Heavy-Flavour measurements by ALICE from a Quark-Gluon Plasma perspective

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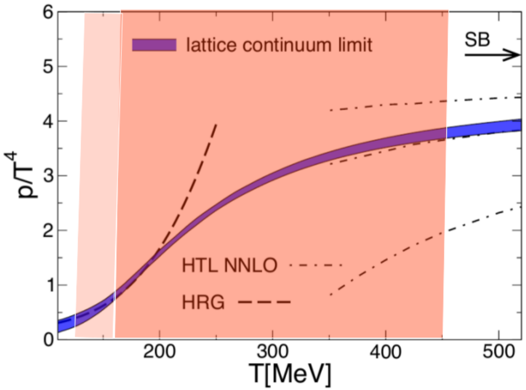
LHC: a laboratory for QCD fluids



p/T^4: pressure over temperature^4

HRG: Hadron Resonance Gas

HTL: Hard thermal loop

SB: Stefan-Boltzmann limit of

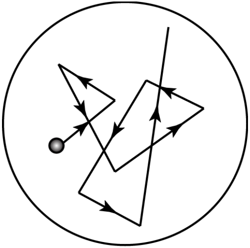
non-interacting quarks and gluons

Figure taken from PLB 370 (2014), T-range from PRC 89, 044910 (2014)

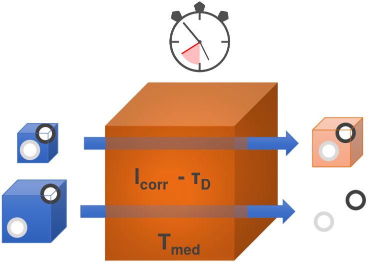
- macroscopic & microscopic equilibrium properties and chiral & deconfinement phase transitions
- understand non-equilibrium dynamics and limits of fluid concepts
- quantify the initial hadronic wave function

What can we address with heavy-flavour observables in ALICE?

Heavy quarks: countable witnesses & test systems



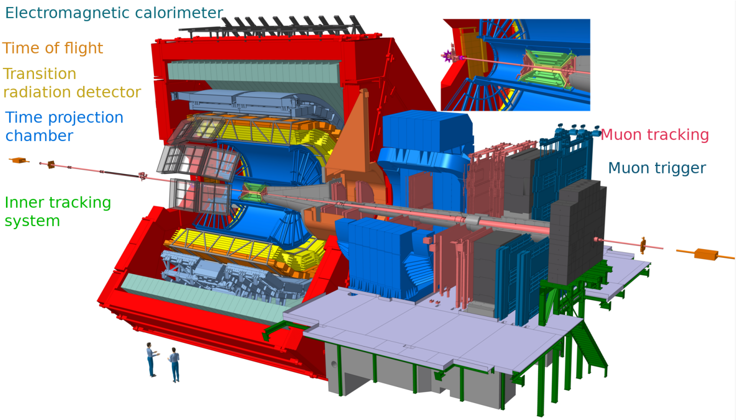
Brownian Movement



Right: taken from Phys. Rep. 858 (2020) 1

- heavy ($M_Q >> \Lambda_{QCD}, T$) quarks: produced early, $\approx$ conserved
- heavy-flavour-medium interaction:
  constrain **heavy quark diffusion & energy loss** $\rightarrow$ G. Luparello's talk link
- heavy quarkonium:
  the hydrogen atom of QCD exposed to medium – **test of deconfinement**
- from heavy ions to pp collisions:
  The smallest fluid? & **When breaks factorisation?**

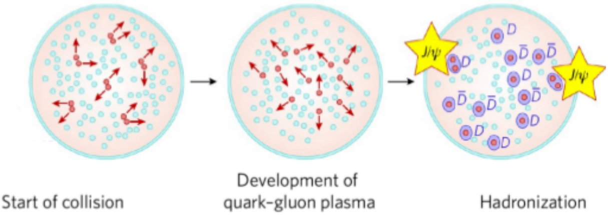
Measuring quarkonia and open heavy-flavours with ALICE



JINST 3 (2008) S08002, Int. J. Mod. Phys. A 29 (2014) 1320044

- reconstruction of electrons, PID (dE/dx, TOF, calorimetric information) and displaced vertices at midrapidity
- muon detection at forward rapidity in dedicated spectrometer

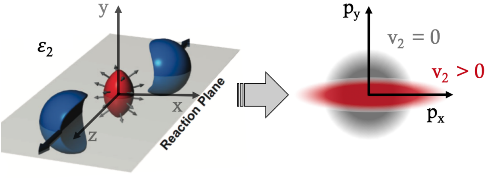
Quarkonium: messenger of deconfinement

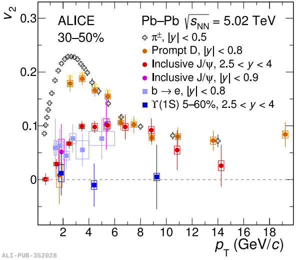


P. Braun-Munzinger and J.Stachel, Nature 448 (2007)

- Quarkonium production modifications by the quark-gluon plasma
  $\rightarrow$ let's see what data tells us

Heavy-flavour azimuthal anisotropies: sign of flow

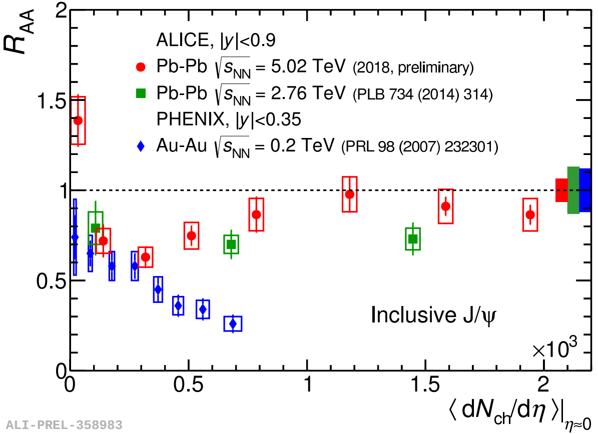




arXiv:2005.14518, arXiv:2005.11131, PRL123(2019)19230

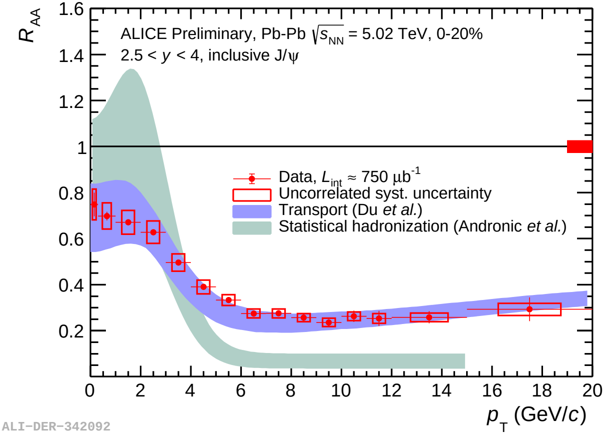
- azimuthal anisotropies in momentum space from initial coordinate space anisotropies
- sizeable impact parameter between nuclei:
  almond-shape interaction zone $\rightarrow \frac{dN}{d\phi} \propto 1 + v_2 \cos(2\phi)$ ϕ w.r.t. reaction plane
- charm, including charmonium, flow with bulk!
- indicate strong interaction & suggest (partial) thermalisation of charm

J/ψ production: collision energy dependence



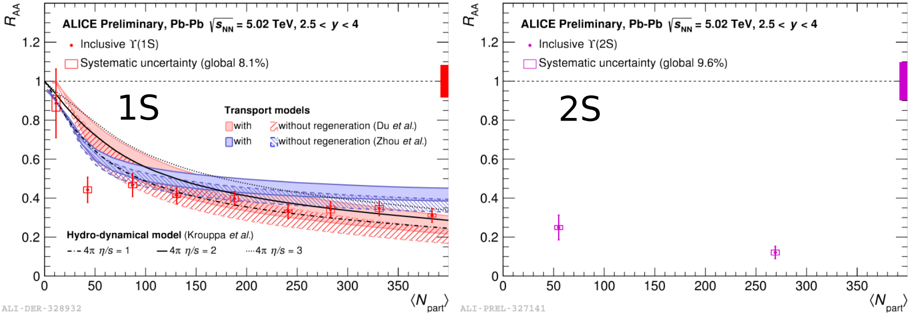
- quarkonium suppression $R_{AA} = \frac{N^{AA}_{J/\psi}}{<N_{coll}> \cdot N^{pp}_{J/\psi}}$: weaker suppression at higher collision energy despite higher energy density
- predicted behaviour from (re)generation of unbound charm quarks $\rightarrow$ deconfinement at work

J/ψ production: transverse momentum dependence



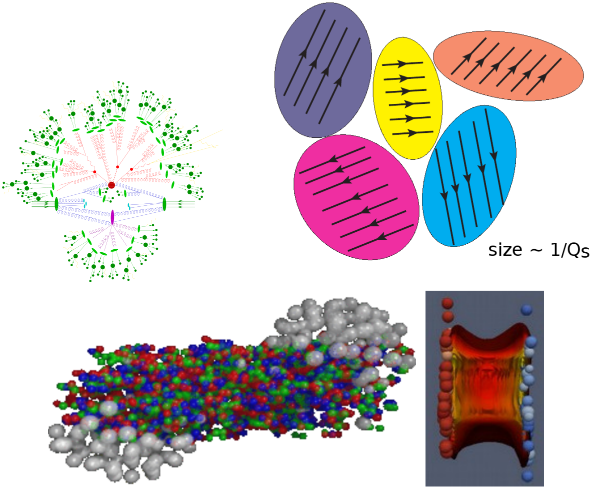
- weaker suppression at lower transverse momentum
- predicted by regeneration from deconfined medium
- unable to discriminate between regeneration dynamically in QGP or at phase boundary
- model uncertainties dominated by total $c\bar{c}$ cross section uncertainty: open heavy flavour crucial as external input!

Υ production: strong suppressions to characterize the interaction



- strong suppression for $\Upsilon(1S)$: $R_{AA} \approx 0.3$ in most central collisions
- 3 times stronger suppression for $\Upsilon(2S)$ in most central collisions
- overall level of suppression for $\Upsilon(1S)$ captured by models
- more precise data, in particular differential in rapidity to be released soon!

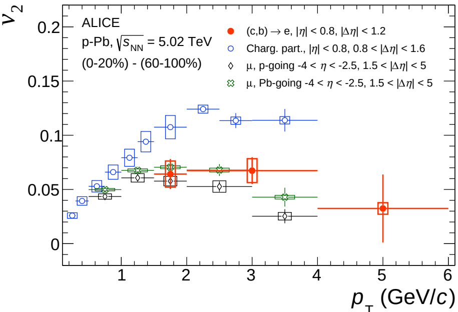
Heavy flavour in pp, p-Pb collisions

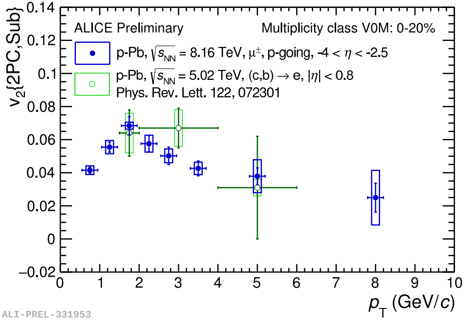


different pictures: 'collinear' MPI, CGC colour domains, few-touch transport, fluid.

- What is right picture for a pp or p-Pb collision?
- Hadronisation, anisotropies as in nucleus-nucleus even for heavy-flavour?

Azimuthal anisotropy: Electrons and muons from heavy-flavour hadrons in p-Pb

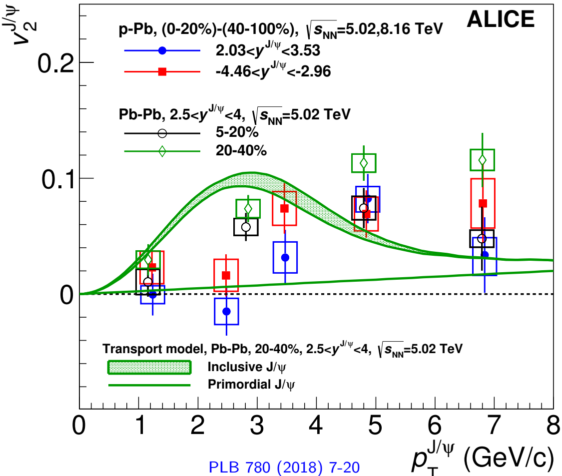




PRL 122, 072301 (2019), preliminary in muon-channel

- sizeable v_2 modulation of correlation between charged-particles and decay lepton observed
- analogue to Pb-Pb collisions and similar in magnitude

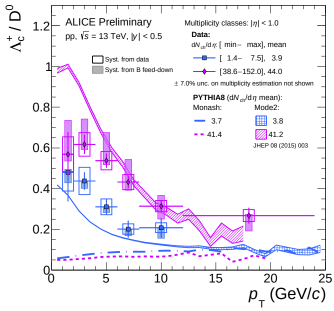
Azimuthal anisotropy: J/ψ production in p-Pb collisions



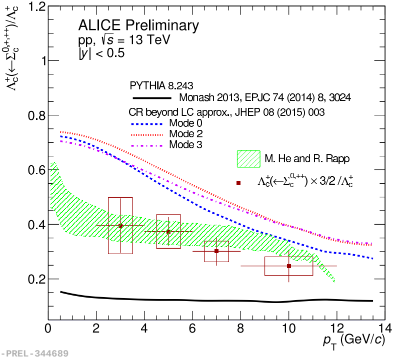
PLB 780 (2018) 7-20

- p-Pb data similar v_2 magnitude as in Pb-Pb data, hint of different p_T-dependence
- models describing experimental Pb-Pb data (slide 6) underestimating effect: a puzzle
- initial state models describing data – the prediction: same effect for Υ

Hadronisation of open heavy flavour: universality between e^+e^- and pp broken



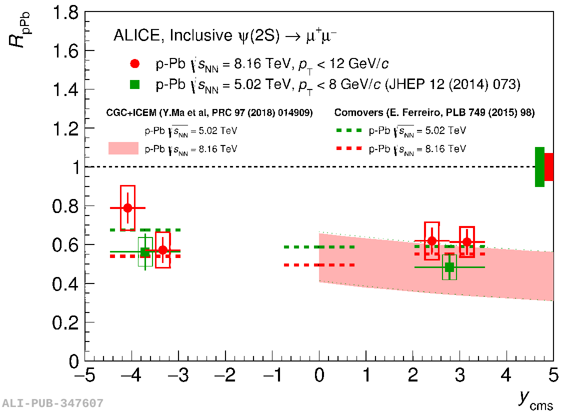
ALI-PREL-336442



ALI-PREL-344689

- strong modification of Λ_c/D^0 compared to e^+e^-: no naïve transfer
- control parameter: final state multiplicity
- not captured by standard hadronisation models
- possible venues: colour reconnections between different partonic interactions beyond leading colour ('Mode 2' left) or hadronisation fraction of charm based on the statistical hadronisation model with more c-baryons than in PDG

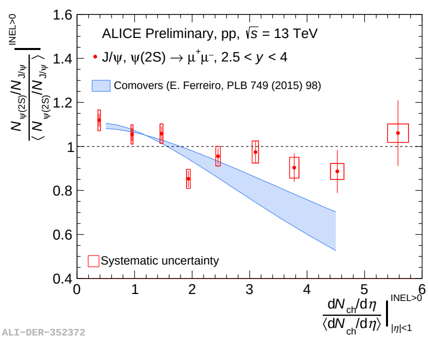
Quarkonium hadronisation: modifications as well...

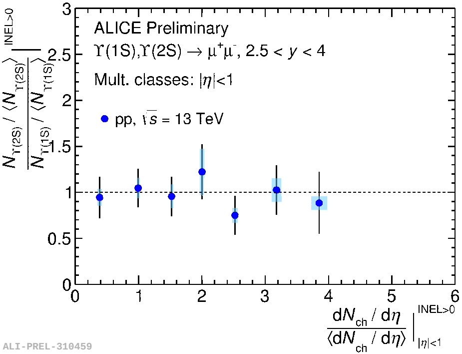


JHEP07 (2020) 237, hints of similar phenomena in Υ-data PLB 806 (2020) 135486 and in JHEP 11 (2018) 194, JHEP 02 (2020) 093 (erratum)

- ground state main mechanism: partonic luminosity reduction or even gluon saturation, alternatively energy loss at forward rapidity
- excited quarkonium states: stronger suppressed than ground state
- breaking of factorisation universality between pp and p-Pb: 2ndary interactions proposed as mechanism

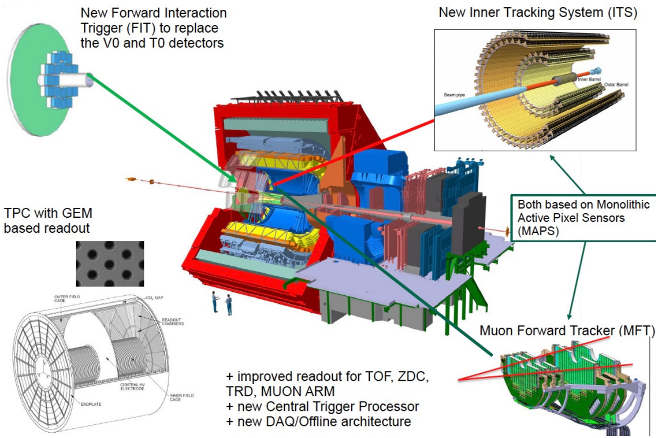
Quarkonium hadronisation: ...and searching for continuity





- investigating phenomena of hadronisation modification as function of multiplicity as control parameter
- no relative modification as function of multiplicity observed in pp
- if present: effect too feeble for current precision and set-up with rapidity-gap between measurements

Outlook



ALICE Upgrade LOI, HL/HE-LHC Working group 5 report

- Run 3: replacement of inner tracking system, TPC read-out plane and new silicon vertexing for muon arm + full read-out of Pb-Pb luminosity
- better and new heavy-flavour and quarkonium measurements central goals

Conclusions

- Heavy-flavour observables in heavy-ion collisions:
  $\rightarrow$ let test colour charges interact
- J/ψ in Pb-Pb:
  $\rightarrow$ observing regeneration from the deconfined medium
- Bottomonium: strong nuclear modifications
- pp and p-Pb collisions:
  $\rightarrow$ aspects of heavy-ion collision for hadronisation and azimuthal anisotropies
  $\rightarrow$interesting and puzzling: competing explanations – to be clarified with more precise data to come & modelling
- Going from qualitiative to quantitative:
  $\rightarrow$ more precision for heavy-flavour
  $\rightarrow$ a major part of the heavy-ion programme in the 20ies and 30ies