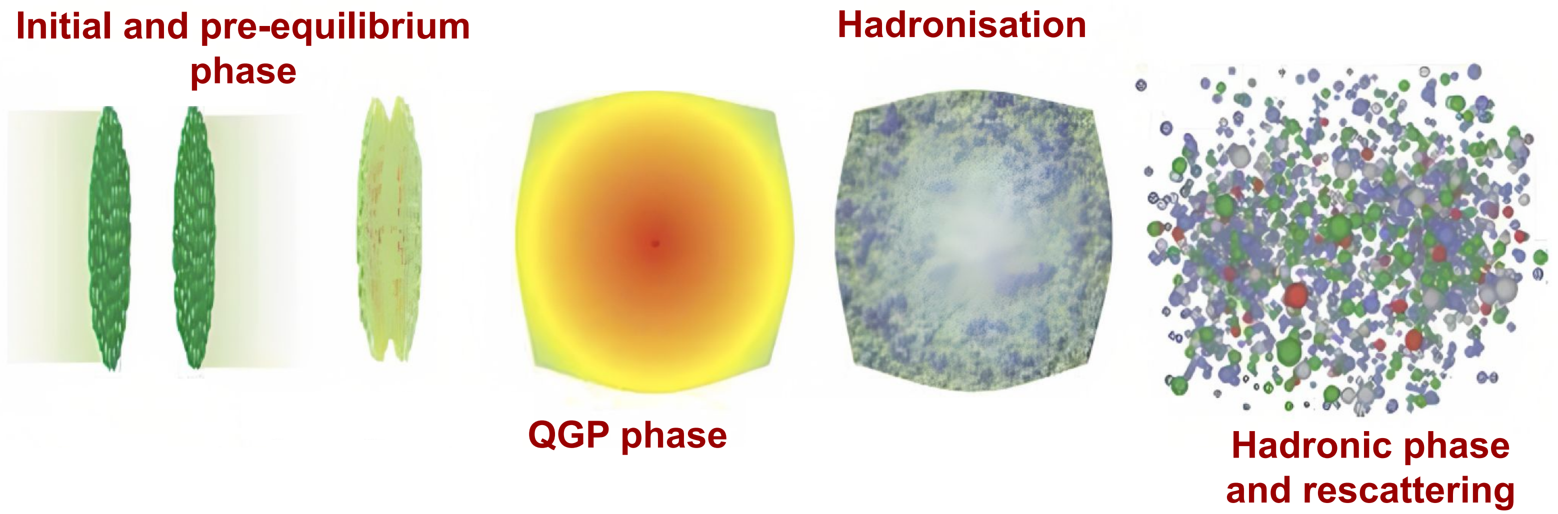
Heavy flavors and quarkonia: highlights, open questions and perspectives

Andrea Dubla

Heavy-ion collisions with heavy quarks

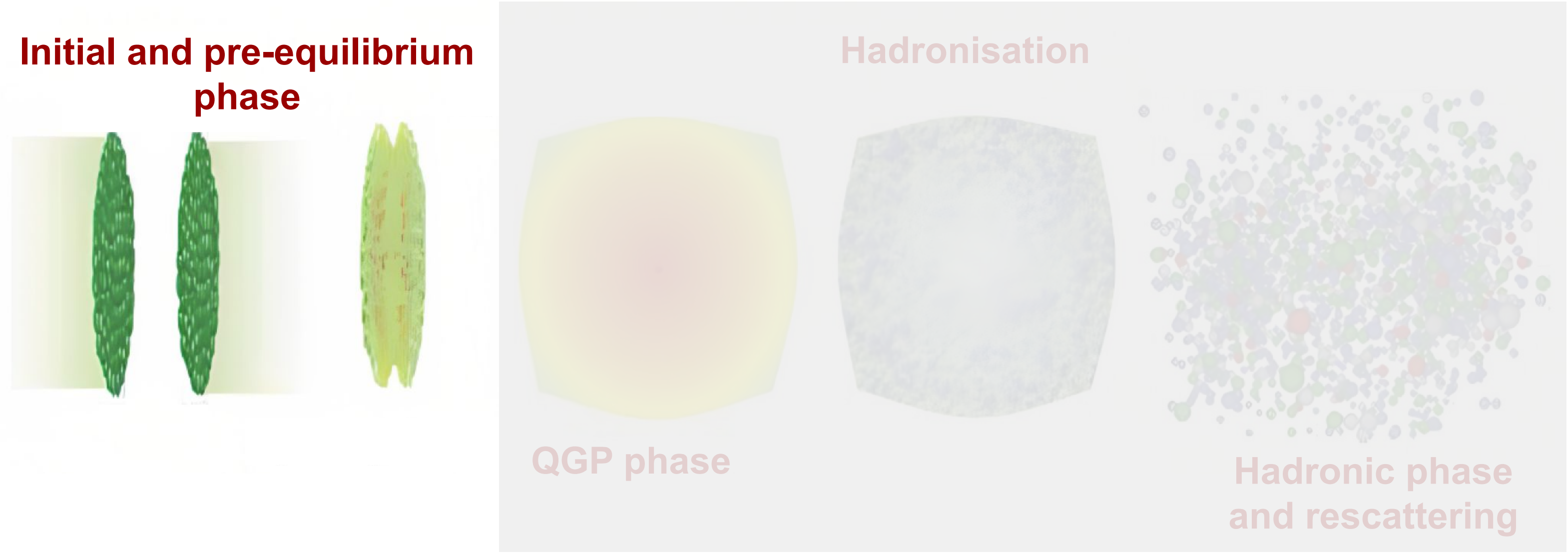


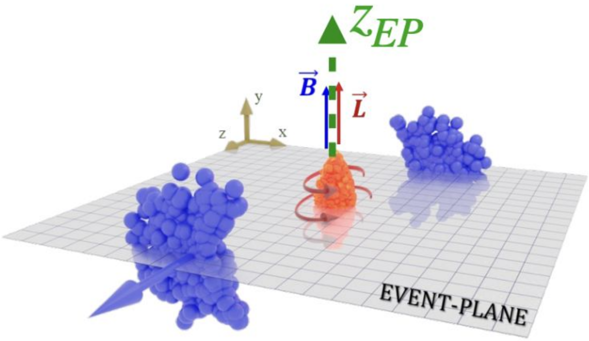
- **Opportunity** → heavy quarks can be used to characterise the QGP phase and not only → they are a tool that can be used to investigate all collision stages

Sensitivity to:

- Initial conditions
- QGP properties
- Hadronisation mechanisms
- Rescattering in the hadronic phase

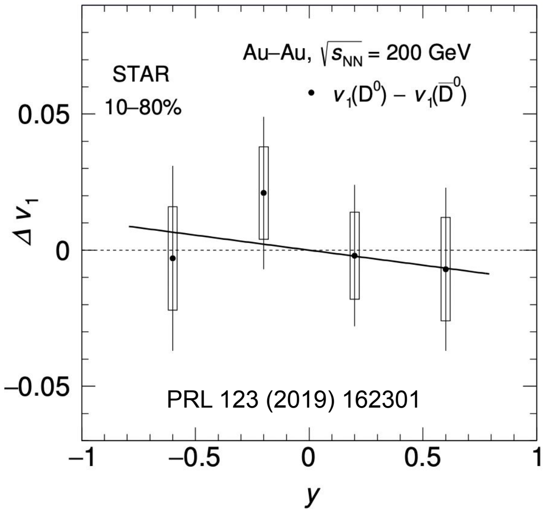
Heavy-ion collisions with heavy quarks

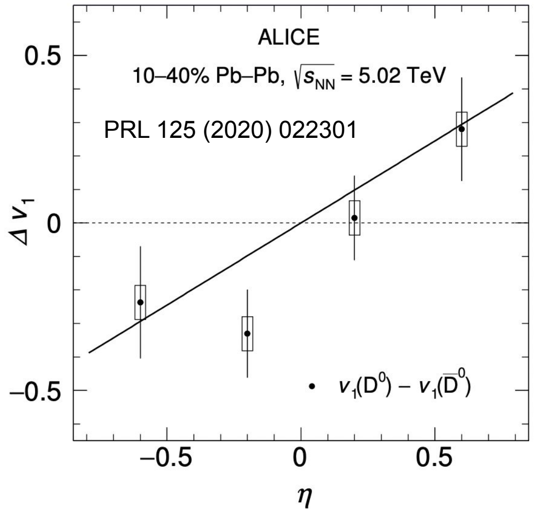




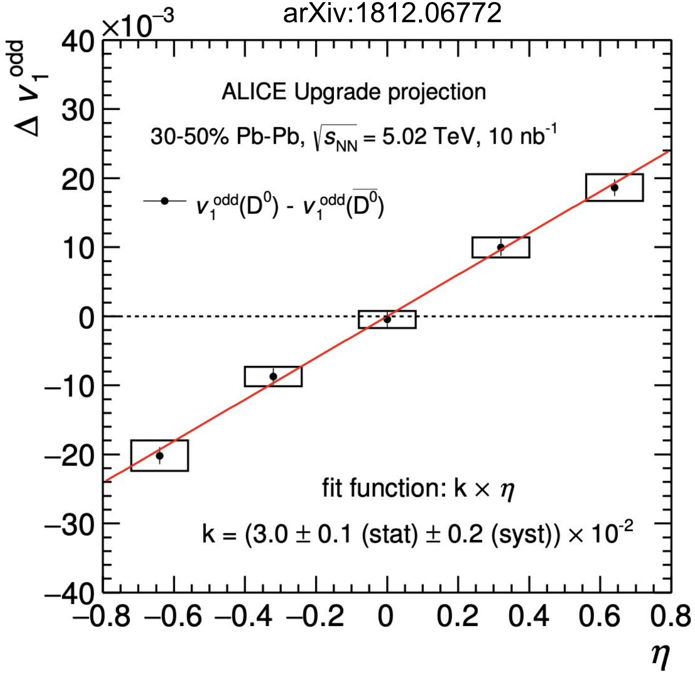
- Large **magnetic field** ($B \sim 10^{14}$T) and **angular momentum** ($L \sim O(10^7\hbar)$) are produced in HI and are perpendicular to the event plane
  - Might have an influence on open charm and quarkonia originating from the early phases

Charge dependent directed flow





arXiv:1812.06772



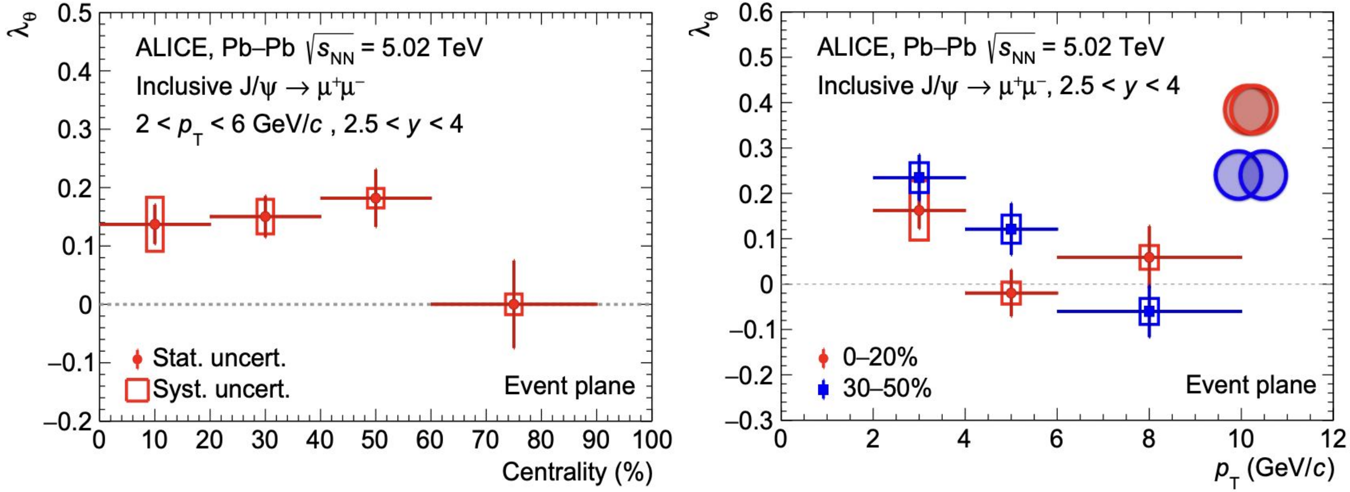
- ➢ Important and intriguing results on the Δv_1 of D mesons
  - **situation is not yet completely settled**. Opposite slope at the two energies? Large signal at LHC?
  - Future measurements (centrality and p_T differential) will clarify the picture and will put constraints on the electrical conductivity of the QGP

AD et al. MPLA Vol. 35, No. 39, 2050324 (2020)

- ➢ **Extremely good significance is expected** in Run3/4

J/ψ polarisation in Pb-Pb

➢ Polarisation of J/ψ meson studied in the direction orthogonal to the reaction plane



arXiv:2204.10171

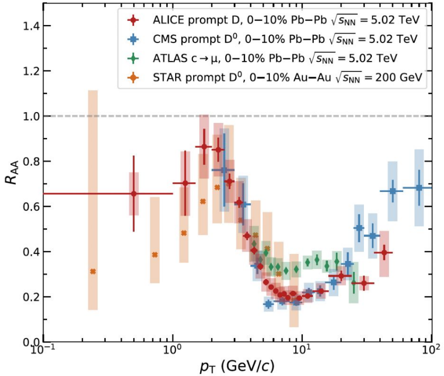
$$\lambda_\theta \propto (3\rho_{00} - 1)/(1 - \rho_{00})$$

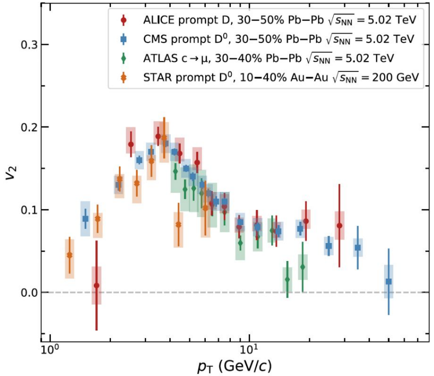
$\rho_{00} = 1/3$ → No spin alignment
$\rho_{00} \neq 1/3$ → Spin alignment

➢ Connected with the existence of a strong B field in the early stage of QGP formation in Pb-Pb collisions, as well as with its behaviour as a rotating fluid with large vorticity

➢ **Significant non-zero polarisation** is measured from central collisions down to the 40-60% centrality
- Model calculations would help in understanding the measured effect and will give an additional handle about the coupling of quarkonia with nuclear matter

Heavy-ion collisions with heavy quarks

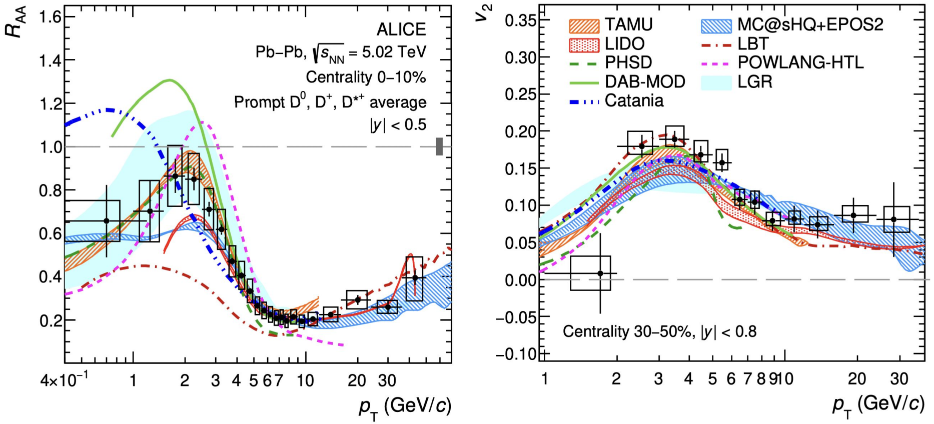


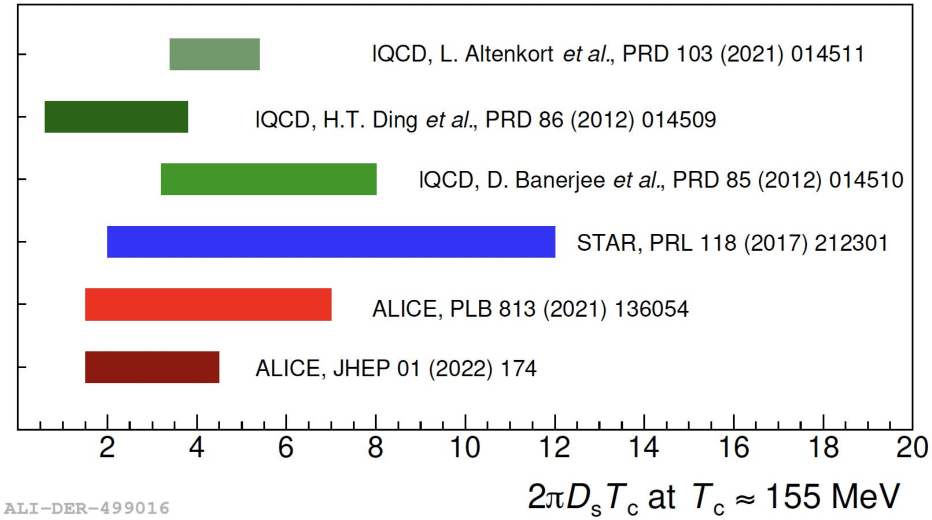


- **Low p_T**: Elastic collision with medium constituents
  - Diffusion (Brownian) motion
  - Possible thermalisation in the medium
- **High p_T**: Radiative energy loss (gluon emission)
  - Study properties of in-medium energy loss

Constraining QGP properties

JHEP 01 (2022) 174



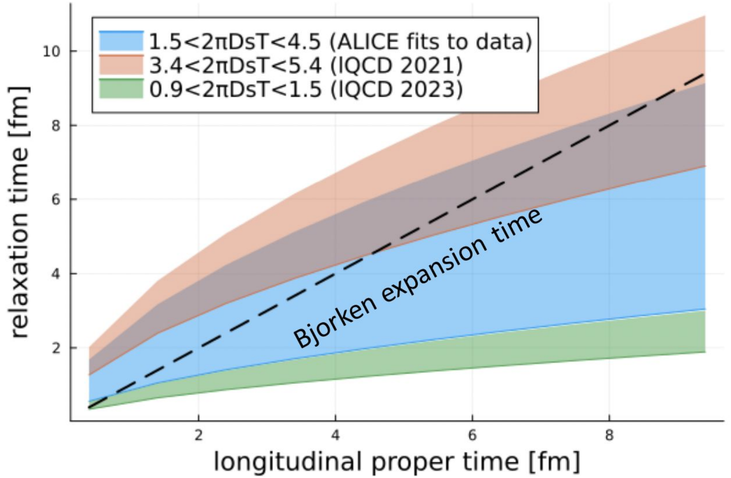


- Interval of spatial diffusion coefficient, which is related to the thermalisation time of charm quark, is obtained considering the values used in transport models that reproduce the data
  - **1.5 > $2\pi D_s T_c$ < 4.5** which correspond to a **3 < τ_{charm} < 9 fm/*c***

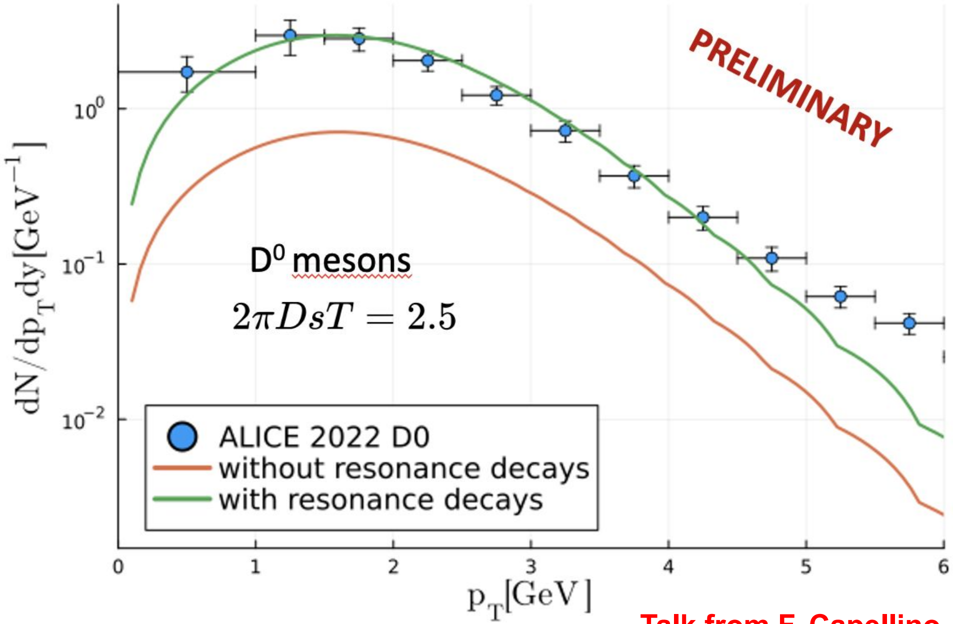
- Indicates a thermalisation time of charm quark compatible with the QGP lifetime
  - D_s and other QGP parameters from global Bayesian analyses

What about a fluid description?

F. Capellino et al. PRD 106 (2022) 3, 034021



F. Capellino et al. *in preparation*

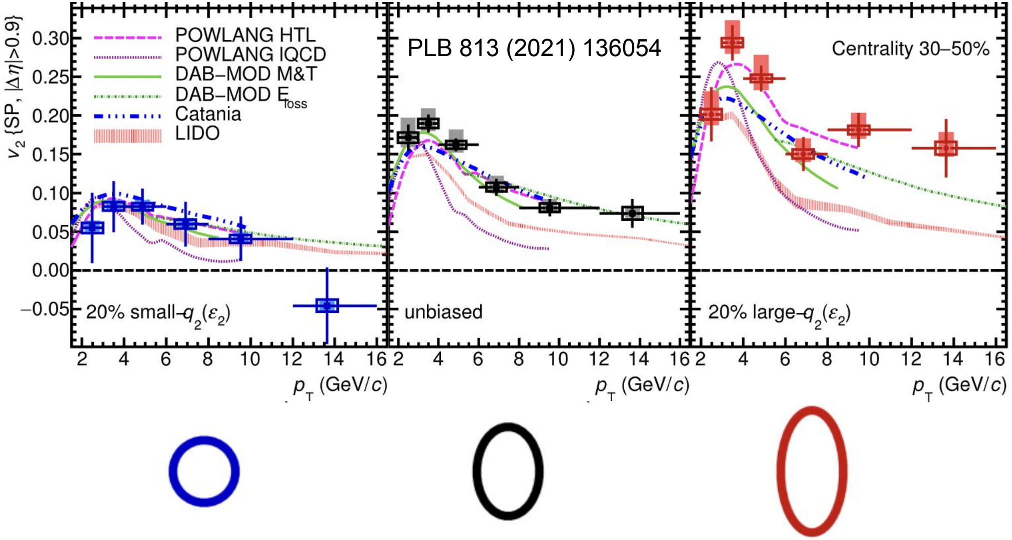


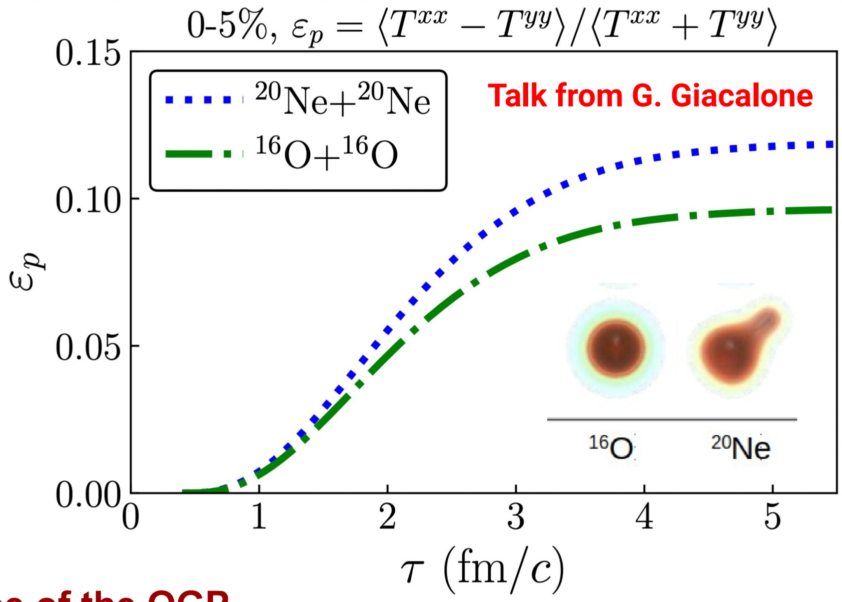
- ➢ Relaxation time might be shorter than typical expansion time of the QGP in Bjorken flow
  - **Fluid-dynamic description of charm seems meaningful**

Talk from F. Capellino
New lQCD: O. Kaczmarek

- ➢ Spectra are computed with a Cooper-Frye prescription
- ➢ The fluid-dynamic description of charm captures the physics **up to 5-6 GeV**

Deformed nuclei - a possibility?

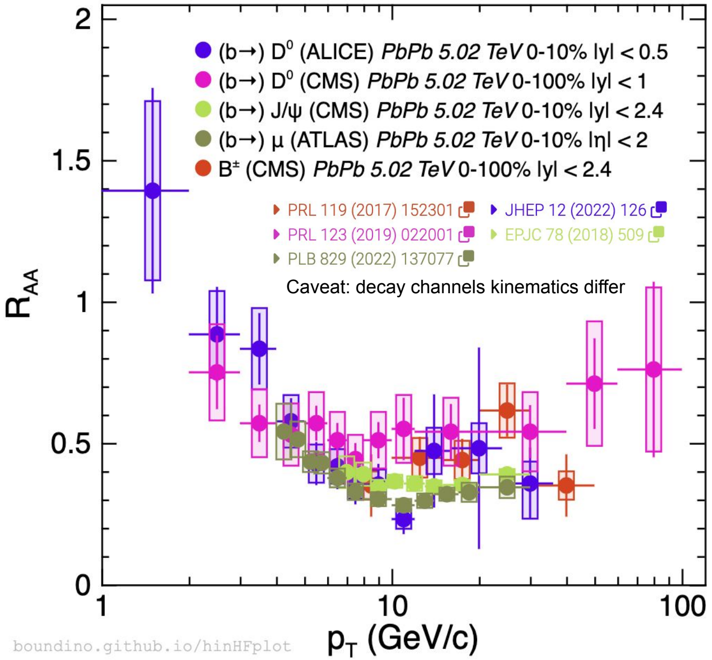


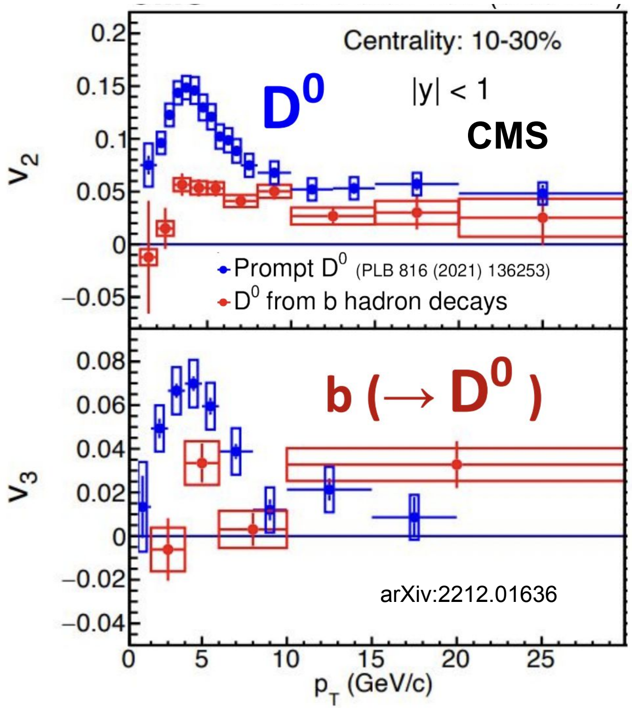


- ➢ It was demonstrated that **charm meson see the shape of the QGP**
- ➢ Can we use collision of **deformed nuclei to study possible charm collectivity in small system**? Larger v_2 in Ne-Ne wrt to O-O due to the initial deformed geometry. Would charm feel the shape?

- ➢ For larger systems, similar enhancement of J/ψ (D meson) elliptic flow in collisions of deformed ions relative to Pb-Pb baseline would help in understanding the origin of charm v_2

The needs of beauty measurements

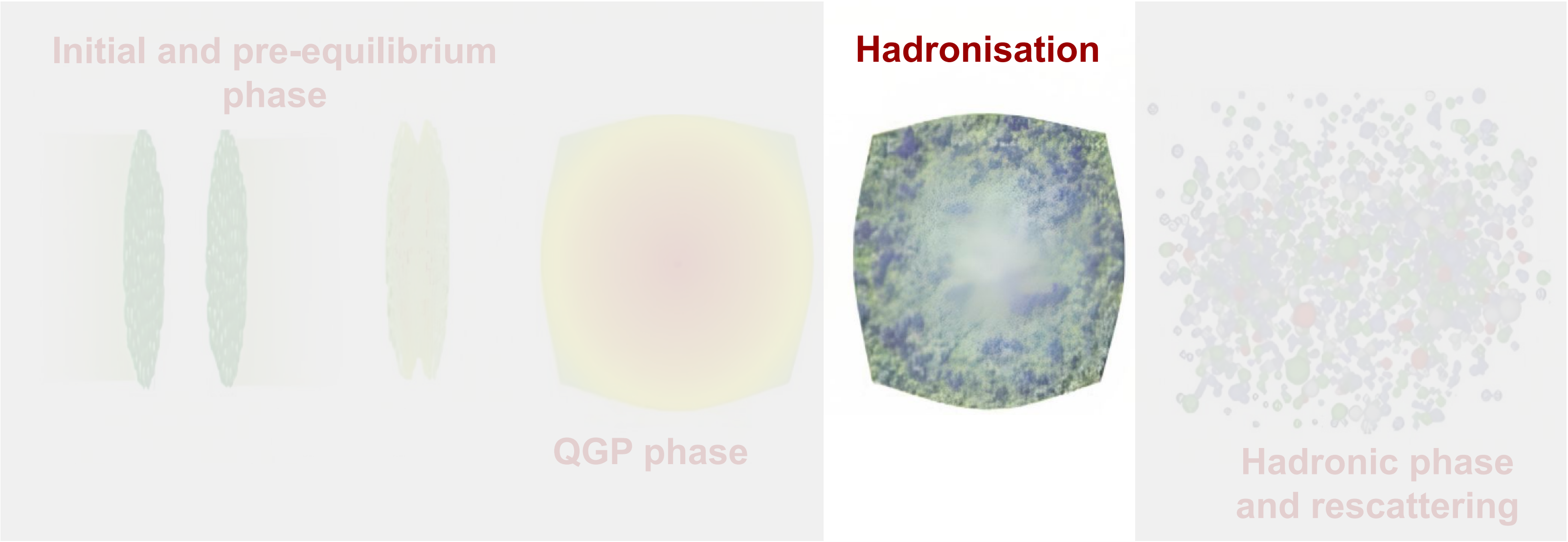


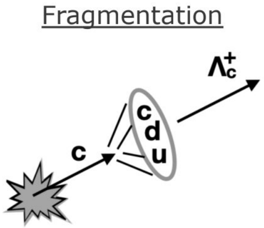


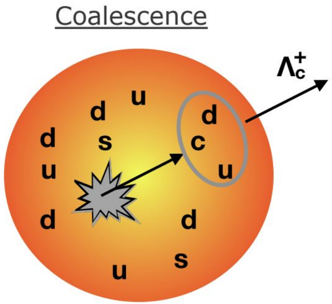
➢ Beauty measurements start to be available. Mainly via non prompt charm hadrons.
- **Need to measure fully reconstructed beauty mesons and baryons** with small uncertainties to further constrain QGP properties

Talks from M. Stojanovic and M. Völkl

Heavy-ion collisions with heavy quarks



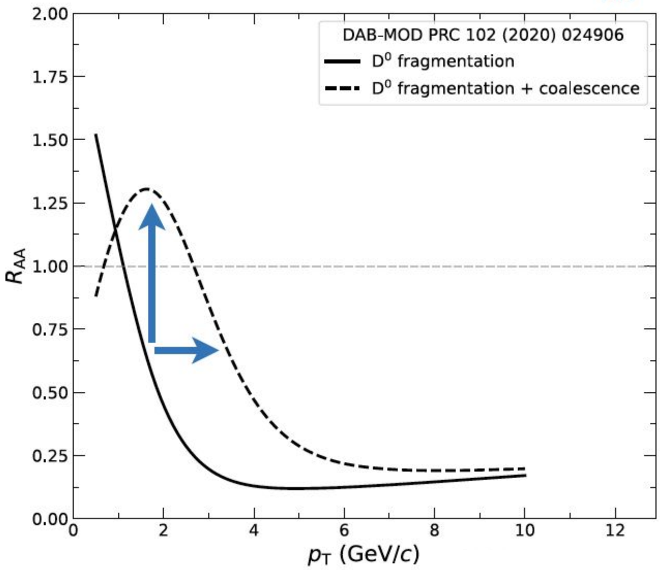




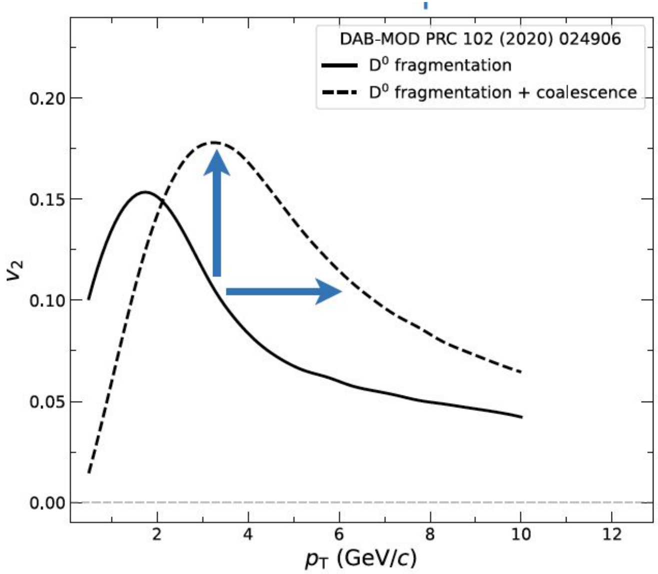
- **Probe hadronisation** in presence of a deconfined medium
  - **Fragmentation**: ‘break up’ of charm quark - as in e^+e^- collisions (also expected in pp)
  - **Coalescence**: combination of quarks close in phase space

Modification of p_T distributions

Nuclear modification factor



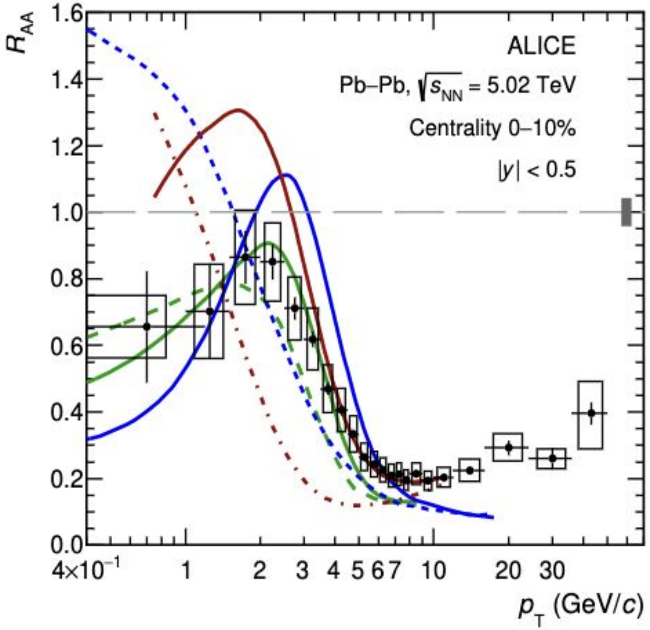
Elliptic flow



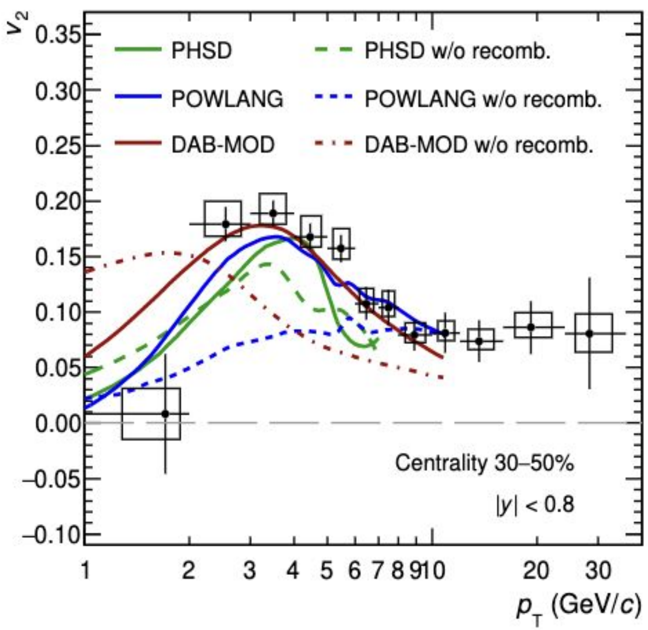
- **Coalescence** of heavy quarks with light quarks from the QGP affects **HF hadron momentum distributions**
  - HF hadrons pick-up the radial and elliptic flow of the light quark

Modification of p_T distributions

Nuclear modification factor



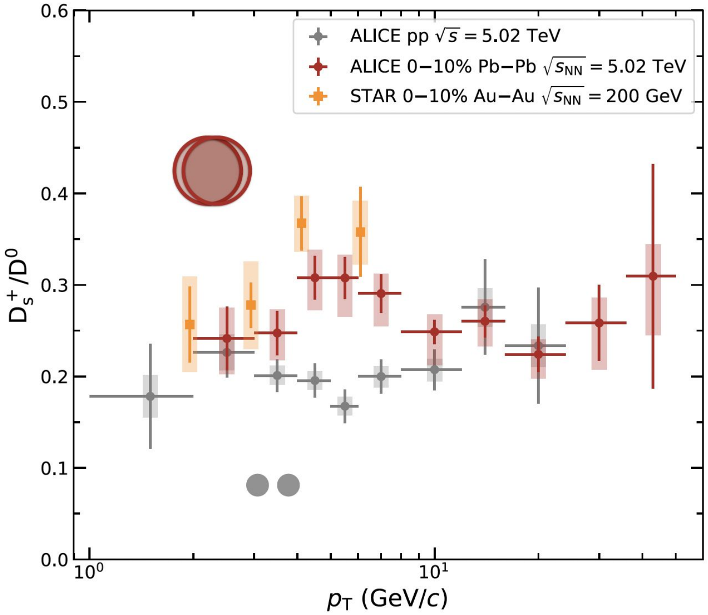
Elliptic flow

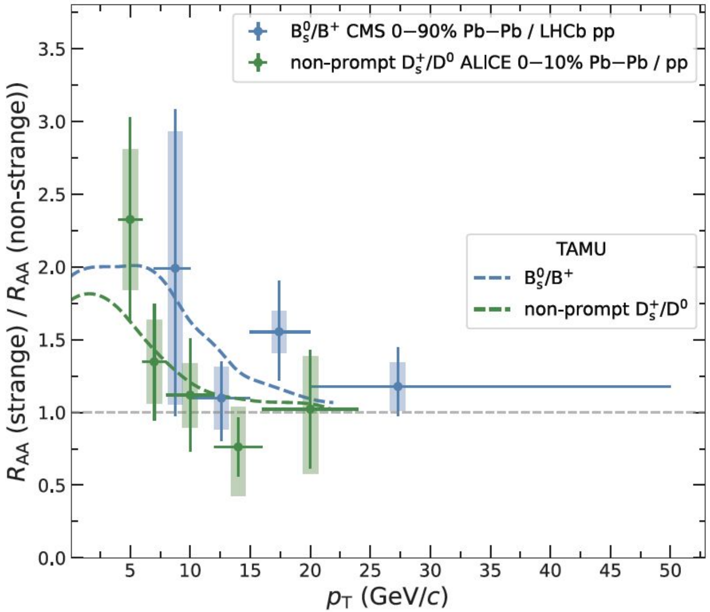


➢ **Coalescence component is crucial to describe the data at low/mid p_T**

Open charm and beauty hadrochemestry

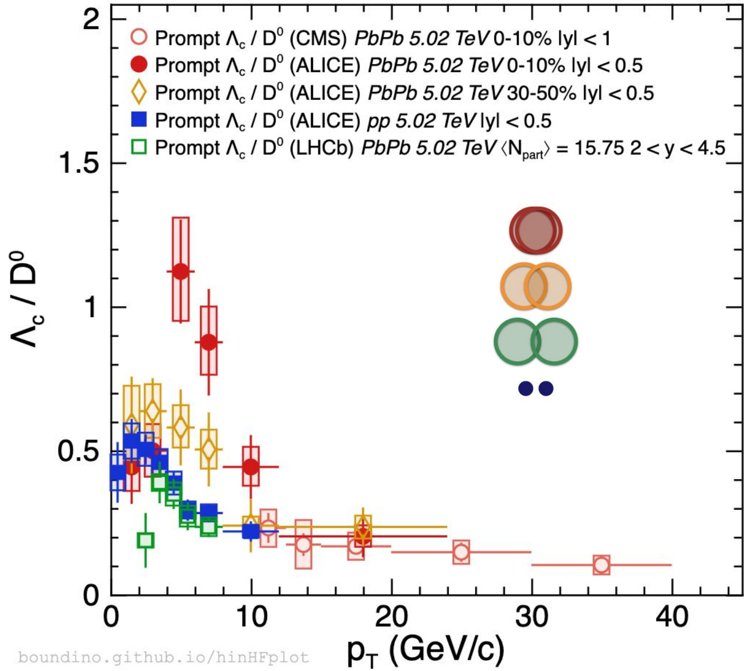
ALICE:
JHEP 05 (2021) 220
PLB 827 (2022) 136986
arXiv:2204.10386
CMS:
PLB 829 (2022) 137062
STAR:
PRL 127 (2021) 092301





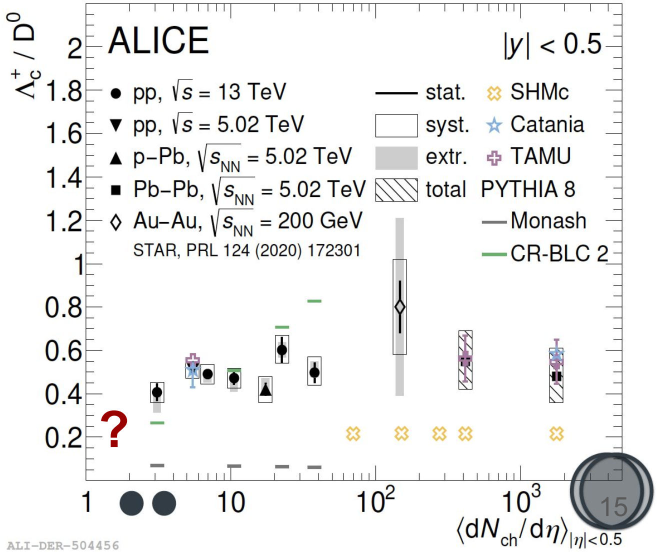
- Abundant production of strange quark in the QGP → coalescence of heavy quarks with strange quarks from the QGP affects the **HF hadrochemestry**
  - **Enhanced $D_s(B_s)$** yield relative to non-strange mesons
  - D_s/D^0 ratios in central Pb-Pb hint at enhancement at mid-p_T relative to pp

Λ_c/D^0 yield ratio



- ➢ Largely enhanced charm and beauty baryon to meson yield ratio in pp collision wrt e^+e^- collisions
  - Fragmentation universality?
  - Colescence in pp?
- ➢ **Λ_c/D^0 in heavy-ion collision** is even higher at intermediate p_T wrt pp
  - Higher coalescence probability or radial flow?
  - An interplay of the two effect?

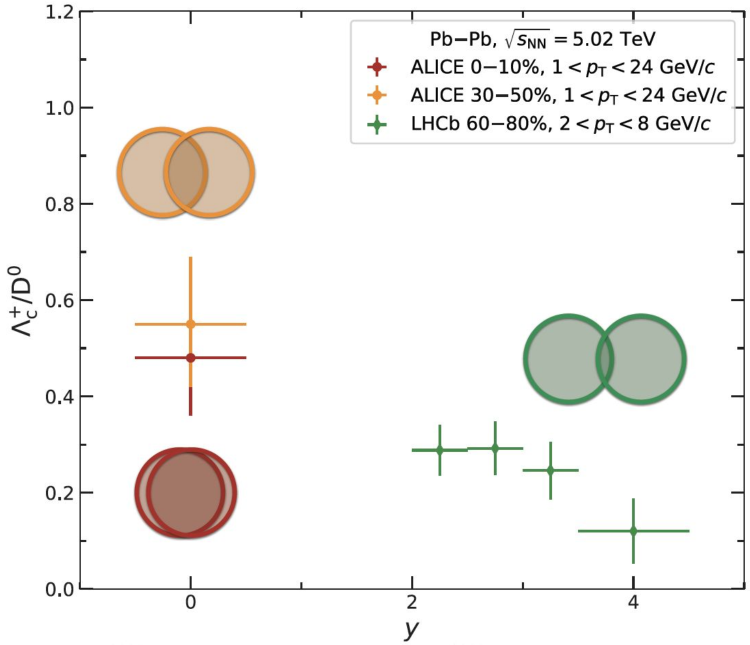
LHCb:
arXiv:2210.06939
Phys. Rev. D 100, 031102
CMS:
PLB 803 (2020) 135328
CMS-PAS-HIN-21-004
ALICE:
arXiv:2112.08156
PLB 839 (2023) 137796
PRL 127 (2021) 202301

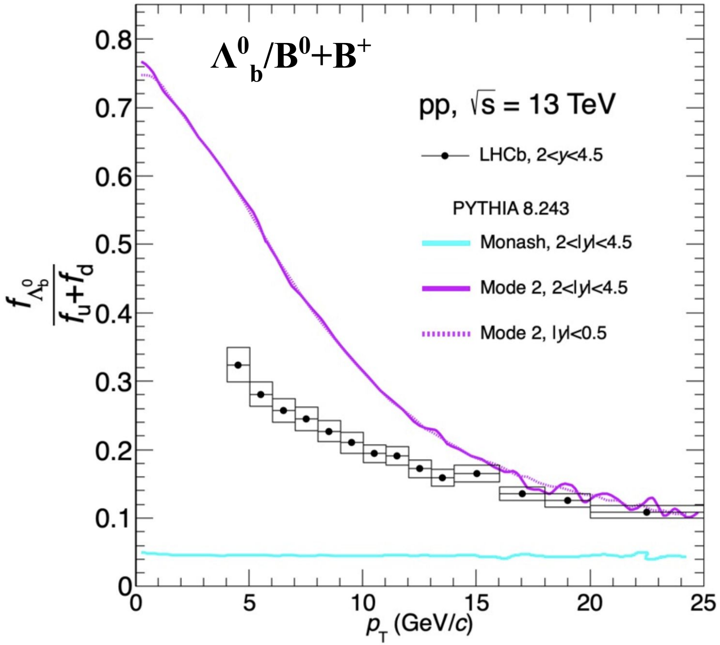


- ➢ Need to measure other baryons with strange component in HI
- ➢ No modification of p_T-integrated Λ_c/D^0 from pp to Pb-Pb
- ➢ **Towards very low multiplicity** - would it be possible to reach an e^+e^- limit?

Talks from A. Kalteyer and Y. Zhang

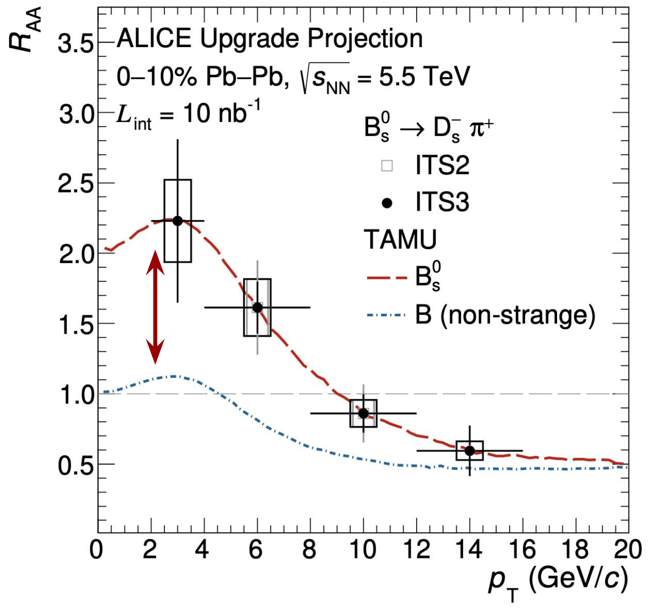
A rapidity puzzle?



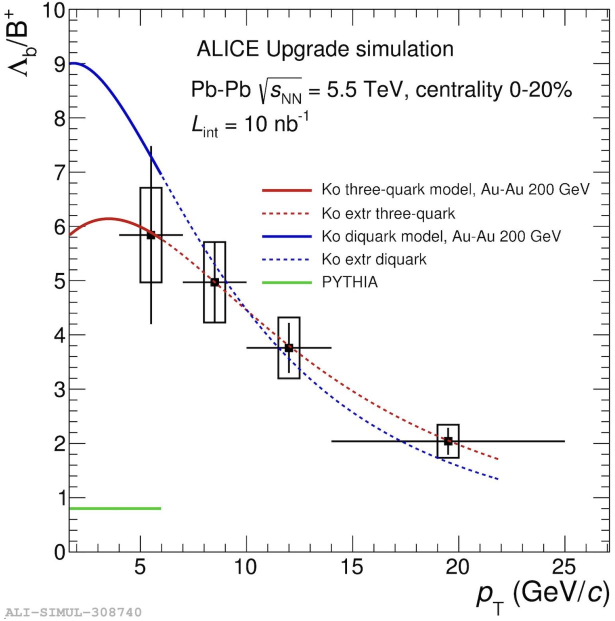


- ➢ **Rapidity dependence?** - what do models (coalescence) predict?
- ➢ Need a systematic comparison of mid and forward rapidity both in pp and HI
- ➢ Similar observation for beauty in pp, will it be at reach in HI?

Beauty hadrons in Pb-Pb



arXiv:1812.06772

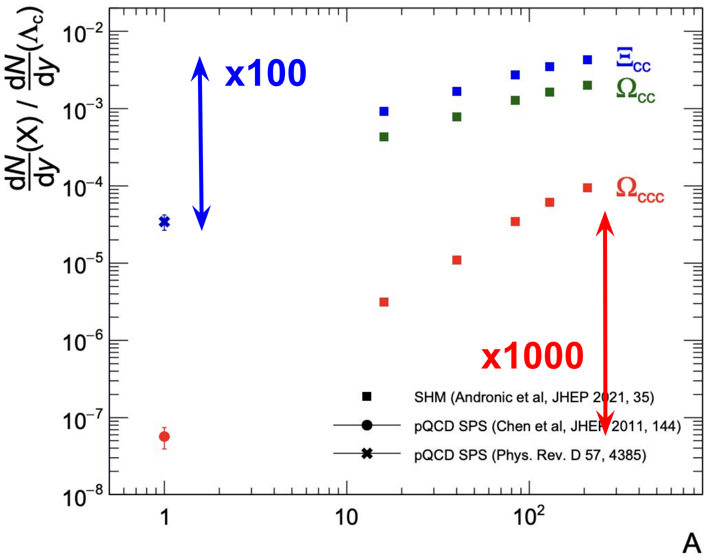


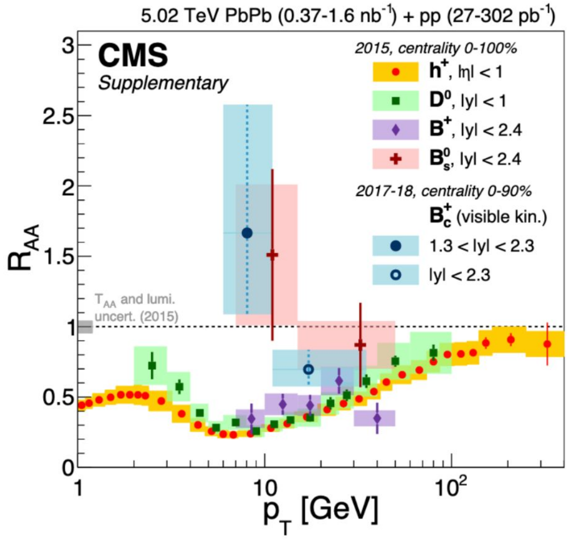
➢ **Full reconstruction of beauty hadrons will be at reach in Run 3-4**

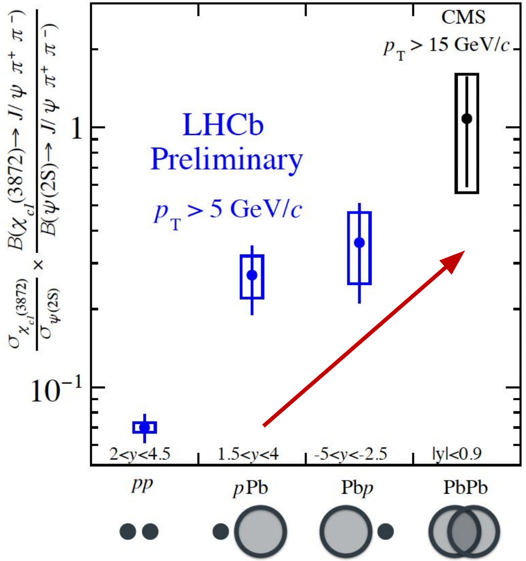
- Expected enhancement in B^0_s in Pb-Pb collisions will be quantifiable for the first time
- Reconstruction of $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ (BR = 4.9 10-3)
  - Will be affected by large uncertainties and limited to p_T > 4-5 GeV/c in Run 3 and Run 4

Additional windows on hadronisation

- Yields of multi-charm/single-charm hadrons predicted to be largely enhanced in A-A compared to pp collisions in SHM and coalescence models - production in single hard scattering disfavored
- B_c^+ production in heavy-ion collisions is an ideal probe: sensitive to dead cone and recombination
- X(3872) - Crucial to measure low p_T and centrality dependence
  - Stress test with system size scan - *ep → eA → pp → pO → OO → pA → PbPb*

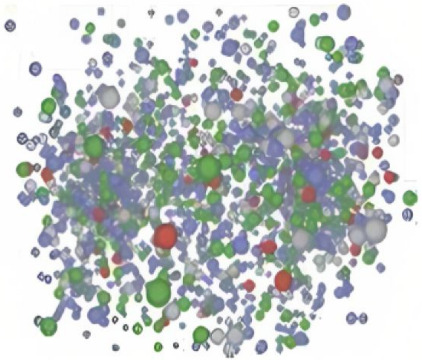




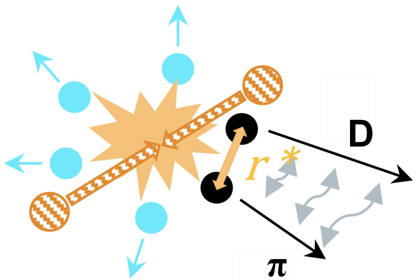


Talks from C. Gomez, T. Sheng, D. Chinellato, A. Grelli

Heavy-ion collisions with heavy quarks

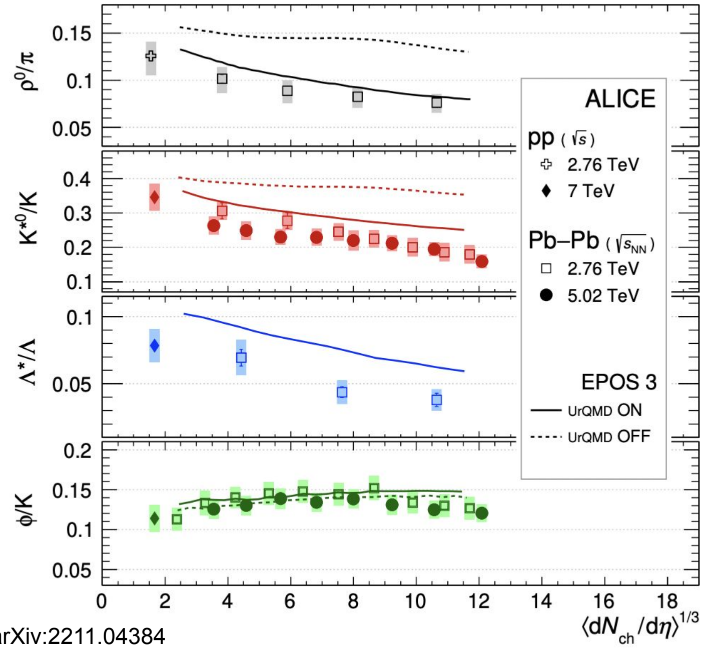


Hadronic phase and rescattering

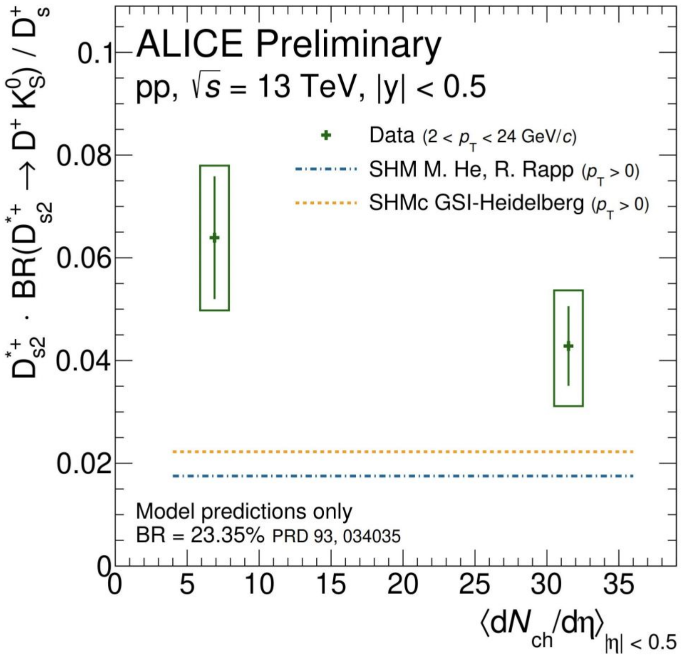


- **The hadron-gas phase** lasts approximately 5-10 fm/*c*
  - Resonances with a lifetimes of the same timescale are good probes of the dynamics of the hadronic phase since they are likely to decay before the kinetic freeze-out.
  - Direct measurement of two-body interactions with charm

HF hadronic resonances



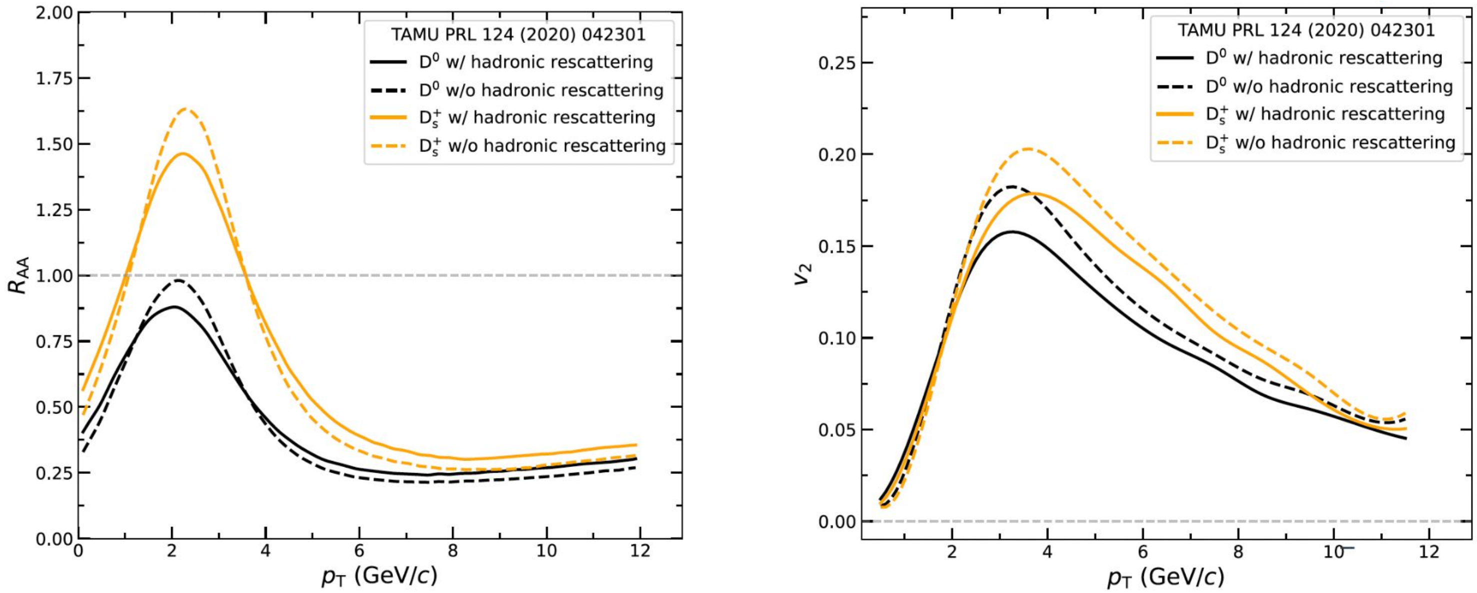
arXiv:2211.04384



- ➢ Decay products of resonances are subject to elastic interactions in the hadron gas, which modify their momenta and prevent the reconstruction of the resonance signal by means of an invariant mass analysis
- ➢ D^{*}_{s2} has a life time of ~12 fm/*c* → do we see a similar effect as observed in the strange sector?

Talks from S. Politano

HF hadrons in the hadronic phase



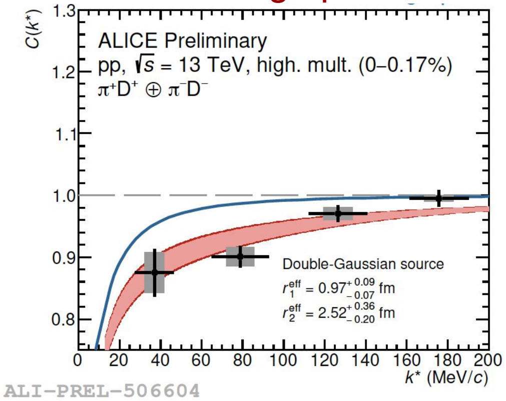
- In the TAMU model the used scattering lengths for πD and KD are:
  - $a_{\pi D}(I = 3/2) = -0.1$ fm
  - $a_{KD}(I = 1) = -0.22$ fm

- **No experimental constraints available**

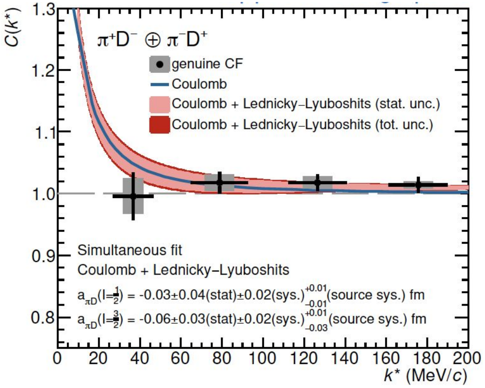
TAMU:
PRL 124 (2020) 042301
PLB 701 (2011) 445-450

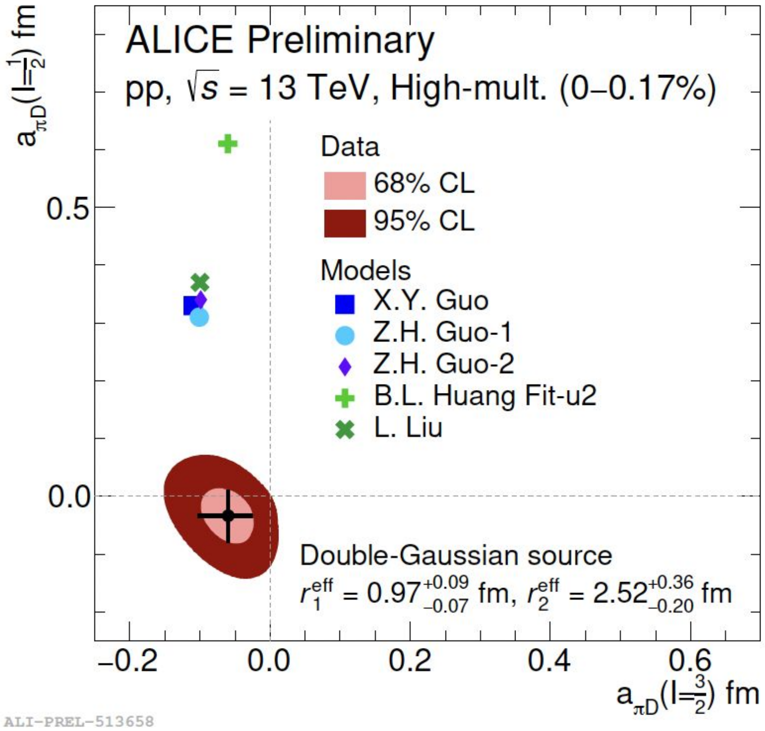
HF hadrons in the hadronic phase

same charge pairs



opposite charge pairs

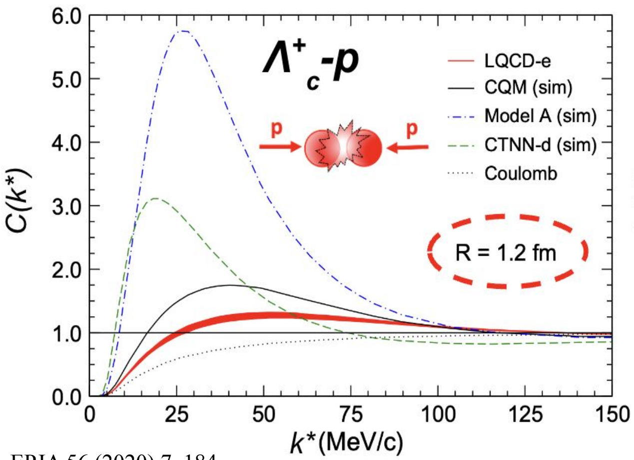




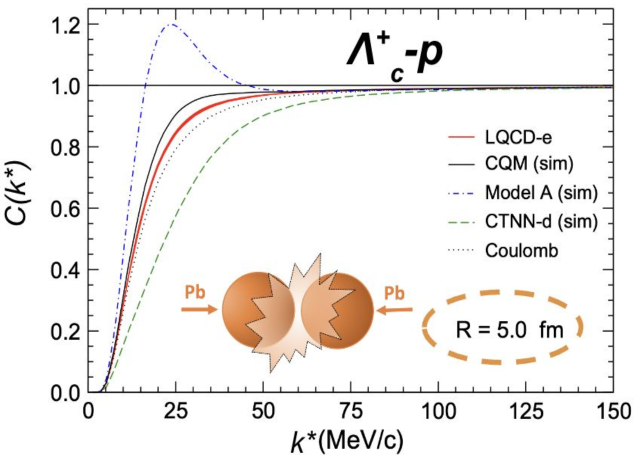
- Scattering length for I = 3/2 in agreement with models
- Scattering length for I = 1/2 significantly smaller than models

- The values indicate a **small rescattering of D mesons in the hadronic phase of heavy-ion collisions**

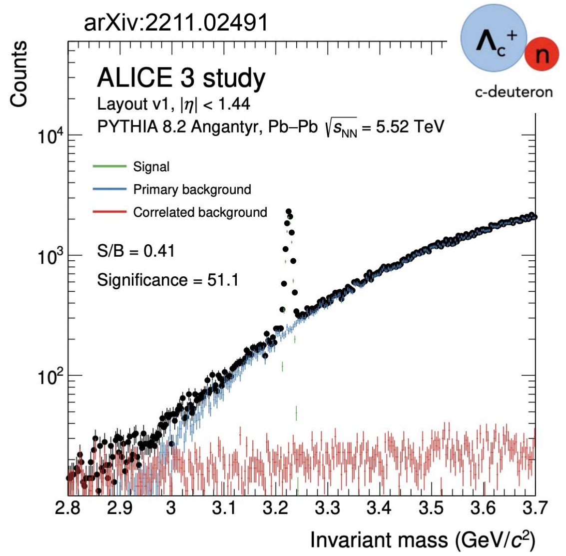
Charm hypernuclei



EPJA 56 (2020) 7, 184



arXiv:2211.02491

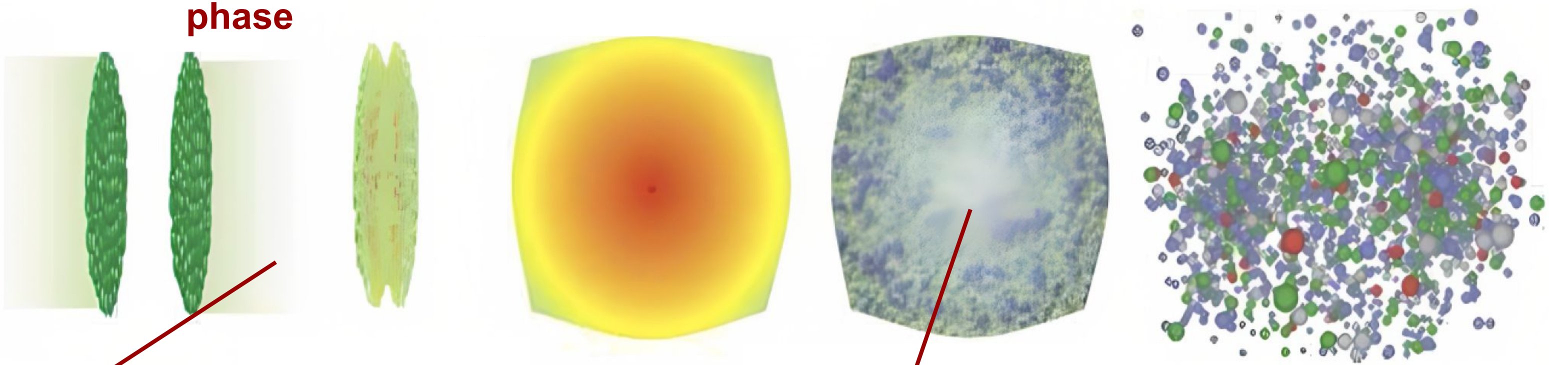


- Possibility to **constrain the Λ_c-N interaction potential**
  - Distinct source size dependence of the correlation function in presence of bound states
- Possibility of performing a **full decay reconstruction** will soon become feasible $c_d \rightarrow dK^-\pi^+$

Outlook

Initial and pre-equilibrium phase

Hadronisation



QGP phase

Hadronic phase and rescattering

Sensitivity to B fields
- precise Δv_1
- polarization of J/ψ and D*

Diffusion, energy loss, thermalization?
- QGP diffusion coefficient with b quarks: larger mass, further from thermalization
- Interplay of melting and regeneration vs. binding energy

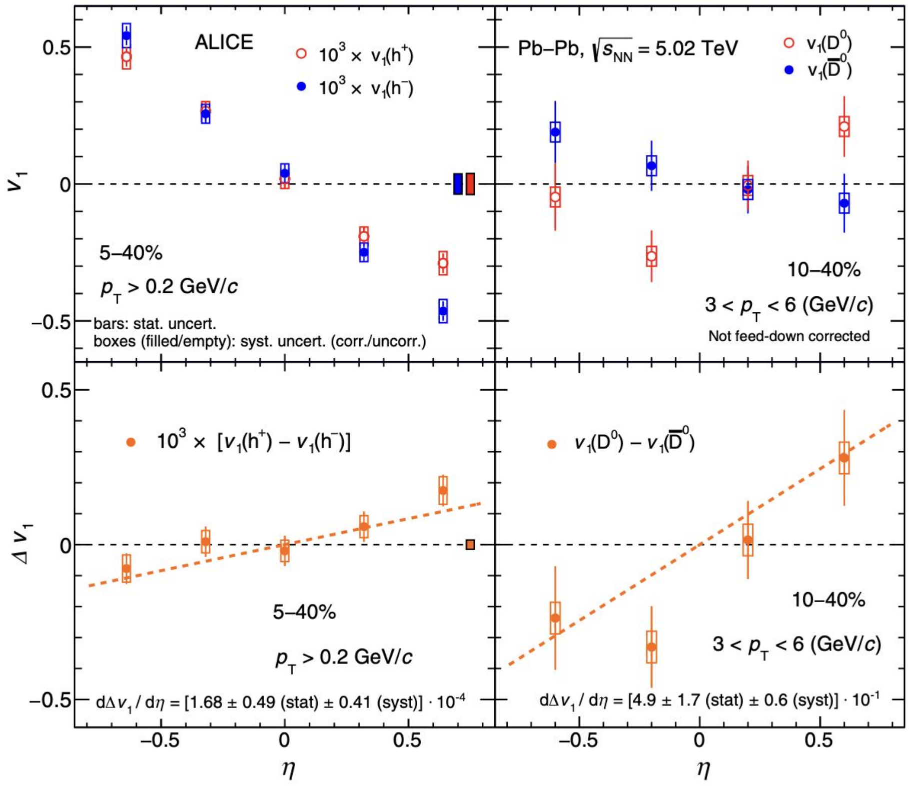
A universal process?
- Precise measurements of charm and beauty baryons in AA (including charm-strange baryons)
- Multi-HF hadrons as ultimate probe ("pure recombination")

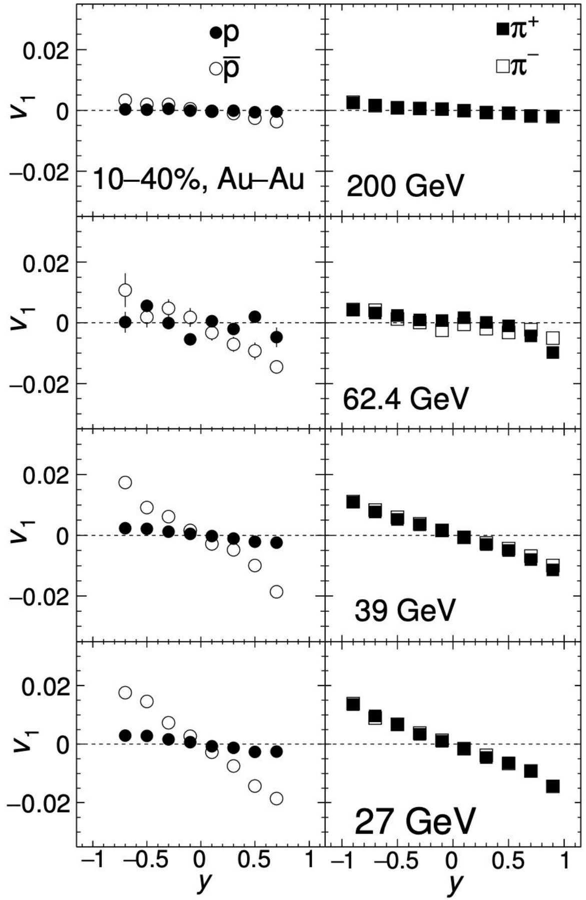
Interaction potential and bound states
- precise measurements of scattering length parameters
- possibility to study bound states

Thanks for your attention

Thanks for inputs and discussions to:
A. Beraudo, F. Capellino, A. Dainese, G. Giacalone, A. Grelli, A. Rossi, J. Sun

Directed flow

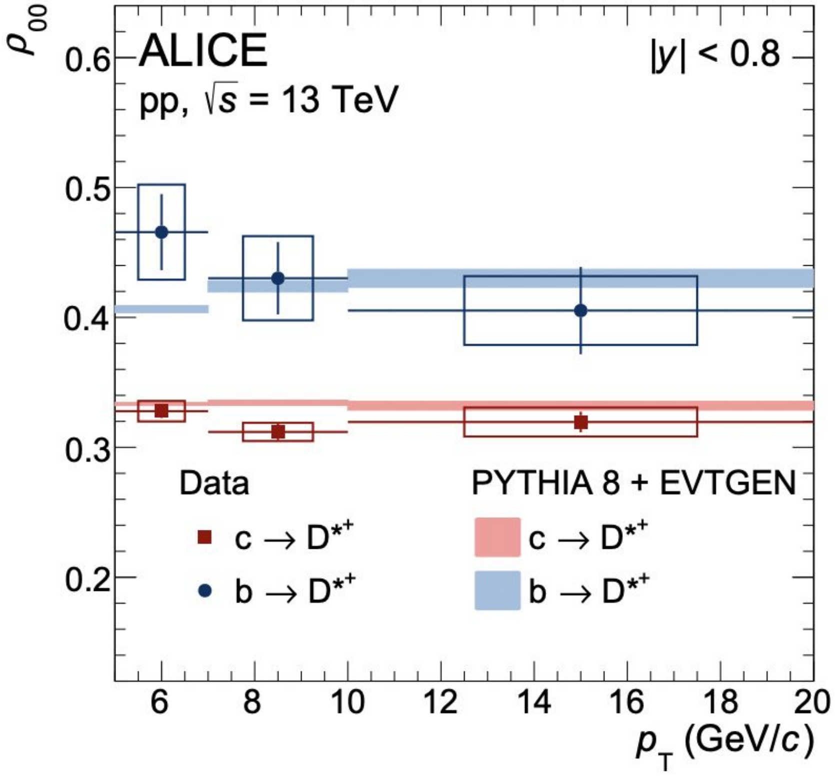




Andrea Dubla

Open charm vector meson

arXiv:2212.06588

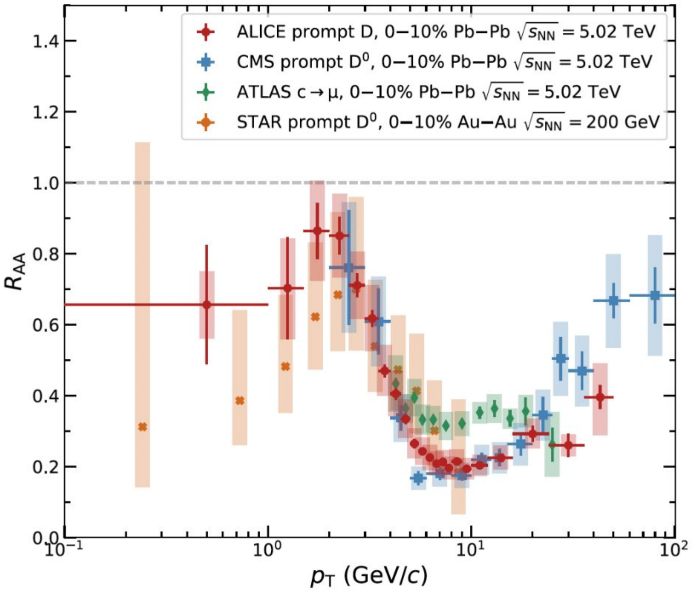


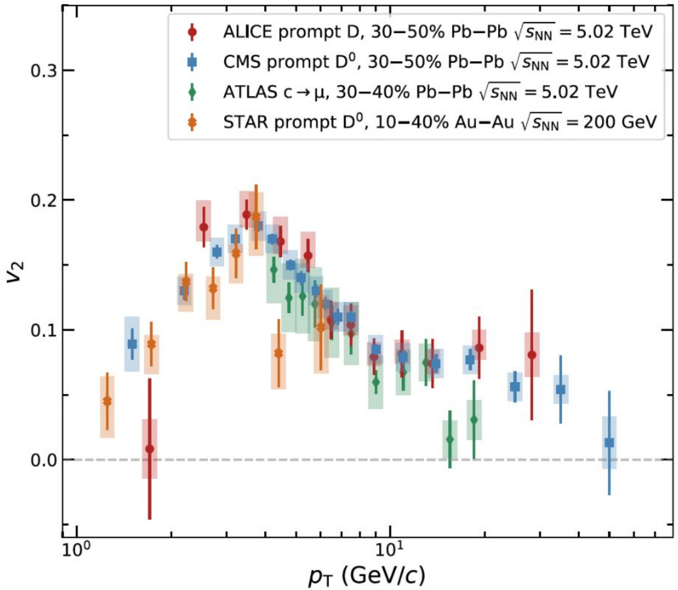
- **Spin alignment of prompt and non-prompt charm vector meson** with respect to helicity plane axis in pp collisions
  - prompt D* compatible with no polarisation
  - ρ_{00} > 1/3 for non-prompt D* (helicity conservation in B meson decays)

- **Measurement of D* vector meson in heavy-ion collisions is crucial** to complete the picture for the charm quark

The main observables

ALICE:
JHEP 01 (2022) 174
PLB 813 (2021) 136054
CMS:
PLB 782 (2018) 474
PLB 816 (2021) 136253
ATLAS:
PLB 829 (2022) 137077
PLB 807 (2020) 135595
STAR:
PRC 99 (2019) 34908
PRL 118 (2017) 212301

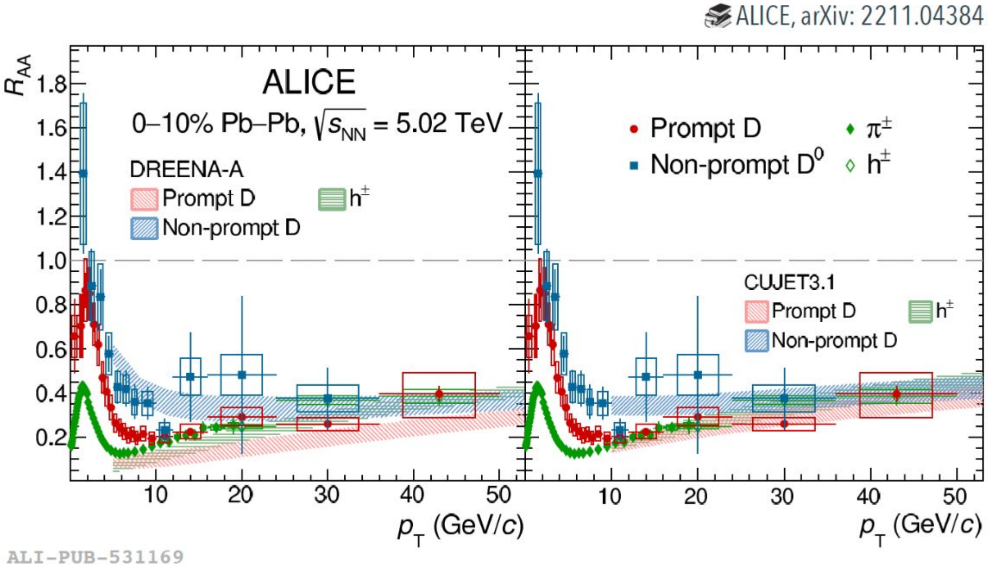




- Measured **significant spectra modification and positive v_2** for open charm and J/ψ in HI collisions
  - substantial interactions with the medium constituents
  - Strong indication of possible thermalisation of charm quark in the QGP

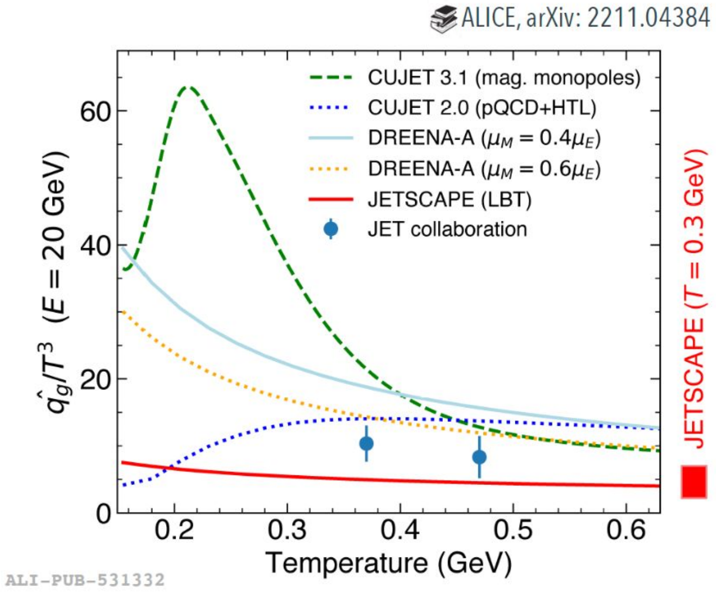
- Systematic studies of beauty not available yet - open beauty might flow (contribution from the light component?) but Υ does not seems to flow. Needs of precise measurements

The high p_T regime



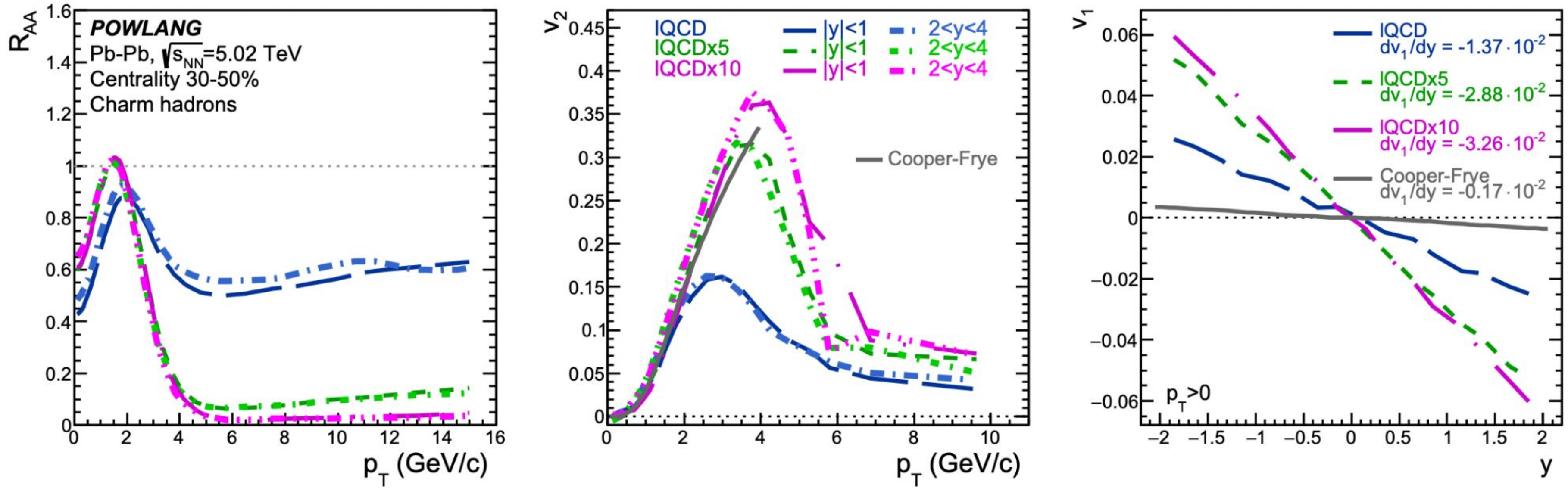
- Hierarchy of suppression as expected from dead cone effect

$$R_{AA}(b) > R_{AA}(c) \gtrsim R_{AA}(\text{light})$$



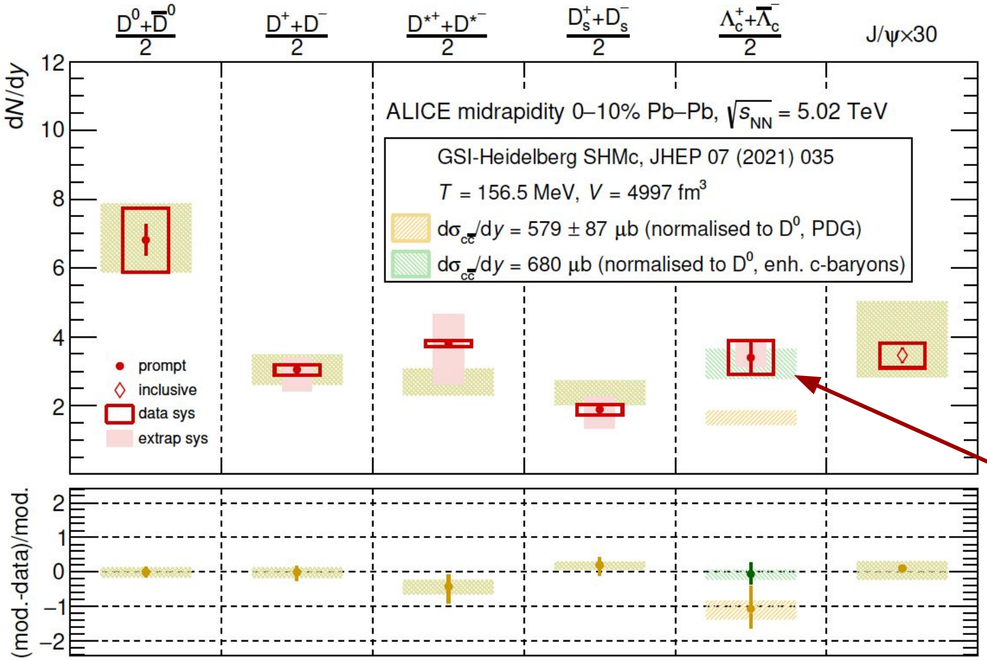
- Data-to-model comparison seems to favour the scenario of weak coupling for high temperatures
- Less constraints for models at low temperatures
  - ➡ Different observables needed

Can we look at additional observables?



SHM with charm

Extremely good description of particle yield in the light flavour sector!



arXiv:2211.04384

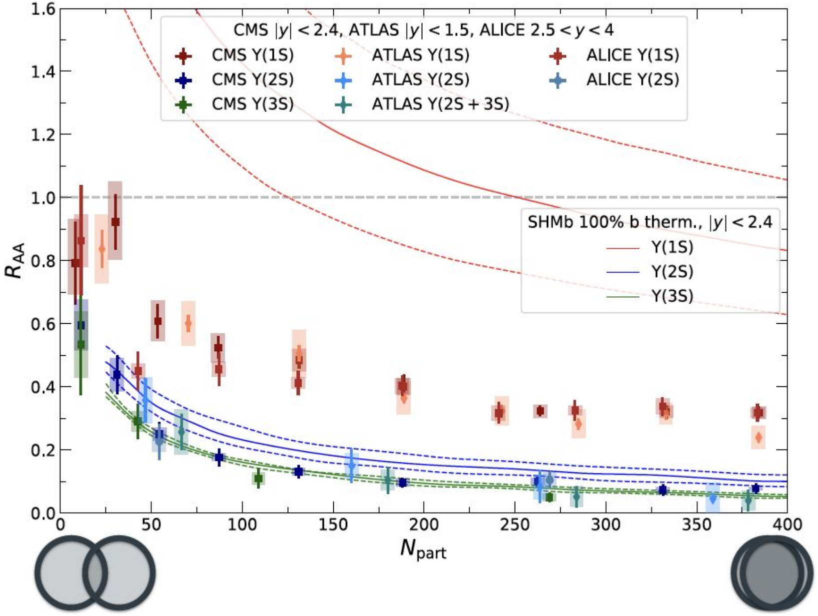
- ➢ Measured p_T-integrated yields of open charm mesons and J/Ψ midrapidity described by SHMc within uncertainties
  - Charm content determined by cross section and not by fireball temperature
  - Assume (full) charm quark thermalisation in the QGP
  - Charm quarks distributed to hadrons according to thermal weights

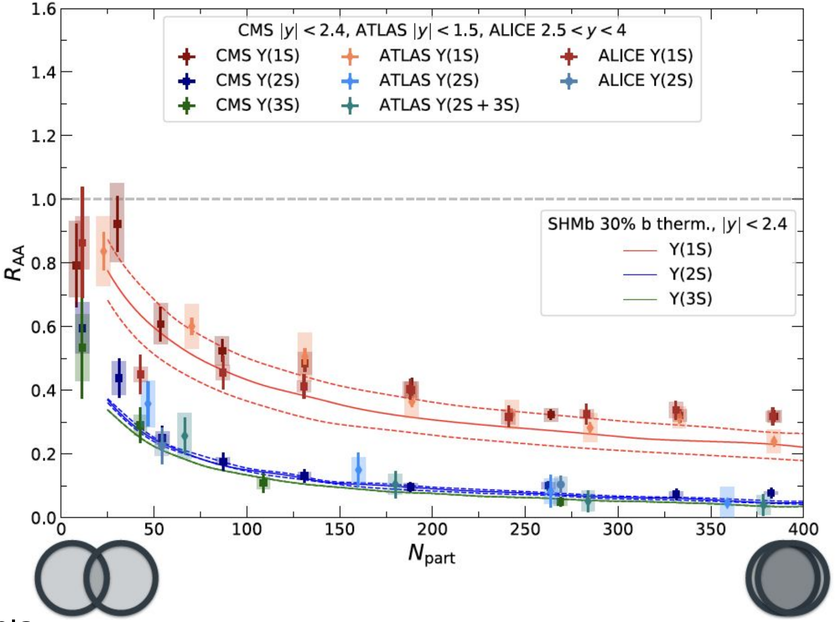
- ➢ **Yield of Λ_c baryons underestimated**
  - Captured assuming an enhanced production of charmed baryons

Bottomonia states

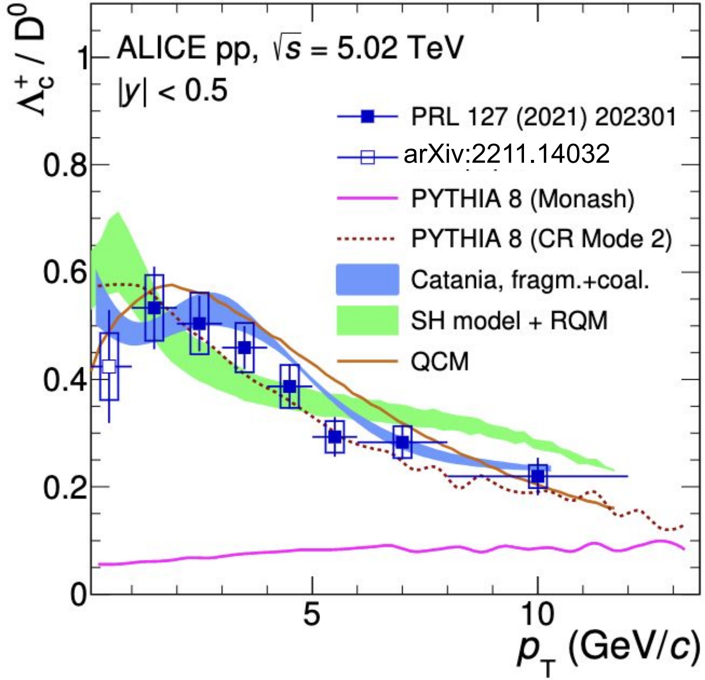
- ϒ largely overestimated if 100% of beauty quarks assumed to be thermalized.
  - Does beauty quark reach thermal equilibrium
  - v_2 is compatible with zero

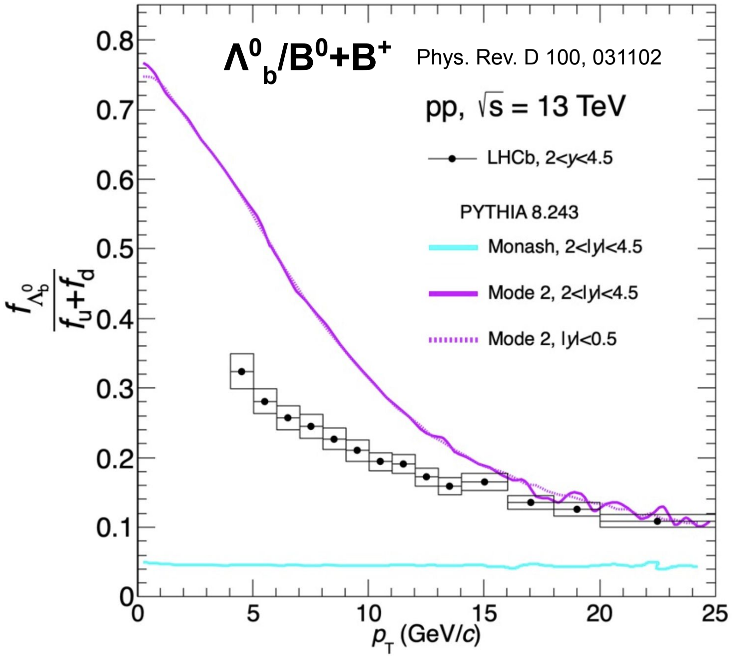
- **ϒ described if 30% of beauty quarks assumed to thermalize.**
  - Reach partial equilibrium?
  - **Presence of currently unknown open beauty states will lead to a reduction of the bottomonia yields.**





Baryon/meson ratio in pp

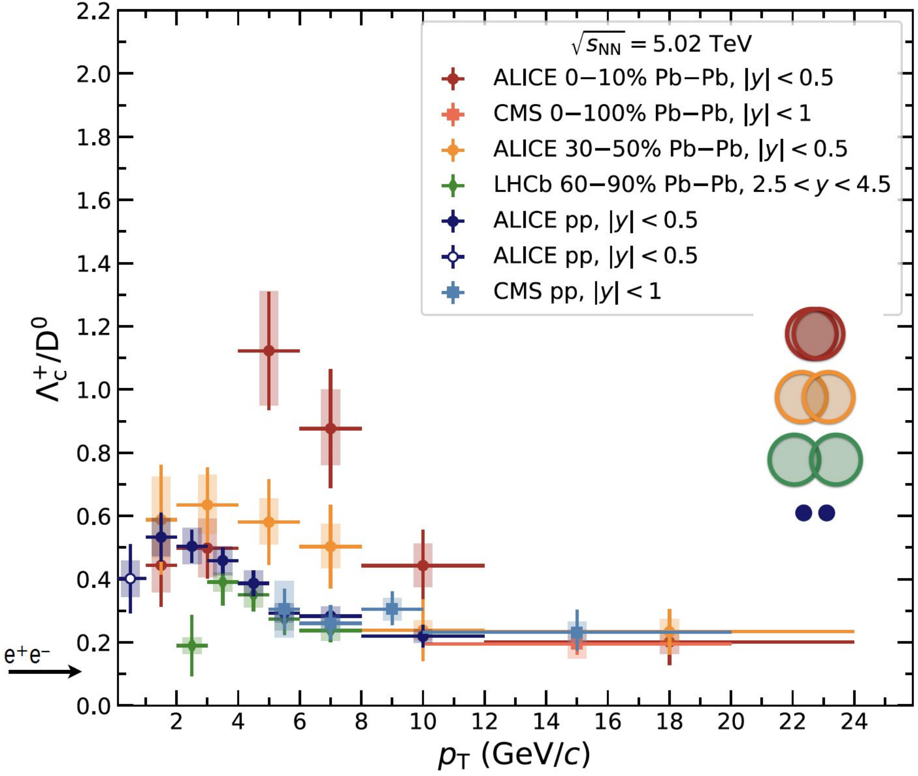




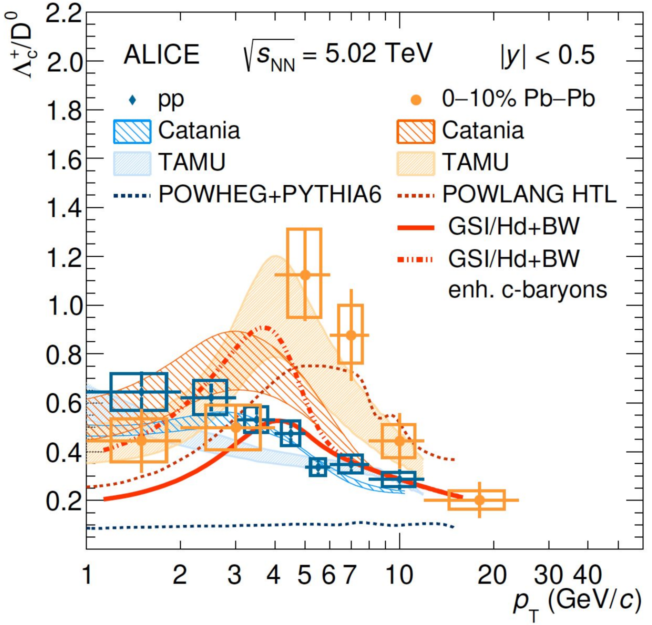
- ➢ Largely enhanced charm and beauty baryon to meson yield ratio in pp collision wrt e^+e^- collisions
- ➢ **Do the model also describe measurements at forward rapidity?**
  - Is there any obvious difference (parton density, charm density)?

PYTHIA: JHEP 1508 (2015) 003
SHM+RQM: PLB 795 117-121 (2019)
Catania: PLB 821 (2021) 136622
QCM: EPJC 78 no. 4, (2018) 344

Λ_c in Pb-Pb

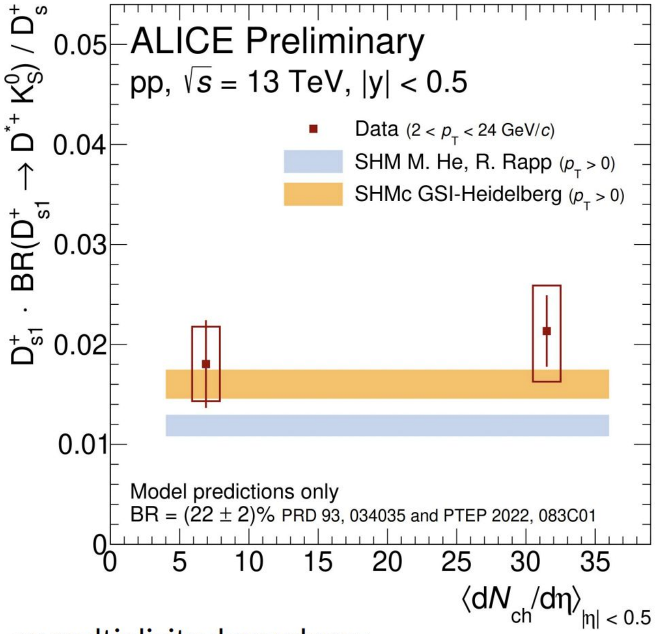


- **Λ_c/D^0 in heavy-ion collision** is higher at intermediate p_T wrt e^+e^- and pp
  - Higher probability to hadronise via coalescence?
  - Radial flow?
  - An interplay of the two effect?

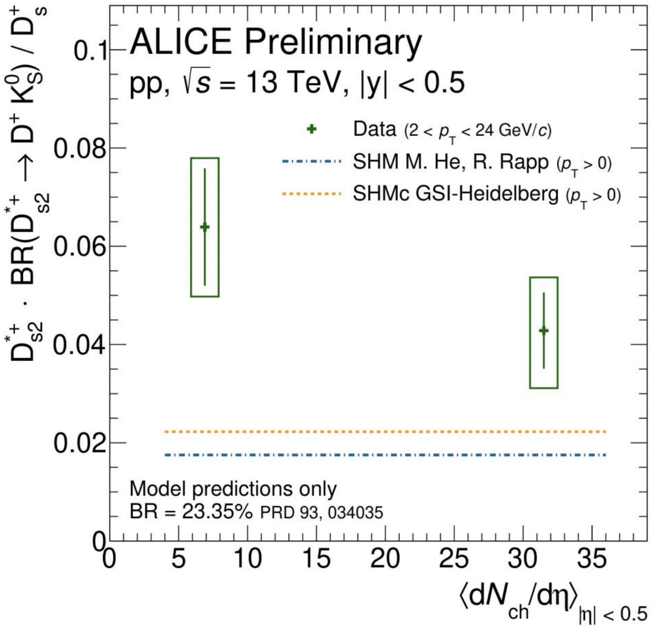


Andrea Dubla

HF hadronic resonances



- no multiplicity dependence explicitly expected from SHM and SHMc
  - ➡ no multiplicity dependence observed in data (τ ~ 219 fm/c)



- no multiplicity dependence explicitly expected from SHM and SHMc
  - ➡ multiplicity dependence not expected in SHM, but might arise from hadronic rescattering due to D_{s2}^{**} lifetime (τ ~ 11.61 fm/c)

HF hadrons in the hadronic phase

- Charm molecules?

System	$I\,(J^{P(C)})$	Candidate
np	0 (1+)	deuteron
ND	0 (1/2−)	$\Lambda_c(2765)$
ND*	0 (3/2−)	$\Lambda_c(2940)$
ND	0 (1/2−)	$\Sigma_c(2800)$
$D^*\bar{D}$	0 (1++)	X(3872)
D*D	0 (1+)	T_{cc}
$D_1\bar{D}$	0 (1−−)	Y(4260)
$D_1\bar{D}^*$	0 (1−−)	Y(4360)
$\Sigma\bar{D}$	1/2 (1/2−)	$P_c(4312)$
$\Sigma\bar{D}^*$	1/2 (1/2−)	$P_c(4457)$
$\Sigma\bar{D}^*$	1/2 (3/2−)	$P_c(4440)$

105, 034028 (2022)