The Little-Bang in heavy-ion collisions

Andrea Beraudo

INFN - Sezione di Torino - SIM collaboration

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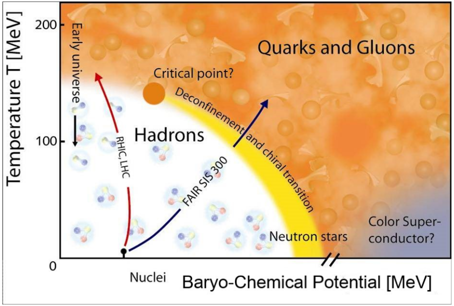
Istituto Nazionale di Fisica Nucleare

Who we are

- INFN staff:
  - Marzia Nardi (local coordinator)
  - Andrea Beraudo (national coordinator)
  - Arturo De Pace (50%)
  - Marco Monteno (10%)
- Fellini researcher: Daniel Pablos
- Unito Staff: Paolo Parotto (RTDA)
- PhD students: Jorge Manuel Vazquez Vera

Other INFN units involved: Firenze, Catania, LNS

Heavy-ion collisions: exploring the QCD phase-diagram



QCD phases identified through the *order parameters*

- Polyakov loop $\langle L \rangle \sim e^{-\beta \Delta F_Q}$: energy cost to add an isolated color charge
- Chiral condensate $\langle \overline{q} q \rangle \sim$ effective mass of a "dressed" quark in a hadron

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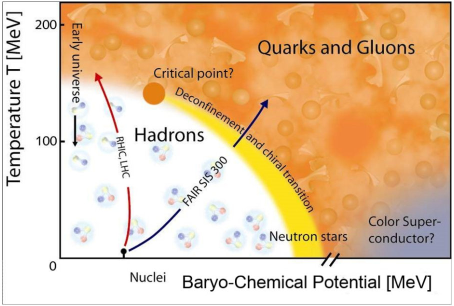

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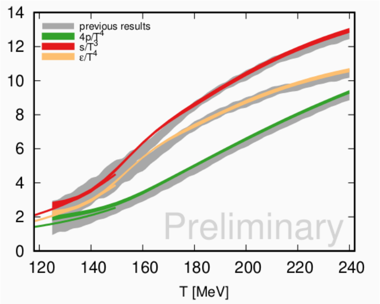
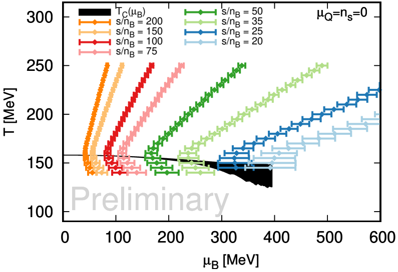
Heavy-Ion Collision (HIC) experiments performed to study the transition

- From QGP (color deconfinement, chiral symmetry restored)
- to hadronic phase (confined, chiral symmetry broken)

NB QCD chiral transition responsible for most of the baryonic mass of the universe: *only* $\sim$*35 MeV of the proton mass from* $m_{u/d} \neq 0$

Heavy-ion collisions: exploring the QCD phase-diagram





- Region explored at the LHC ($\sqrt{s_{\rm NN}} \approx 5$ TeV) and highest RHIC energy: *high-T/low-density* (early universe, $n_B/n_\gamma \sim 10^{-9}$). The region currently accessible by lattice-QCD simulations (P. Parotto, UniTo and Wuppertal-Budapest collaboration);

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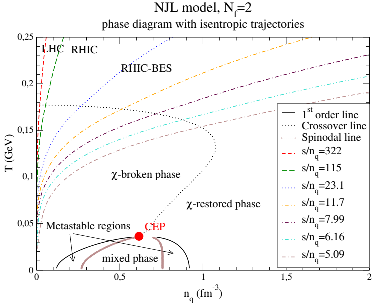

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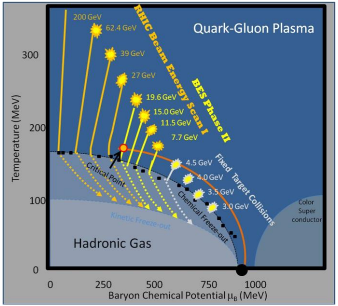

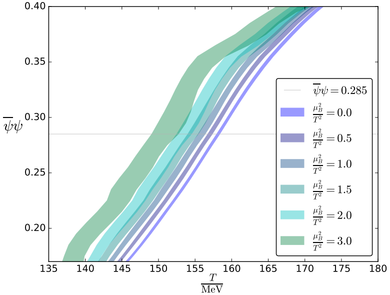

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Is there a Critical End-Point in the QCD phase diagram? If so, is it accessible?

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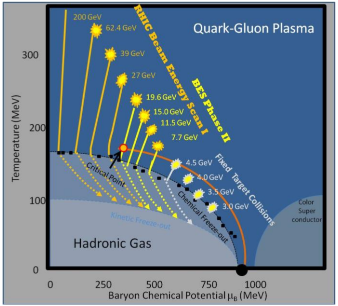

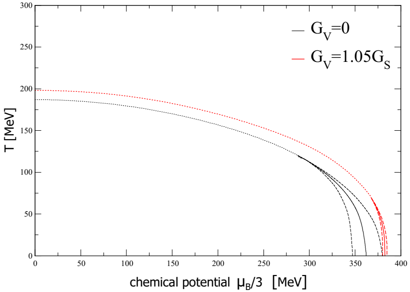

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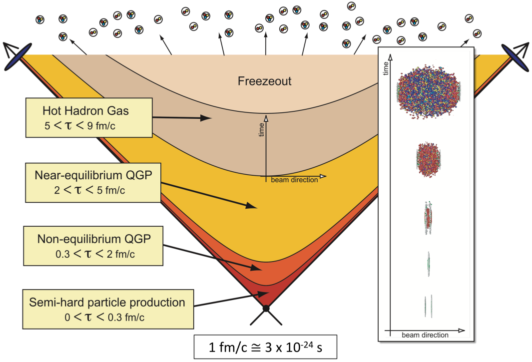
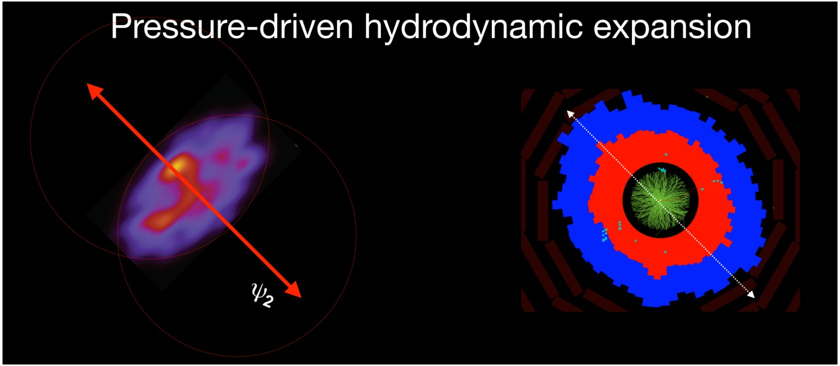
Heavy-ion collisions: a cartoon of space-time evolution



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

A medium displaying a collective behavior



$$(\epsilon + P)\frac{dv^i}{dt} \underset{v \ll c}{=} -\frac{\partial P}{\partial x^i}$$

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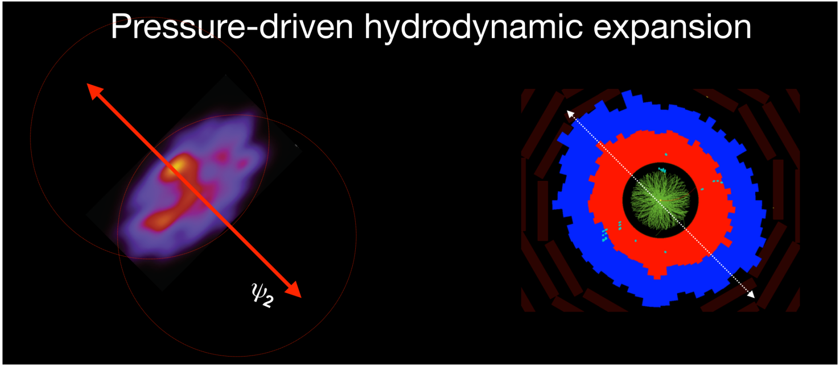

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NB picture relying on the condition $\lambda_{\mathrm{mfp}} \ll L$

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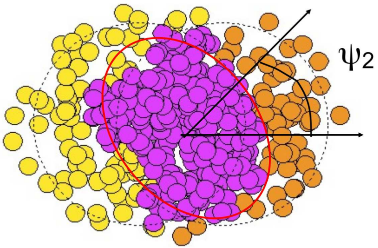

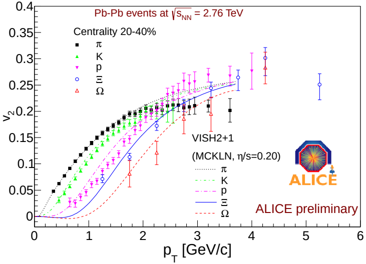

- Anisotropic azimuthal distribution of hadrons as a response to pressure gradients quantified by the *Fourier coefficients* v_n

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2\sum_n v_n \cos[n(\phi - \psi_n)] + \ldots\right) \quad \text{with} \quad v_n \equiv \langle \cos[n(\phi - \psi_n)] \rangle$$

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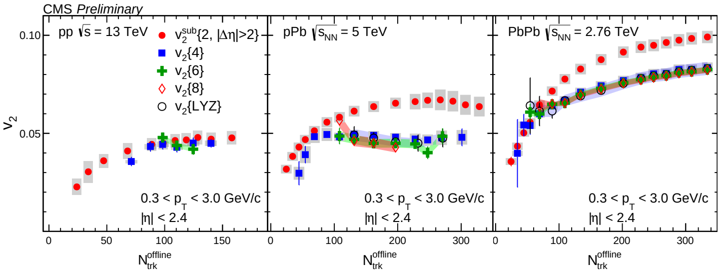

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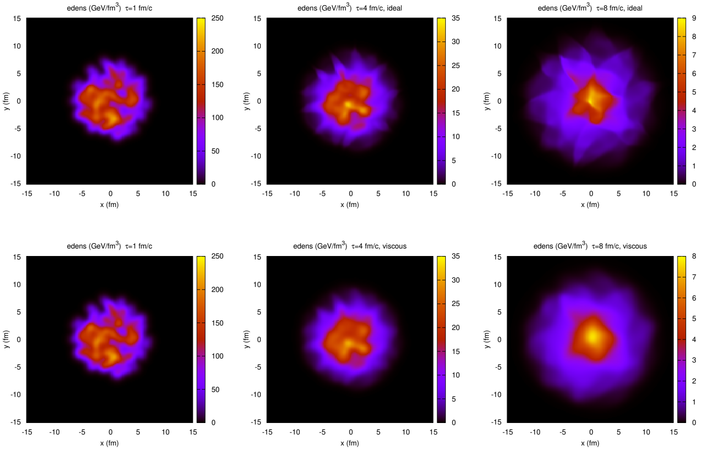
- Collective effects observed also in pp events (first LHC paper)! A small QGP droplet also in pp collisions?

Relativistic viscous hydrodynamics for heavy-ion collisions with ECHO-QGP

L. Del Zanna[1,2,3,a], V. Chandra[2], G. Inghirami[1,2], V. Rolando[4,5], A. Beraudo[6], A. De Pace[7], G. Pagliara[4,5], A. Drago[4,5], F. Becattini[1,2,8]



Viscous hydrodynamics: the theoretical challenge

$$\partial_\mu T^{\mu\nu} = 0\,, \quad \text{with} \quad T^{\mu\nu} = T^{\mu\nu}_{\rm id} + \pi^{\mu\nu}$$

- Relativistic Navier-Stokes first-order theory violates causality

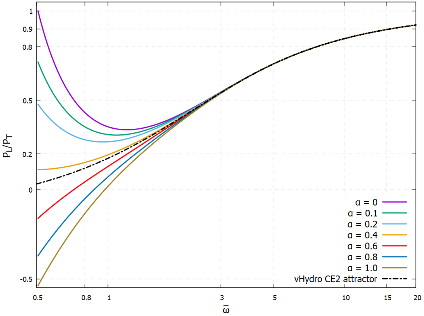
$$\pi^{\mu\nu} = 2\eta\,\nabla^{<\mu} u^{\nu>}$$

- Second-order theory (Israel-Stewart and developments) respects causality

$$\dot{\pi}^{\mu\nu} \approx -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\,\nabla^{<\mu} u^{\nu>}\right)$$

Viscosity damps short-wavelength modes!

Why does hydrodynamics work so well?



$\overline{\omega} \equiv \tau / \tau_R$, a_0 quantifies initial anisotropy

- Viscous hydrodynamics (2^{nd} order Chapman-Enskog expansion)

$$T^{\mu\nu}(x) = \int \frac{d\vec{p}}{(2\pi)^3 E} p^\mu p^\nu f(x, \vec{p})$$

Evaluating longitudinal and transverse pressure from the moments of the single-particle distribution arising from the Boltzmann Equation ($f \equiv f_{\mathrm{eq}} + \delta f$)

$$p^\mu \partial_\mu f = -\frac{p \cdot u}{\tau_R} \delta f$$

one observes convergence to a universal result (hydrodynamic attractor) *well before* the conditions

$$\mathrm{Kn} \equiv \frac{\tau_R}{\tau} \ll 1 \quad \text{and} \quad \mathrm{Re}^{-1} \equiv \frac{\sqrt{\pi^{\mu\nu}\pi_{\mu\nu}}}{e+P} \ll 1$$

are satisfied (F. Frascà's master thesis)

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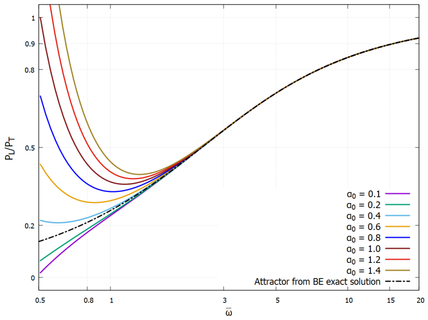

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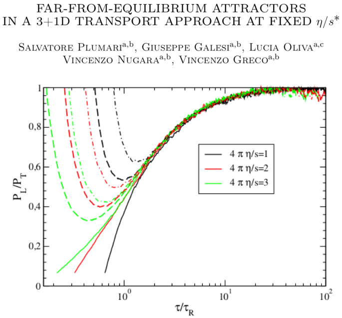

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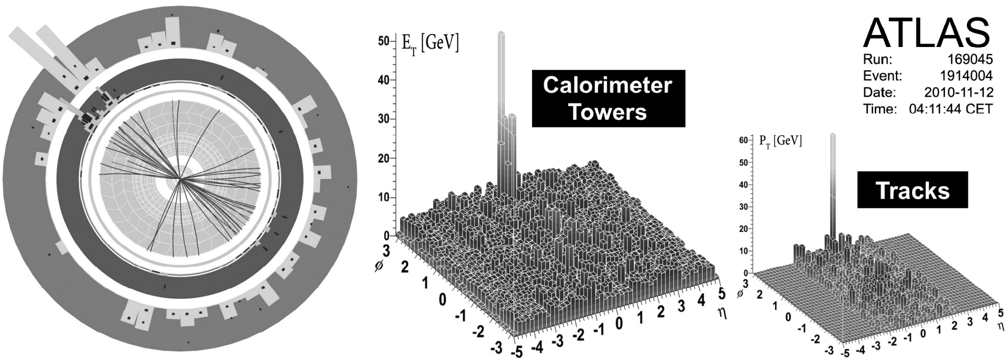
A medium inducing energy-loss of colored probes



Strong unbalance of di-jet events, visible at the level of the event-display itself, without any analysis: jet-quenching

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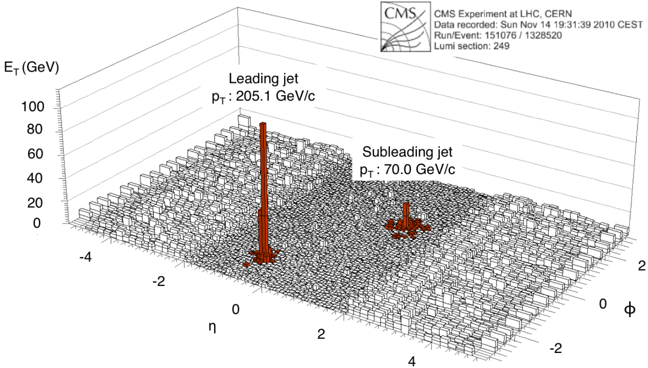

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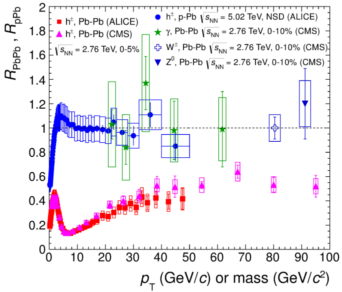
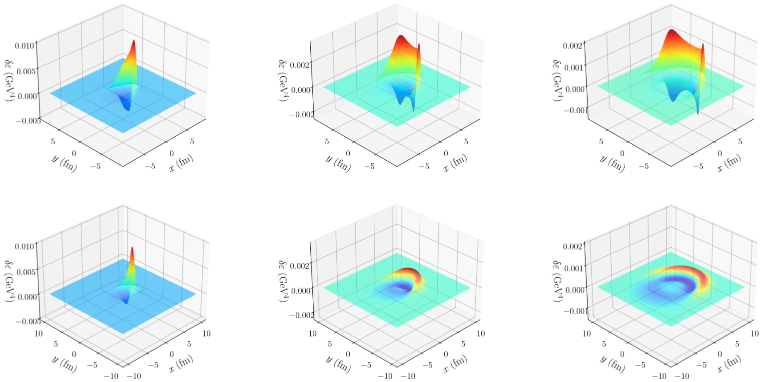


Suppression of high-momentum hadrons and jets quantified through the *nuclear modification factor*

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

interpreted as in-medium energy-loss of *colored* particles

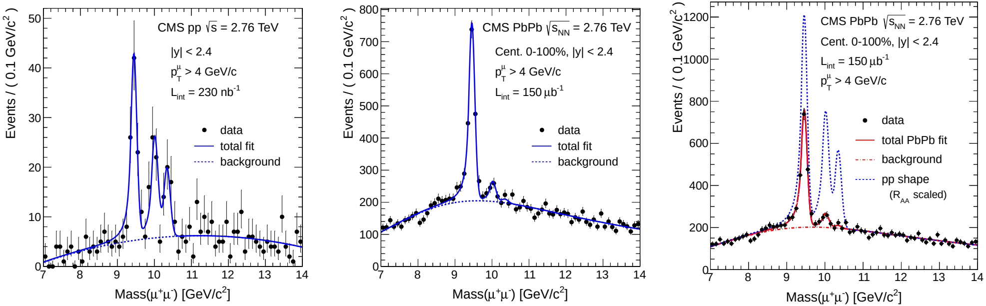
How the medium responds to jets



Wake arising from jet propagation in an ideal and viscous medium studied in *linearized hydrodynamics* (Daniel Pablos et al., JHEP 05 (2021) 230)

$$T^{\mu\nu} \equiv T_0^{\mu\nu} + \delta T^{\mu\nu} \;, \quad \nabla_\mu T^{\mu\nu} = 0 \;, \quad \nabla_\mu \delta T^{\mu\nu} = J^\nu$$

A medium screening the $Q\overline{Q}$ interaction



Suppression of Υ production in Pb-Pb collisions at the LHC, in particular its excited (weaker binding, larger radius!) states.

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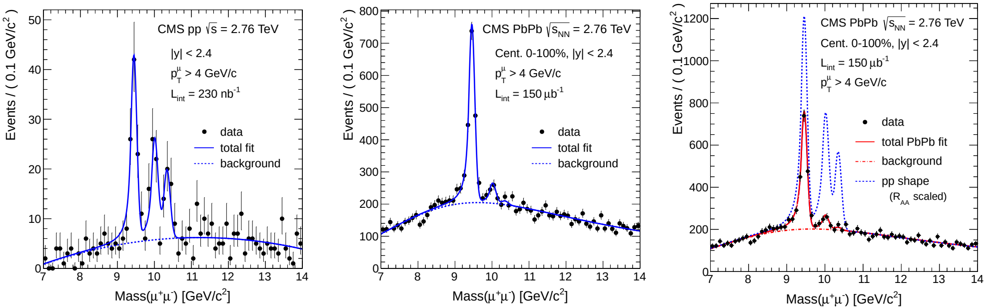

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In first approximation, Debye screening of the $Q\overline{Q}$ interaction (T. Matsui and H. Satz, PLB 178 (1986) 416-422)

$$V_{Q\overline{Q}}(r) = -C_F \frac{\alpha_s}{r} \quad \longrightarrow \quad -C_F \frac{\alpha_s}{r} e^{-m_D r}$$

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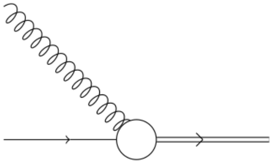
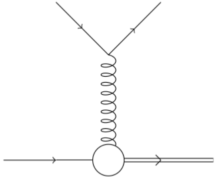
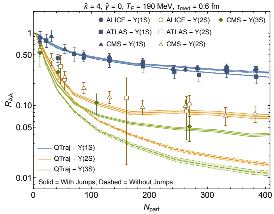


Gluo-dissociation



Inelastic scattering



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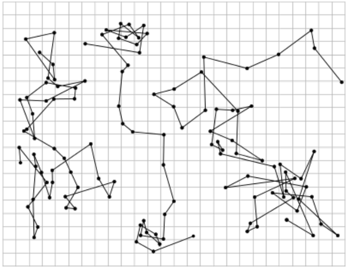
$$-C_F \frac{\alpha_s}{r} \quad \longrightarrow \quad -C_F \alpha_s \left[m_D + \frac{e^{-m_D r}}{r} \right] - i C_F \alpha_s T \phi(m_D r) \quad \longrightarrow \quad \frac{d}{dt} \mathcal{D}_{Q\overline{Q}} = \mathcal{L} \mathcal{D}_{Q\overline{Q}}$$

However, treating quarkonium as an Open Quantum System allows a richer description of its interaction and evolution in the medium in terms of Lindblad evolution equation for reduced $Q\overline{Q}$ density matrix (J.M. Martinez Vera's PhD project)

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



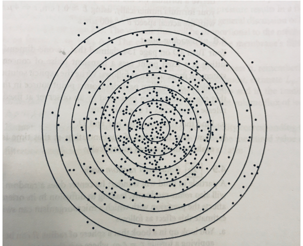


Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

From the random walk of the emulsion particles (follow the motion along one direction!) one extracts the diffusion coefficient

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

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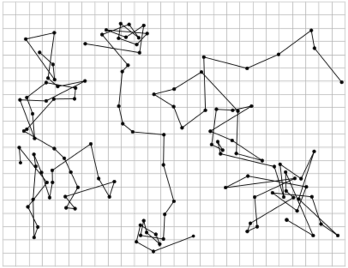

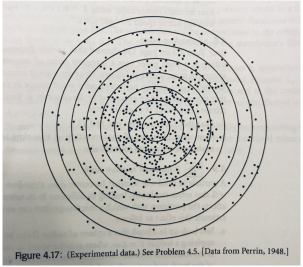

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$$\mathcal{N}_A K_B \equiv \mathcal{R} \quad \longrightarrow \quad \mathcal{N}_A = \frac{\mathcal{R}\,T}{6\pi\, a\, \eta\, D_s}$$

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

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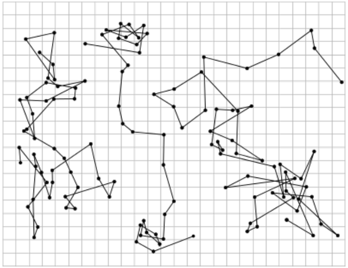

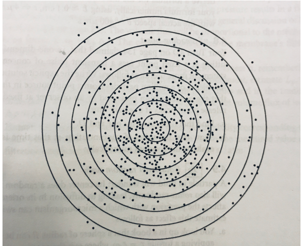

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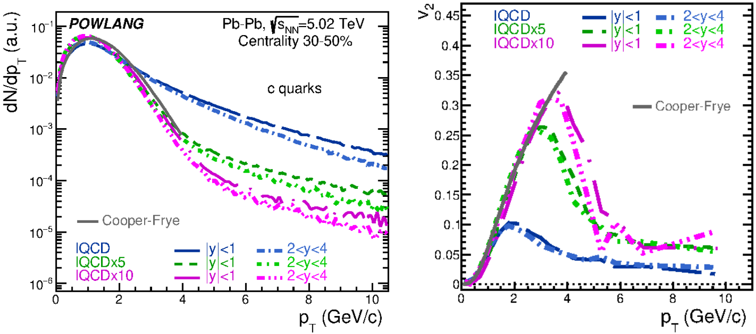
Perrin obtained the values $\mathcal{N}_A \approx 5.5 - 7.2 \cdot 10^{23}$. We would like to derive HQ transport coefficients in the QGP with a comparable precision and accuracy!

We do not have a microscope!

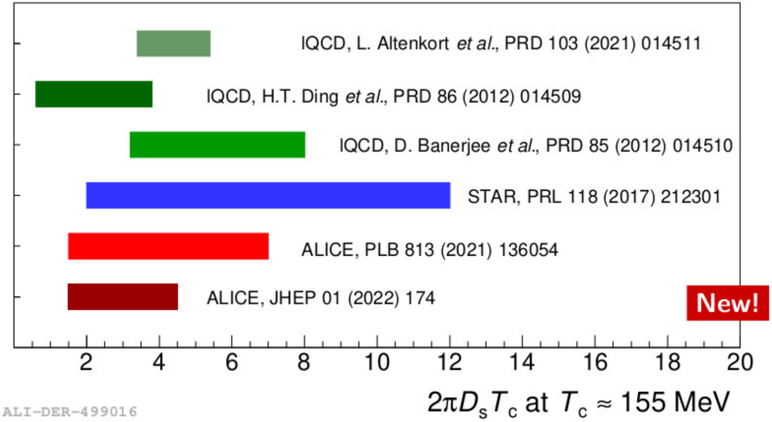


Transport coefficients can be accessed indirectly, comparing transport predictions with different values of momentum broadenig

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

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 $\mathcal{N}_A$...

HQ dynamics in the fireball

To model the HQ propagation in the hot medium we developed a relativistic Langevin equation, obtained from the soft-scattering limit of the Boltzmann 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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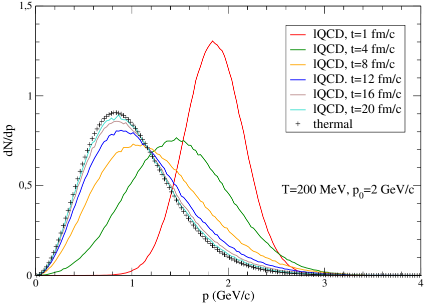
Transport coefficients describe the HQ-medium coupling

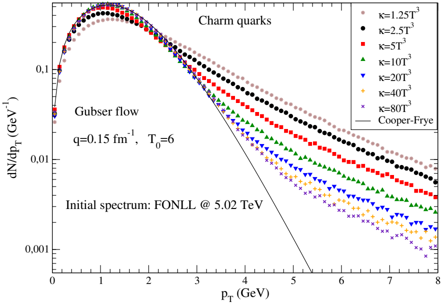
- *Momentum diffusion* $\kappa_{\perp} \equiv \frac{1}{2}\frac{\langle \Delta p_{\perp}^2 \rangle}{\Delta t}$ and $\kappa_{\|} \equiv \frac{\langle \Delta p_{\|}^2 \rangle}{\Delta t}$;
- *Friction* term (dependent on the discretization scheme!)

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

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

Asymptotic approach to thermalization



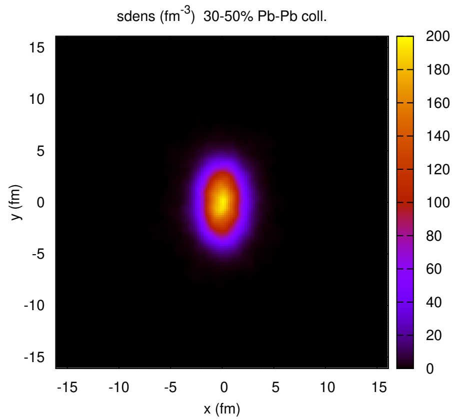


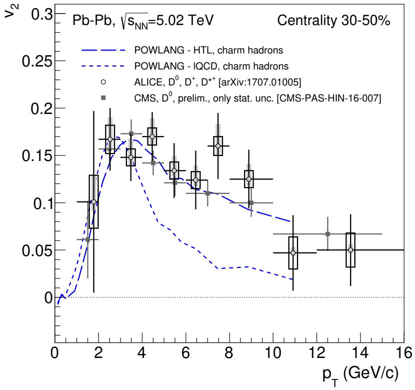
- Left panel: evolution in a static medium
- Right panel: decoupling from expanding medium at $T_{\mathrm{FO}} = 160$ MeV

For late times or for very large transport coefficients HQ's approach local kinetic equilibrium with the medium.

Figures adapted from Federica Capellino master thesis, awarded with *Milla Baldo Ceolin* and *Alfredo Molinari* INFN prizes.

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 Glauber Monte-Carlo initial conditions.

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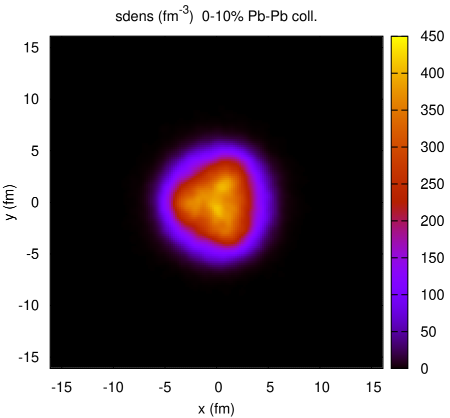

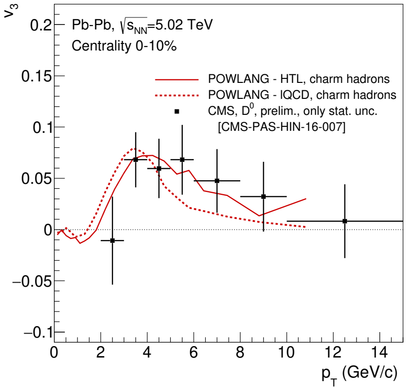

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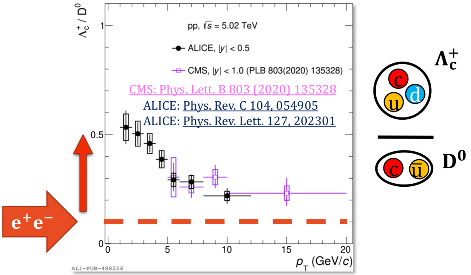
A small QGP droplet also in pp collisions?



- Strong enhancement of charmed baryon/meson ratio, incompatible with hadronization models tuned to reproduce e^+e^- data. Breaking of factorization of hadronic cross-sections in *pp* collisions (fragmentation functions not universal!)

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

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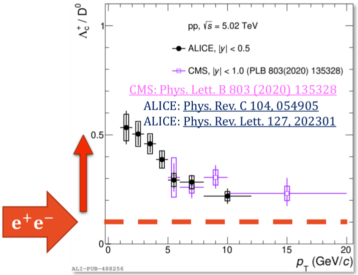

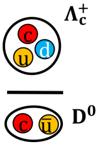

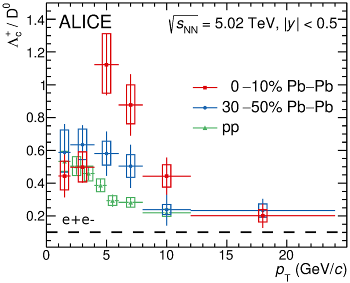

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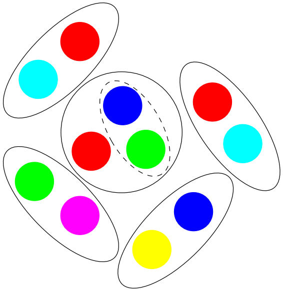

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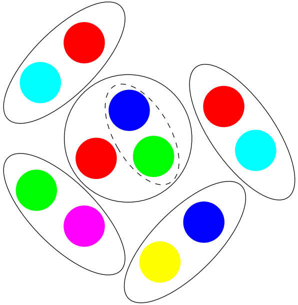
- Ratio very similar to the one observed in AA collisions: is there a reservoir of color-charges available in both systems, where HQ's can undergo recombination?

Local Color Neutralization (LCN): basic ideas



Even in pp collision a small deconfined fireball is formed. Around the QCD crossover temperature quarks undergoes recombination with the *closest* opposite color-charge (antiquark or diquark).

- Why? screening of color-interaction, minimization of energy stored in confining potential
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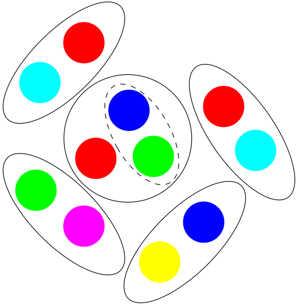

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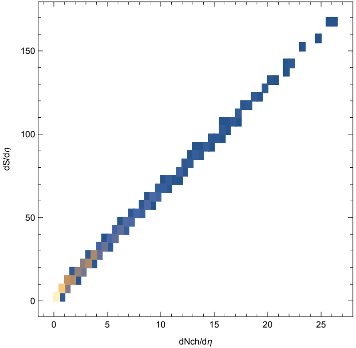
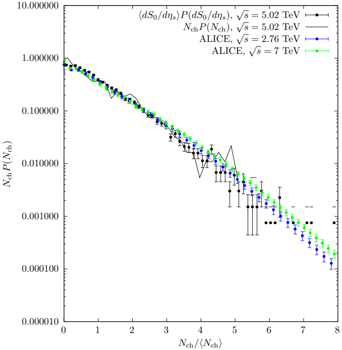
Color-singlet structures are thus formed, eventually undergoing decay into the final hadrons: $2 \to 1 \to N$ process with exact four-momentum conservation

Modelling pp collisions...





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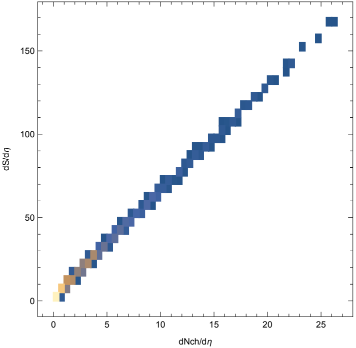

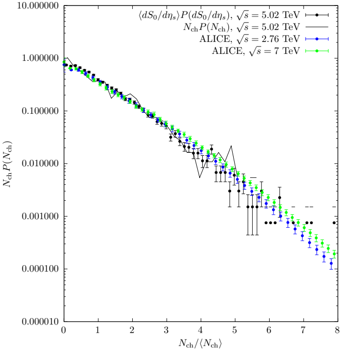

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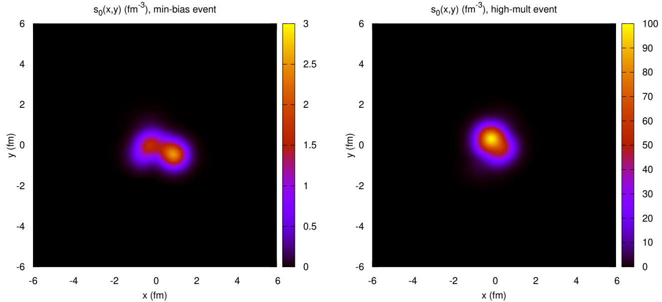

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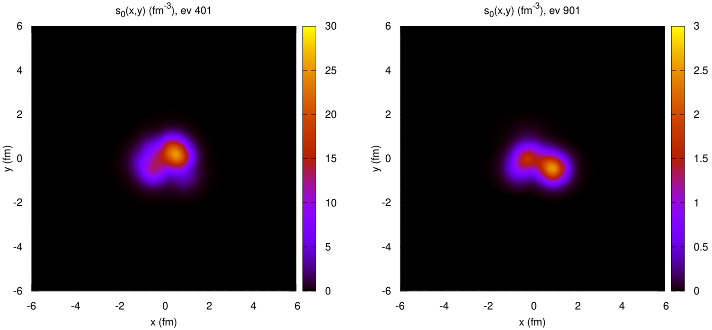
- Perfect correlation between initial entropy (dS/dy) and final particle multiplicity ($dN_{\rm ch}/d\eta$), $S \approx 7.2 N_{\rm ch}$. $P(N_{\rm ch})$ satisfying KNO scaling nicely reproduced;
- Samples of 10^3 minimum-bias ($\langle dS/dy \rangle_{\rm mb} \approx 37.6$, tuned to experimental $\langle dN_{\rm ch}/d\eta \rangle$) and high-multiplicity ($\langle dS/dy \rangle_{0-1\%} \approx 187.5$) events used to simulate HQ transport and hadronization.

Why in-medium hadronization also in pp?



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

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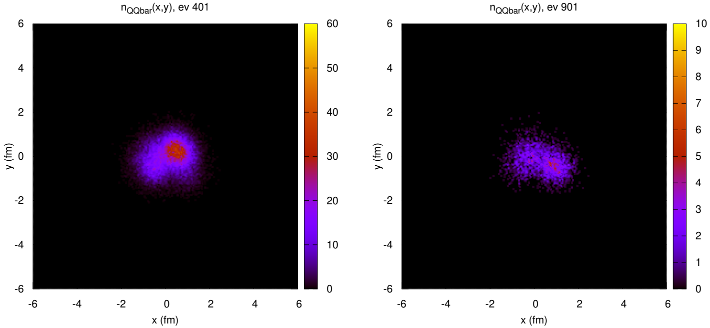

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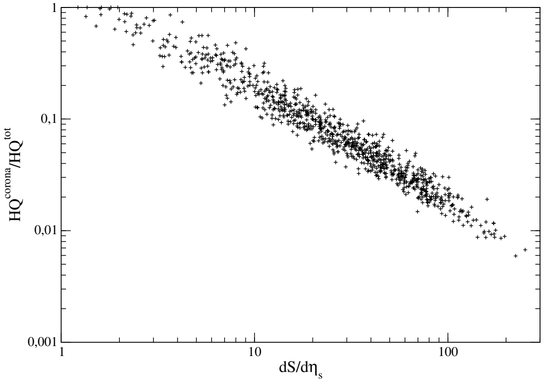
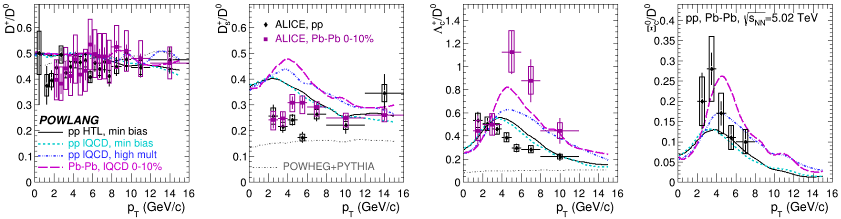


$Q\overline{Q}$ production biased towards hot spots of highest multiplicity events $\longrightarrow$ only about 5% of $Q\overline{Q}$ pairs initially found in fluid cells below T_c

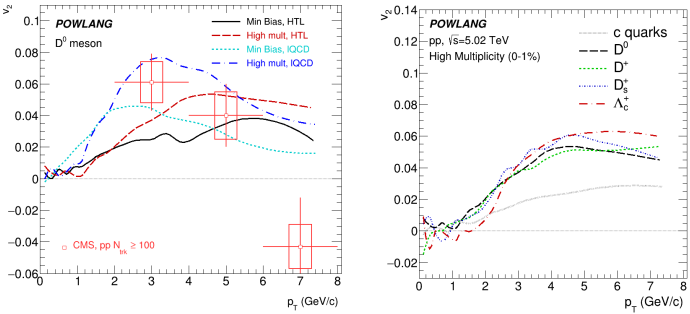


First results for particle ratios[1]:

- 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): $\langle u_\perp \rangle^{\rm mb}_{\rm pp} \approx 0.33$, $\langle u_\perp \rangle^{\rm hm}_{\rm pp} \approx 0.53$, $\langle u_\perp \rangle^{0-10\%}_{\rm PbPb} \approx 0.66$

[1] In collaboration with D. Pablos, A. De Pace, F. Prino et al., 2306.02152 [hep-ph]

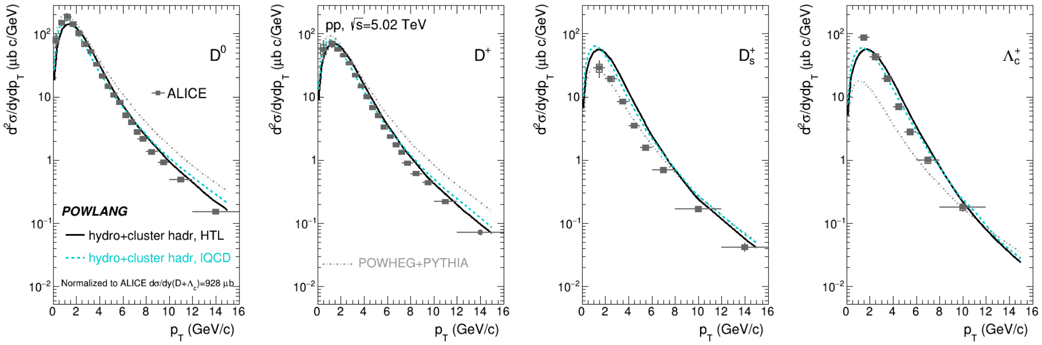
Results in pp: elliptic flow



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



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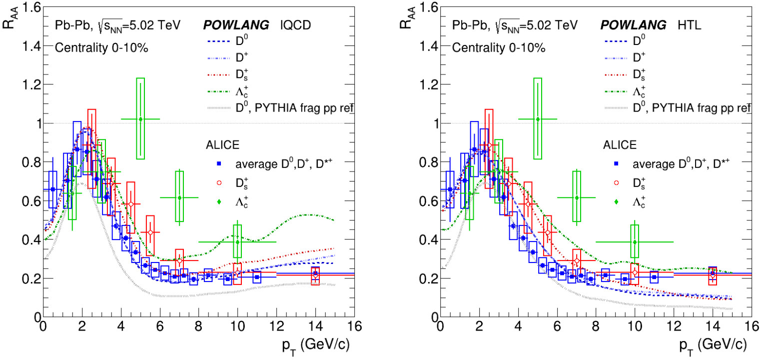

- Slope of the spectra in pp collisions better described including medium effects
- Inclusion of medium effects in minimum-bias pp benchmark fundamental to better describe charmed hadron R_{AA}, both the radial-flow peak and the species dependence

Thank you for your attention