An overview on Strongly-Interacting Matter

Andrea Beraudo

INFN - Sezione di Torino

Cortona, 11-13 October 2023

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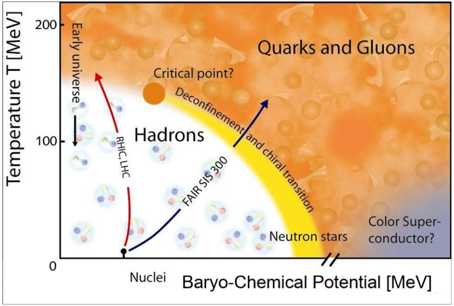
Catania	Siringo	4	0	1	1
Firenze	Becattini	2	1	1	1
LNS	Greco, Plumari	3	1	3	0
Torino	Nardi	5+1	0	1	1

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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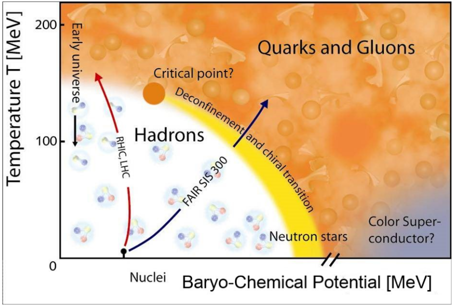

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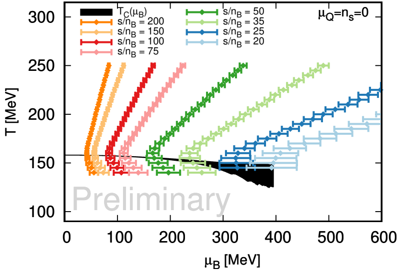
Heavy-Ion Collision (HIC) experiments performed to study the transition

- 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 on by lattice-QCD simulations (P. Parotto, UniTo and Wuppertal-Budapest collaboration);

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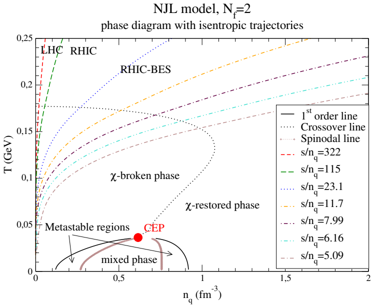

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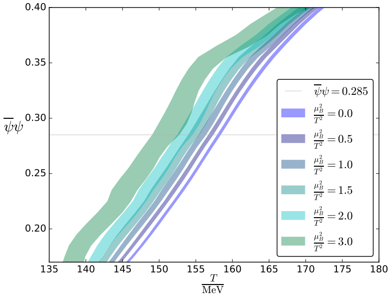

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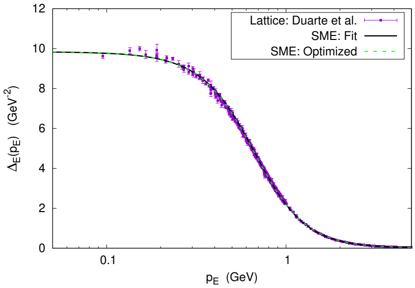
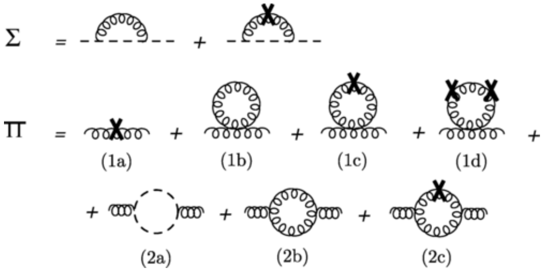
Is there a Critical End-Point in the QCD phase diagram?

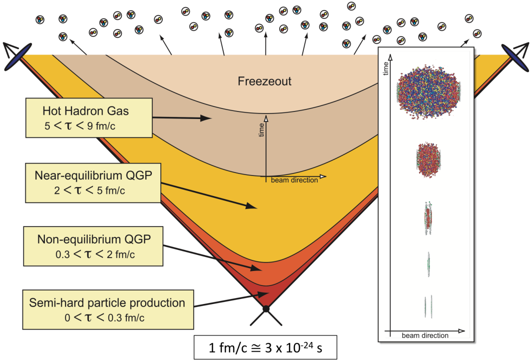
Non-perturbative QCD: screened perturbation theory vs lattice





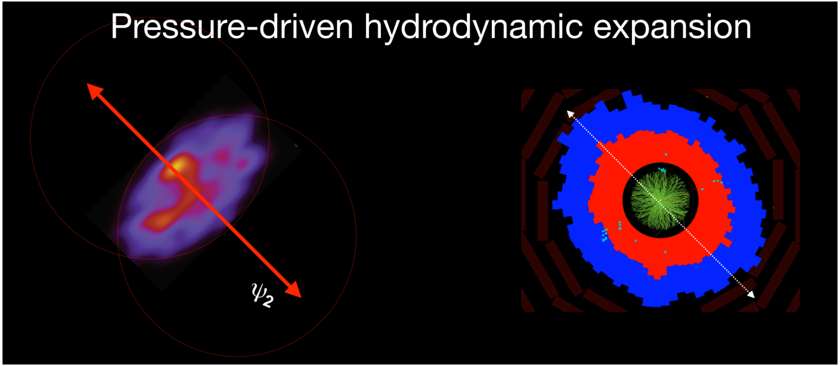
Perturbation theory is re-organized, inserting an explicit mass term into the tree-level transverse gluon propagator and adding a corresponding mass counterterm to the interaction Lagrangian (G. Comitini, D. Rizzo, M. Battello and F. Siringo, PRD 104 (2021) 7, 074020)

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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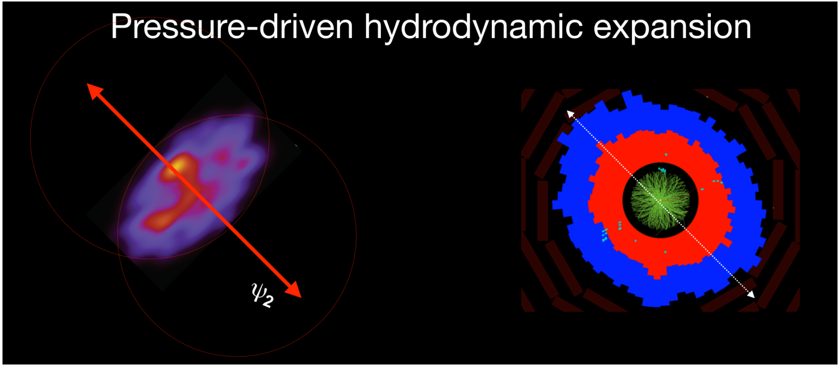

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NB picture relying on the condition $\lambda_{\mathrm{mfp}} \ll L$

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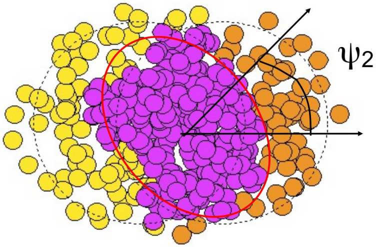
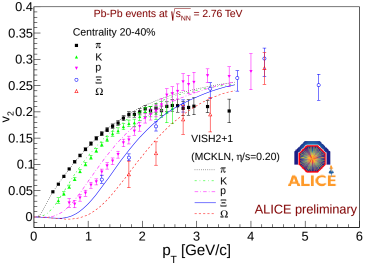
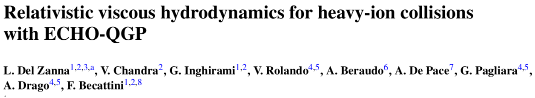




Anisotropic azimuthal distribution of hadrons as a response to pressure gradients quantified by the *Fourier coefficients* v_n

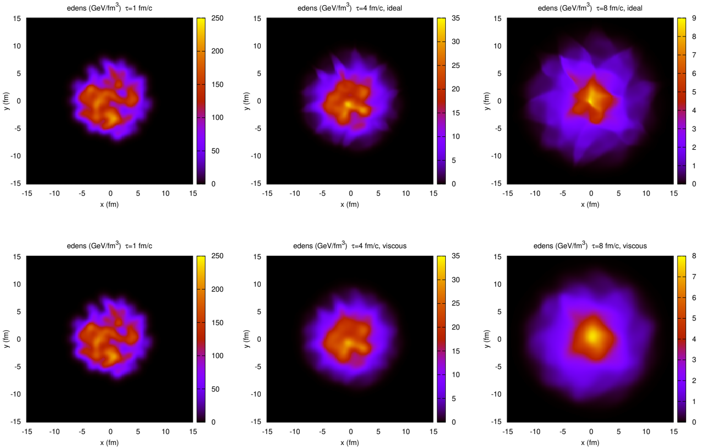
$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2\sum_n v_n \cos[n(\phi - \psi_n)] + \dots\right)$$

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



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

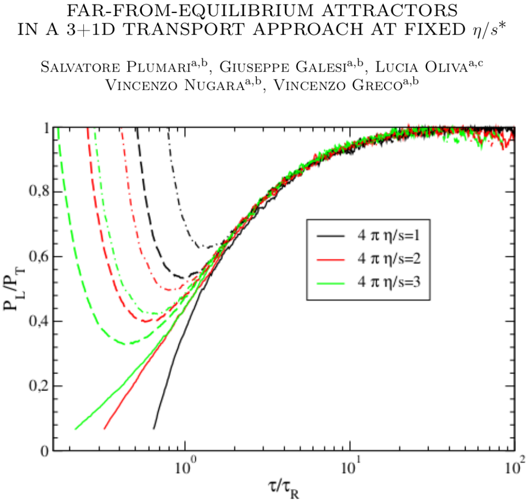
$$\pi^{\mu\nu} = 2\eta\,\nabla^{<\mu}u^{\nu>}$$

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

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

Viscosity damps short-wavelength modes!

Why does hydrodynamics work so well?



FAR-FROM-EQUILIBRIUM ATTRACTORS
IN A 3+1D TRANSPORT APPROACH AT FIXED η/s^*

Salvatore Plumari[a,b], Giuseppe Galesi[a,b], Lucia Oliva[a,c]
Vincenzo Nugara[a,b], Vincenzo Greco[a,b]

Evaluating longitudinal and transverse pressure from the moments of the single-particle distribution arising from the Boltzmann Equation

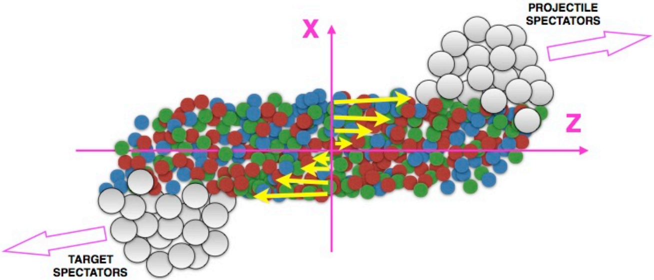
$$p^\mu \partial_\mu f(x, \vec{p}) = C[f]$$

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

Vorticity and polarization



- In non-central HIC's huge amount of orbital angular momentum ($|J_y| \sim 10^3 - 10^4 \hbar$) deposited in the interaction region;

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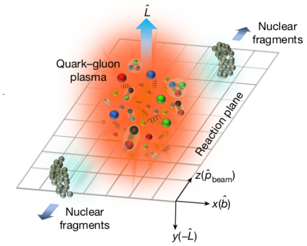

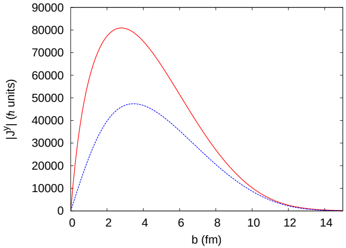

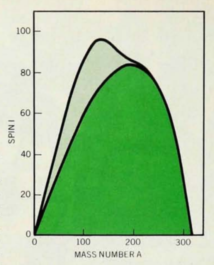

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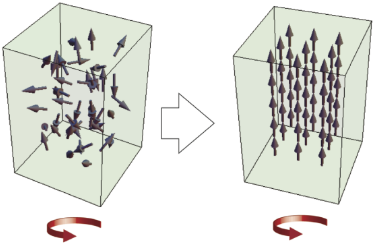

- In non-central HIC's huge amount of orbital angular momentum ($|J_y| \sim 10^3 - 10^4 \hbar$) deposited in the interaction region;
- Fireball acquires sizable vorticity (most vortical fluid in Nature) $\vec{\omega} \equiv \frac{1}{2}(\vec{\nabla} \times \vec{v}) \sim 10^{22}\mathrm{s}^{-1}$, partially transferred to polarization of produced particles assuming thermalization of spin degrees of freedom (analogous of Barnett effect in condensed matter)

$$\widehat{\rho} \equiv \frac{1}{Z} \exp\left[-(\widehat{H} - \boldsymbol{\omega} \cdot \widehat{\boldsymbol{J}} - \mu_Q \widehat{Q})/T\right] \quad \longrightarrow \quad \langle \boldsymbol{S} \rangle \approx \frac{S(S+1)}{3} \frac{\boldsymbol{\omega}}{T}$$

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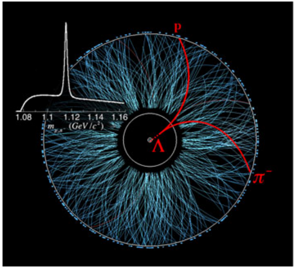

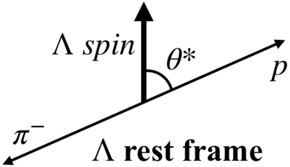

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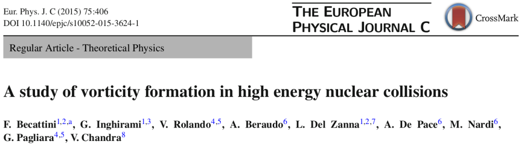

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DOI 10.1140/epjc/s10052-015-3624-1

THE EUROPEAN PHYSICAL JOURNAL C

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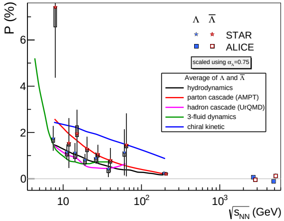
Regular Article - Theoretical Physics

A study of vorticity formation in high energy nuclear collisions

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



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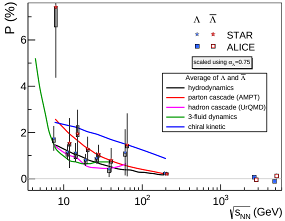
- Above formulas generalized to relativistic systems (Becattini et al.)

Vorticity and polarization

Annual Review of Nuclear and Particle Science

Polarization and Vorticity in the Quark–Gluon Plasma

Francesco Becattini[1] and Michael A. Lisa[2]



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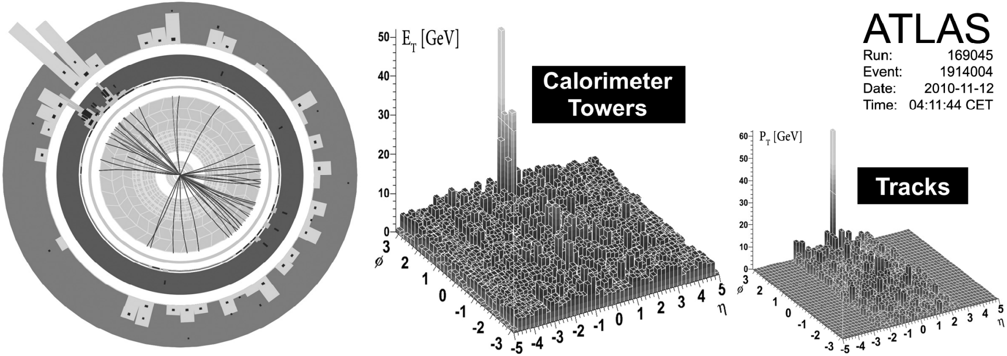
A medium inducing energy-loss of colored probes



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

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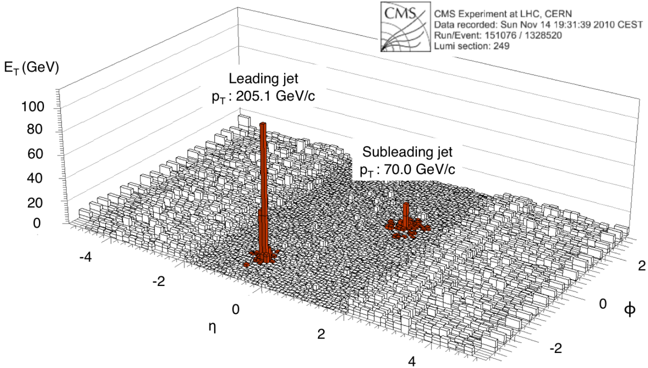

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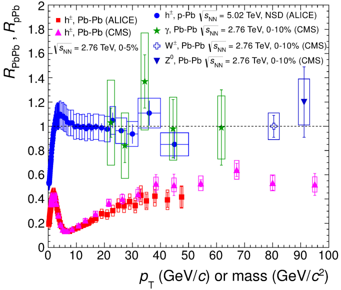
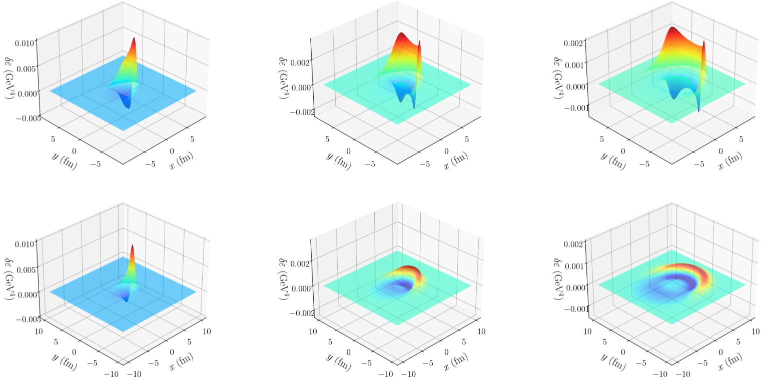


Suppression of high-momentum hadrons and jets quantified through the *nuclear modification factor*

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

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

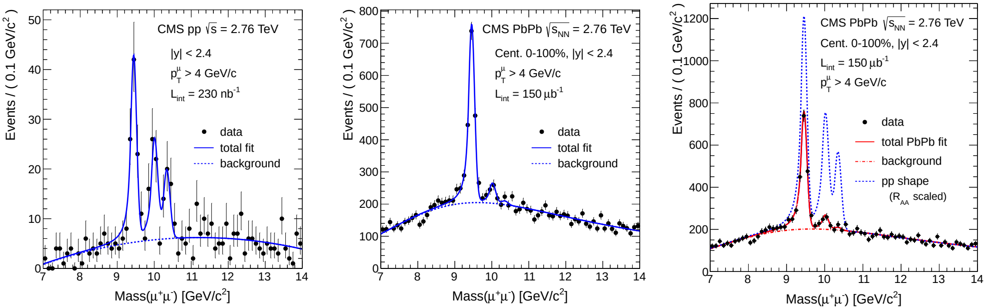
How the medium responds to jets



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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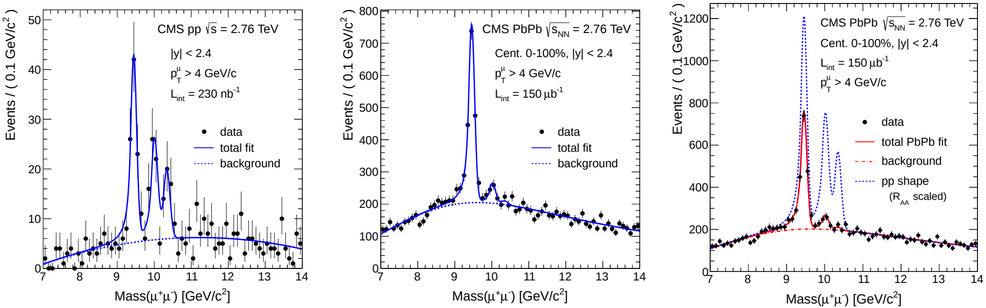

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In first approximation, Debye screening of the $Q\overline{Q}$ interaction(T. Matsui and H. Satz, PLB 178 (1986) 416-422)

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

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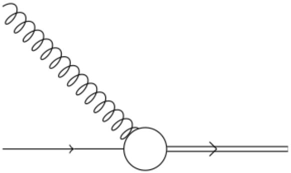
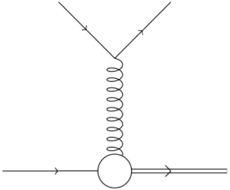
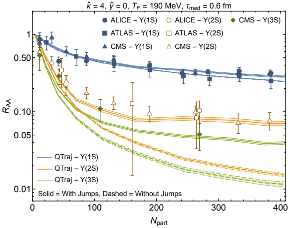


Gluo-dissociation



Inelastic scattering



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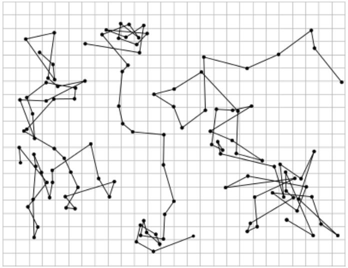
However, treating quarkonium as an Open Quantum System allows a richer description of its interaction and evolution in the medium (see J.M. Martinez Vera's talk)

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



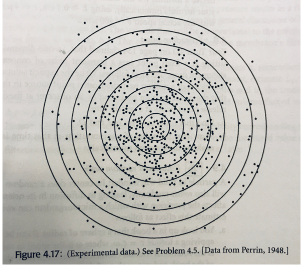


Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

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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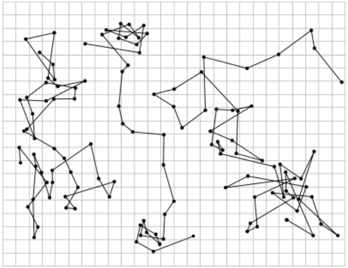

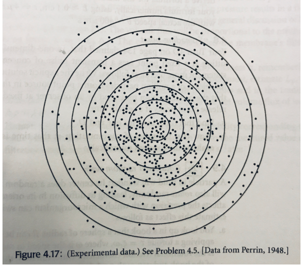

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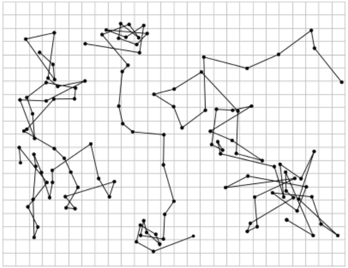
and from Einstein formula one estimates the Avogadro number:

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

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

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



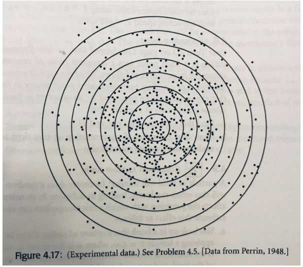


Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

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

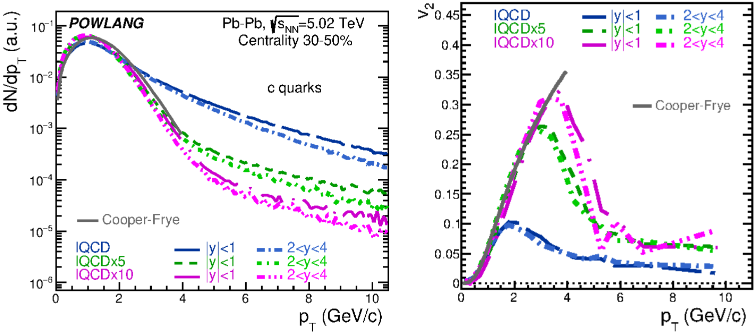
$$\langle x^2 \rangle \underset{t\to\infty}{\sim} 2D_s t$$

and from Einstein formula one estimates the Avogadro number:

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

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

We do not have a microscope!

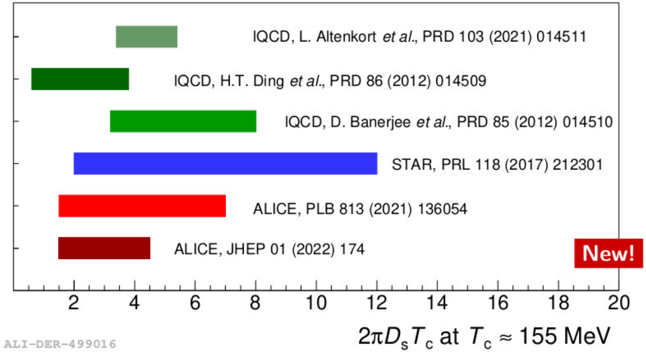


Transport coefficients can be accessed indirectly, comparing transport predictions with different values of momentum broadenig

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

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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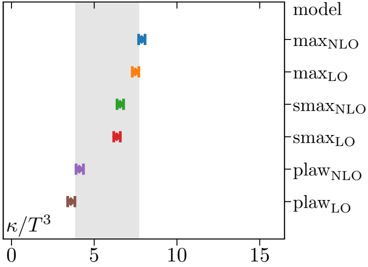

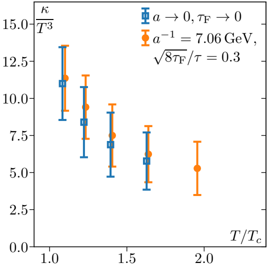

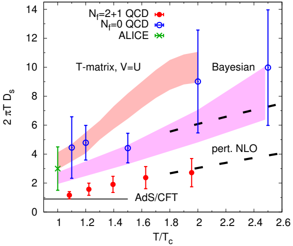

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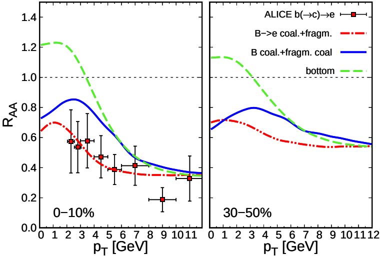

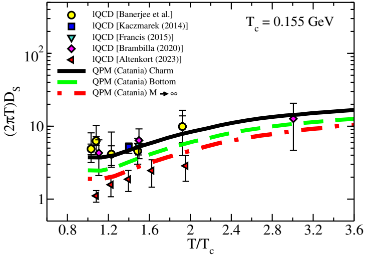

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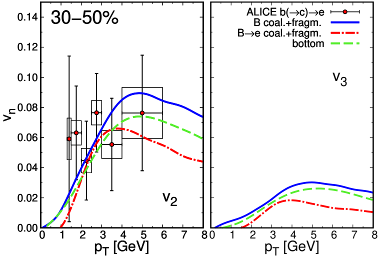

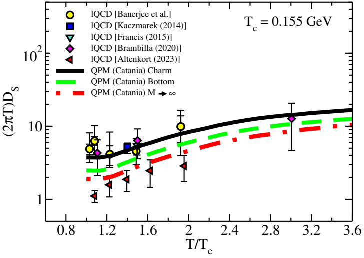

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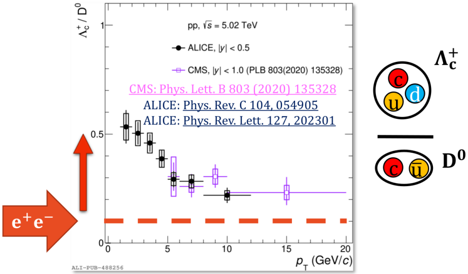
A small QGP droplet also in pp collisions?



CMS: Phys. Lett. B 803 (2020) 135328
ALICE: Phys. Rev. C 104, 054905
ALICE: Phys. Rev. Lett. 127, 202301

- 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

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

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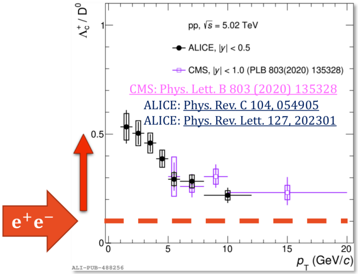

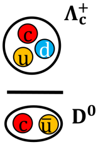

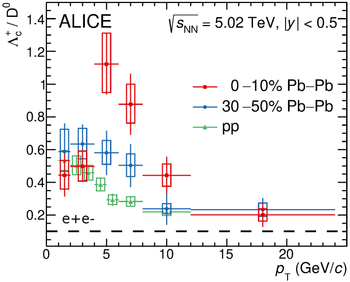

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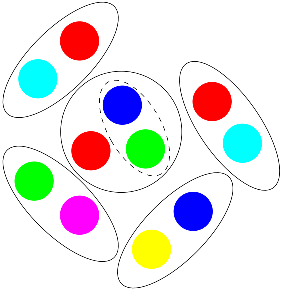

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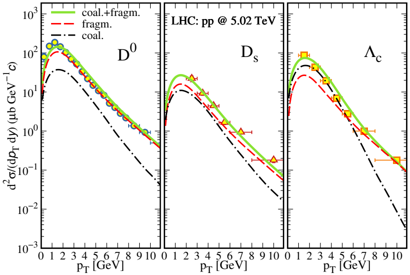

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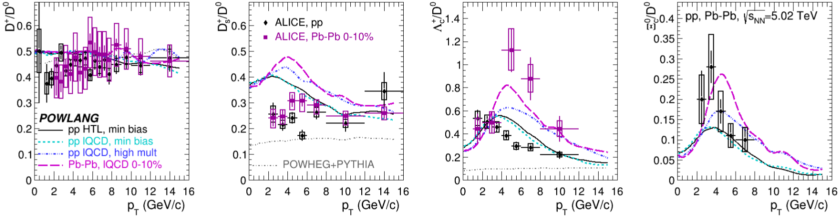

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Further projects not covered in this talk...

- Evaluation of transport coefficients from Gauge-Gravity duality (Florence);
- More advanced issued on spin-polarization in dissipative relativistic fluids (Florence);
- Quantum corrections to cosmological EoS (Florence);
- Delevoment of viscous resistive RMHD code (Torino+Florence);
- Role on dimension-2 condensates on dynamical gluon mass (Catania);
- Initial stages of the collision (LNS and Catania)
- Multi-charm production in HIC's (LNS)