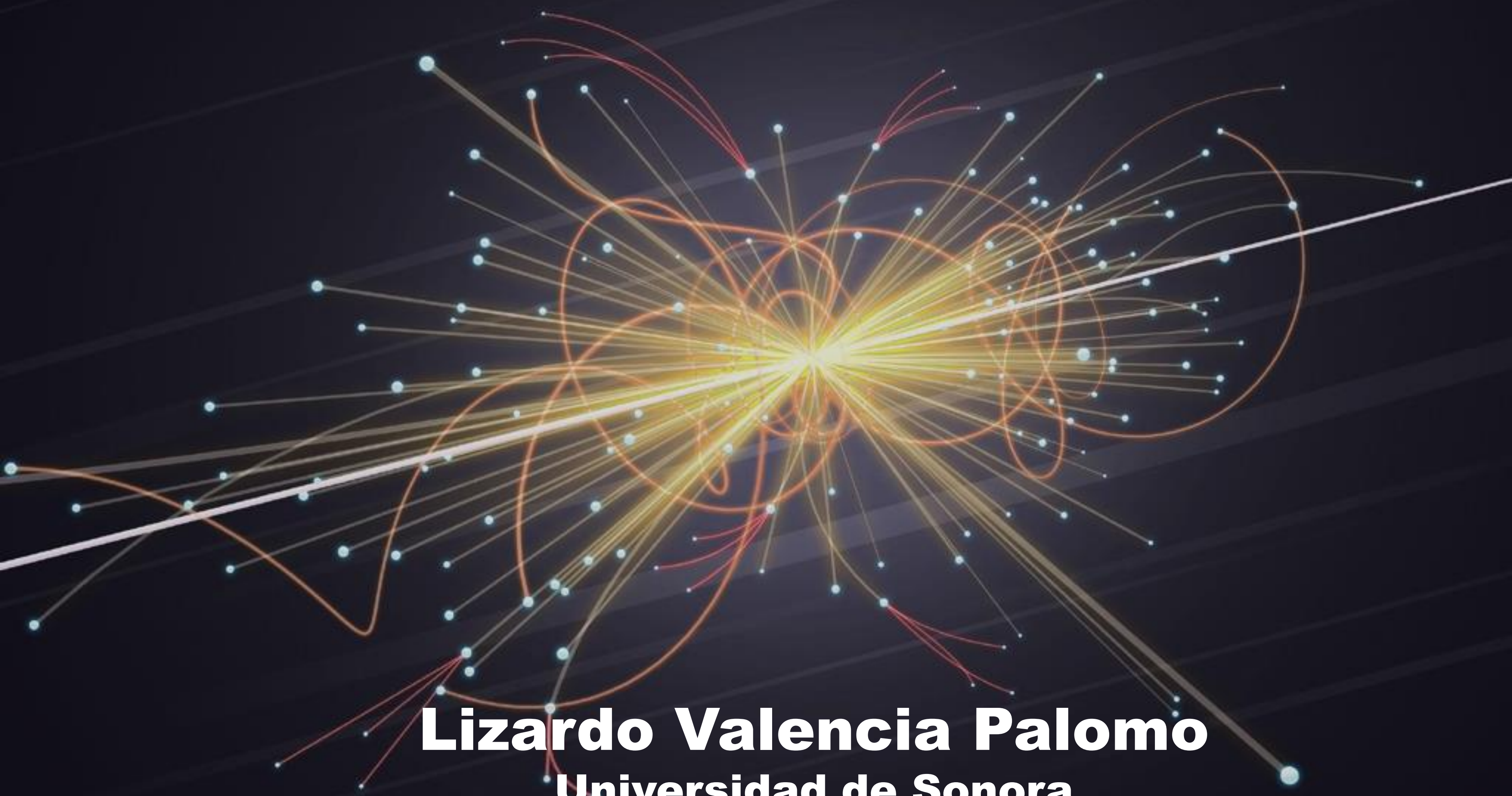
Physics opportunities with heavy quarks beyond LHC run 4



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LHC: past present and future

European Particle Physics Strategy Update recommends full exploitation of the LHC, including the heavy-ion physics programme.

2022: commemorate twelve years since first Pb-Pb collisions at the LHC and almost at the middle of the LHC lifetime.

Good moment to take a look to what we have achieved. But also a moment to think about what we want to do in the future…

HEAVY QUARKS:
THE BIG PICTURE

Small systems: pp and p-A

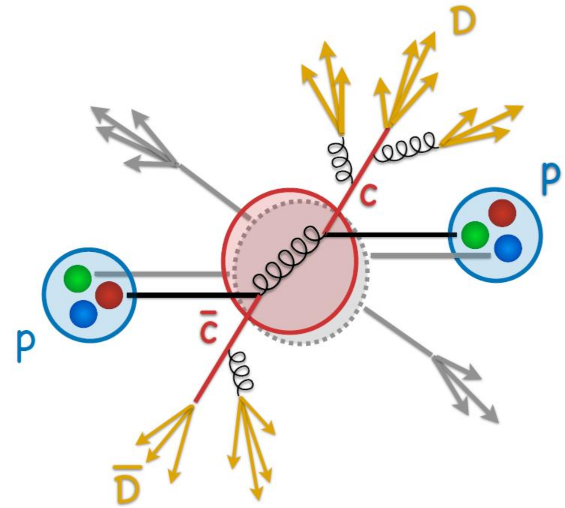
Cross sections calcultations based on the factorisation theorem

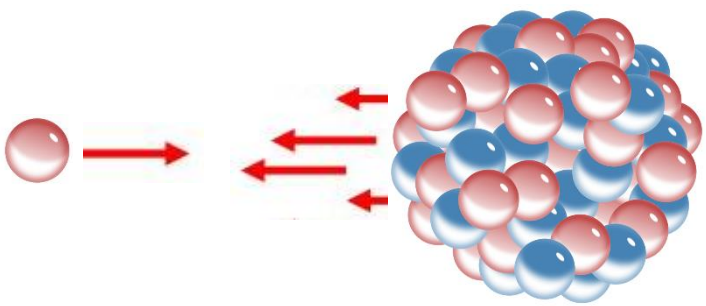
$$\sigma_{\mathrm{hh}\to\mathrm{Hh}} = \mathrm{PDF}(x_{\mathrm{a}}, Q^2)\ \mathrm{PDF}(x_{\mathrm{b}}, Q^2) \otimes \sigma_{\mathrm{ab}\to\mathrm{q}\bar{\mathrm{q}}} \otimes D_{\mathrm{q}\to\mathrm{h}}(z_q, Q^2)$$

Parton distribution functions (non perturbative)

Partonic cross section (perturbative)

Fragmentation functions (non perturbative)



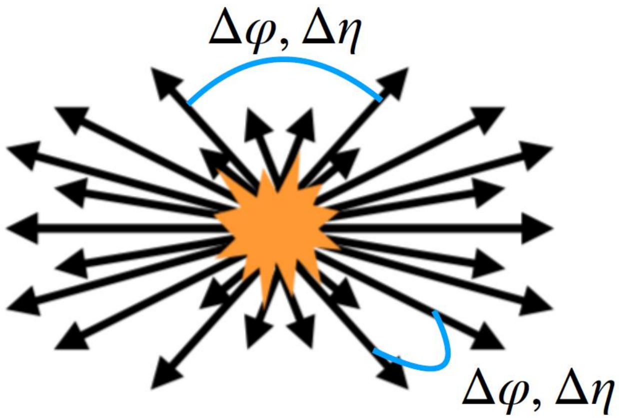


Understand initial and final state cold nuclear matter effects: shadowing, comovers interactions, energy loss in the nucleus, etc.

Intermediate step between pp and A-A collisions.

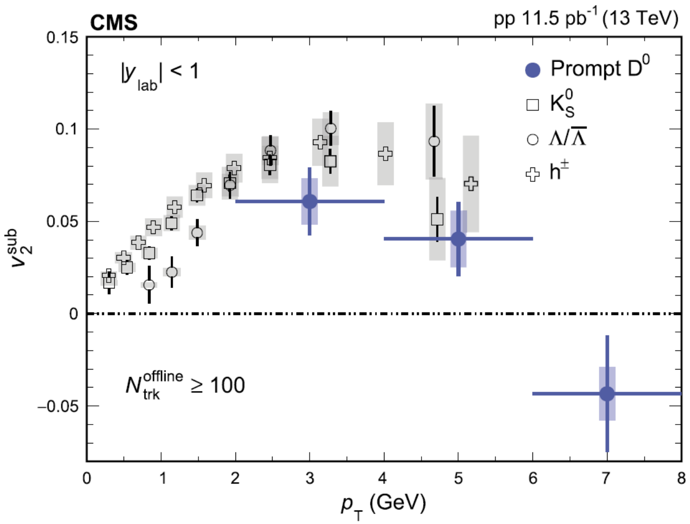
pp and p-A baseline scenario for A-A collisions

Small systems: collectivity



Azimuthal correlation of emitted particles can be characterized by its Fourier components:

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2 \cdot v_1 cos(\varphi - \Psi_1) + 2 \cdot v_2 cos[2(\varphi - \Psi_2)] + \ldots\right)$$

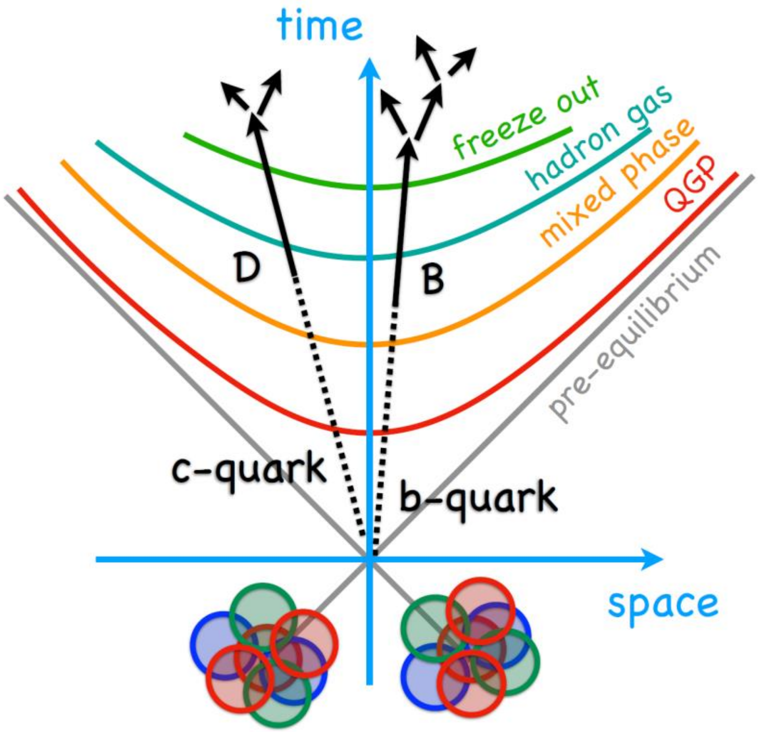


Elliptic flow (v_2) directly reflects the medium response to the initial collision geometry and its fluctuations.

Light flavours exhibit heavy-ion like behaviour: mass ordering and particle grouping.

It was recently shown that charmed hadrons also exhibit a positive elliptic flow.

Heavy ions



Lattice-QCD: phase transition from ordinary nuclear matter to a colour deconfined medium (QGP):

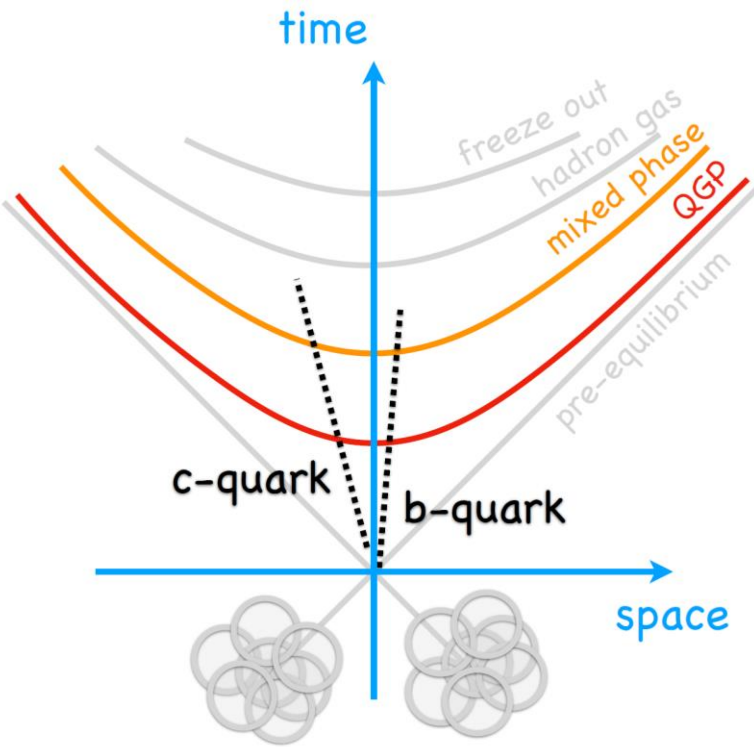
- Expands hydrodinamically.
- Energy density > 15 GeV/fm^3.
- QGP formation ≈ 0.3 fm/c
- QGP lifetime ≈ 10 fm/c

Heavy quarks are produced in shorter time scales than QGP: HQ production < 0.1 fm/c

HQ experience complete evolution of the system.

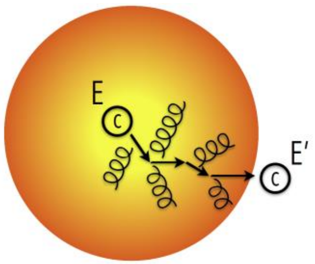
Unique probes to study the QGP!

Heavy ions



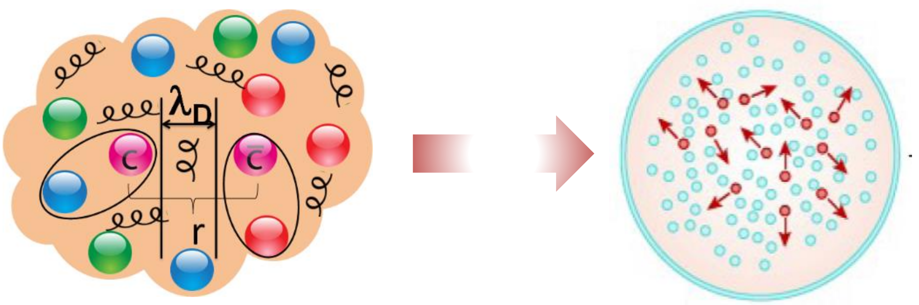
Open heavy flavours:

- Energy loss via ellastic collisions and radiative processes.
- Gluon radiation suppression for small angles: smaller energy loss for large partonic mass.

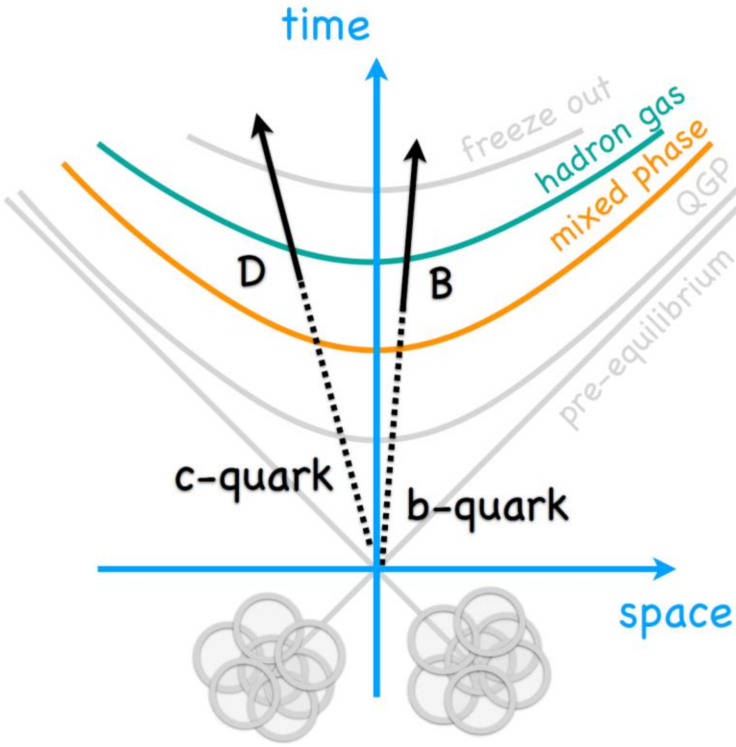


Quarkonium:

- Dissociation due to Debye screening.
- Modification of spectral properties.



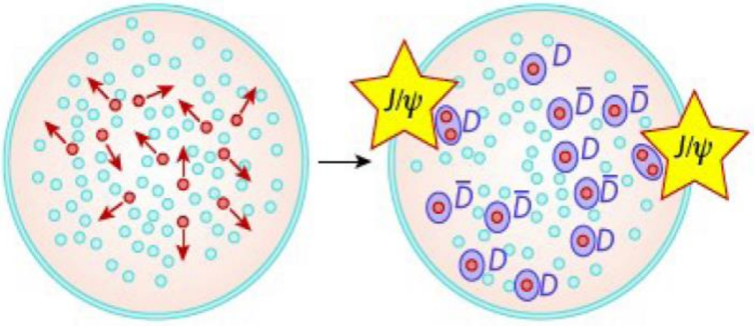
Heavy ions



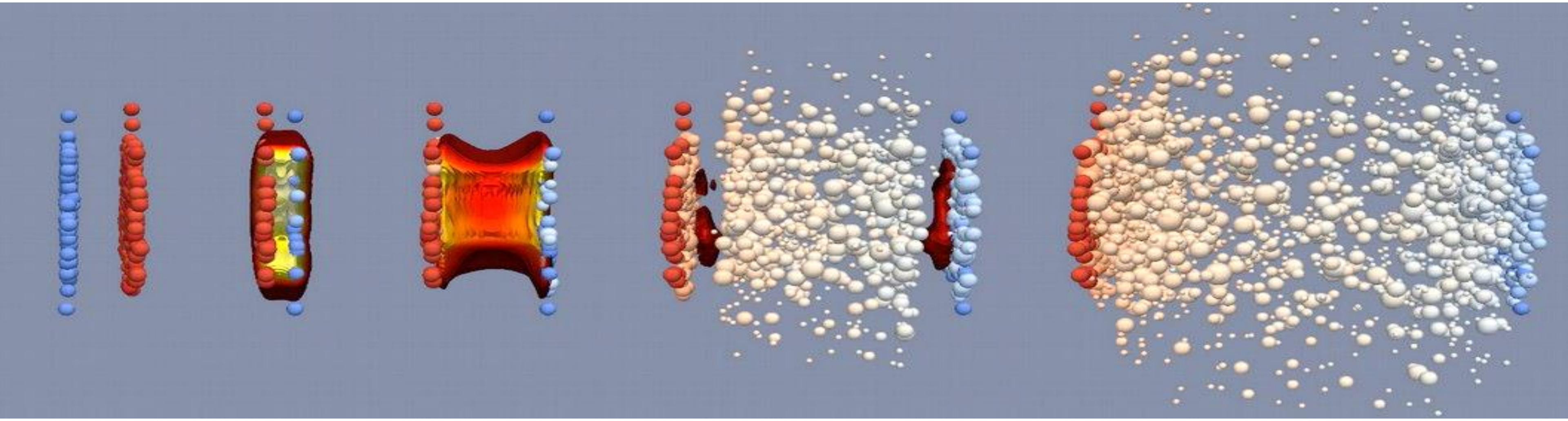
Competing mechanisms for HF hadronization.

- Fragmentation: presence of QGP modifies fraction of parton momentum taken by the hadron. Dominant at high-p_T.

- Coalescence: partons close in phase space can recombine into hadrons. Effective at low-p_T.



Open questions



Despite many years of heavy-ion physics, there are still unanswered questions:

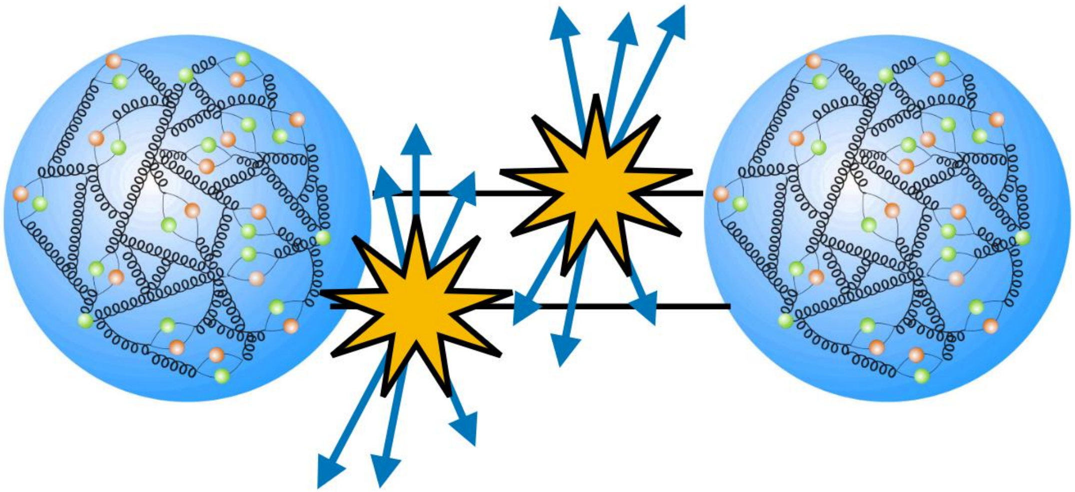
- How is the equilibrium phase reached?
- What are the properties of deconfined medium? Viscosity, difusión coeficientes, electromagnetic emision, etc.
- Is QGP really produced in small collisions systems?
- Can heavy-ion collisions shed some light on beyond the standard model physics?

PHYSICS OPPORTUNITIES

Quarkonium in Double Parton Scattering

Quarkonium production still not understood: models can not describe all the observables.

Hadrons are composite objects: possibility to have MPI, sensitive to interplay between perturbative and non-pQCD.



Double Parton Scattering (DPS): two quarkonia produced in different partonic interactions.

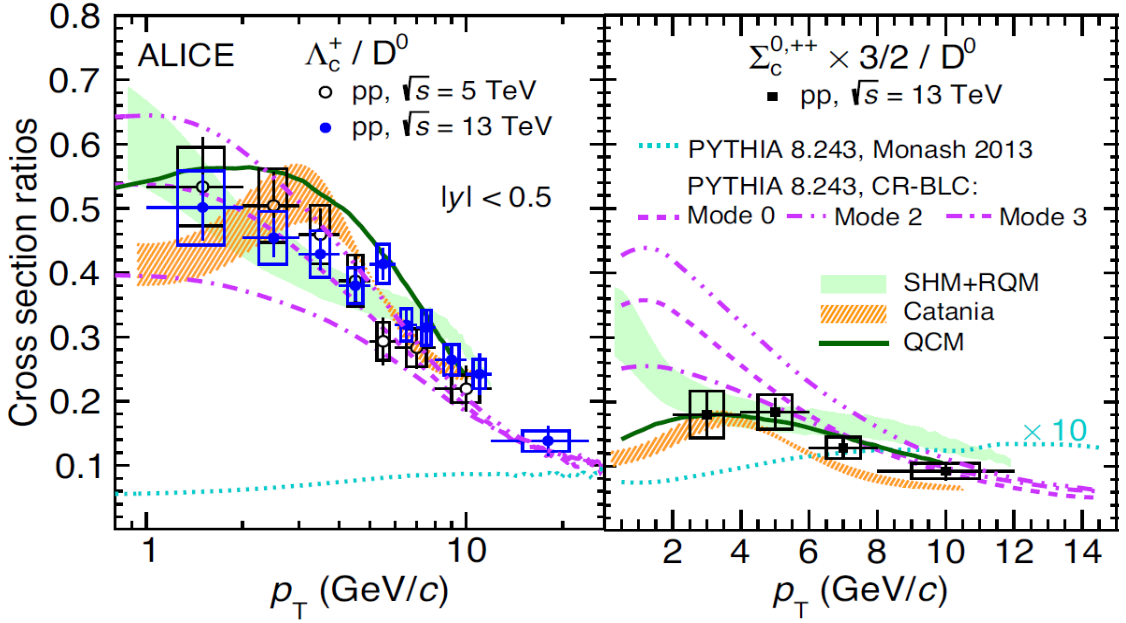
DPS suppressed compared to Single Parton Scattering (SPS):

$$\frac{\sigma_{DPS}}{\sigma_{SPS}} \sim \frac{\Lambda^2}{Q_h^2}$$

Λ^2 → Hadronic scale (1 GeV)

Q_h^2 → Hadronic interaction scale

Barion to meson ratios in pp



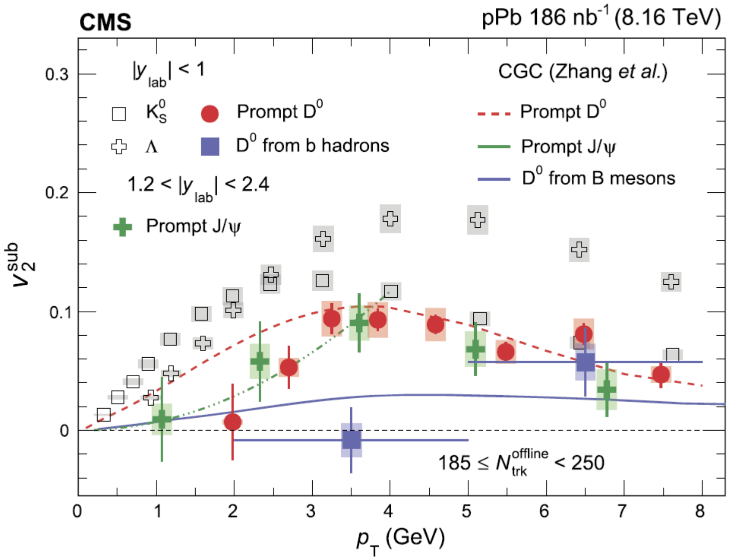
Barion to mesons ratios underestimated by MC with FF tuned from e^-e^+ and e^-p results. Indication that charm FF are not universal accross collision system and CM energy.

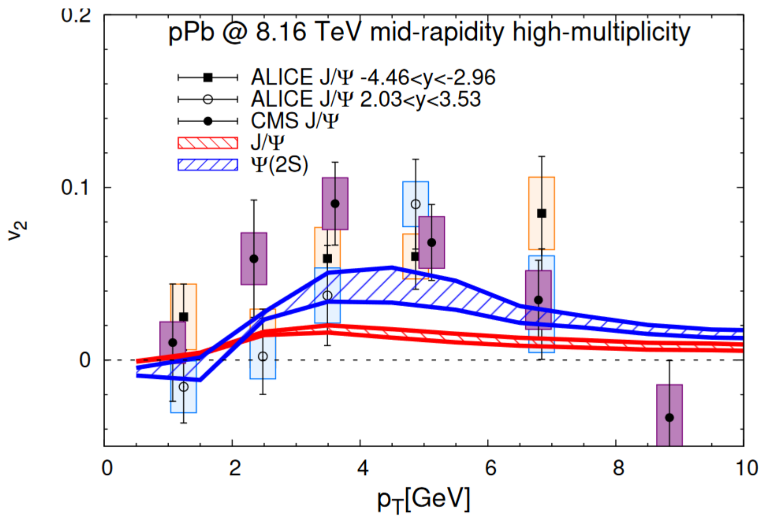
SHM+RQM: strong feed down from augmented set of excited charm baryons.

- PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c and 2 Ω_c
- RQM additional: 18 Λ_c, 42 Σ_c, 62 Ξ_c and 34 Ω_c

Will it be posible to prove their existence?

Charm elliptic flow in p-Pb





Positive v_2 for light hadrons, closed and open charm for $2 < p_T < 6$ GeV/c.

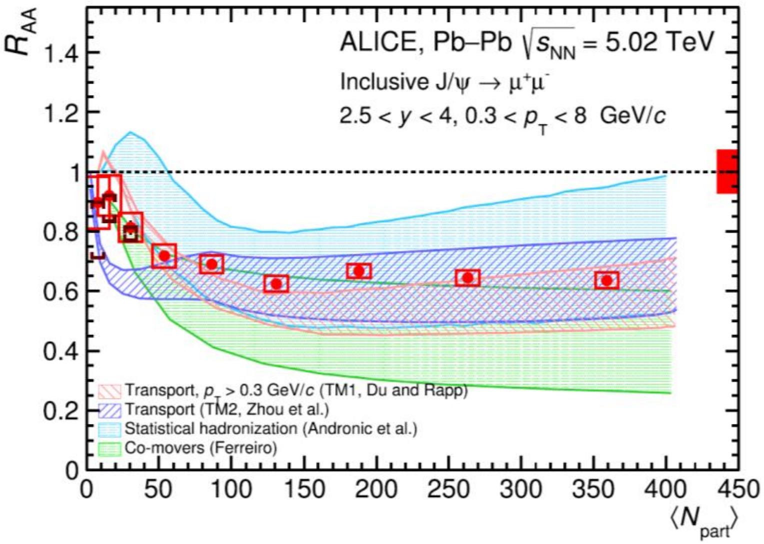
Prompt J/ψ and D mesons have smaller v2 relative to light flavors: charm quarks develop weaker collective dynamics than light quarks.

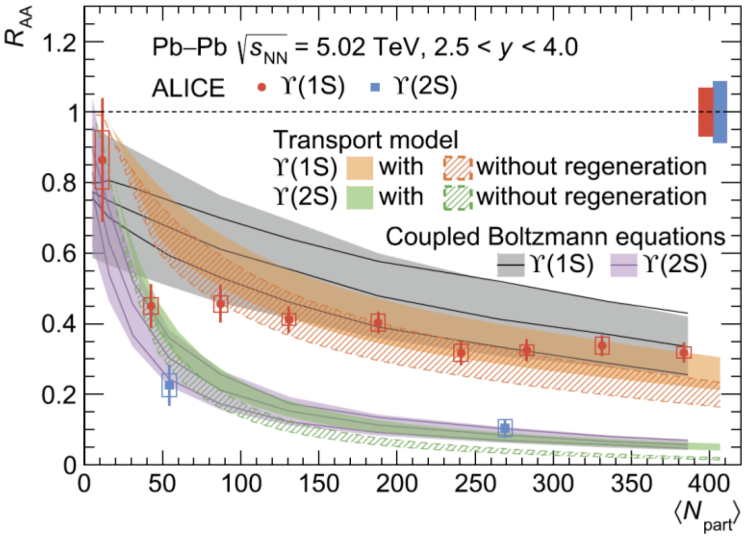
But prompt J/ψ comparable to D mesons results! Furthermore, transport model underestimates data.

Can not be explained by final state effects of a QGP medium only, as the contribution from recombinations to J/ψ production is not expected to be significant in small systems.

Initial state correlation effects? Further detailed investigations needed.

J/ψ and Υ in Pb-Pb





J/ψ production consistent with models including an important regeneration component at low-p_T.

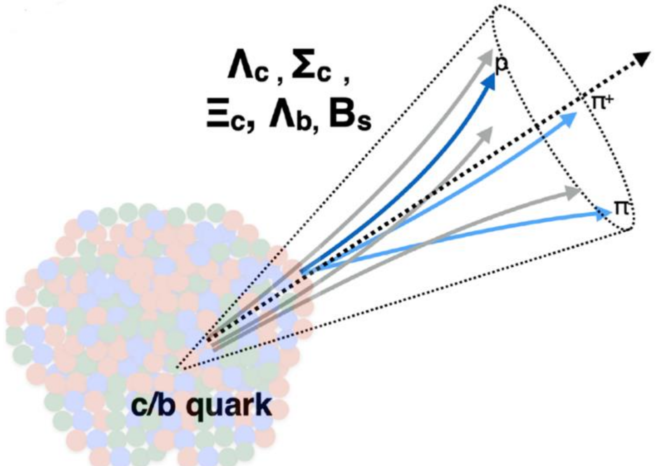
Upsilon family indicate a sequential suppression scenario.

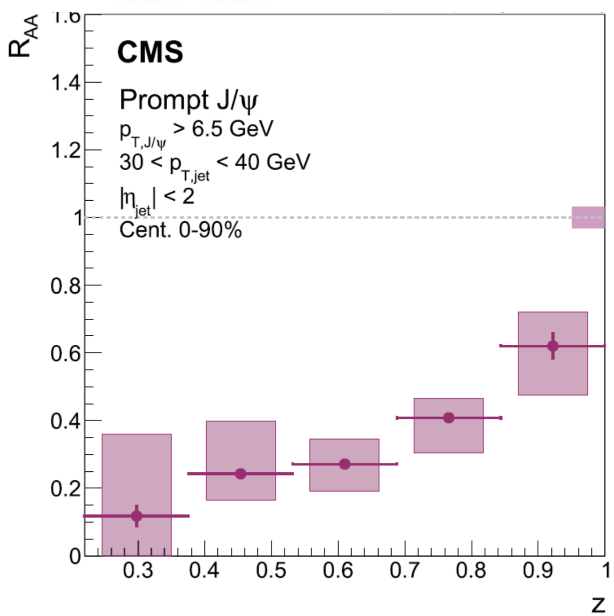
Width of the bands reflect uncertainties due to input parameters in the models.

Most importants: are charm pair production cross section, nuclear modification of PDF and feed down contributions from excited states.

Need more precise measurements if we want to discriminate among different models.

Quarkonium & HF in jets





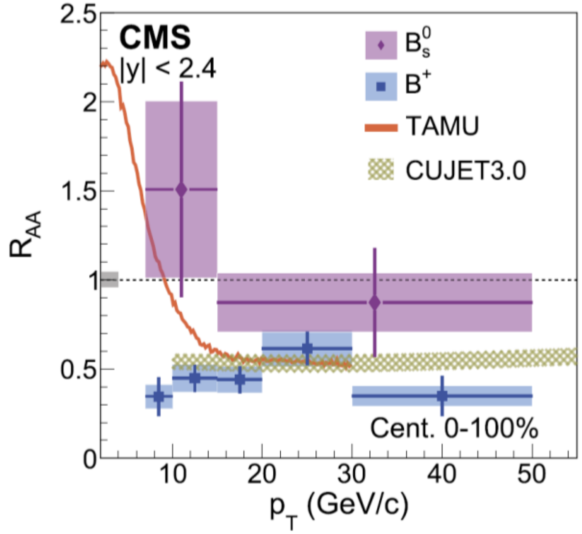
Jets provide energy and direction scale for HQ fragmentation process.

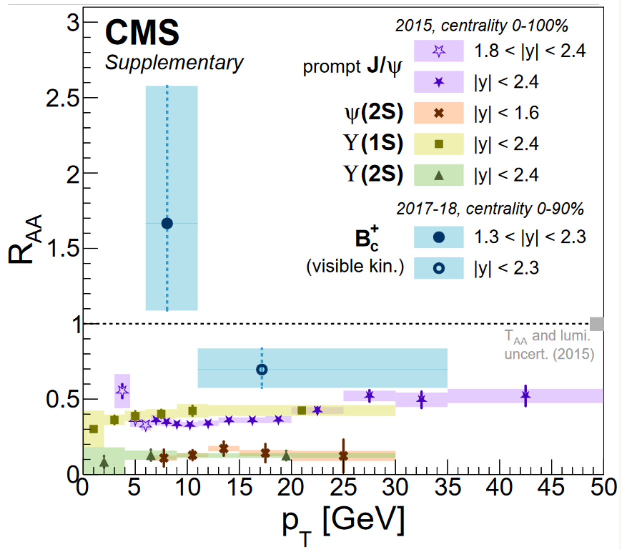
Studying fragmentation shower of quarkonium and open heavy flavours inside jets in nucleus collisions will provide new insights into the properties of medium propagation of heavy quarks in the QGP.

Currently only measurements for J/ψ in jets down to p_T = 6.5 GeV.

Low-p_T measurements are neeeded for a complete picture of the fragmentation functions.

B hadrons in Pb-Pb





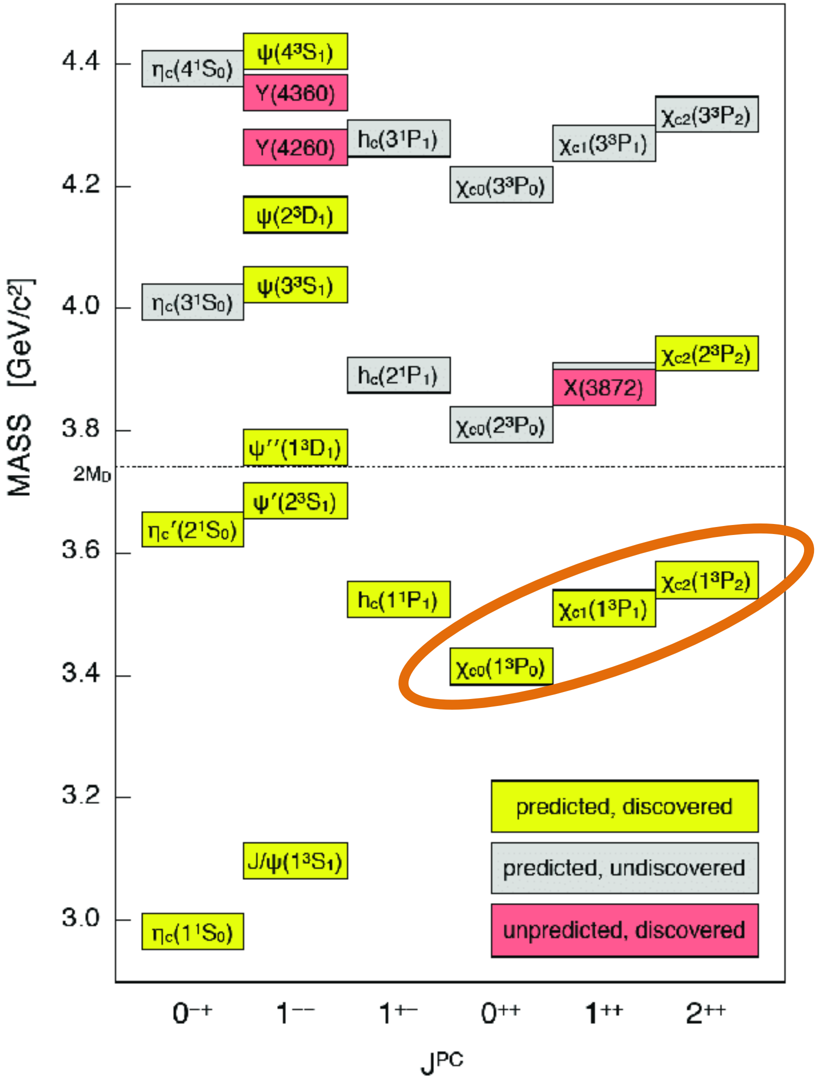
Beauty measurements provide constraints to achieve a microscopic description of heavy-quark interactions as a probe of the QGP.

Beauty quarks relaxation (thermalization) time > QGP lifetime, they provide better constraints on heavy-quark propagation at the late stages of the medium evolution.

Current B hadrons R_{AA} limited by statistical and systematic uncertainties and no posible measurements for Λ_b nowadays.

Still room for improvements!

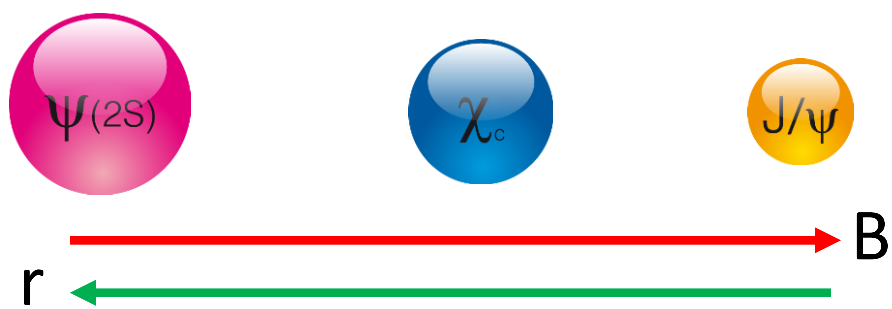
Charmonium in A-A



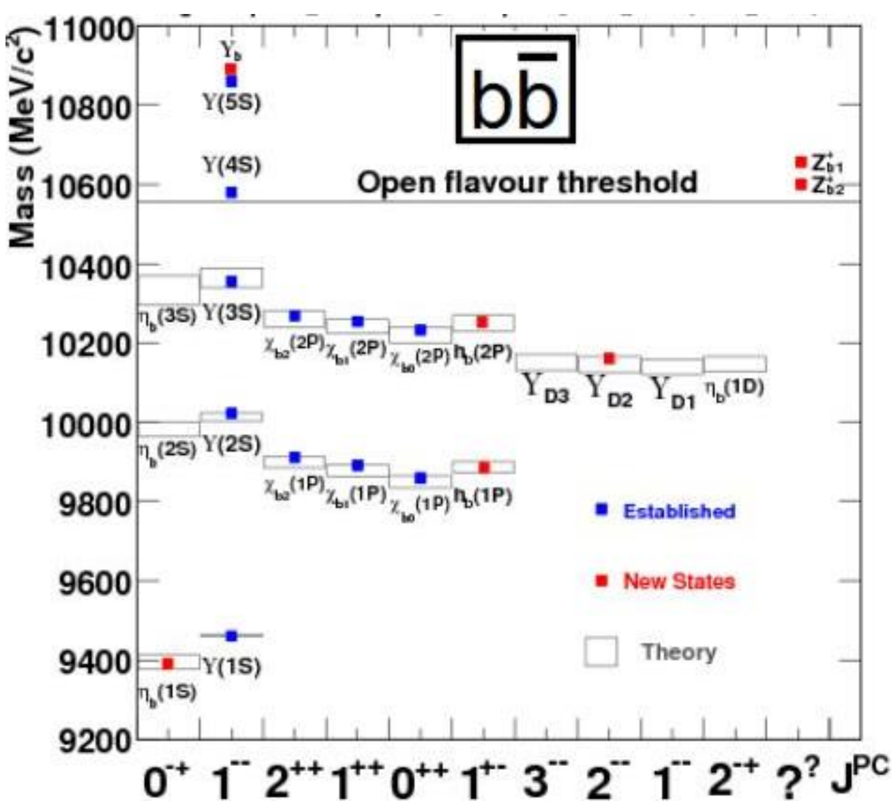
Binding energies (B) and spatial extent (r) for pseudoescalar P-wave states are in-between ground and excited vector states.

For potential models the survival of χ_c is up to 1.2 T_c, lattice-QCD indicates significantly lower temperatures.

If we manage to compare the suppression patterns from P and S-wave states, we'll have important information on formation and propagation of quarkonium through QGP!



Bottomonium in A-A



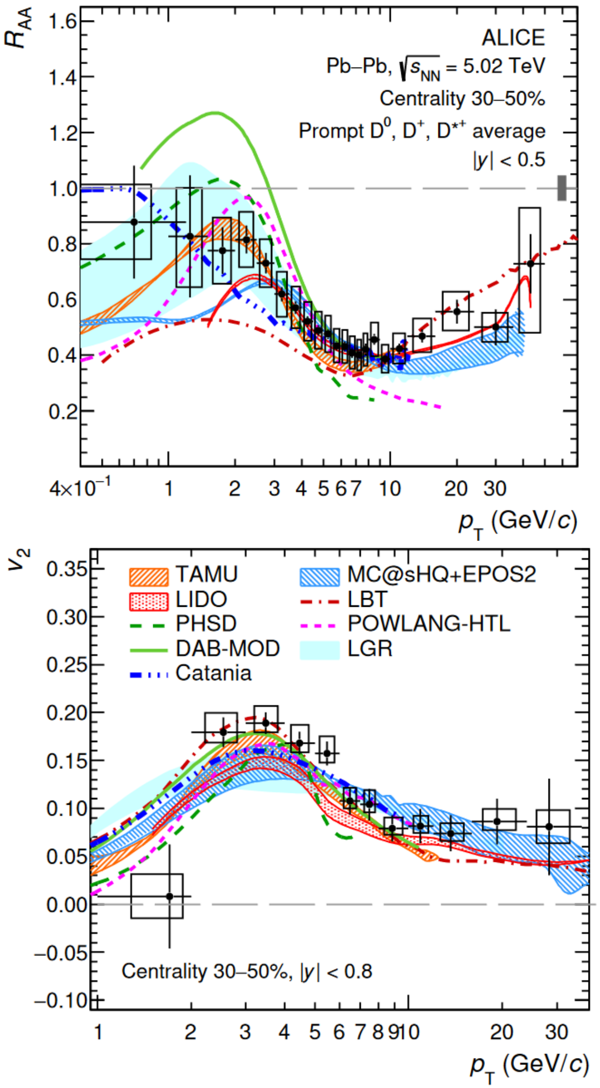
Similar case for bottomonium.

Estimates of melting temperatures for P-wave states (χ_b) indicate that the fate of bottomonium is not yet understood.

Models require precise experimental inputs from p_T and rapidity dependence of S states.

S vs P –wave states will help to characterize dissipative effects of the QGP.

Spatial Diffusion Coefficient



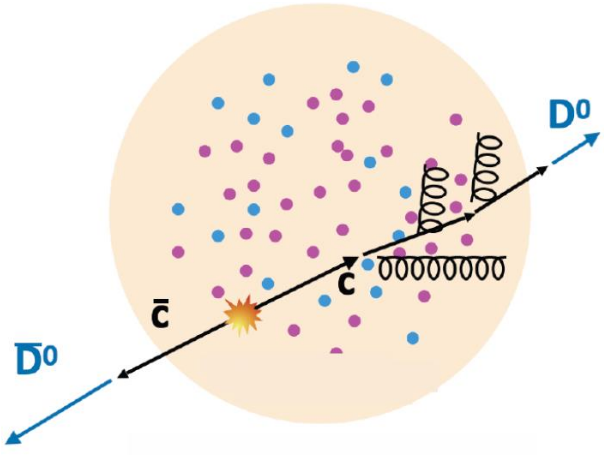
Spatial Diffusion Coefficient (D_s) describes quark transport in a hidrodynamically expanding medium.

Current value of D_s is extracted from D mesons nuclear modification factor and elliptic flow: $1.5 < 2\pi D_s T_c < 4.5$ at T_c = 155 MeV.

Currently limited by low-p_T experimental results.

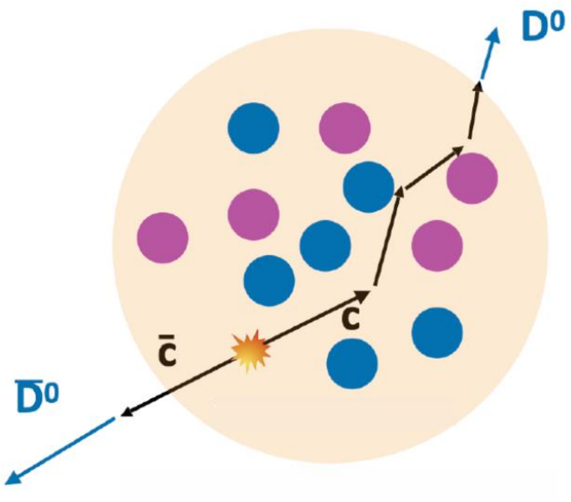
Full picture: measurement of R_{AA} and v_2 for B mesons down to p_T = 0.

Angular correlations



"Rutherford-like experiment": measurements of azimuthal and p_T correlations between HQ and the recoil parton produced in the hard scaterring process.

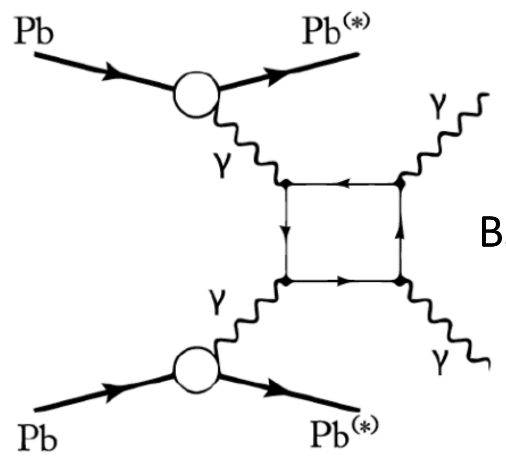
These measurements constrain the modification of both the momentum and direction.



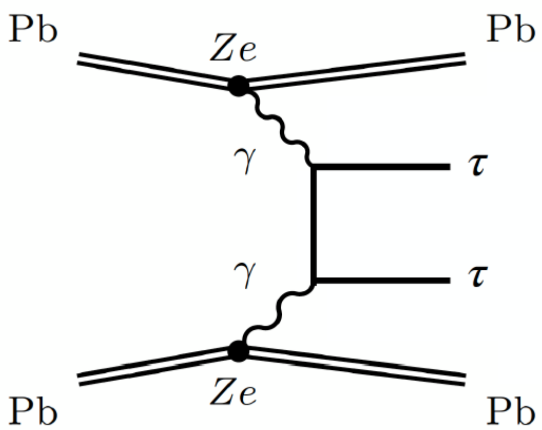
They also provide additional insight into the in-medium path length dependence of energy loss.

But also an access to the inner structure of the QGP by observing how it affects the relative direction and momenta of HQ pairs traversing it.

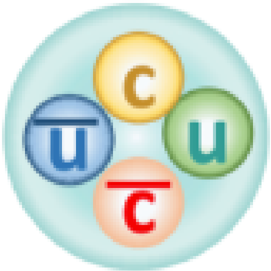
Many more...



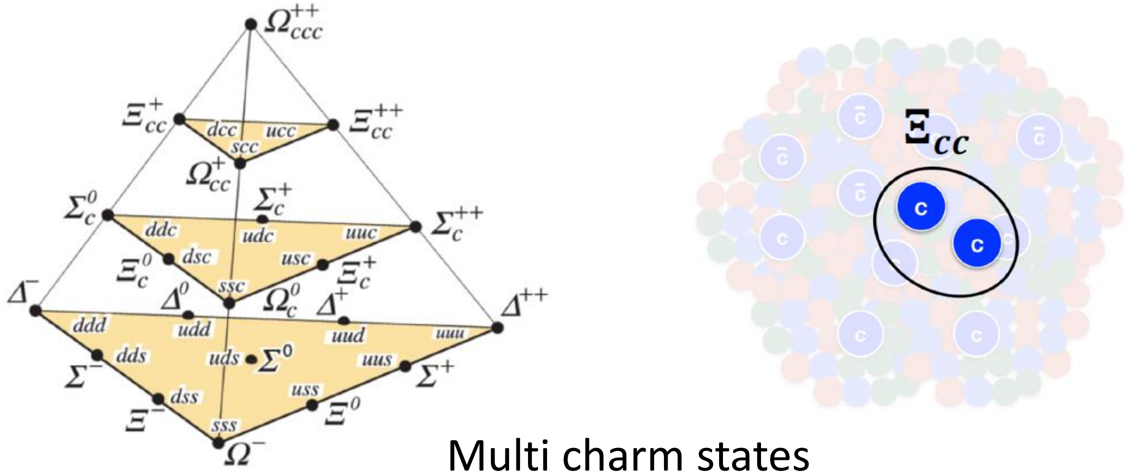
BSM in UPC



Tau g2



Tetraquarks



Multi charm states

Summary

The LHC has provided a wealth of data during the last 12 years, improving our underestanding on heavy quark production in hadronic collisions.

We are currently in the precision era measurements for heavy quarks. However, there are still many open questions awaiting to be solved.

This is the exact moment to start planning how to address these questions

Summary

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Thanks for your attention