Accessing initial conditions of ultra-relativistic collisions & QGP properties through open and hidden heavy flavor

Acronym: **Chart_HF**

Spokesperson:

Vincenzo Greco – University of Catania/INFN-LNS

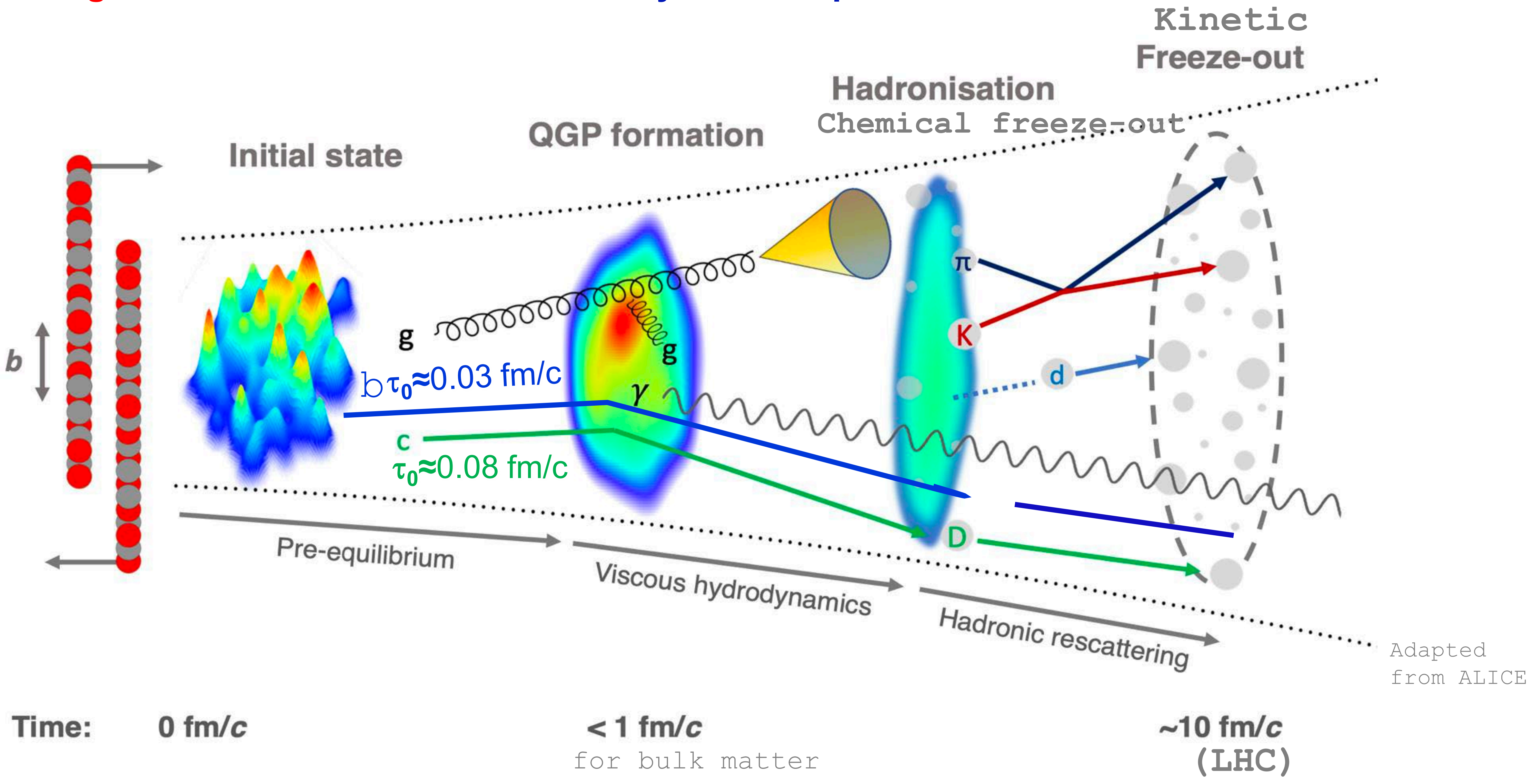
Replacement (election of the rector of the University): Joerg Aichelin

Who: Theory groups of Barcelona, Beograd, Budapest, Catania, Firenze, Frankfurt, GSI, Jyväskylä, Nantes, TU Munich, Torino, Vienna

Why: To allow to fulfils the goals of heavy-ion studies in run 3 at LHC

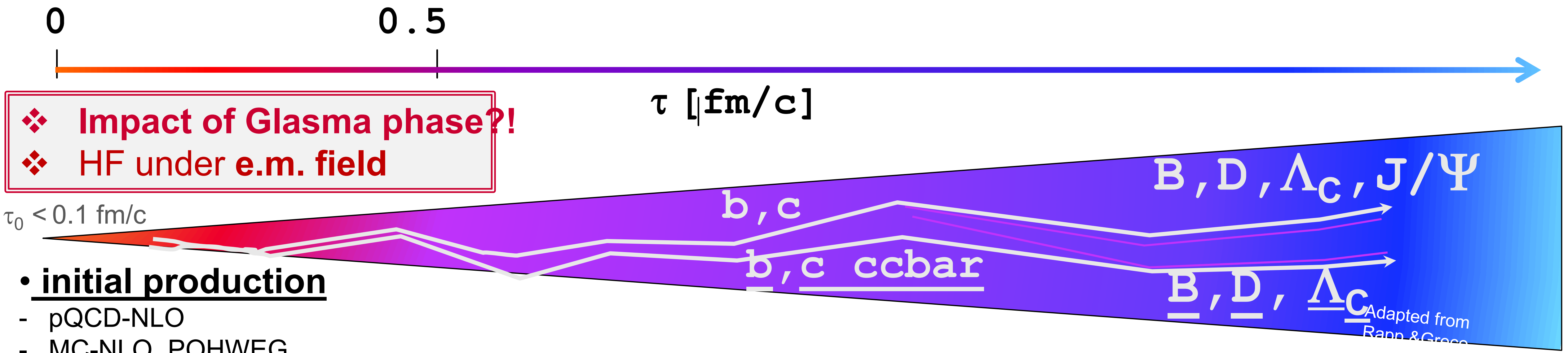
“Use rare particles like heavy quarkonia (e.g., J/ψ, Y) and open heavy flavor mesons (containing charm or beauty quarks) as probes of QGP”

To use heavy quarks as messanger of the initial condition and the QGP is very promising but a difficult issue because many different processes are involved



Heavy quarks are a promising probe because

- the producing processes can be calculated in PQCD
- they do not come to an equilibrium with the QGP

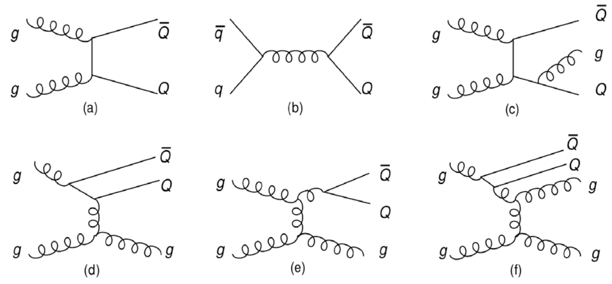


- ❖ **Impact of Glasma phase?!**
- ❖ HF under **e.m. field**

• **initial production**

- pQCD-NLO
- MC-NLO, POHWEG
- **CNM effect [pA, AA, exp.]**

$$d\sigma^{Q+X} \simeq \sum_{i,j} f_i^A \otimes f_j^B \otimes d\tilde{\sigma}_{ij\to Q+X}$$



• **Dynamics of HF in QGP**

- **Themalization?**
- **Transp. Coeff. of QCD matter $D_s(T)$**
- Radiative E_{loss} & Jet Quenching
- **Transport of c cbar pair**

• **Hadronization**

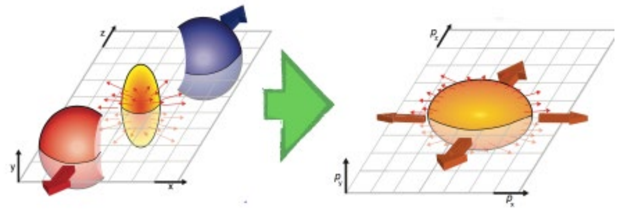
- coalescence and/or fragm.
- large Λ_c/D in pp, pA, AA

→ affects observables

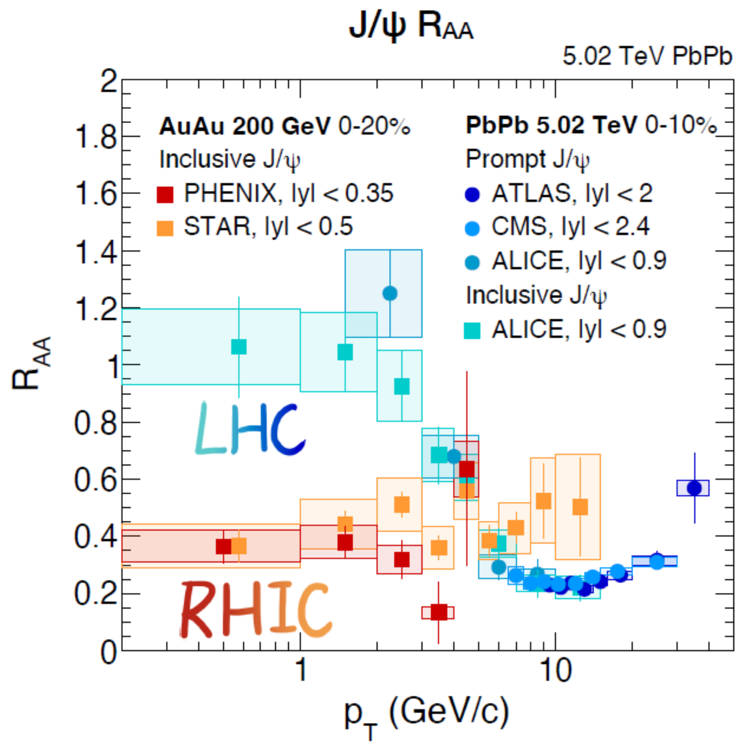
How hadronizes color neutral pairs

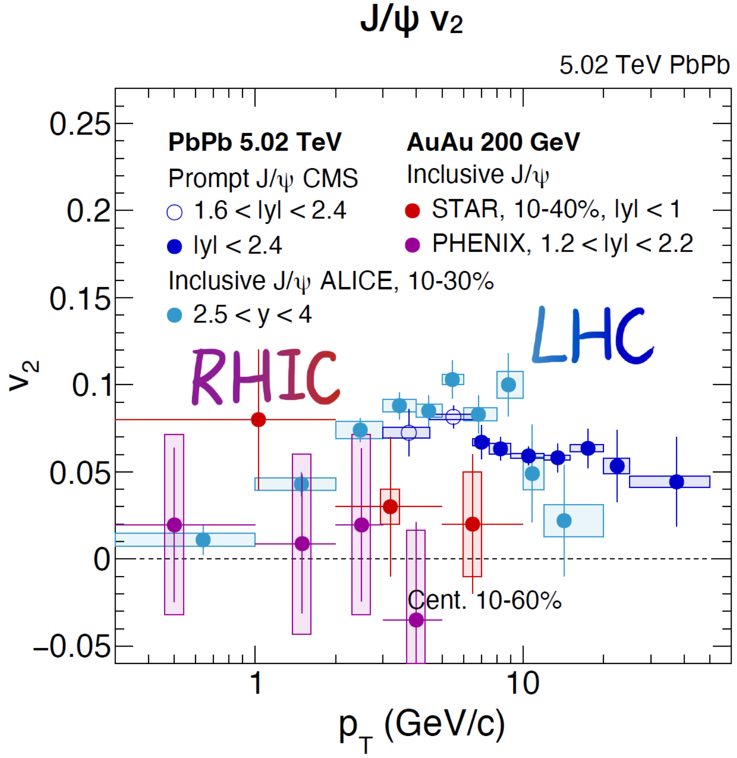
Experimental surprises from LHC, run 2 for pp and heavy-ions:

$$R_{AA}(p_T) = \frac{dN_D^{AA}/dp_T}{\langle N_{coll}\rangle \, dN_D^{pp}/dp_T}$$



$$\frac{dN}{d\phi} \propto 1 + 2v_1 cos\phi + 2v_2 cos(2\phi).....$$



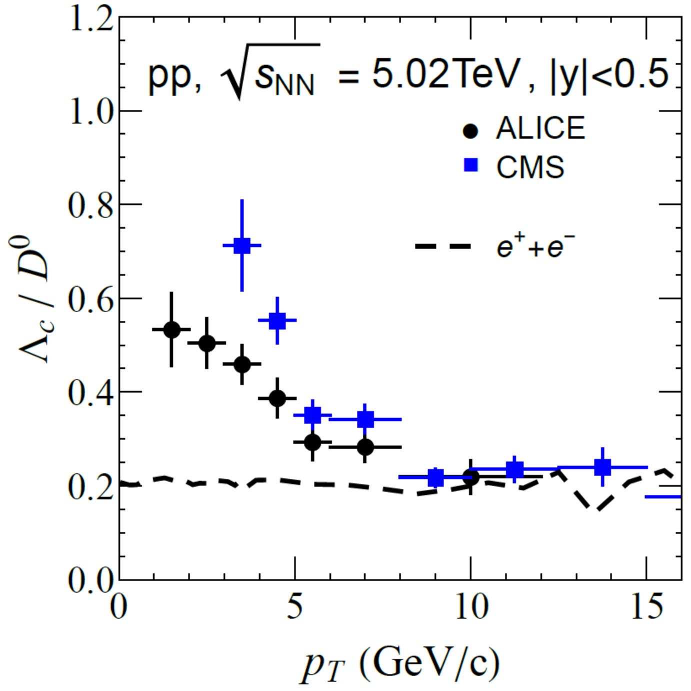


J/ψ mesons:

- show quite different results for key observables at RHIC and LHC

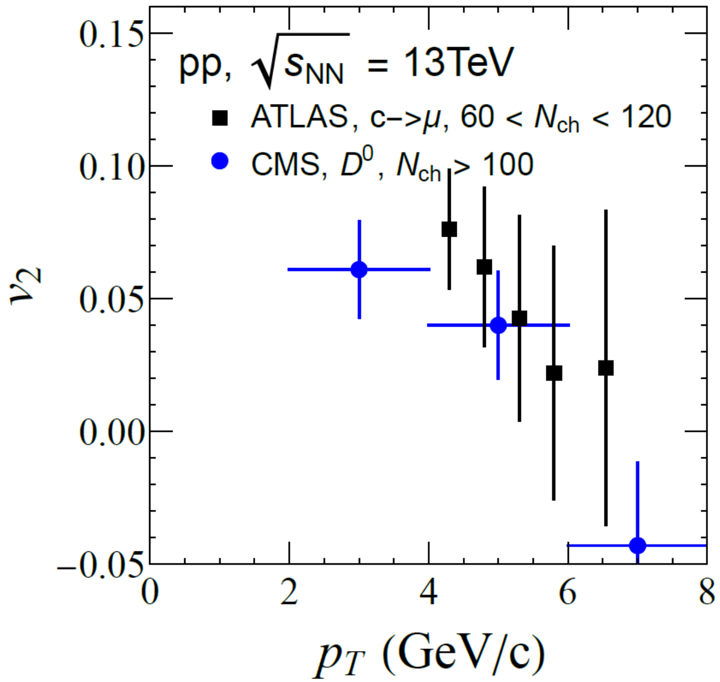
Experimental surprises from LHC, run 2, for pp and heavy-ions :

Λ_c / D^0 ratio



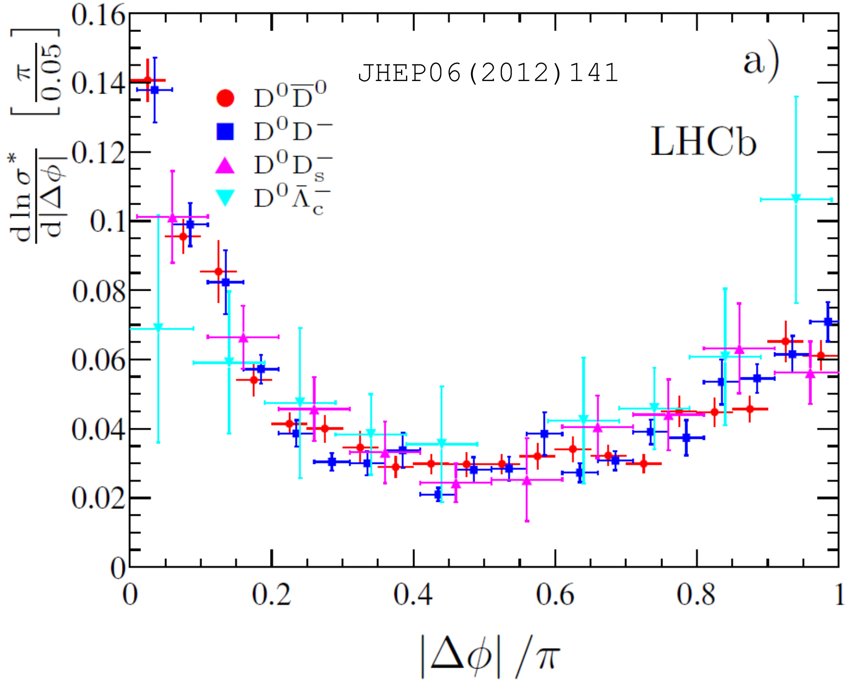
Are fragmentation functions not universal?

elliptic flow v_2



In pQCD: v_2 =0
Where does the finite v_2 comes from?

azimuthal $\Delta\varphi(p_D, p_{Dbar})$



What causes this structure of the correlation function?

Challenges for the next years:

- How do the different QCD production mechanisms for $c\bar{c}$ pairs influence open and hidden heavy flavour observables like rapidity distributions, p_T spectra, HF baryon/meson ratio, correlations and what they tell us about QCD in a medium?

- What we can learn from heavy flavour observables about the different initial states in pp and HI

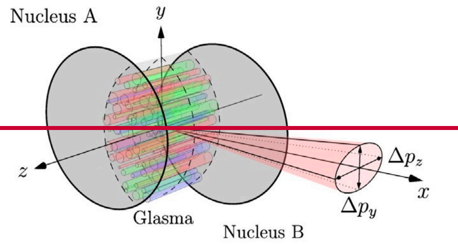
- How can we understand the different R_{AA} (P_T) for different charmed hadrons? Will they be in agreement with the transport coefficient Ds(T) of unquenched LQCD (2024)?

- What is the origin of HF v_2 observed in pp as well as in heavy-ion collisions?

- How traverse $c\bar{c}$ pairs a QGP (color exchange, color screening)? Do we succeed to treat $c\bar{c}$ pairs in heavy-ion collisions as open quantum systems including color observables ? To derive the time evolution of quarkonia directly from a quantal density matrix would present a major step forwards.

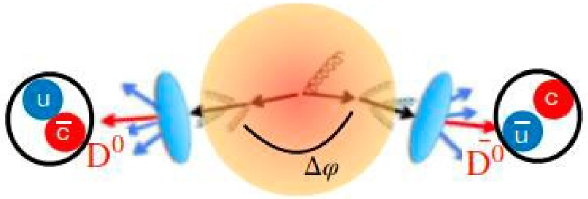
Novel insights should emerge and help moving from PbPb to lighter systems down to OO, pA and pp which *perfectly match to HL-LHC program*

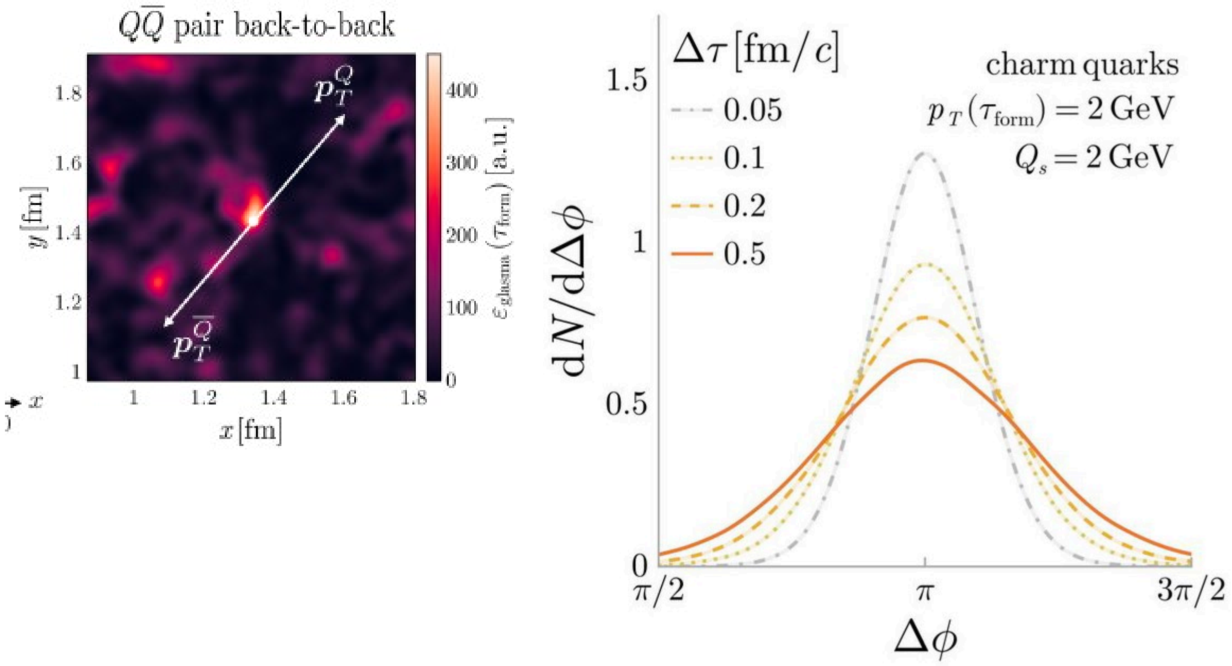
Glasma impact on angular $Q\bar{Q}$



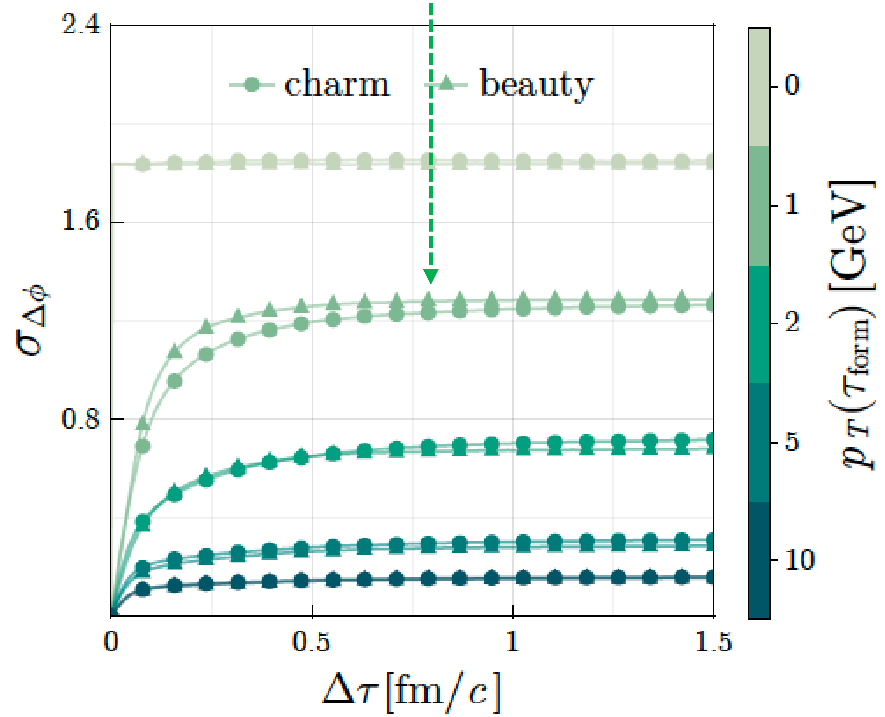
First study of azimuthal $Q\bar{Q}$ correlation: large decorrelation **in only 0.2 fm/c**

Calculation in **SU(3) +longitudinal expansion**
D. Avramescu et al., PRL 134 (2025)





Nearly identical for bottom, despite larger mass thanks to smaller τ_{form} and v_T



Significant effect of glasma on HQ! Quite Stronger than on R_{AA}

Width at t~0.2 fm/c comparable that induced by QGP in AA

M. Nahrgang et al, PRC90 (2014)

Quarkonia in a QGP: Treatment as open quantum systems

“pure” state (**wavefunction**) -> “mixed” state (**density operator**)

Open quantum system (OQS)

$\hat{\rho}_{tot} = \sum_i p_i |\psi_i\rangle\langle\psi_i|$ von Neumann equation: $\frac{d\hat{\rho}_{tot}}{dt} = -i[\hat{H}_{tot}, \hat{\rho}_{tot}]$

$$\hat{H}_{tot} = \underbrace{\hat{H}_s \otimes I_e}_{\text{Subsystem}} + \underbrace{I_s \otimes \hat{H}_e}_{\text{Environment}} + \underbrace{\hat{H}_{int}}_{\text{Interaction}},$$

Trace over the environment degrees of freedom :

Quantum master equation

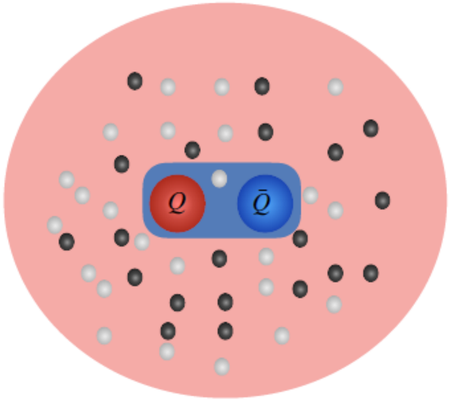
$$i\hbar\dot{\hat{\rho}}_s(t) = \mathrm{Tr}_e[\hat{H}_{tot}, \hat{\rho}_{tot}] = [\hat{H}_s, \hat{\rho}_s] + \mathrm{Tr}_e[I_s \otimes \hat{H}_e + \hat{H}_{int}, \hat{\rho}_{tot}]$$

➡ Separation of time-scales:

Environment relaxation time scale $\tau_e \sim \frac{1}{\pi T}$.

Intrinsic time scale of subsystem $\tau_s \sim \frac{1}{E_{bind}}$.

Subsystem relaxation time scale $\tau_r \sim \frac{1}{\eta} \approx \frac{M}{T^2}$.



The reduction of the open quantum systems to calculable equations depends onthe time scales involved

Estimated budget request for Chart-HF : 400 000 Euro

- **3 years of postdoc,** thematically center around topics, discussed above, to make a common and collective approach possible: **200 000 Euro**

- **2 network workshops to discuss, synchronize and exchange the ideas and the work progress**.
  They are also the events where the graduate student and postdocs involved in the project meet, get acquainted with each other and form collaborative work: **60 000 Euro**

- **1 network at the ECT* for a broader community** including the concerned experimental groups and colleagues outside of Europe: **15 000 Euro**

- **Partial support for 2 PhD projects**, common between the laboratories of the network: **40 000 Euro**

- **Mutual visits** (short term for senior scientist, longer term for PhD students/postdocs): **85 000 Euro**

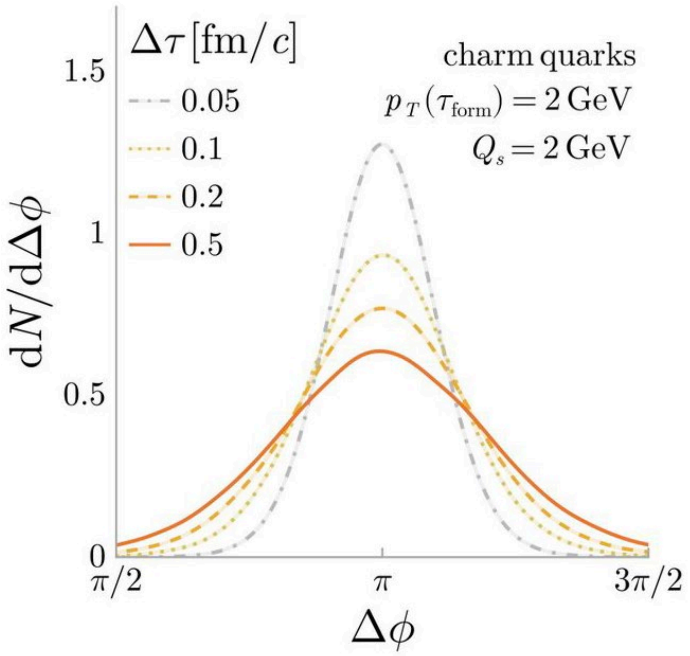
Back-up

Participating and partner institutions

1) Barcelona Univ. (Escobedo, Torres-Rincon)
2) Belgrade Univ. (Djordjevic)
3) CNRS/IN2P3/SUBATECH (Aichelin, Boguslavski, Gossiaux, Werner)
4) Frankfurt Univ. (Greiner)
5) GSI (Bratkovskaya)
6) INFN-LNS/ Catani Univ. (Greco, Plumari, Minissale, Oliva)
7) INFN-CT (Ruggieri)
8) INFN-Firenze (Lombardo)
9) INFN-Torino (Beraudo, Nardi)
10) Jyväskylä Univ. (Eskola, Lappi, Mäntysaari, Niemi)
11) TU Munich (Brambilla, Vairo)
12) TU Wien (Ipp, Muller)
13) Wigner RCP - Budapest (Barnafoldi)

Glasma impact on angular $Q\bar{Q}$

D. Avramescu et al., PRL 134 (2025)



In pA smaller width wrt AA may allow to:

- solve the puzzle od R_{pA} ~1 and v_2 large ?
- disentagle shadowing from glasma ?

<u>To be done toward a full realistic calculation</u>:

- beyond back-to-back : flavor excitation, gluon splitting
- Matching with QGP kinetic transport
- Inclusion of hadronization [mainly p_T reshaping]

Is τ_{th} of charm (bottom) sufficiently large to keep memory of early stage dynamics?

New estimate of τ_{th}(charm)~ 1 fm/c from $2\pi T D_s$ from LQCD, to answer is not trivial

It is likely necessary to go to:

- Small systems like OO and pA
- Bottom less affected by flavor excitation and gluon splitting

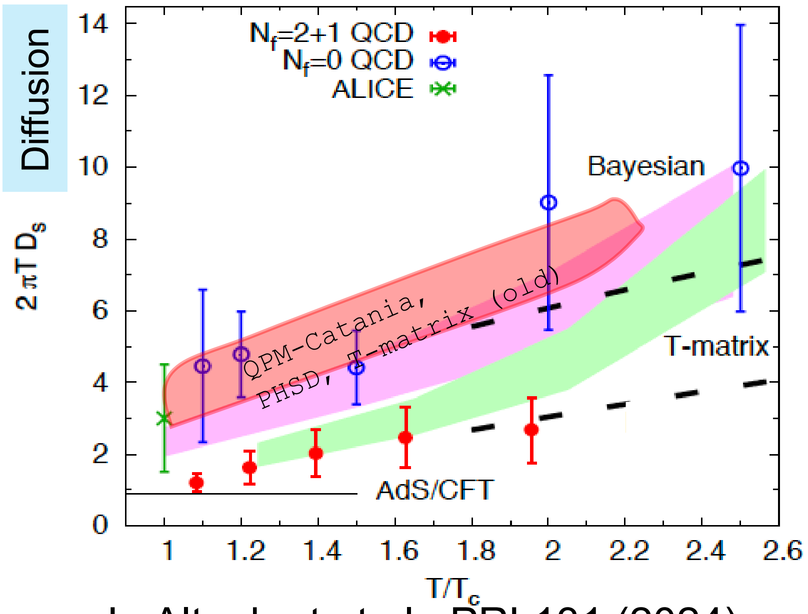
Main suprising and exciting aspect of open HF

a) Strong non-perturbative coupling to the bulk QGP medium [τ_{th}~ 3-5 fm/c<<τ_{th}(pQCD)]

b) Modified hadronization in AA and even in pp@TeV wrt to e+e-, e-p [B/M ~ O(1)]

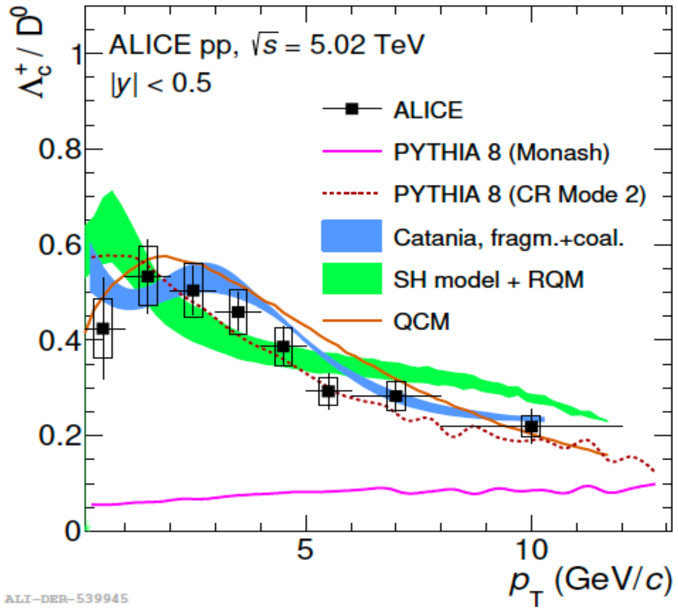
c) Potential New Probe of the very Early Stage / Glasma dynamics

D_s (T, p→0) lattice QCD



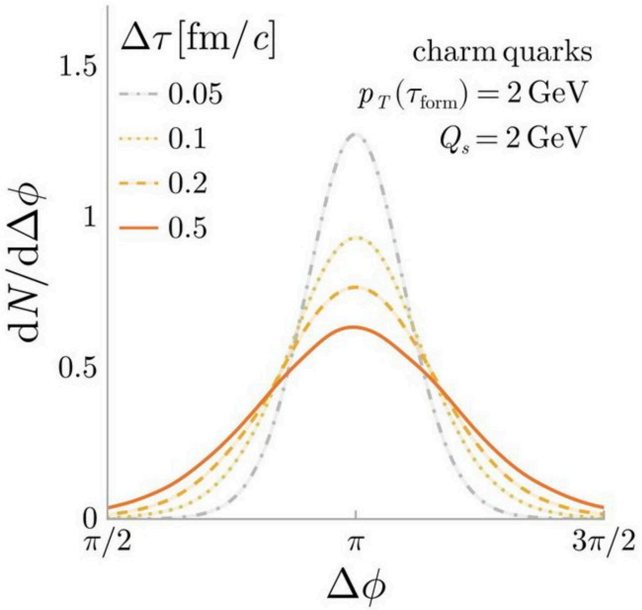
L. Altenkort et al., PRL131 (2024)

pp@LHC vs e+e⁻



S. Acharya et al., PRL122 (2022)

$c\bar{c}$ angular correlation



D. Avramescu et al., PRL134 (2025)

MAIN SCIENTIFIC MOTIVATION

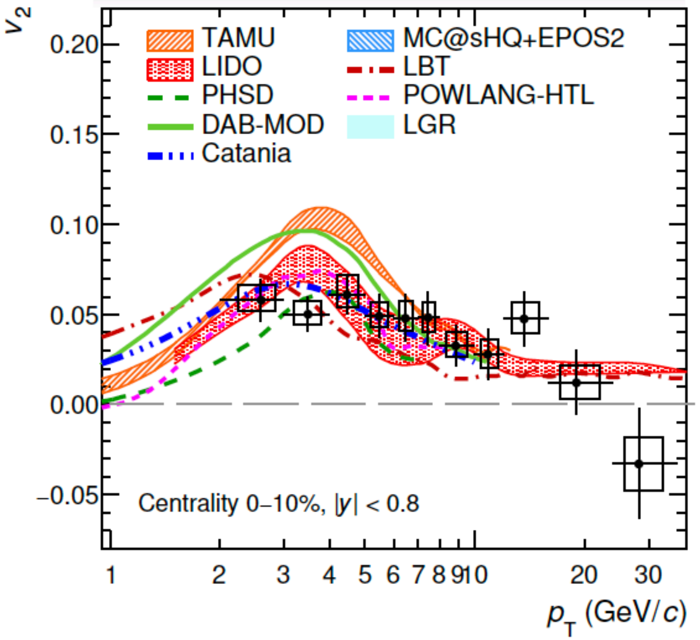
Approaching precision era for HF → a solid & quantitative determination of HF interaction

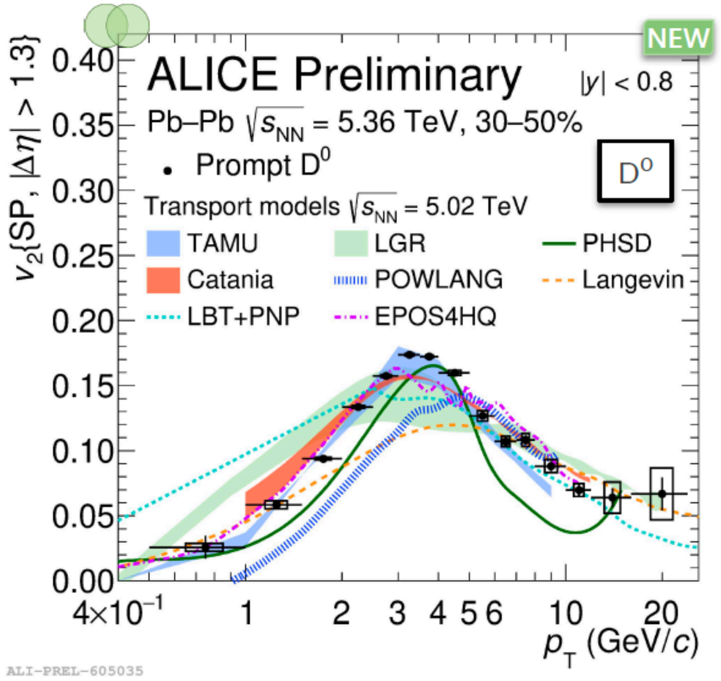
HF physics have driven the main investements for HI-LHC (Run 3-5) of ALICE and partially CMS and LHCb.

EXPERIMENTS:

- From Run 3 high precision data for R_{AA}, v_2, v_3 on D meson and even Λ_c and B mesons down to low p_T essential for the comparison to LQCD
- Access to new more exclusive observables: vn(soft)- vn(hard), D-Dbar angular correlations, prompt B meson observables

A first example from QM2025





MAIN SCIENTIFIC MOTIVATION

We are approaching the precision era for heavy flavor physics that will allow a solid and quantitative determination of QGP dynamics and properties.

HF physics have driven main investements for HI-LHC (Run 3-5) of ALICE/CMS and LHCb.

THEORY:

- In 2023-24 **first calculation of Ds(T) for unquenched QCD** combining LQCD &NREFT: implying a very small thermalization time (τ~1 fm/c for p→0) whose phenomenological consequences on observables have still to be explored
- **STRONG2020 has led to strong developments** toward a realistic transport simulation of HQ (*for some group including event-by-event simulations*) and hadronization mechanism
- **Scan over light systems** (OO, ArAr, pA) should allow early stage non-equilibrium to emerge (especially for bottom), lack of studies till now (would unmatched the CERN infrastructure program)
- New data would need a Bayeasian statistical study and/or development of a ML approach

MAIN OBJECTIVES for OPEN HEAVY FLAVOR

a) Quantify the QGP's coupling strength to heavy quarks via **transport coefficients**;

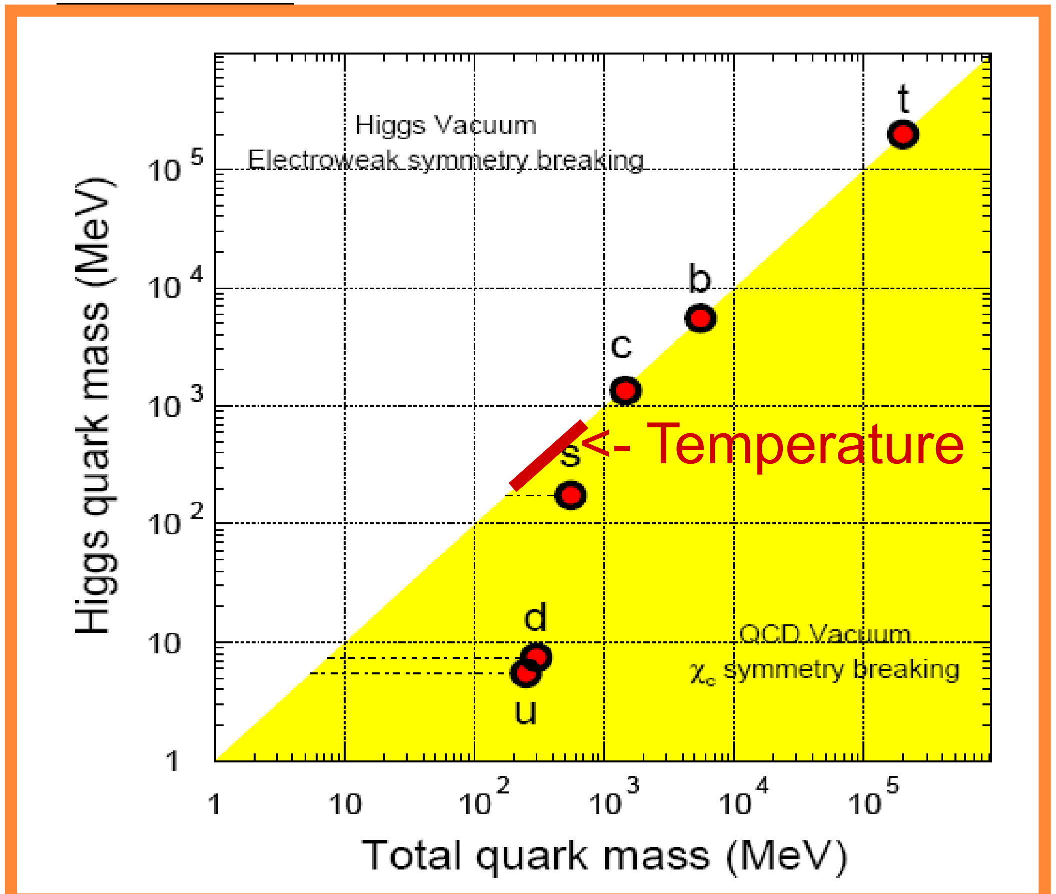
b) Elucidate the complex mechanisms of **heavy quark hadronization in pp, pA and AA** collisions and the violation of universality wrt e^+e^- and e^-p collisions;

c) Explore heavy flavor as a novel **window into the Glasma** (very early stage of ultra-relativistic collisions) and pre-equilibrium dynamics.

For b) and c) a key strategy will be to move from PbPb exploring for the lighter systems down to OO [*perfect match to HI-LHC infrastructure program*] collisions and pA:

- ✓ For hadronization this supplies the new opportunity of a varying medium, essential to study its role.
- ✓ For probing the Glasma phase the system scan size supplies a short-lived plasma to have HF non fully thermalized, keeping more significant signals from Early Stage.

Basic Scales and specific of HQ



Why Heavy?

- *PARTICLE Physics*: $\mathbf{m_{c,b}} \gg \Lambda_{QCD}$ pQCD initial production
- *PLASMA Physics*:
  - $\mathbf{m_{c,b} \gg T_{RHIC,LHC}}$ no thermal production
  - $\mathbf{m_{c,b} \gg gT_{RHIC,LHC}}$ soft scatterings → Brownian motion

Specific Features:

- $\tau_0 \approx \mathbf{1/2m_Q}$ (<0.1 fm/c) $\ll \tau_{QGP}$ witness of all QGP evolution
- $\tau_{th} \approx \tau_{QGP} \gg \tau_{q,g}$ carry more information of their evolution

* For HQ we know initial p_T distribution at variance with light quark & gluons

* HQ not created at hadronization by string breaking **+** const. quarks close to energy conservation