Heavy-flavor particles: a tool to access the properties of the hot matter produced in the Big and Little Bang

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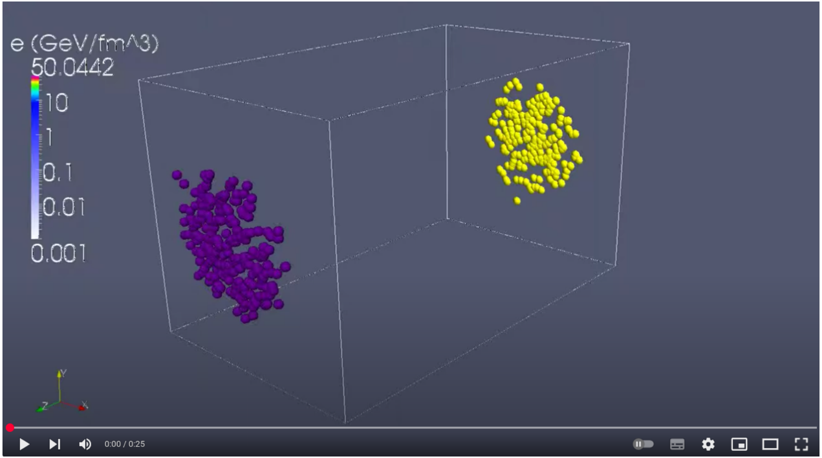
Istituto Nazionale di Fisica Nucleare

Simulating a HIC



(simulations with IEBE-VISHNU hydro code)

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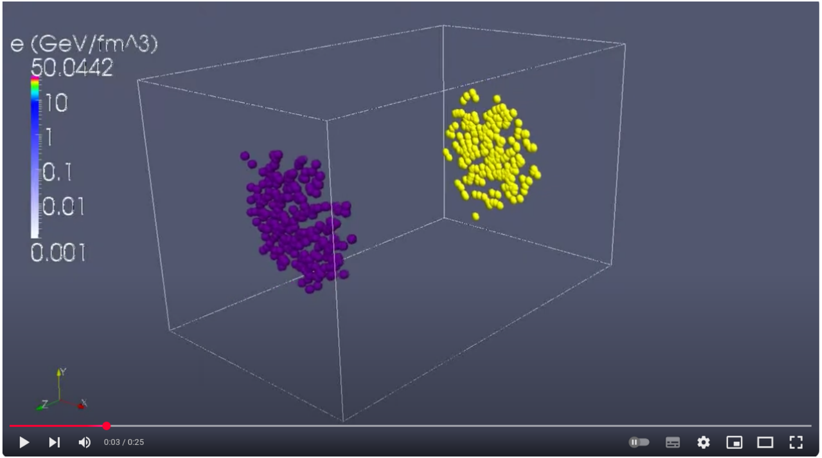

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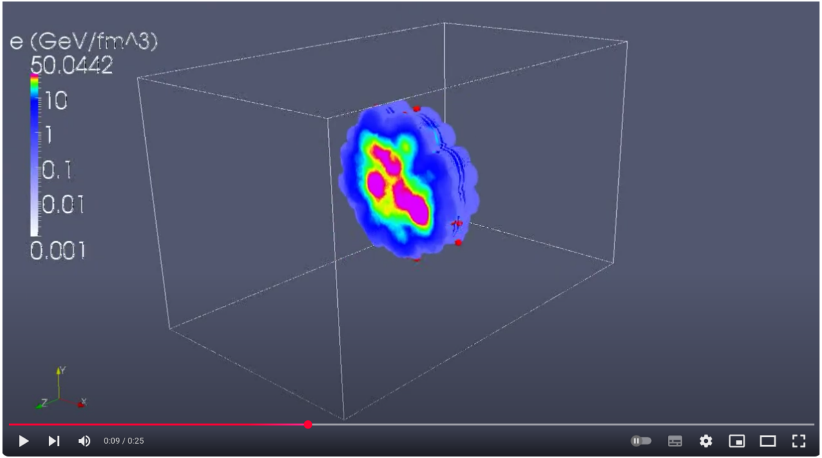

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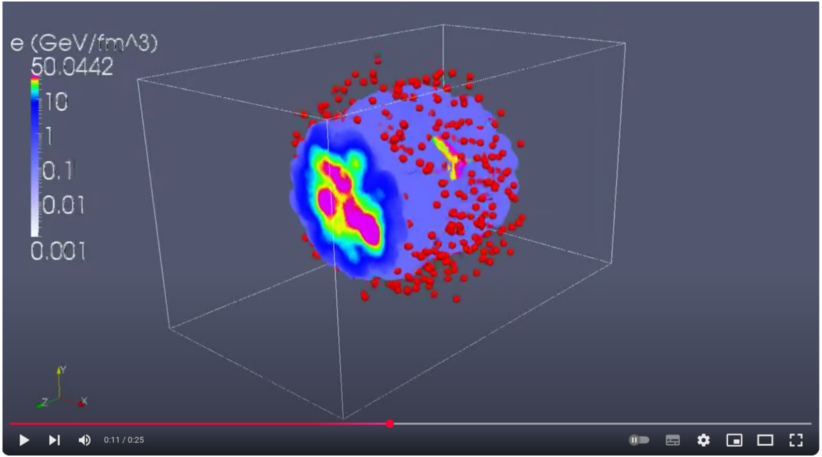

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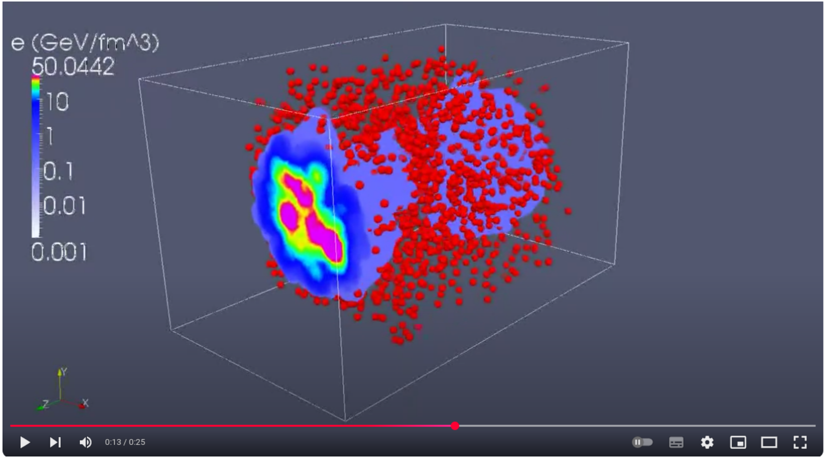

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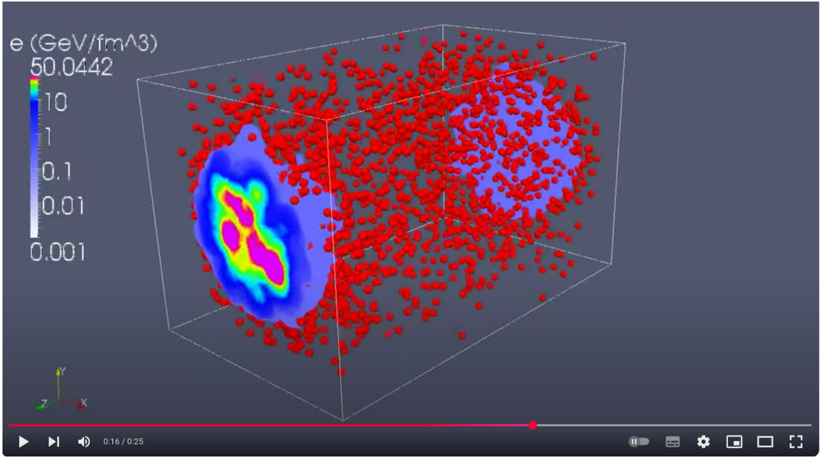

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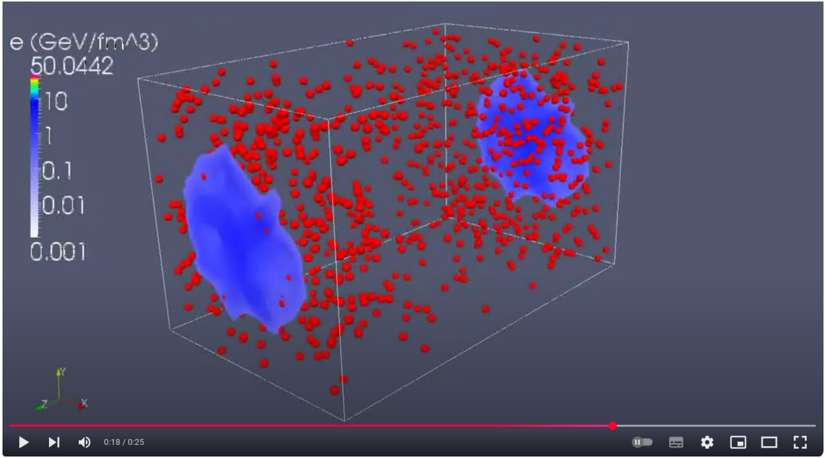

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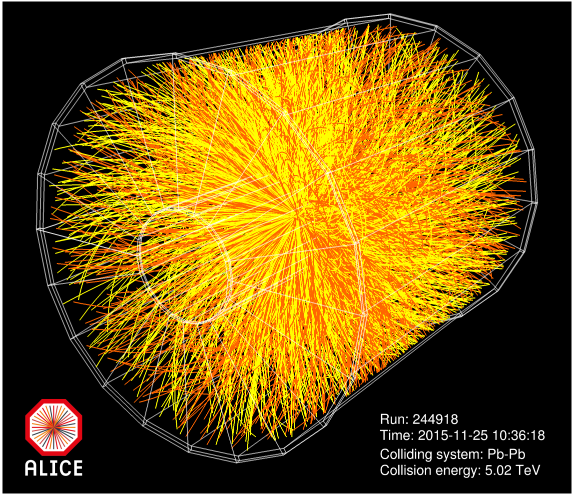
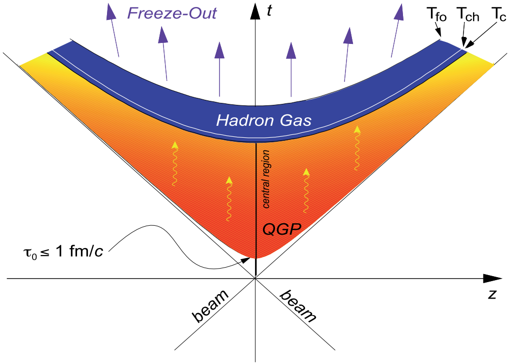
An event as seen by the detectors

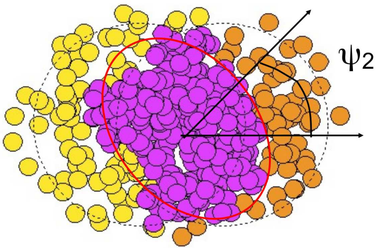


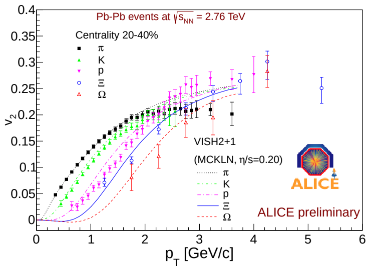
Getting information on what happened before



- Soft probes (low-p_T hadrons): collective behavior of the *medium*;
- Hard probes (high-p_T particles, heavy quarks, quarkonia): produced in *hard pQCD processes* in the initial stage, allow to perform a tomography of the medium

A medium displaying a collective behavior



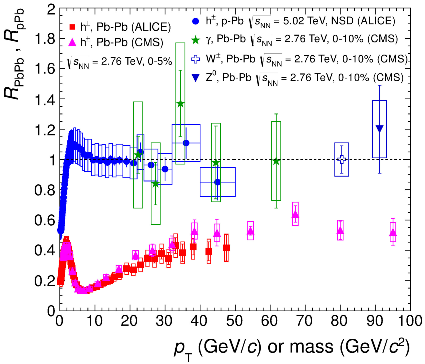


Anisotropic azimuthal distribution of hadrons as a response to pressure gradients quantified by the *Fourier coefficients* v_n

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2\sum_n v_n \cos[n(\phi - \psi_n)] + \dots\right)$$

$$v_n \equiv \langle \cos[n(\phi - \psi_n)] \rangle$$

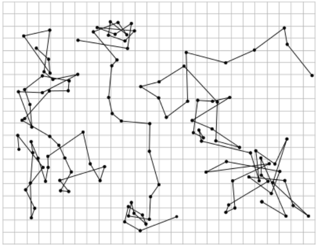
A medium inducing energy-loss to colored probes



Medium-induced suppression of high-momentum hadrons and jets quantified through the *nuclear modification factor*

$$R_{AA} \equiv \frac{\left(dN^h/dp_T\right)^{AA}}{\langle N_{\rm coll}\rangle \left(dN^h/dp_T\right)^{pp}}$$

HF in HIC's: what do we want to learn? A bit of history...



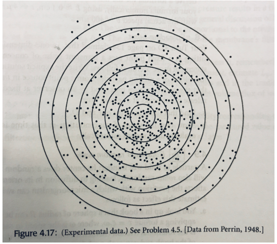


Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

Einstein (1905) and Perrin (1909) study of Brownian motion: from the random walk of small grains ($a \sim 0.5\mu$m) in water one extracts the diffusion coefficient

$$\langle x^2 \rangle \underset{t\to\infty}{\sim} 2D_s t$$

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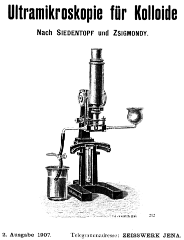

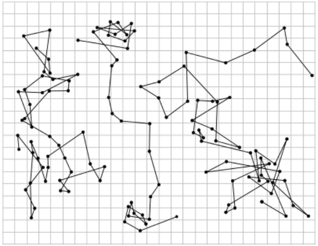

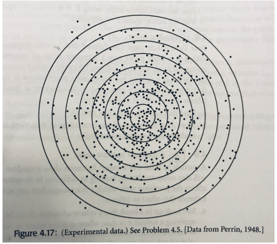

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and estimates the Avogadro number (proof of the *granular structure of matter*):

$$\mathcal{N}_A K_B \equiv \mathcal{R} \quad \longrightarrow \quad \mathcal{N}_A = \frac{\mathcal{R}\, T}{6\pi\, a\, \eta\, D_s}$$

Perrin obtained the values $\mathcal{N}_A \approx 5.5 - 7.2 \cdot 10^{23}$.

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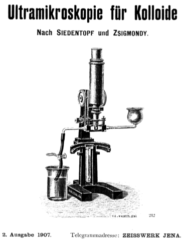

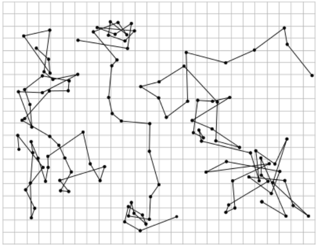

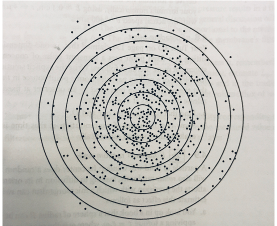

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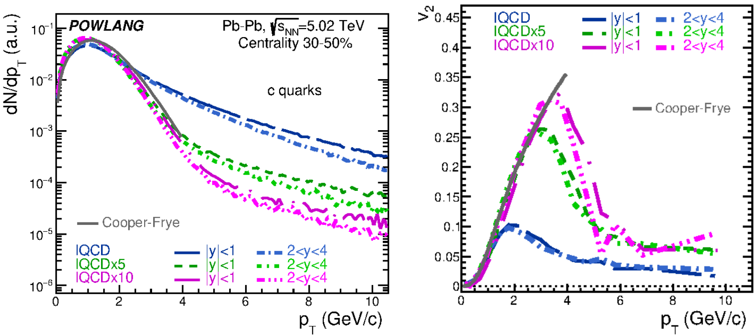
Perrin obtained the values $\mathcal{N}_A \approx 5.5 - 7.2 \cdot 10^{23}$. We would like to derive HQ transport coefficients in the QGP with a comparable precision and accuracy!

We do not have a microscope!

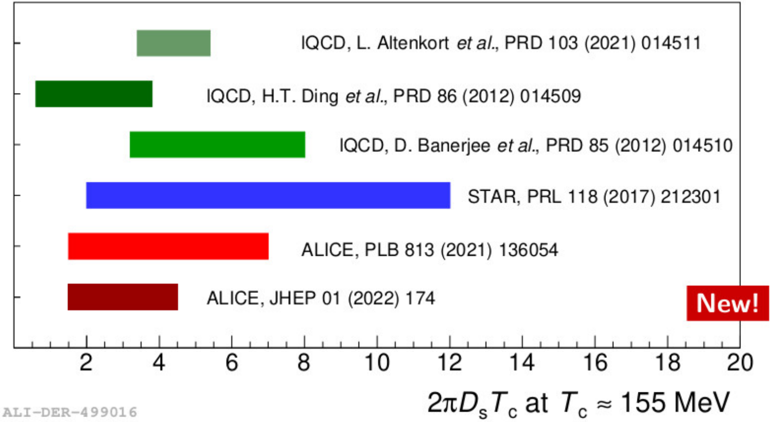


Transport coefficients can be accessed indirectly, comparing transport predictions with different values of momentum broadenig

$$\kappa = \frac{2T^2}{D_s}$$

with experimental results for momentum (left) and angular (right) HF particle distributions (figure from A.B. *et al.*, JHEP 05 (2021) 279)

Where do we stand?



Still far from accuracy and precision of Perrin result for $\mathcal{N}_A$...

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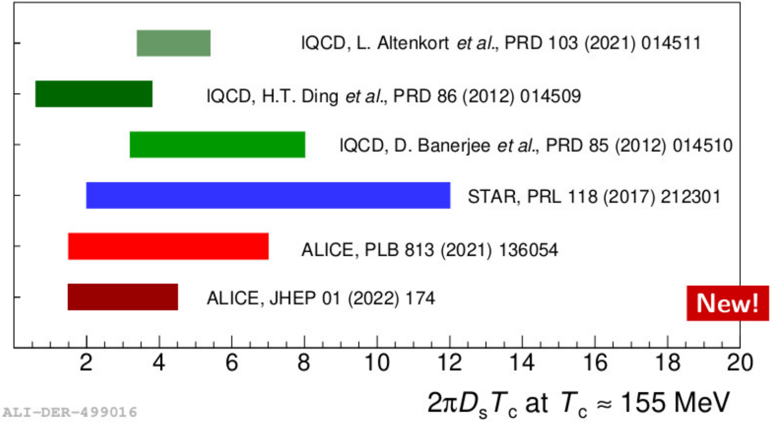

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Why such large systematic uncertainties?

HQ transport: the relativistic Langevin equation

HQ diffusion through the fireball simulated via the relativistic Langevin equation (A.B. et al., Nucl.Phys. A831 (2009) 59)

$$\frac{\Delta p^i}{\Delta t} = -\underbrace{\eta_D(p)p^i}_{\text{determ.}} + \underbrace{\xi^i(t)}_{\text{stochastic}},$$

with the properties of the noise encoded in

$$\langle \xi^i(\boldsymbol{p}_t)\rangle = 0 \quad \langle \xi^i(\boldsymbol{p}_t)\xi^j(\boldsymbol{p}_{t'})\rangle = b^{ij}(\boldsymbol{p})\frac{\delta_{tt'}}{\Delta t} \quad b^{ij}(\boldsymbol{p}) \equiv \kappa_{\|}(p)\hat{p}^i\hat{p}^j + \kappa_{\perp}(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

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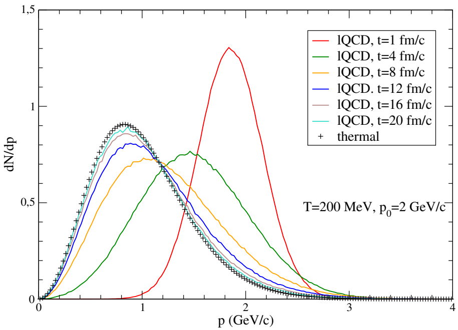
Transport coefficients describe the HQ-medium coupling

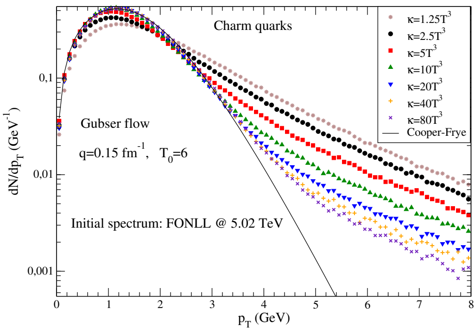
- *Momentum diffusion* $\kappa_\perp \equiv \frac{1}{2}\frac{\langle \Delta p_\perp^2 \rangle}{\Delta t}$ and $\kappa_\| \equiv \frac{\langle \Delta p_\|^2 \rangle}{\Delta t}$;
- *Friction* term (dependent on the discretization scheme!)

$$\eta_D{}^{\text{Ito}}(p) = \frac{\kappa_\|(p)}{2TE_p} - \frac{1}{E_p^2}\left[(1-v^2)\frac{\partial \kappa_\|(p)}{\partial v^2} + \frac{d-1}{2}\frac{\kappa_\|(p) - \kappa_\perp(p)}{v^2}\right]$$

fixed in order to assure approach to equilibrium (Einstein relation)

Asymptotic approach to thermalization



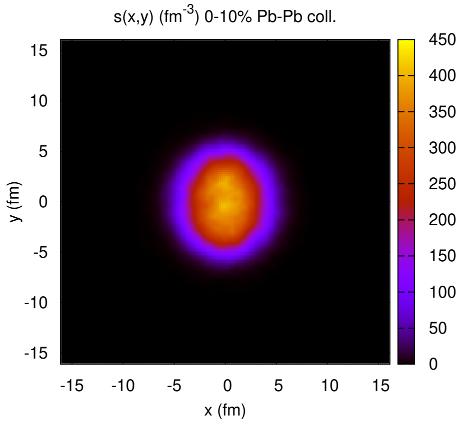


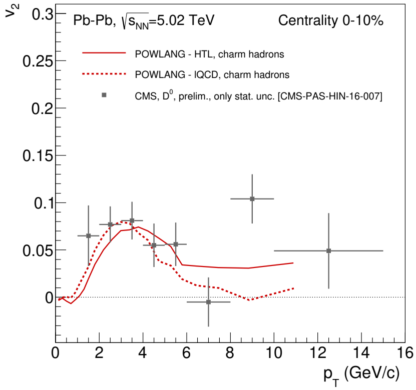
Validation of the model (figures adapted from Federica Capellino master thesis):

- Left panel: evolution in a static medium
- Right panel: decoupling from an expanding medium at $T_{\rm FO} = 160$ MeV

For late times or very large transport coefficients HQ's approach local kinetic equilibrium with the medium. For an expanding medium high-p_T tail remains off equilibrium.

Some results: D-meson v_2 and v_3 in Pb-Pb





Transport calculations carried out in JHEP 1802 (2018) 043, with hydrodynamic background calculated via the ECHO-QGP code (EPJC 73 (2013) 2524) starting from EBE Glauber Monte-Carlo initial conditions: $v_2 \neq 0$ in central collisions, $v_3 \neq 0$

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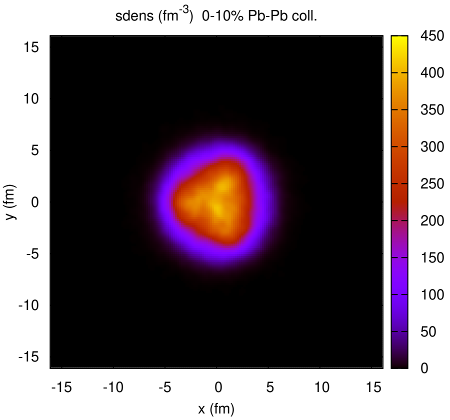

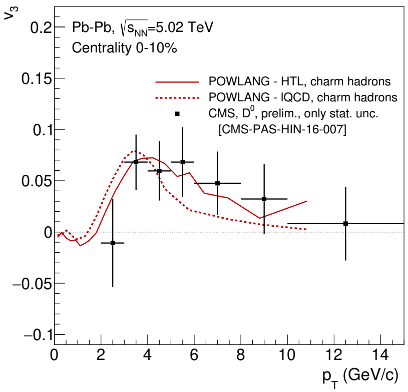

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HQ momentum diffusion: lattice-QCD

From the non-relativistic limit of the Langevin equation one gets

$$\frac{dp^i}{dt} = -\eta_D p^i + \xi^i(t), \quad \text{with} \quad \langle \xi^i(t)\xi^j(t')\rangle = \delta^{ij}\delta(t-t')\kappa$$

$$\text{hence} \quad \kappa = \frac{1}{3}\int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0)\rangle_{\rm HQ} = \frac{1}{3}\int_{-\infty}^{+\infty} dt \underbrace{\langle F^i(t)F^i(0)\rangle_{\rm HQ}}_{\equiv D^>(t)}$$

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Lattice-QCD simulations provide *Euclidean* ($t = -i\tau$) electric-field ($M = \infty$) correlator

$$D_E(\tau) = -\frac{\langle \mathrm{Re}\,\mathrm{Tr}[U(\beta,\tau) gE^i(\tau,\mathbf{0}) U(\tau,0) gE^i(0,\mathbf{0})]\rangle}{\langle \mathrm{Re}\,\mathrm{Tr}[U(\beta,0)]\rangle}$$

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How to proceed? κ comes from the $\omega \to 0$ limit of the FT of $D^>$. In a thermal ensemble $\sigma(\omega) \equiv D^>(\omega) - D^<(\omega) = (1 - e^{-\beta\omega})D^>(\omega)$, so that

$$\kappa \equiv \lim_{\omega\to 0} \frac{D^>(\omega)}{3} = \lim_{\omega\to 0} \frac{1}{3}\frac{\sigma(\omega)}{1-e^{-\beta\omega}} \underset{\omega\to 0}{\sim} \frac{1}{3}\frac{T}{\omega}\sigma(\omega)$$

HQ momentum diffusion: systematic uncertainties

The spectral density $\sigma(\omega)$ has to be extracted from the euclidean correlator

$$D_E(\tau) = \int_0^{+\infty} \frac{d\omega}{2\pi} \frac{\cosh(\tau - \beta/2)}{\sinh(\beta\omega/2)} \sigma(\omega)$$

An ill-posed problem! $D_E(\tau)$ known for a limited set (~ 20) of points, while one wishes to obtain a fine scan of the the spectral function $\sigma(\omega_j)$. A direct χ^2-fit is not applicable.

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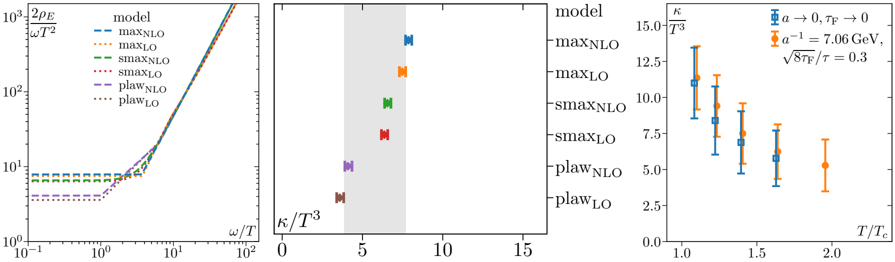
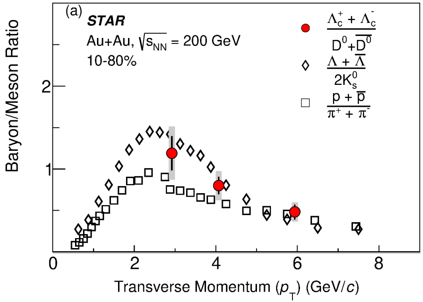
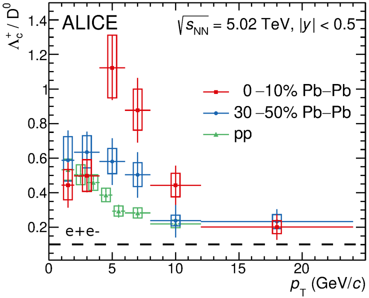
- Bayesian techniques (Maximum Entropy Method)
- Theory-guided ansatz for the behaviour of $\sigma(\omega)$ to constrain its functional form (new results for $N_f = 2+1$ HotQCD, PRL 130 (2023) 23, 231902)

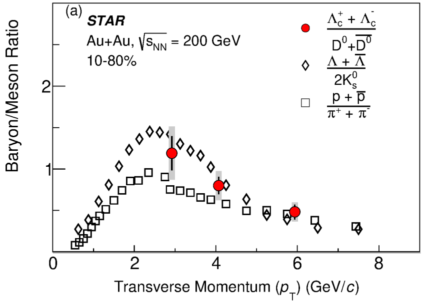


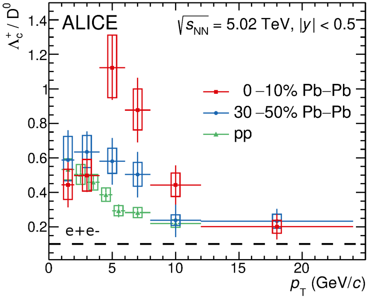




Strong enhancement of charmed baryon/meson ratio, incompatible with hadronization models tuned to reproduce e^+e^- data

Systematic uncertainties II: hadronization





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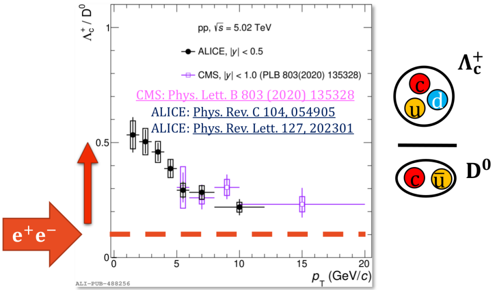

Strong enhancement of charmed baryon/meson ratio, incompatible with hadronization models tuned to reproduce e^+e^- data

- pattern similar to light hadrons
- baryon enhancement observed also in *pp* collisions: is a dense medium formed also there? Breaking of factorization description in *pp* collisions

$$d\sigma_h \neq \sum_{a,b,X} f_a(x_1)\, f_b(x_2) \otimes d\hat{\sigma}_{ab\to c\bar{c}X} \otimes D_{c\to h_c}(z)$$

Hadronization models: common features

Grouping colored partons into color-singlet structures: strings (PYTHIA), clusters (HERWIG), hadrons/resonances (coalescence/recombination).

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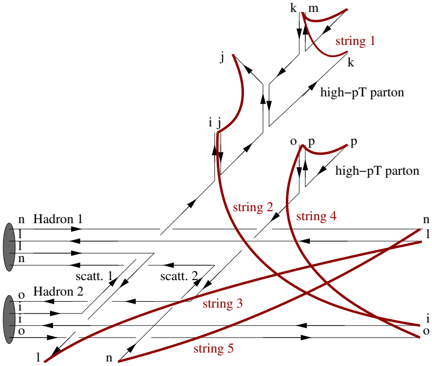

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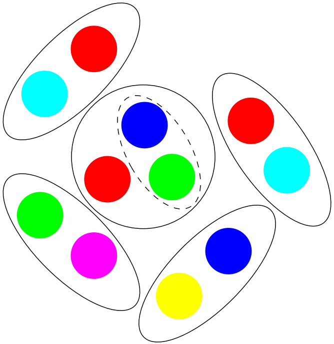
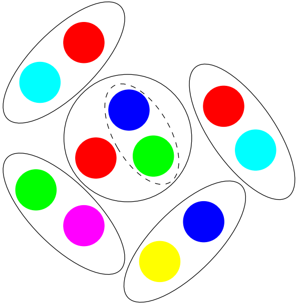


- in "elementary collisions" (what is elementary?): from the hard process, shower stage, underlying event and beam remnants;
- in heavy-ion collisions (only?): from the hot medium produced in the collision. NB Involved partons closer in space in this case and this has deep consequence!

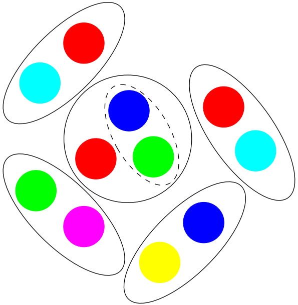
Local Color Neutralization (LCN): basic ideas



Both in AA and pp collisions a big/small deconfined fireball is formed. Around the QCD crossover temperature quarks undergoes recombination with the *closest* opposite color-charge (antiquark or diquark, favoring baryon production).

- Why? screening of color-interaction, minimization of energy stored in confining potential
- Implication: recombination of particles *from the same fluid cell* $\longrightarrow$ Space-Momentum Correlation (SMC), recombined partons tend to share a common collective velocity

Local Color Neutralization (LCN): basic ideas



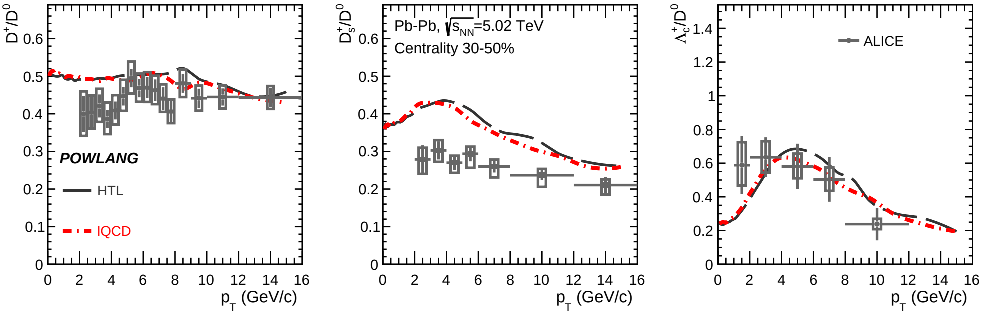
Both in AA and pp collisions a big/small deconfined fireball is formed. Around the QCD crossover temperature quarks undergoes recombination with the *closest* opposite color-charge (antiquark or diquark, favoring baryon production).

- Why? screening of color-interaction, minimization of energy stored in confining potential
- Implication: recombination of particles *from the same fluid cell* $\longrightarrow$ Space-Momentum Correlation (SMC), recombined partons tend to share a common collective velocity

Color-singlet structures are thus formed, eventually undergoing decay into the final hadrons: $2 \to 1 \to N$ process, usually a charmed hadron plus a very soft particle

- Exact four-momentum conservation;
- No direct bound-state formation, hence no need to worry about overlap between the final hadron and the parent parton wave-functions

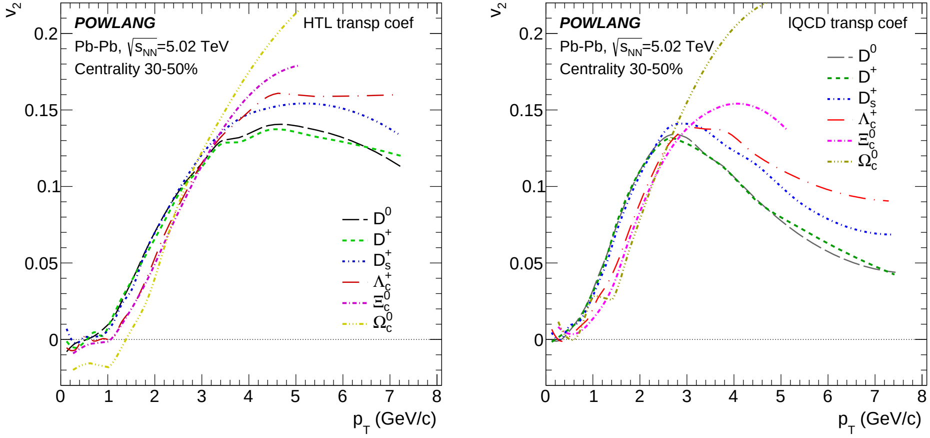
LCN in AA collisions: charmed-hadron ratios



- Enhanced HF baryon-to-meson ratios up to intermediate p_T nicely reproduced, thanks to formation of *small invariant-mass* charm+diquark clusters[1]
- Smooth approach to e^+e^- limit ($\Lambda_c^+/D^0 \approx 0.1$) at high p_T: high-M_c clusters fragmented as Lund strings, as in the vacuum

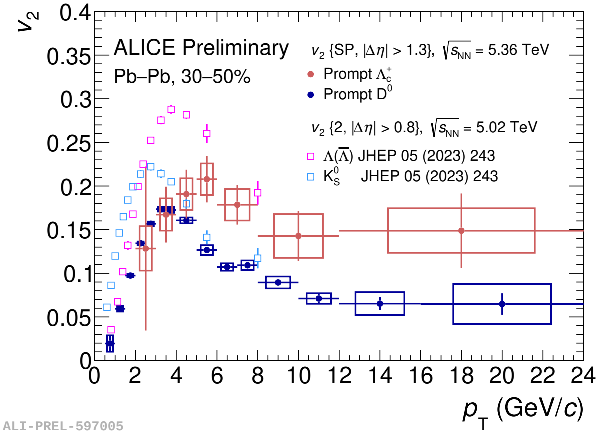
[1] A.B. et al., EPJC 82 (2022) 7, 607

LCN in AA collisions: elliptic flow



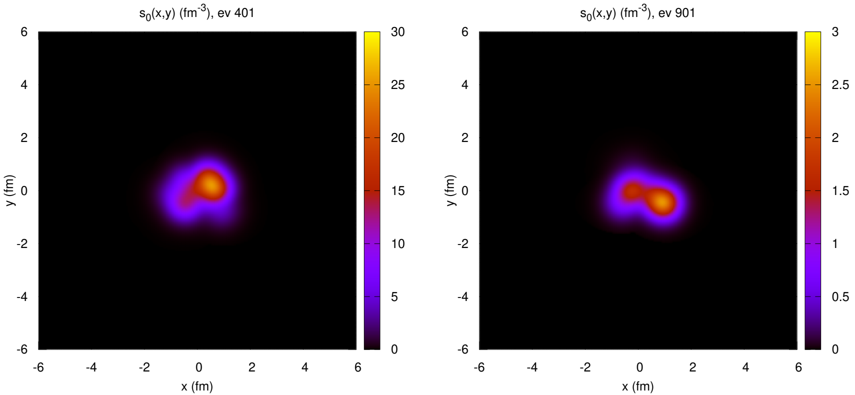
Mass ordering of the v_2 coefficient!

LCN in AA collisions: elliptic flow



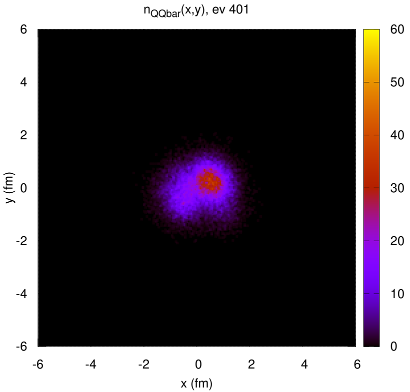
Mass ordering of the v_2 coefficient!

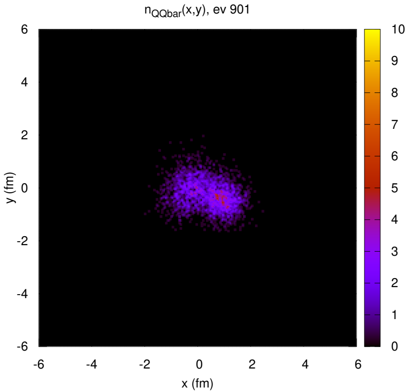
Addressing pp collisions...



$Q\overline{Q}$ production biased towards hot spots of highest multiplicity events

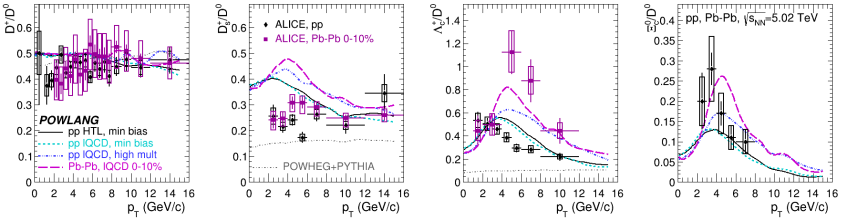
Addressing pp collisions...





$Q\overline{Q}$ production biased towards hot spots of highest multiplicity events

Results in pp: particle ratios

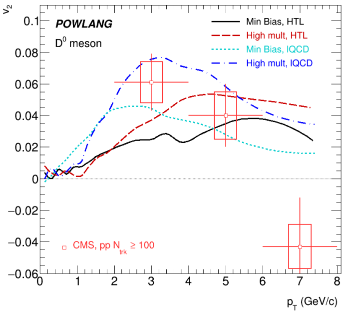


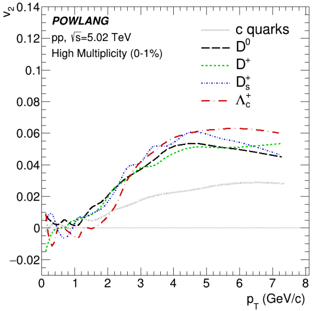
First results for particle ratios[2]:

- POWHEG+PYTHIA standalone strongly underpredicts baryon-to-meson ratio
- Enhancement of charmed baryon-to-meson ratio *qualitatively* reproduced if propagation+hadronization in a small QGP droplet is included
- Multiplicity dependence of radial-flow peak position (just a reshuffling of the momentum, without affecting the yields): $\langle u_\perp \rangle_{\rm pp}^{\rm mb} \approx 0.33$, $\langle u_\perp \rangle_{\rm pp}^{\rm hm} \approx 0.53$, $\langle u_\perp \rangle_{\rm PbPb}^{0-10\%} \approx 0.66$

[2] In collaboration with D. Pablos, A. De Pace, F. Prino et al., PRD 109 (2024) 1, L011501

Results in pp: elliptic flow

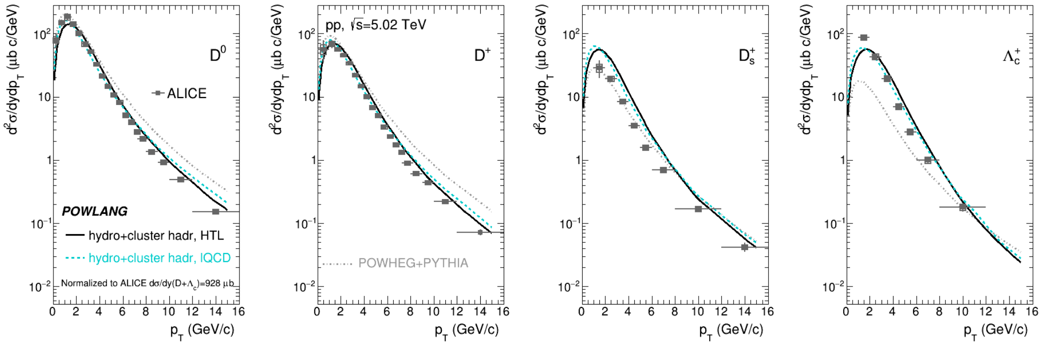




Response to initial elliptic eccentricity ($\langle\epsilon_2\rangle^{\rm mb}\approx\langle\epsilon_2\rangle^{\rm mh}\approx 0.31$) $\longrightarrow$ non-vanishing v_2 coefficient

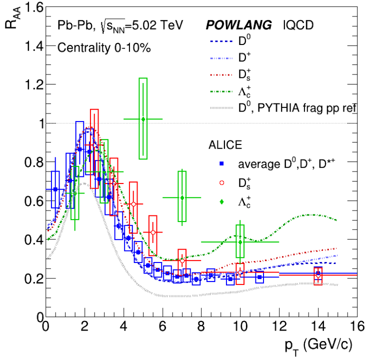
- Differences between minimum-bias and high-multiplicity results only due to longer time spent in the fireball ($\langle\tau_H\rangle^{\rm mb}\approx 1.95$ fm/c vs $\langle\tau_H\rangle^{\rm hm}\approx 2.92$ fm/c)
- Mass ordering at low p_T ($M_{qq} > M_q$)
- Sizable fraction of v_2 acquired at hadronization

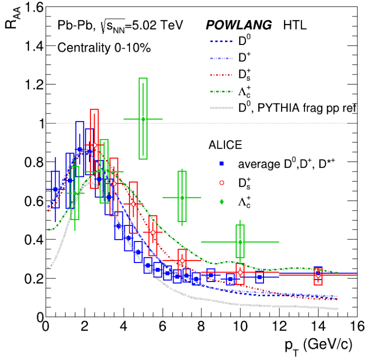
Relevance to quantify nuclear effects



- Slope of the spectra in pp collisions better described including medium effects

Relevance to quantify nuclear effects





- Slope of the spectra in pp collisions better described including medium effects
- Inclusion of medium effects in minimum-bias pp benchmark fundamental to better describe charmed hadron R_{AA}, both the radial-flow peak and the species dependence

To summarize

- What we learnt: A rich set of experimental data shows evidence of at least *partial* kinetic equilibration of charm in heavy-ion collisions and of the *breaking of universality* of the hadronization process;
- What is only partially known: the transport coefficients
  - lattice-QCD calculations getting better (e.g. from $N_f = 0$ to $N_f = 2 + 1$), BUT unavoidable systematic uncertainties;
  - theory-to-data comparison (e.g. Bayesian analysis) has to focus on kinematic windows where transport equations are reliable (e.g. beauty at low-p_T): just a matter of time to improve;
  - systematic uncertainty from hadronization: if recombination occurs, same flow of HF hadrons with smaller partonic transport coefficients. Modified hadrochemistry (integrated yields) allows one to quantify the relevance of recombination, both in pp and AA.
- The same Local Color-Neutralization (LCN) model developed to describe medium-modification of HF hadronization in AA collisions has been applied to the pp case. Consistent description of several HF observables: shape of the p_T-distributions, enhanced baryon-to-meson ratio, charmed-hadron R_{AA} and non-vanishing v_2 coefficient,