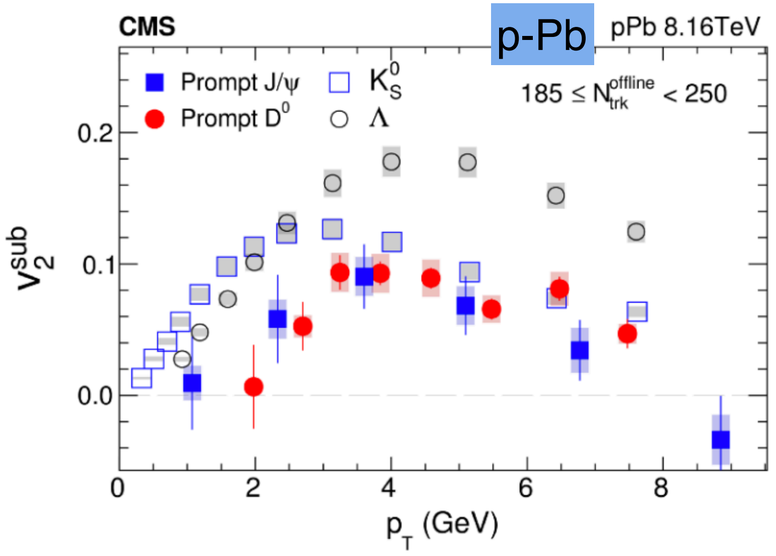
PRL 124 (2020) 082301

p-Pb



Phys. Rev. Lett. 122, 072301

p-Pb

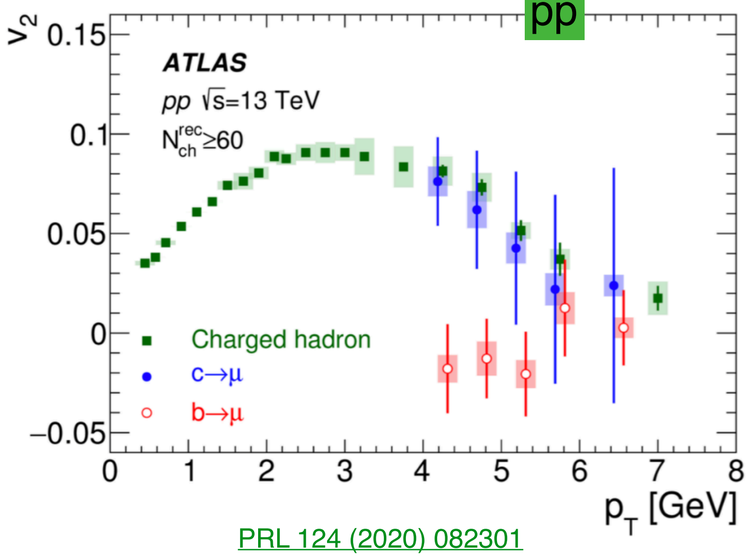


PRL 121(2018)082301, PLB 791 101016

- Positive v_2 of **heavy-flavor** decay **muons** and **electrons, D mesons** and **J/ψ** in high-multiplicity pp and p-Pb collisions from experiments at LHC (also at RHIC in d-Au collisions):
- Smaller v_2 of HF-hadrons wrt charge particles, similar v_2 for **D mesons** and **J/ψ (open vs hidden hf hadrons)**: weaker collective motion for charm quarks, as compared to that of the bulk medium
  - initial-state effects or final-state? in Pb—Pb: recombination of charm quarks thermalized in the medium for p_T < 3-4 GeV/c.

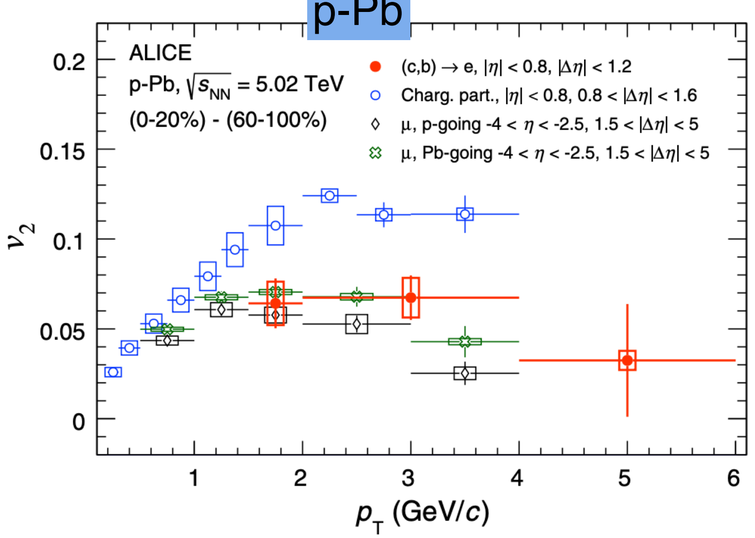
Collectivity in small systems? v_2 in high multiplicity collisions

pp



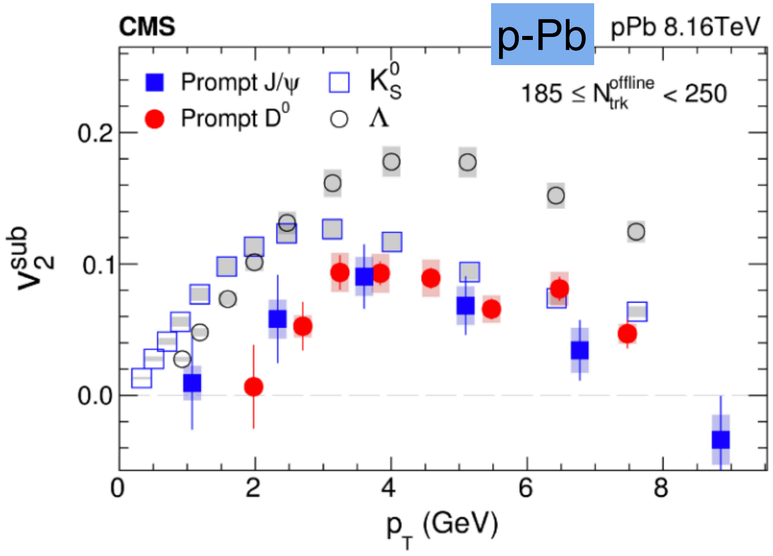
PRL 124 (2020) 082301

p-Pb



Phys. Rev. Lett. 122, 072301

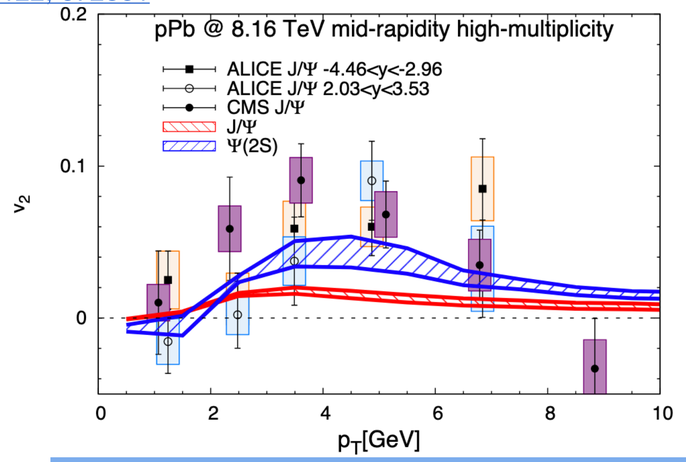
p-Pb



PRL 121(2018)082301, PLB 791 101016

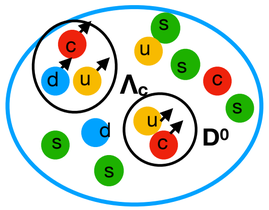
Du, Rapp High Energ. Phys. (2019) 2019

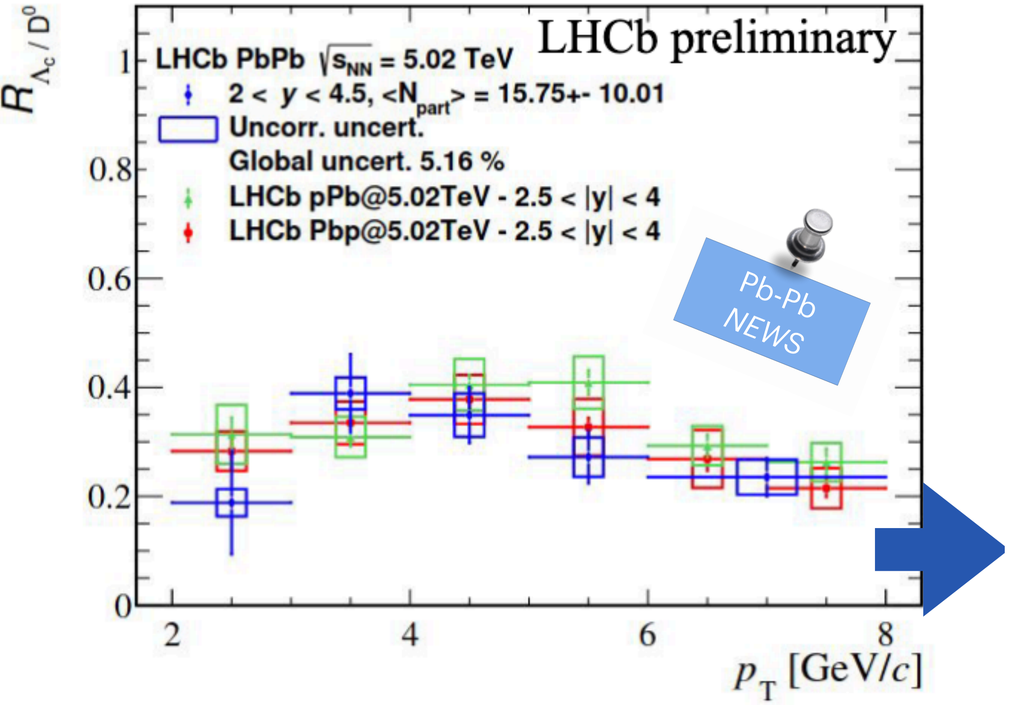
final-state effects, from the formation of an expanding medium: large v_2 observed in p-Pb collisions at the LHC is unlikelyto be due to the final-state collectivity of the fireball alone.

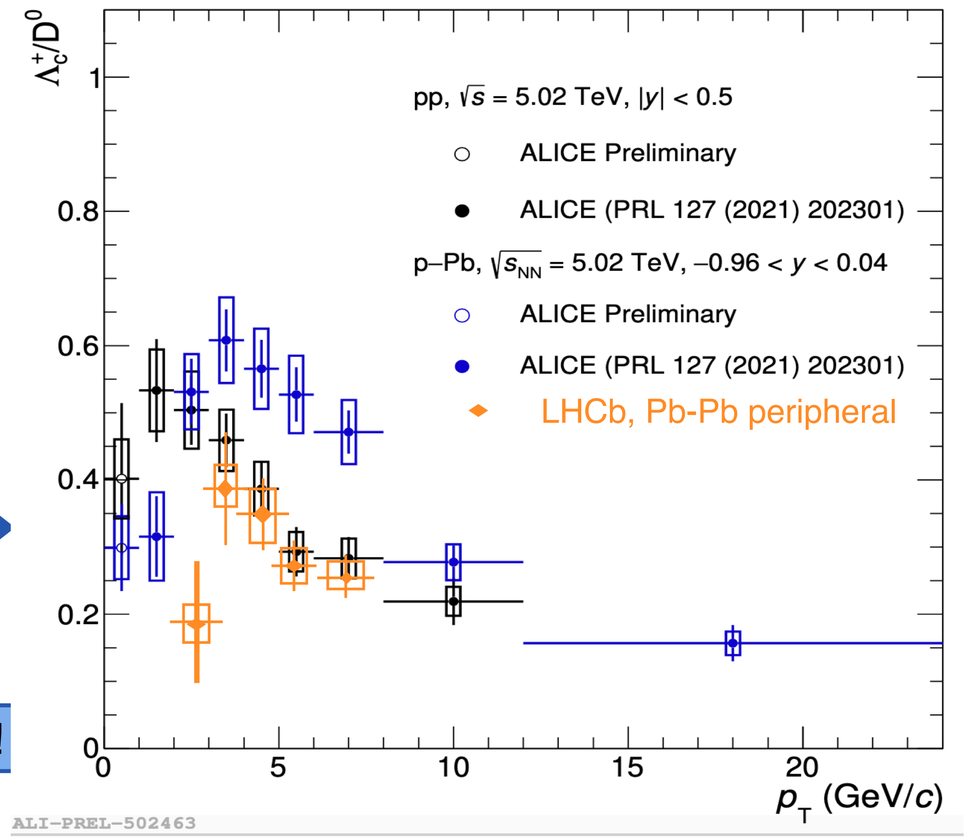


comparison with models to constraint the collective dynamics

Hadronisation: baryon-to-meson







N_{part} (pPb) = 7.7
Npart(Pb-Pb LHCb)=15

increasing trend of the Λ^+_c/D^0 at intermediate p_T from **pp**, to **semi-central** and **most central** Pb-Pb events

LHCb: enter the games with Pb-Pb measurements!

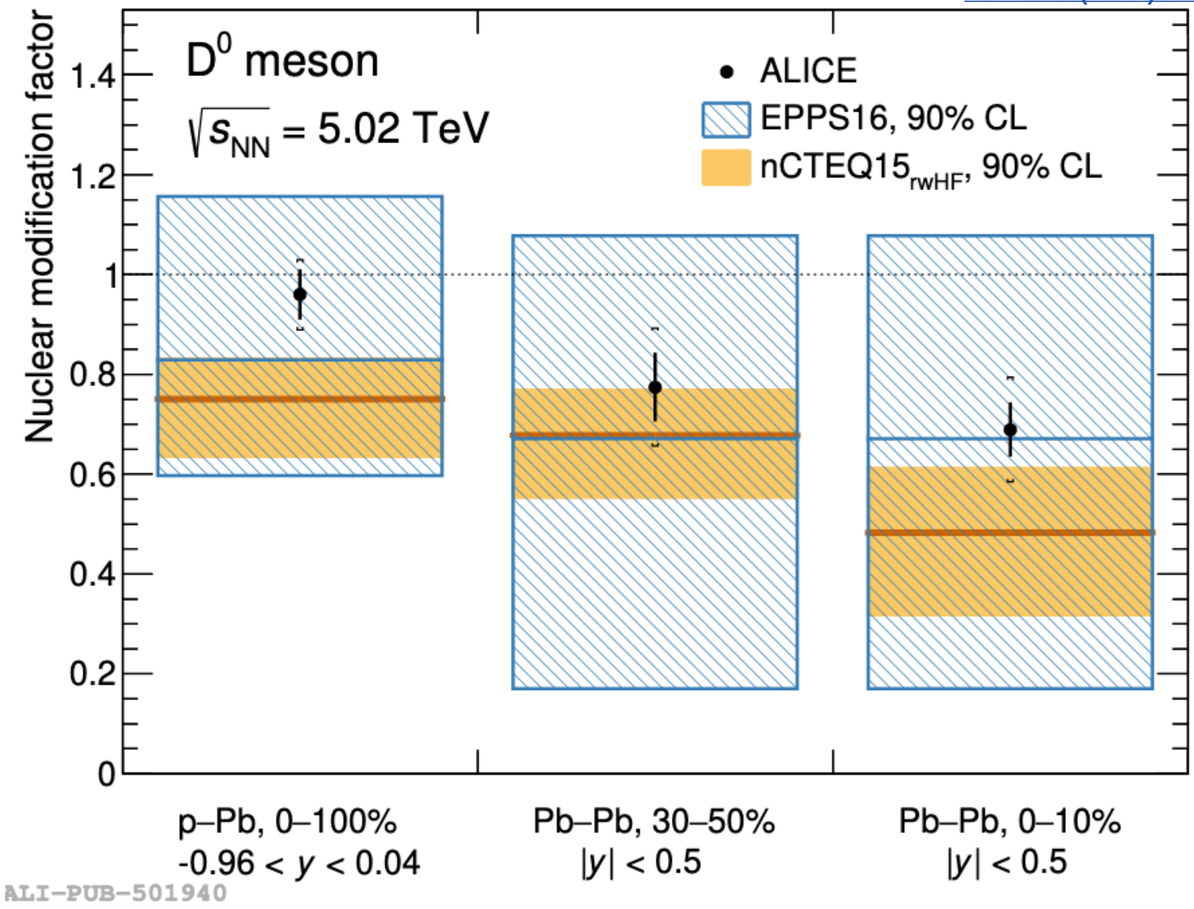
centrality 65-90% Pb-Pb

Is there a **transition of the hadronization mechanisms with multiplicity across different systems?** the same formalisms describe results from small to large systems?

p_T-integrated nuclear modification factor: from p-Pb to Pb-Pb

D^0 R_{AA} measured down to $p_T = 0$: investigating if there is a modification of total yields in different systems

JHEP 01 (2022) 174



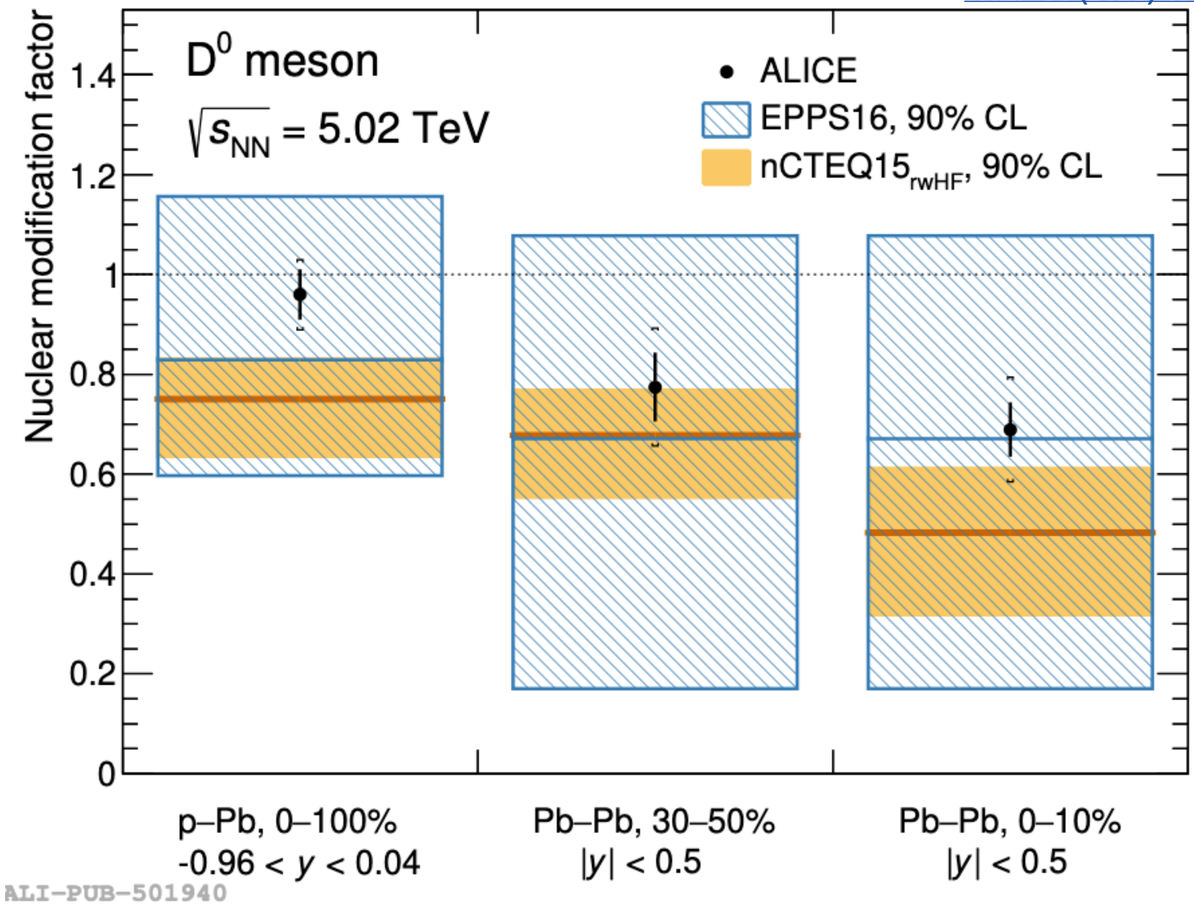
p_T-integrated D^0 $R_{AA} < 1$ in Pb-Pb collisions and $R_{AA} < R_{pPb}$

- ➡ nuclear shadowing effect reduces charm production in Pb-Pb and in p-Pb
- ➡ R_{pPb} close to unity → small shadowing effect
  - ➡ comparison with pQCD including only initial-state effects with two different nPDF

p_T-integrated nuclear modification factor: from p-Pb to Pb-Pb

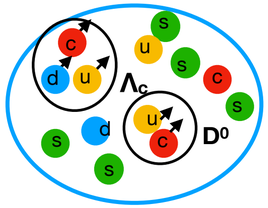
D^0 R_{AA} measured down to $p_T = 0$: investigating if there is a modification of total yields in different systems

JHEP 01 (2022) 174



p_T-integrated D^0 R_{AA} < 1 in Pb-Pb collisions and $R_{AA} < R_{pPb}$

➡ possible enhancement of D_s, Λ_c due to recombination could decrease the fraction of D^0 in Pb-Pb collisions



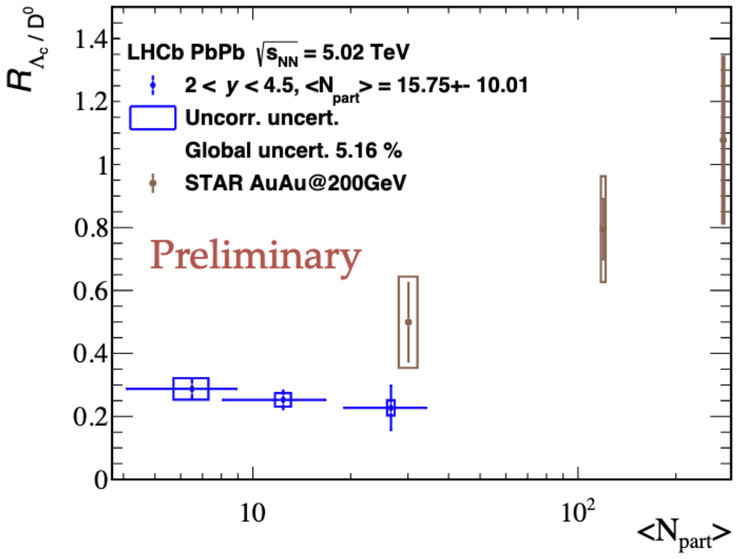
crucial to measure HF hadron production down to 0 for more charm hadrons

EPPS16, EPJC 77 (2017) 163, nCTEQ15$_{rwHF}$, PRD 104 (2021) 014010

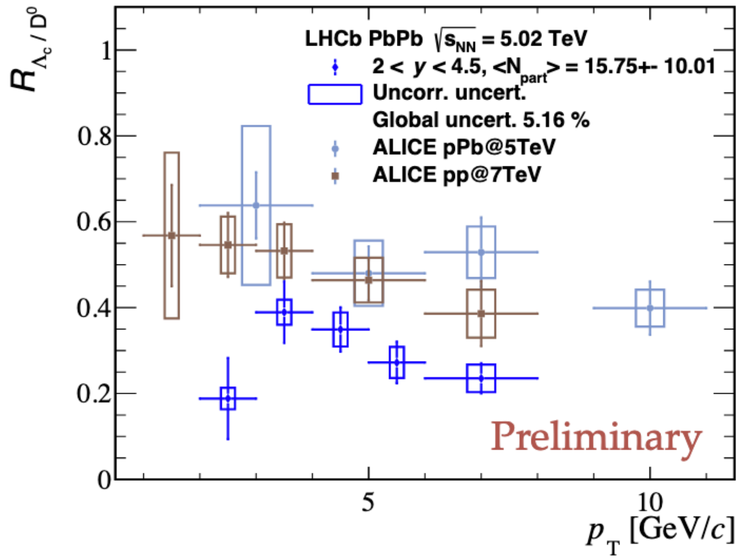
New Λ_c^+-to-D^0 ratio in peripheral PbPb collisions

LHCB-PAPER-2021-046

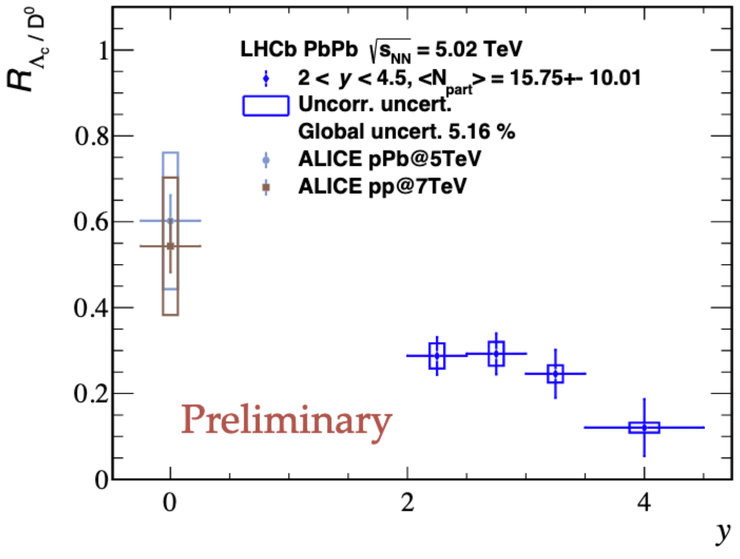
First Λ_c^+-to-D^0 production ratio measured in peripheral PbPb collisions at forward rapidity.



- Most central point compatible with STAR measurements.
- Rising trend ?

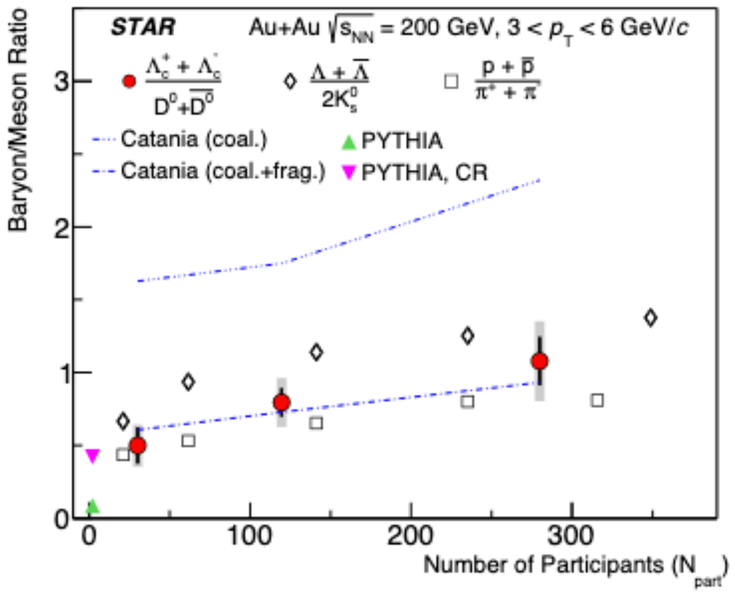


- Similar p_T trend between ALICE and LHCb for $p_T > 4$ GeV/c.

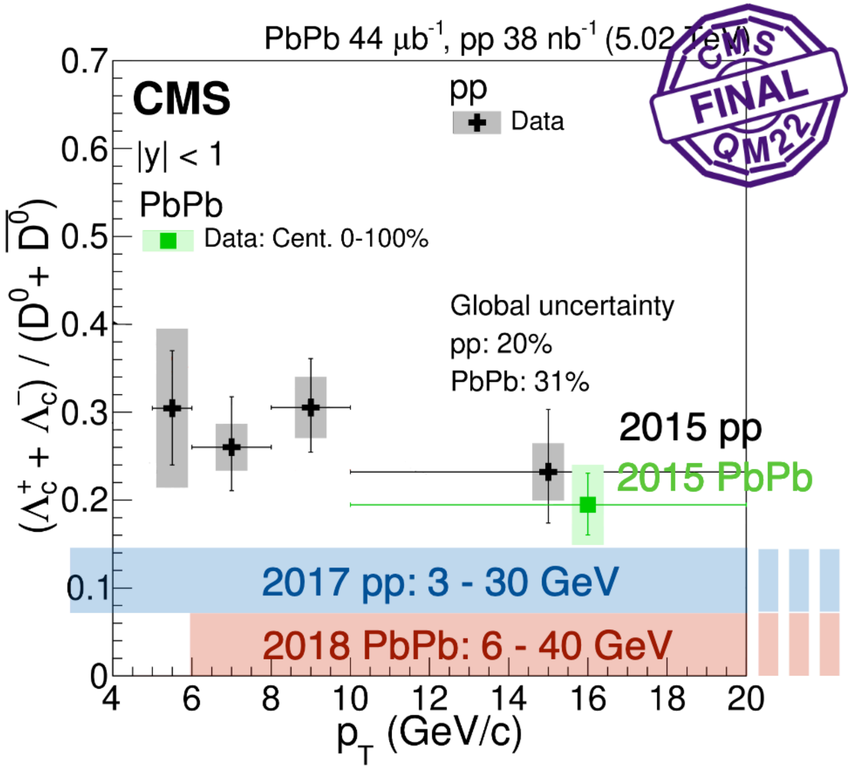


- Difference between LHCb and ALICE data versus rapidity.

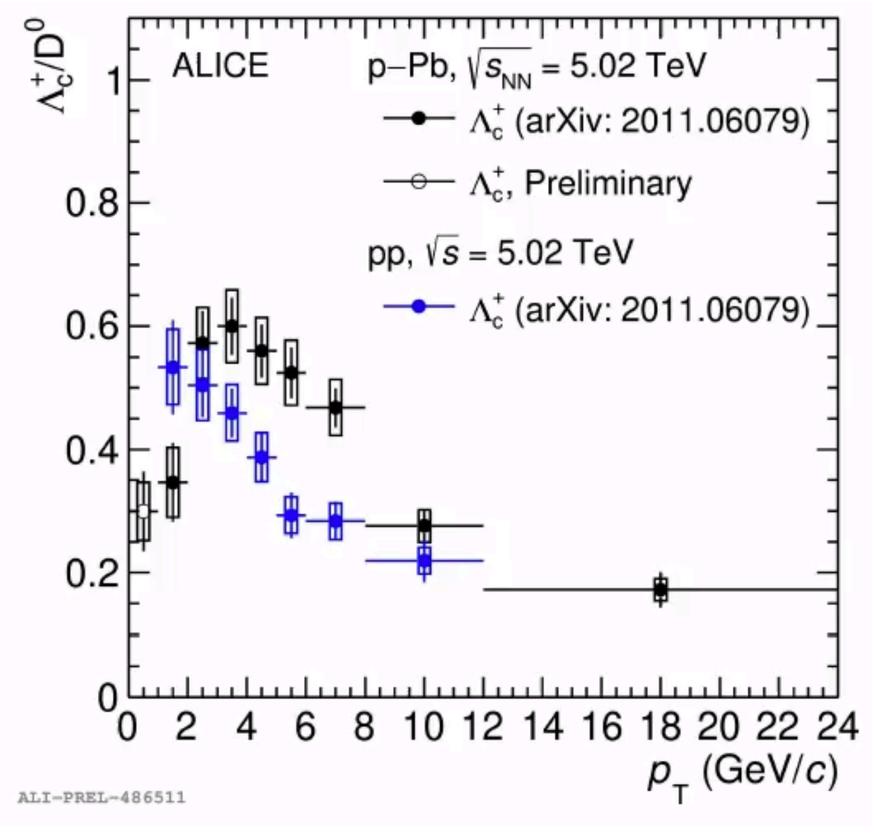
Λ^+_c/D^0 measurements in STAR, CMS, ALICE

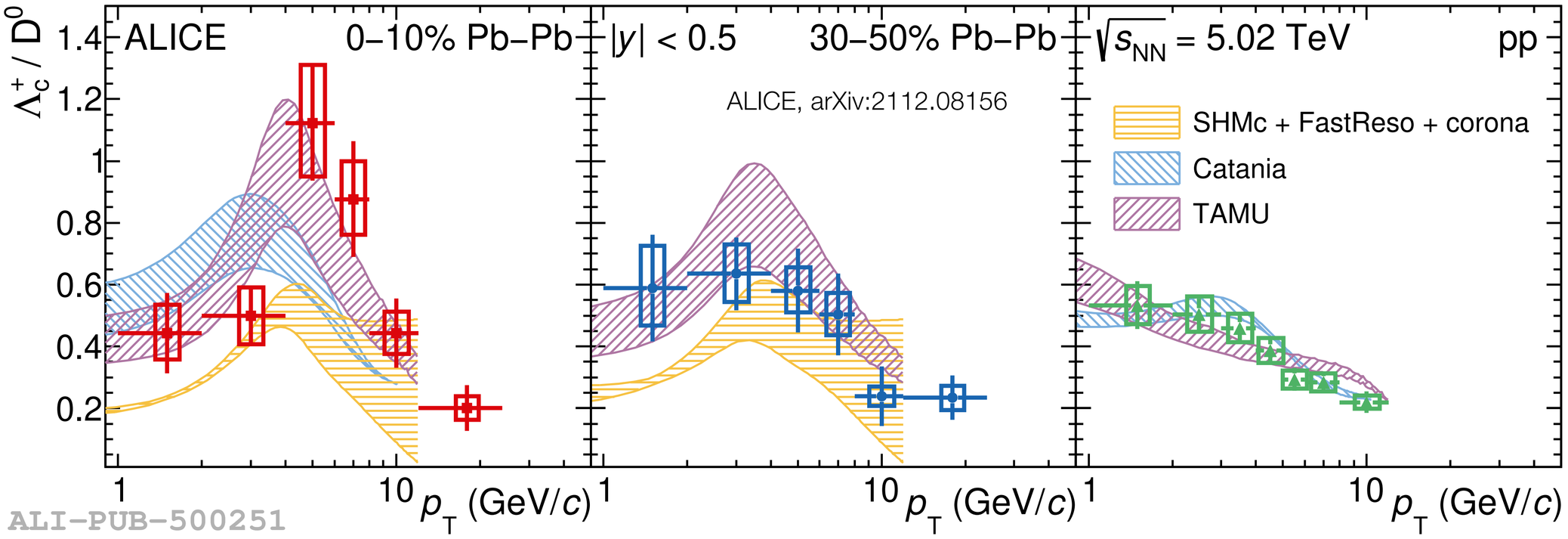


Phys. Rev. Lett. 124, 172301 (2020)



PLB 803 (2020) 135328

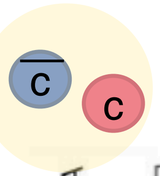




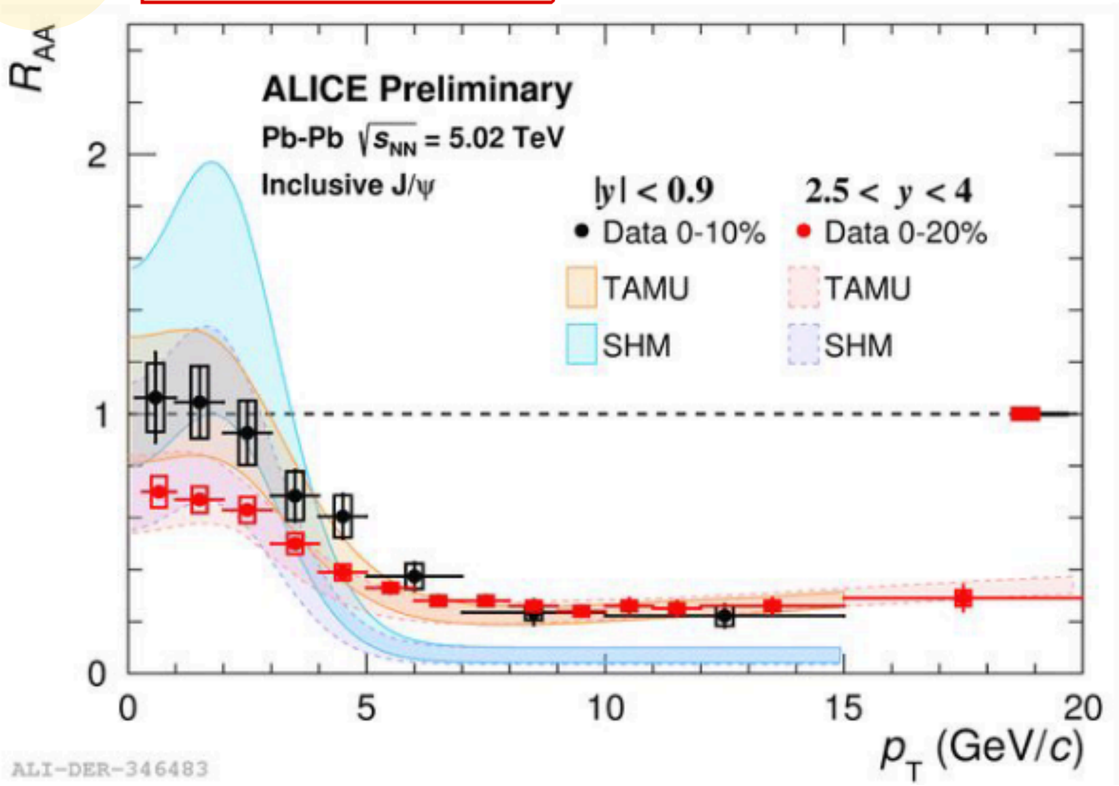
- Hint of enhanced Λ^+_c/D^0 in Pb–Pb compared to pp collisions for $4<p_T<8$ GeV/c
  - *interplay* of radial flow and hadronisation via coalescence
- Described by models with charm hadronisation via fragmentation+coalescence, slightly underestimated by SHMc

SHMc: JHEP 07 (2021) 035 TAMU: PRL 124, 042301 (2020) CATANIA: EPJC, 78 4 (2018) 348

Quarkonia suppression/regeneration in the QGP: R_{AA}



$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$



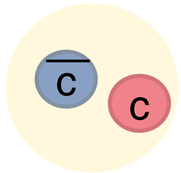
Models implementing **charmonium regeneration**, either at the freeze-out (SHM) or during the fireball lifetime (transport models), in agreement to data:

➡ large model uncertainties prevent conclusions

Precise measurement of total charm cross section needed

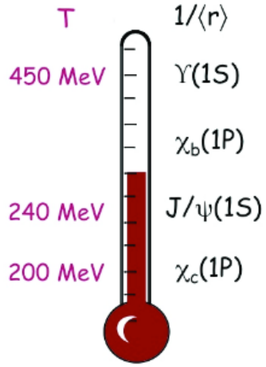
- quarkonia R_{AA}:
  - Debye-like screening of qq in QGP
    - sequential suppression
  - **recombination of charmonium:** enhanced at hadronization of in QGP (dominant at low p_T)

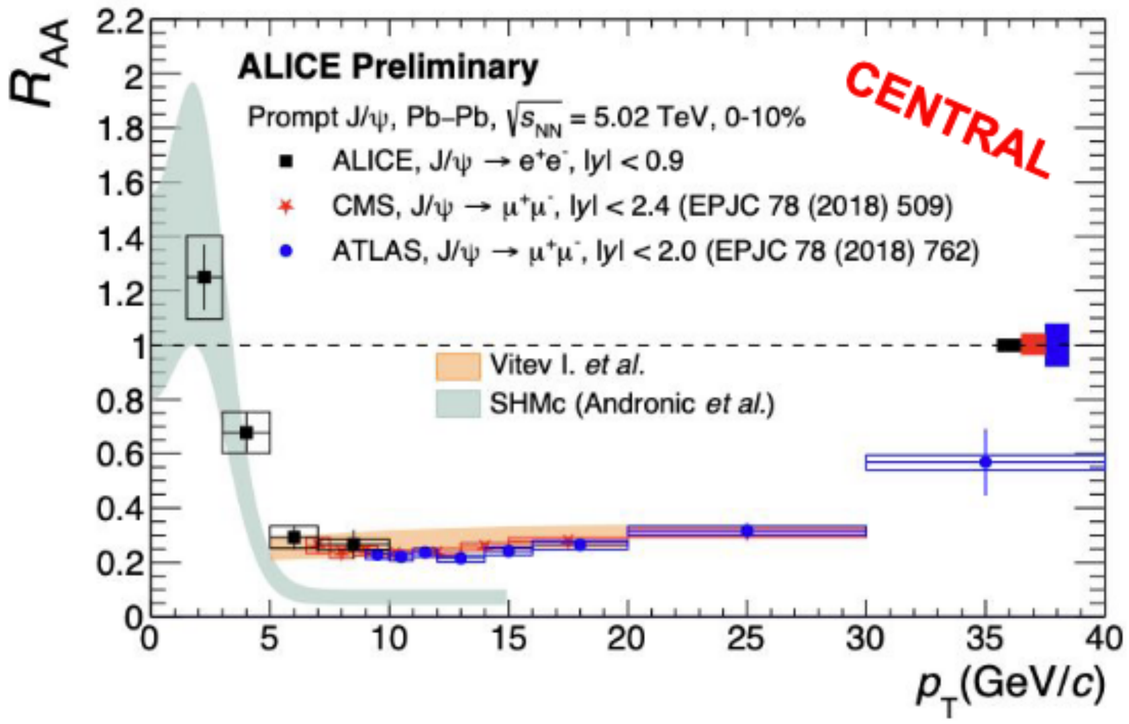
Quarkonia suppression/regeneration in the QGP: R_{AA}



$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

Probing the sequential suppression and **possible recombination in the QGP**





J/ψ also measured at mid rapidity:

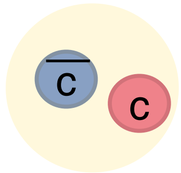
- low-p_T: models implementing **charmonium regeneration**, in agreement to data:
  ➡large model uncertainties prevent conclusions

Precise measurement of total charm cross section needed

TAMU: Nucl.Phys.A 943 (2015) 147-15

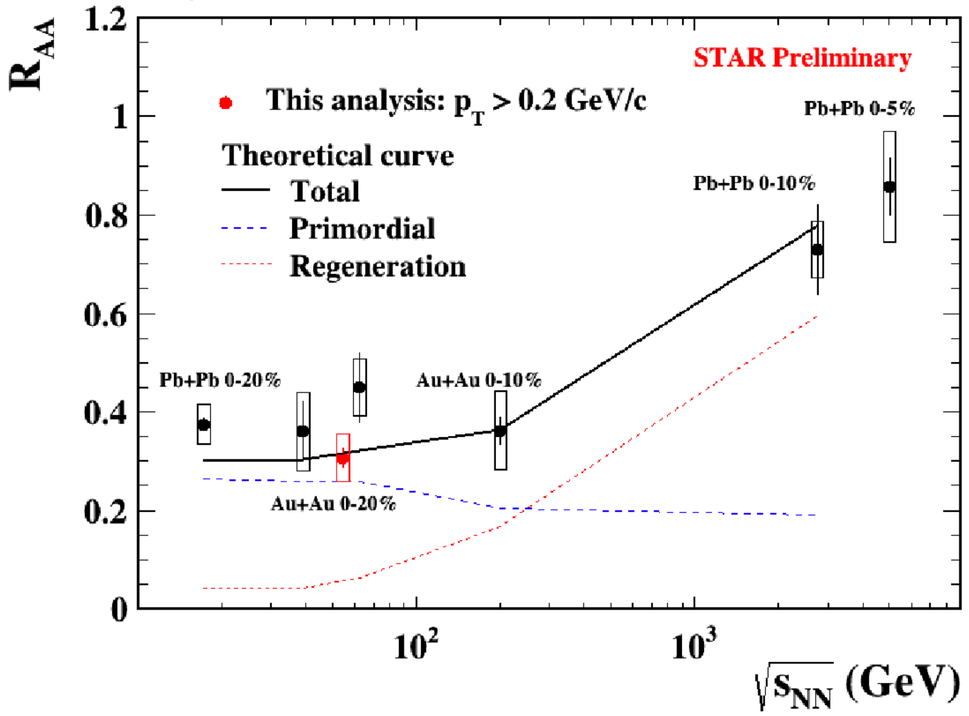
- **quarkonia R_{AA}:**
  - Debye-like screening of qq in QGP
    - sequential suppression
  - **regeneration of charmonium:** enhanced at hadronization of in QGP

Quarkonia suppression/regeneration in the QGP: R_{AA}



$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

J/ψ R_{AA} measured at 39, 54.4 and 62.4 GeV



R_{AA}: unique energy scan by STAR

R_{AA} vs energy in comparison with models:
no significant energy dependence up to 200 GeV
- **interplay of dissociation, regeneration and cold nuclear matter effects**

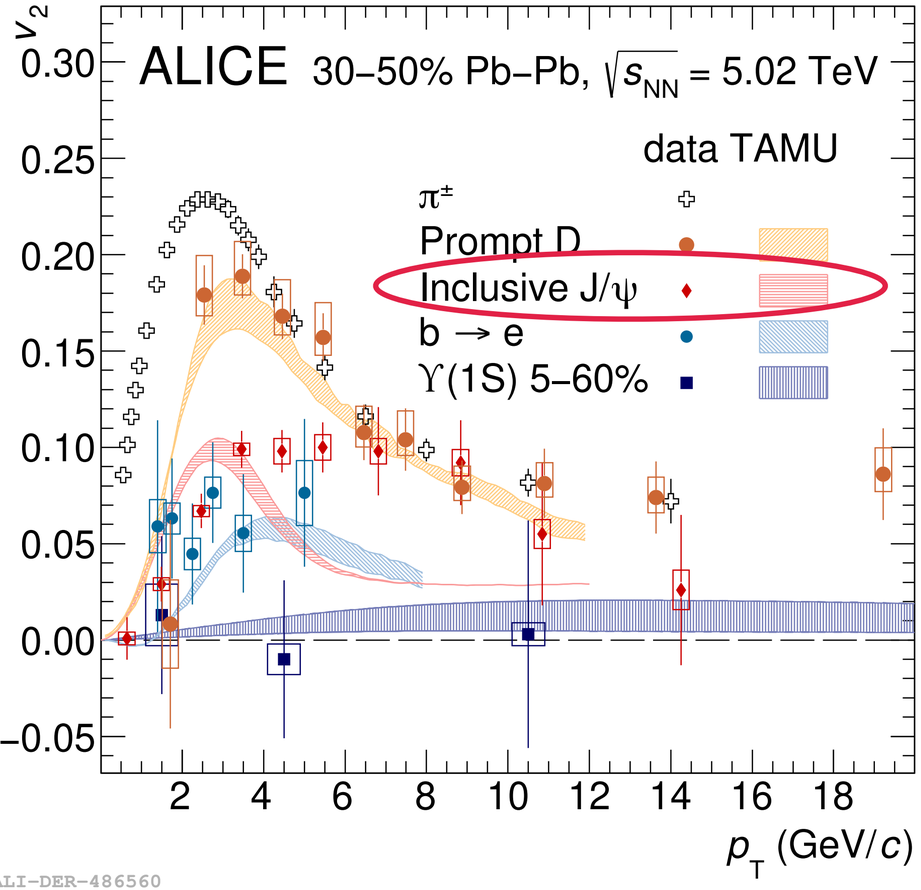
X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
L. Kluberg, Eur. Phys. J. C 43 (2005) 145.
NA50 Collaboration, Phys. Lett. B 477 (2000) 28.
ALICE Collaboration, Phys. Lett. B 734 (2014) 314
STAR Collaboration, Phys. Lett. B 771 (2017) 13-20
STAR Collaboration, Phys. Lett. B 797 (2019) 134917
ALICE Collaboration, Nucl. Phys. A 1005 (2021) 121769

- **quarkonia R_{AA}:**
  - Debye-like screening of qq in QGP
    - sequential suppression
  - **regeneration of charmonium:** enhanced at hadronization of in QGP

Overview of charm, beauty and charmonium, bottomonium v_2

➡Positive v_2 of hadrons with charm observed at RHIC and LHC
- **charm quarks largely thermalize in QGP until hadronization**
- **smaller v_2 of open-beauty hadrons**

L. Bichon, Apr 7



charmonia: recombining charm quarks, inherit thermalized charm flow
- described by models that implement suppression+recombination
  - RHIC: less recombination that at LHC —> v_2(J/ψ,Au-Au) ~ 0