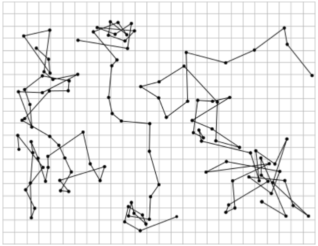
Heavy quarks as probes of QGP transport properties and hadronization dynamics

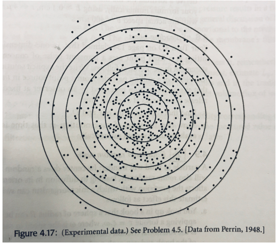
Andrea Beraudo

INFN - Sezione di Torino

SIM e PRIN meeting, Catania, 10-11 settembre 2024

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

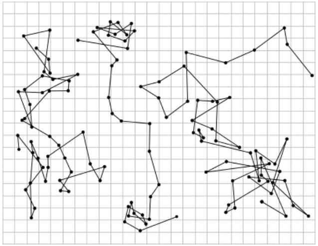




Einstein (1905) and Perrin (1909) study of Brownian motion: from the random walk of small grains ($a \sim 0.5\mu$m) in water one extracts the diffusion coefficient

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

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



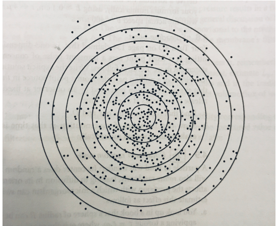


Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

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

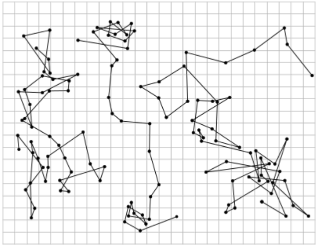
$$\langle x^2 \rangle \underset{t\to\infty}{\sim} 2D_s t$$

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

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



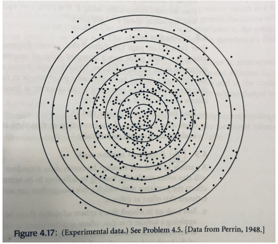


Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

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

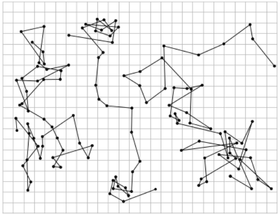
$$\langle x^2 \rangle \underset{t\to\infty}{\sim} 2D_s t$$

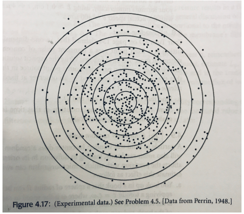
and estimates the Avogadro number (proof of the *granular structure of matter*):

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

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

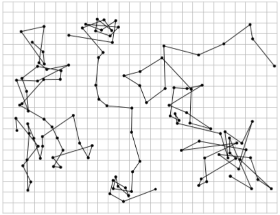
HF in HIC's: what do we want to learn? A bit of history...





- "Brownian motion cannot be stopped suppressing convection currents, which are easy to recognize" (Perrin 1909): it is a random motion superimposed to the collective flow of the fluid. Do HQ's in HIC's have enough time to become part of the fluid?

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



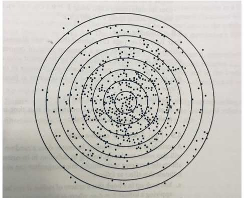
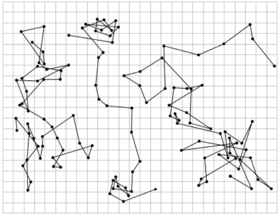


Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

- "Brownian motion cannot be stopped suppressing convection currents, which are easy to recognize" (Perrin 1909): it is a random motion superimposed to the collective flow of the fluid. Do HQ's in HIC's have enough time to become part of the fluid?
- Experiments took time: several months to go from 1 kg of gumgutta to 10^{-4} kg of grains of the same size;

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



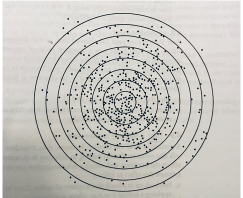
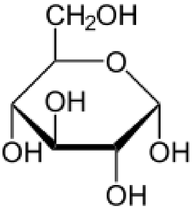


Figure 4.17: (Experimental data.) See Problem 4.5. [Data from Perrin, 1948.]

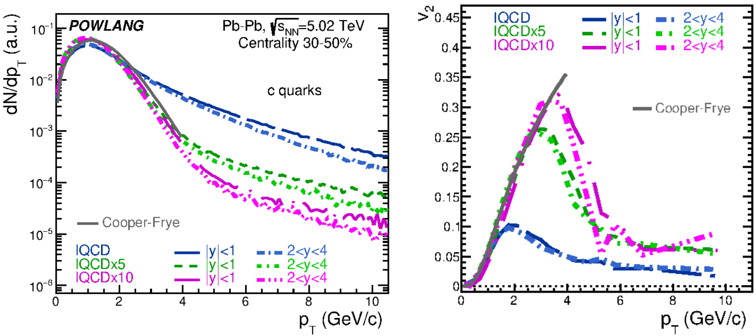


- "Brownian motion cannot be stopped suppressing convection currents, which are easy to recognize" (Perrin 1909): it is a random motion superimposed to the collective flow of the fluid. Do HQ's in HIC's have enough time to become part of the fluid?
- Experiments took time: several months to go from 1 kg of gumgutta to 10^{-4} kg of grains of the same size;
- Equations for Brownian motion work also at the molecular level, describing diffusion of sugar ($C_6H_{12}O_6$) in water (H_2O)

$$\mathcal{N}_A = 6.5 \cdot 10^{23}$$

Notice that $M_{\rm sugar} \approx 10 M_{\rm water}$, as HQ to light-quasiparticle mass ratio

We do not have a microscope!

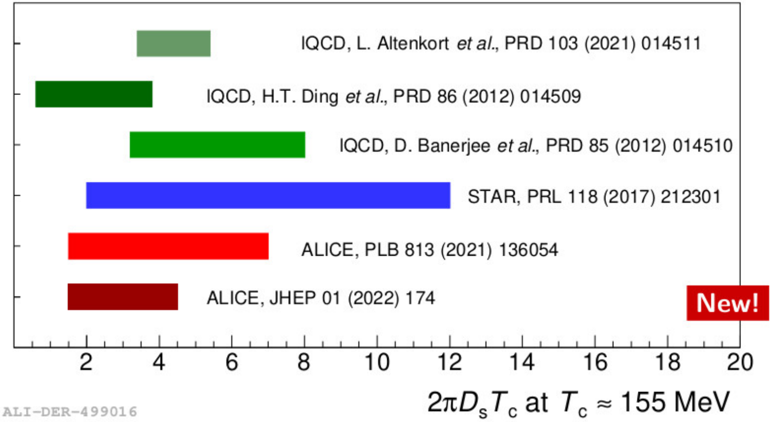


Transport coefficients can be accessed indirectly, comparing transport predictions with different values of momentum broadenig

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

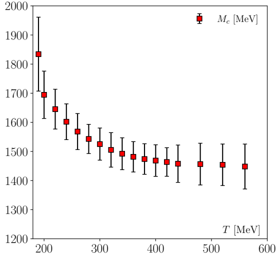
with experimental results for momentum (left) and angular (right) HF particle distributions (figure from A.B. *et al.*, JHEP 05 (2021) 279)

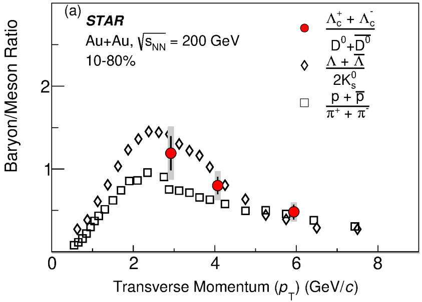
Where do we stand?



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

A crucial difference

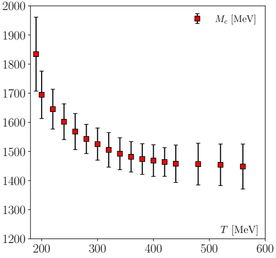


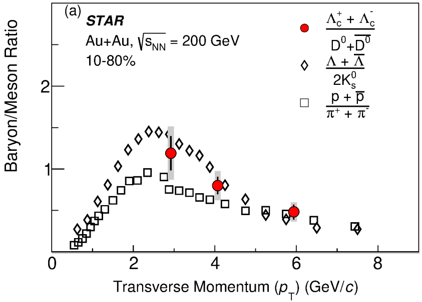


In HF studies in nuclear collisions the nature of the Brownian particle changes during its propagation through the medium

- possible thermal mass-shift, see 2311.01525 [hep-lat] (here neglected)
- hadronization (impossible to neglect)

A crucial difference

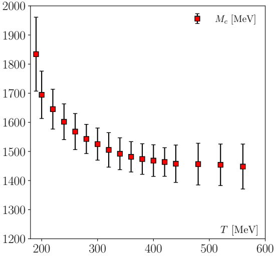


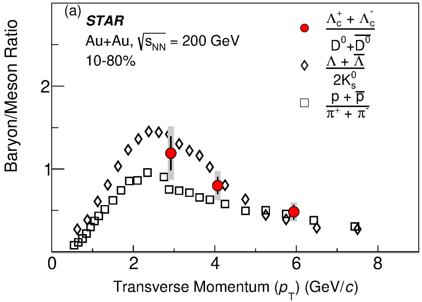


In HF studies in nuclear collisions the nature of the Brownian particle changes during its propagation through the medium

- possible thermal mass-shift, see 2311.01525 [hep-lat] (here neglected)
- hadronization (impossible to neglect)
  - source of systematic uncertainty in extracting transport coefficients;

A crucial difference

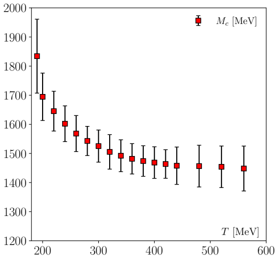


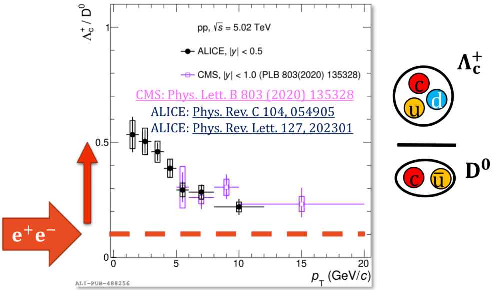


In HF studies in nuclear collisions the nature of the Brownian particle changes during its propagation through the medium

- possible thermal mass-shift, see 2311.01525 [hep-lat] (here neglected)
- hadronization (impossible to neglect)
  - source of systematic uncertainty in extracting transport coefficients;
  - an issue of interest in itself: how quark → hadron transition changes in the presence of a medium (one of the topics of this talk).

A crucial difference





In HF studies in nuclear collisions the nature of the Brownian particle changes during its propagation through the medium

- possible thermal mass-shift, see 2311.01525 [hep-lat] (here neglected)
- hadronization (impossible to neglect)
  - source of systematic uncertainty in extracting transport coefficients;
  - an issue of interest in itself: how quark → hadron transition changes in the presence of a medium (one of the topics of this talk). How big should the medium be?

HQ dynamics in the fireball

To model the HQ propagation in an expanding fireball one developes 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

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

HQ dynamics in the fireball

To model the HQ propagation in an expanding fireball one developes 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

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

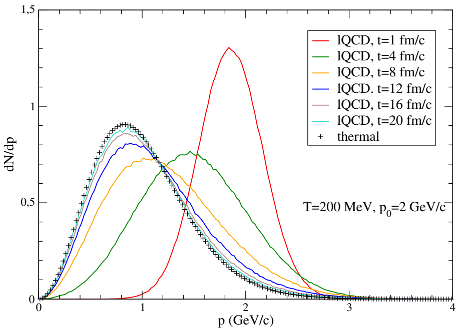
Transport coefficients describe the HQ-medium coupling

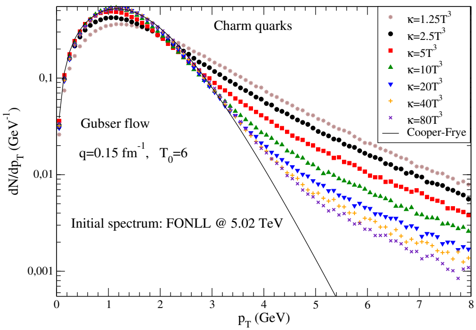
- *Momentum diffusion* $\kappa_\perp \equiv \frac{1}{2}\frac{\langle \Delta p_\perp^2 \rangle}{\Delta t}$ and $\kappa_\parallel \equiv \frac{\langle \Delta p_\parallel^2 \rangle}{\Delta t}$;
- *Friction* term (dependent on the discretization scheme!)

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

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

Asymptotic approach to thermalization



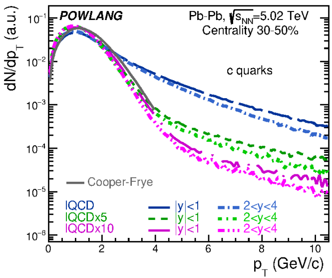


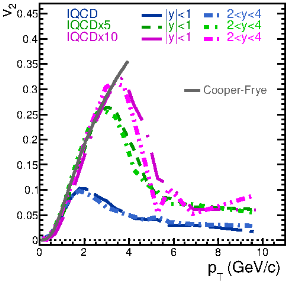
Validation of the model (figures adapted from Federica Capellino master thesis):

- Left panel: evolution in a static medium
- Right panel: decoupling from 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.

Which information can one extract from the data?





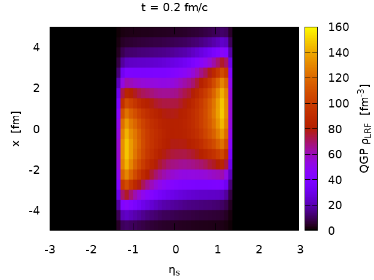
$$D_s \sim \kappa^{-1} \sim \tau_R^{\rm kin}$$

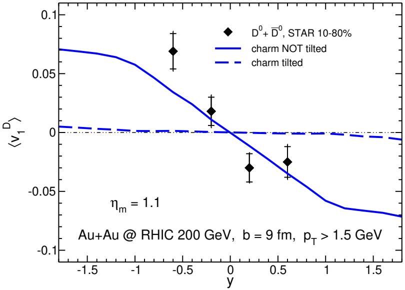
HQ evolve maximizing the entropy:

- Momentum distribution approches local kinetic equilibrium $e^{-p\cdot u/T} = e^{-E_p^*/T}$
- Spatial diffusion cancels any local quark-number excess

However, very efficient kinetic equilibration entails very inefficient spatial equilibration and viceversa. Can one exploit this to extract a richer information on transport coefficients from properly chosen observables?

Which information can one extract from the data?



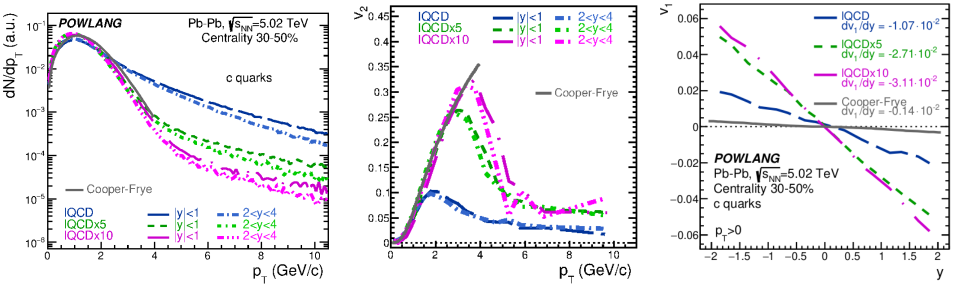


Initial off-equilibrium HQ distribution

- in momentum space: $d\sigma/d\vec{p}_T dy \neq e^{-p\cdot u/T}$
- in coordinate space: $n_{\rm coll}(\vec{x}_\perp) \neq s_0(\vec{x}_\perp, \eta_s)$

Most studies focused only on approach to *kinetic* equilibrium. However, observables sensitive to spatial inhomogeneity of HQ distribution, like the directed flow v_1, can provide a richer information on HF transport coefficients (S. Chatterjee and P. Bozez, PRL 120 (2018) 19, 192301, A.B. et al., JHEP 05 (2021) 279, L. Oliva et al., JHEP 05 (2021) 034)

Which information can one extract from the data?

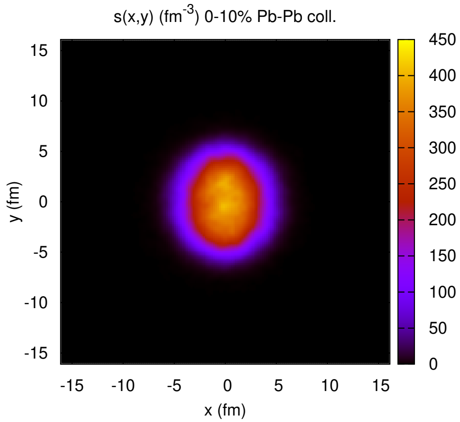


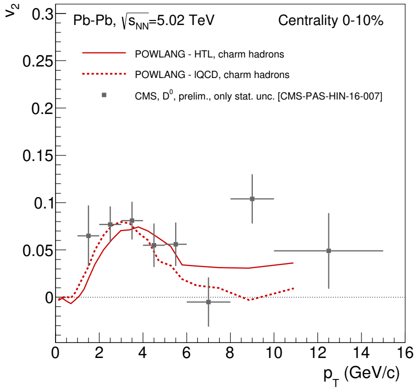
Initial off-equilibrium HQ distribution

- in momentum space: $d\sigma/d\vec{p}_T dy \neq e^{-p\cdot u/T}$
- in coordinate space: $n_{\rm coll}(\vec{x}_\perp) \neq s_0(\vec{x}_\perp, \eta_s)$

Most studies focused only on approach to *kinetic* equilibrium. However, observables sensitive to spatial inhomogeneity of HQ distribution, like the directed flow v_1, can provide a richer information on HF transport coefficients (S. Chatterjee and P. Bozez, PRL 120 (2018) 19, 192301, A.B. et al., JHEP 05 (2021) 279, L. Oliva et al., JHEP 05 (2021) 034)

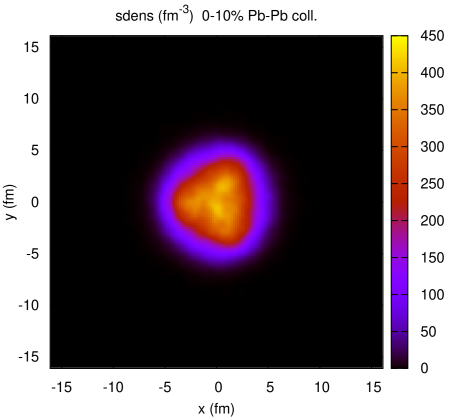
Some results: D-meson v_2 and v_3 in Pb-Pb

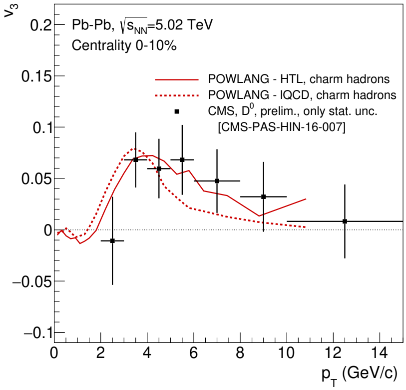




Transport calculations carried out in JHEP 1802 (2018) 043, with hydrodynamic background calculated via the ECHO-QGP code (EPJC 73 (2013) 2524) starting from EBE Glauber Monte-Carlo initial conditions: $v_2 \neq 0$ in central collisions, $v_3 \neq 0$

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, $v_3 \neq 0$

HQ momentum diffusion: lattice-QCD

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

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

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

HQ momentum diffusion: lattice-QCD

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

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

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

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

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

How to proceed?

HQ momentum diffusion: lattice-QCD

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

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

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

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

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

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: lattice-QCD

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

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

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

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

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

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

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

From $D_E(\tau)$ one extracts the spectral density according to

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

HQ momentum diffusion: lattice-QCD

The direct extraction of the spectral density from the euclidean correlator

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

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

HQ momentum diffusion: lattice-QCD

The direct extraction of the spectral density from the euclidean correlator

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

is a ill-posed problem, since the latter is known for a limited set (~ 20) of points $D_E(\tau_i)$, and one wishes to obtain a fine scan of the the spectral function $\sigma(\omega_j)$. A direct χ^2-fit is not applicable. Possible strategies:

- Bayesian techniques (Maximum Entropy Method)

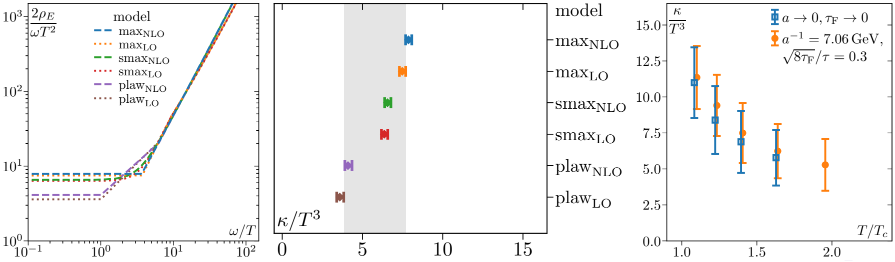
HQ momentum diffusion: lattice-QCD

The direct extraction of the spectral density from the euclidean correlator

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

is a ill-posed problem, since the latter is known for a limited set (~ 20) of points $D_E(\tau_i)$, and one wishes to obtain a fine scan of the the spectral function $\sigma(\omega_j)$. A direct χ^2-fit is not applicable. Possible strategies:

- Bayesian techniques (Maximum Entropy Method)
- Theory-guided ansatz for the behaviour of $\sigma(\omega)$ to constrain its functional form (new results for $N_f = 2+1$ O. Kaczmarek *et al.*, 2302.08501 [hep-lat])



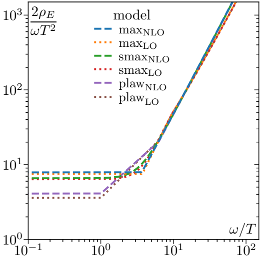
HQ momentum diffusion: lattice-QCD

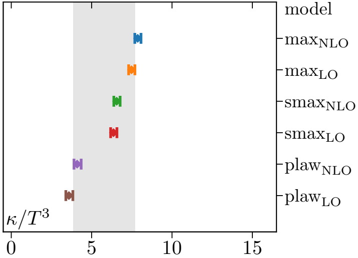
The direct extraction of the spectral density from the euclidean correlator

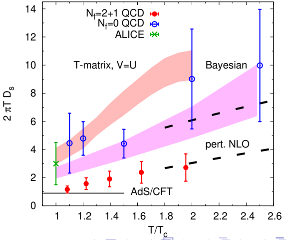
$$D_E(\tau) = \int_0^{+\infty} \frac{d\omega}{2\pi} \frac{\cosh(\tau - \beta/2)}{\sinh(\beta\omega/2)} \sigma(\omega)$$

is a ill-posed problem, since the latter is known for a limited set (~ 20) of points $D_E(\tau_i)$, and one wishes to obtain a fine scan of the the spectral function $\sigma(\omega_j)$. A direct χ^2-fit is not applicable. Possible strategies:

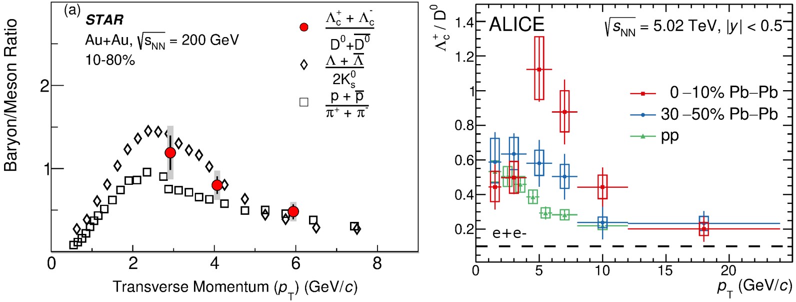
- Bayesian techniques (Maximum Entropy Method)
- Theory-guided ansatz for the behaviour of $\sigma(\omega)$ to constrain its functional form (new results for $N_f = 2+1$ O. Kaczmarek *et al.*, 2302.08501 [hep-lat])





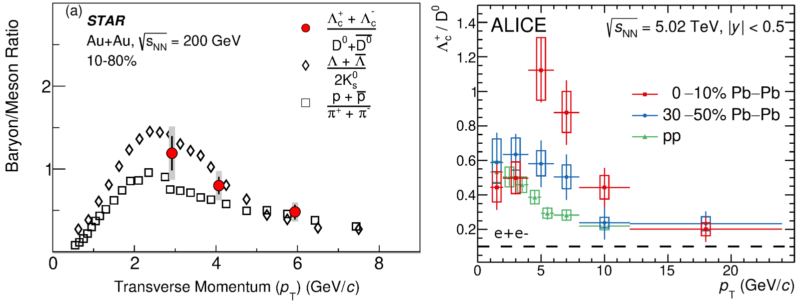


HF hadronization: experimental findings



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

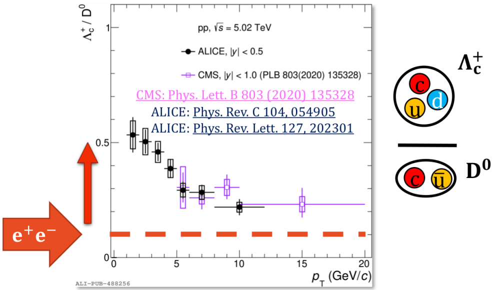
HF hadronization: experimental findings



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

- pattern similar to light hadrons

HF hadronization: experimental findings

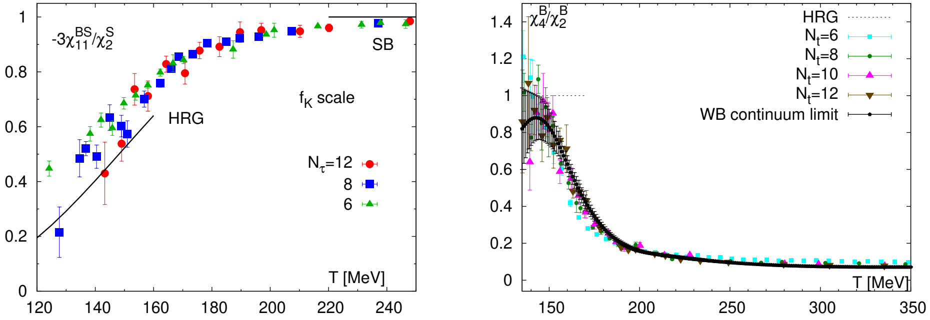


Strong enhancement of charmed baryon/meson ratio, incompatible with hadronization models tuned to reproduce e^+e^- data

- 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

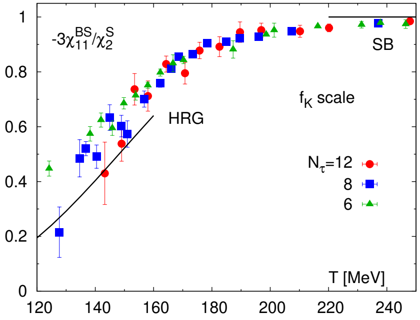
$$d\sigma_h \neq \sum_{a,b,X} f_a(x_1)\, f_b(x_2) \otimes d\hat{\sigma}_{ab\to c\bar{c}X} \otimes D_{c\to h_c}(z)$$

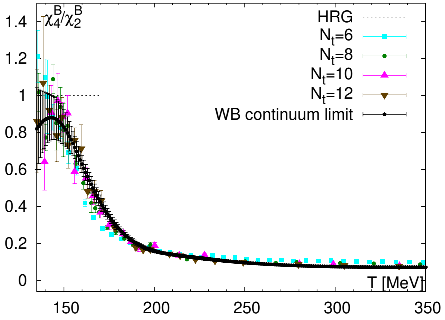
Premise: which are the carriers of conserved charges?



- In the QGP strangeness carried by quarks with $|B|=1/3$, PRD 86, 034509 (2012)
- $\chi_4^B/\chi_2^B = B^2$, with $|B|=1$ (HG) or $|B|=1/3$ (QGP), PRL 111, 062005 (2013)

Premise: which are the carriers of conserved charges?

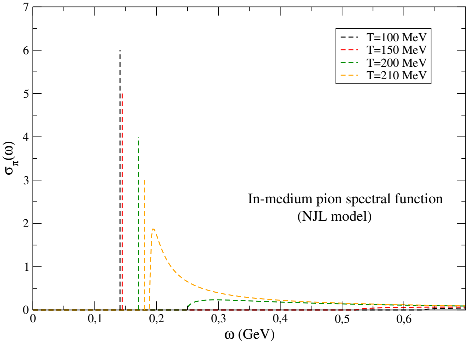


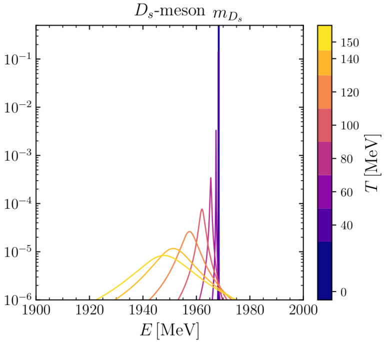


- In the QGP strangeness carried by quarks with $|B|=1/3$, PRD 86, 034509 (2012)
- $\chi^B_4/\chi^B_2 = B^2$, with $|B|=1$ (HG) or $|B|=1/3$ (QGP), PRL 111, 062005 (2013)

One would expect a sharp change in the nature of these carriers...
However, lQCD data show that also this change is very smooth!

What is a hadron around the QCD crossover?

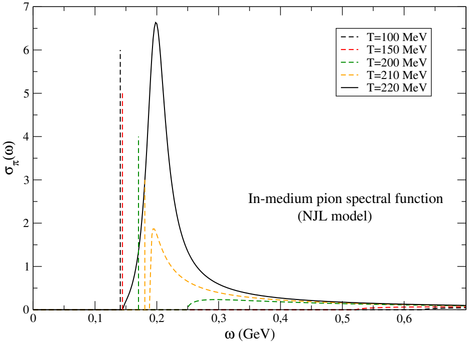


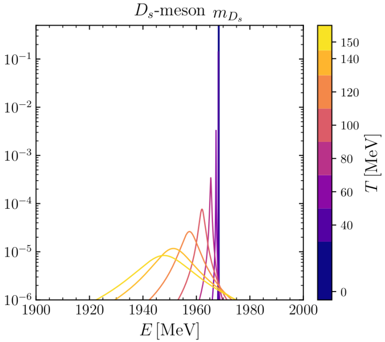


- At $T = 0$ hadrons are stable eigenstates of H_{QCD}
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

[1] G. Montana et al., PLB 806 (2020)

What is a hadron around the QCD crossover?

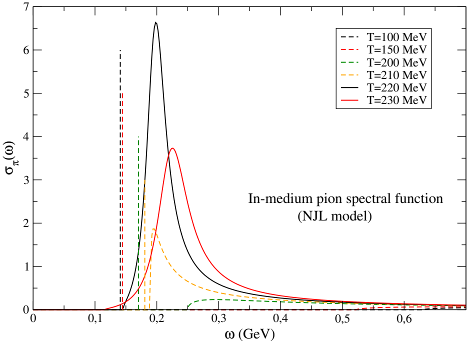


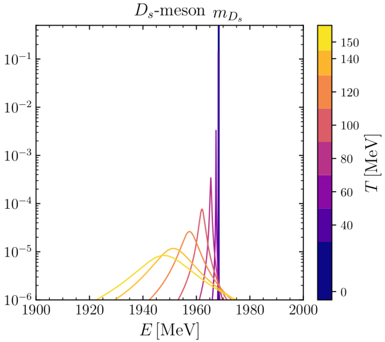


- At $T = 0$ hadrons are stable eigenstates of $H_{\rm QCD}$
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

[1] G. Montana et al., PLB 806 (2020)

What is a hadron around the QCD crossover?

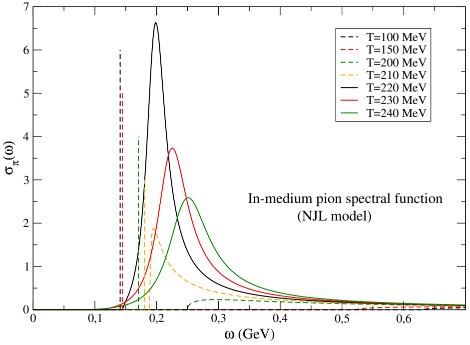


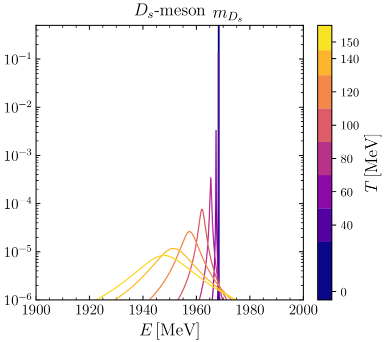


- At $T = 0$ hadrons are stable eigenstates of H_{QCD}
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

[1] G. Montana et al., PLB 806 (2020)

What is a hadron around the QCD crossover?

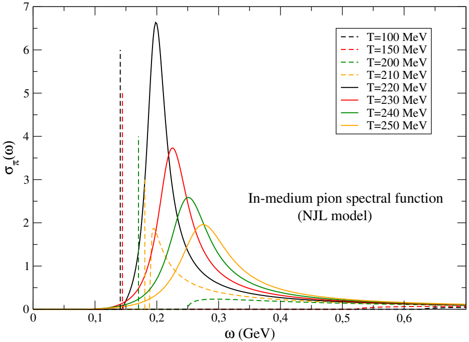


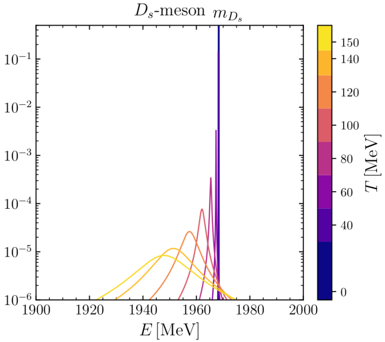


- At $T = 0$ hadrons are stable eigenstates of $H_{\rm QCD}$
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

[1] G. Montana et al., PLB 806 (2020)

What is a hadron around the QCD crossover?





- At $T = 0$ hadrons are stable eigenstates of H_{QCD}
- At $T \neq 0$ effective Lagrangians predict much richer structure of hadronic spectral functions (broadening, mass shift), both for light (NJL model) and heavy (non-linear chiral $SU(3)$ model) hadrons[1]

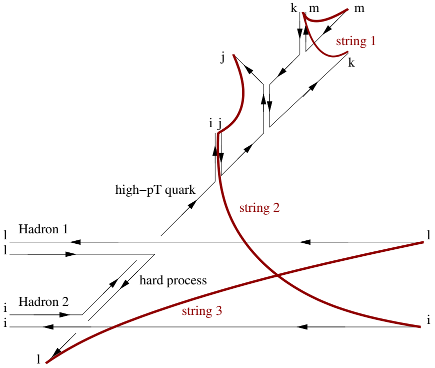
[1] G. Montana et al., PLB 806 (2020)

Hadronization models: common features

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

Hadronization models: common features

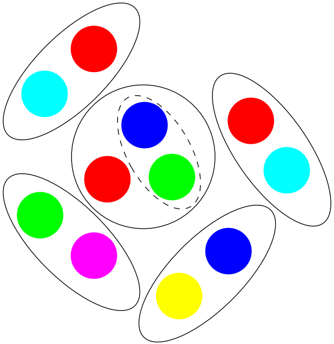
Grouping colored partons into color-singlet structures: strings (PYTHIA), clusters (HERWIG), hadrons/resonances (coalescence). Partons taken



- in "elementary collisions": from the hard process, shower stage, underlying event and beam remnants;

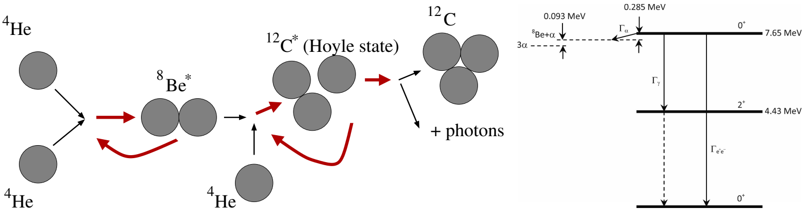
Hadronization models: common features

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



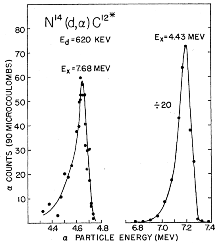
- in "elementary collisions": from the hard process, shower stage, underlying event and beam remnants;
- in heavy-ion collisions: from the hot medium produced in the collision. NB Involved partons closer in space in this case and this has deep consequence!

A warning from nucleosynthesis



- Final yields in stellar nucleosyntesis *extremely sensitive* to existence of excited states just above threshold (not a simple $N \to 1$ process);

A warning from nucleosynthesis



Selected for a Viewpoint in *Physics*
PRL **106,** 192501 (2011) PHYSICAL REVIEW LETTERS week ending 13 MAY 2011

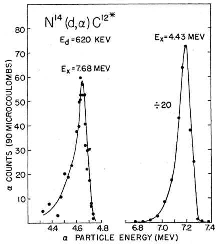
Ab Initio Calculation of the Hoyle State

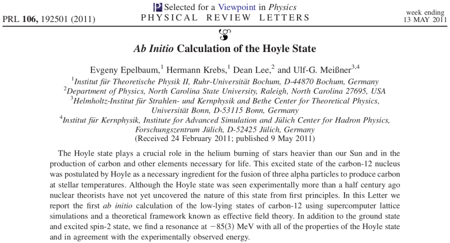
Evgeny Epelbaum,[1] Hermann Krebs,[1] Dean Lee,[2] and Ulf-G. Meißner[3,4]
[1] *Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44870 Bochum, Germany*
[2] *Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA*
[3] *Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*
[4] *Institut für Kernphysik, Institute for Advanced Simulation and Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany*
(Received 24 February 2011; published 9 May 2011)

The Hoyle state plays a crucial role in the helium burning of stars heavier than our Sun and in the production of carbon and other elements necessary for life. This excited state of the carbon-12 nucleus was postulated by Hoyle as a necessary ingredient for the fusion of three alpha particles to produce carbon at stellar temperatures. Although the Hoyle state was seen experimentally more than a half century ago nuclear theorists have not yet uncovered the nature of this state from first principles. In this Letter we report the first *ab initio* calculation of the low-lying states of carbon-12 using supercomputer lattice simulations and a theoretical framework known as effective field theory. In addition to the ground state and excited spin-2 state, we find a resonance at −85(3) MeV with all of the properties of the Hoyle state and in agreement with the experimentally observed energy.

- Final yields in stellar nucleosyntesis *extremely sensitive* to existence of excited states just above threshold (not a simple $N \to 1$ process);
- States well know experimentally and predicted by theory calculations

A warning from nucleosynthesis





Selected for a Viewpoint in *Physics*

PRL **106,** 192501 (2011) PHYSICAL REVIEW LETTERS week ending 13 MAY 2011

Ab Initio Calculation of the Hoyle State

Evgeny Epelbaum,[1] Hermann Krebs,[1] Dean Lee,[2] and Ulf-G. Meißner[3,4]

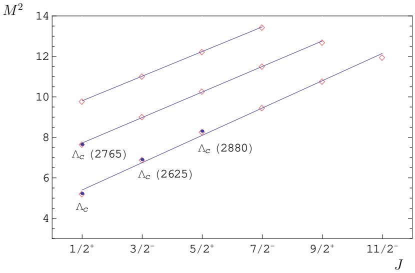
[1]*Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44870 Bochum, Germany*
[2]*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA*
[3]*Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany*
[4]*Institut für Kernphysik, Institute for Advanced Simulation and Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany*

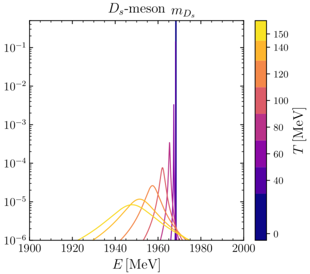
(Received 24 February 2011; published 9 May 2011)

The Hoyle state plays a crucial role in the helium burning of stars heavier than our Sun and in the production of carbon and other elements necessary for life. This excited state of the carbon-12 nucleus was postulated by Hoyle as a necessary ingredient for the fusion of three alpha particles to produce carbon at stellar temperatures. Although the Hoyle state was seen experimentally more than a half century ago nuclear theorists have not yet uncovered the nature of this state from first principles. In this Letter we report the first *ab initio* calculation of the low-lying states of carbon-12 using supercomputer lattice simulations and a theoretical framework known as effective field theory. In addition to the ground state and excited spin-2 state, we find a resonance at −85(3) MeV with all of the properties of the Hoyle state and in agreement with the experimentally observed energy.

- Final yields in stellar nucleosyntesis *extremely sensitive* to existence of excited states just above threshold (not a simple $N \to 1$ process);
- States well know experimentally and predicted by theory calculations
- Stellar temperature $\sim 10^8\,\mathrm{K} \sim$ 10 keV not enough to affect nucleon/nuclear properties (vacuum spectrum)

A warning from nucleosynthesis

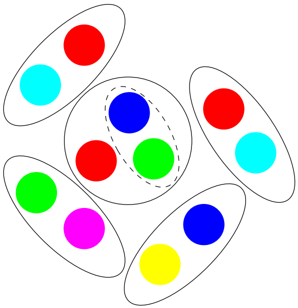




- Final yields in stellar nucleosyntesis *extremely sensitive* to existence of excited states just above threshold (not a simple $N \to 1$ process);
- States well know experimentally and predicted by theory calculations
- Stellar temperature $\sim 10^8\,\mathrm{K} \sim 10$ keV not enough to affect nucleon/nuclear properties (vacuum spectrum)

None of the above conditions is fully under control in the quark to hadron transition: PDG states < RQM states (D. Ebert *et al.*, PRD 84, 014025 (2011)), what is a hadron around T_c?

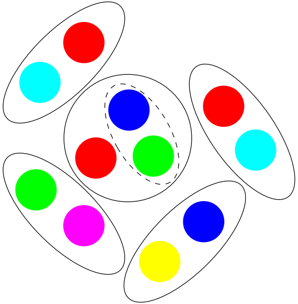
Local Color Neutralization (LCN): basic ideas



Both in AA and pp collision a big/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
- 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



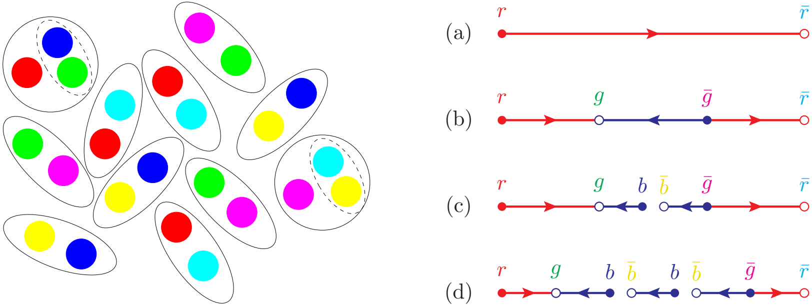
Both in AA and pp collision a big/small deconfined fireball is formed. Around the QCD crossover temperature quarks undergoes recombination with the *closest* opposite color-charge (antiquark or diquark).

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

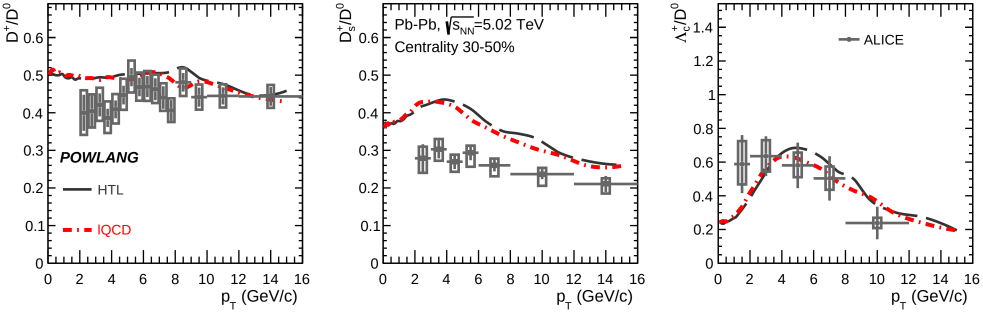
Implementation of global conservation laws



- In LCN and similar *recombination approaches* baryon number (and other charges as well) can be conserved over a very large volume;
- On the other hand in PYTHIA string-breaking (and possibly pop-corn) mechanism charge conservation occurs *locally*[2]

[2] L. Lonnblad and H. Shah, EPJC 83 (2023) 12, 1105

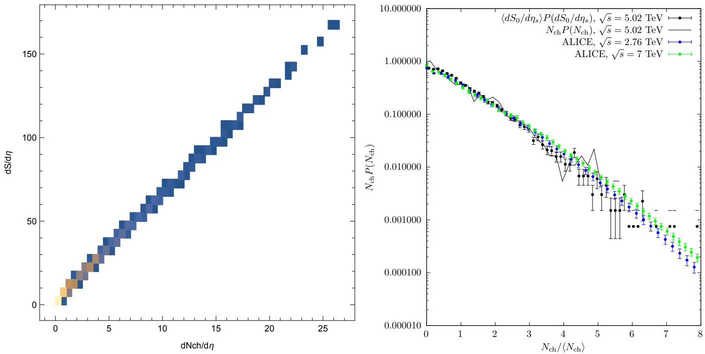
Results in AA collisions



- Enhanced HF baryon-to-meson ratios up to intermediate p_T nicely reproduced, thanks to formation of *small invariant-mass* charm+diquark clusters
- 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

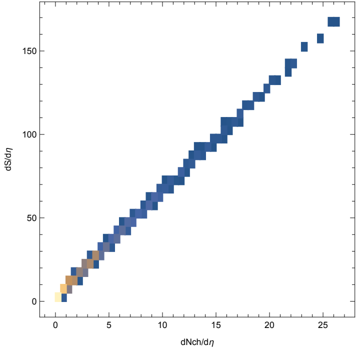
For more details see A.B. et al., EPJC 82 (2022) 7, 607.

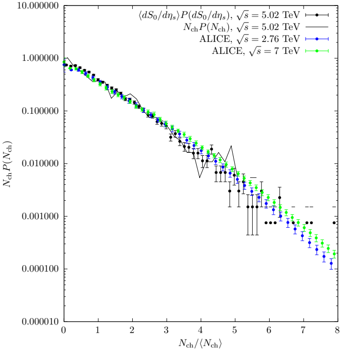
Addressing pp collisions...



- EBE pp initial conditions generated with TrENTo and evolved with hydro codes (MUSIC and ECHO-QGP);

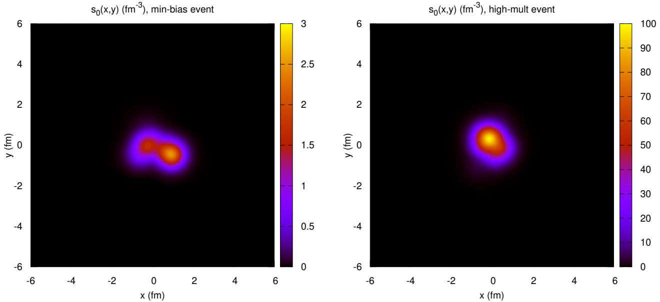
Addressing pp collisions...





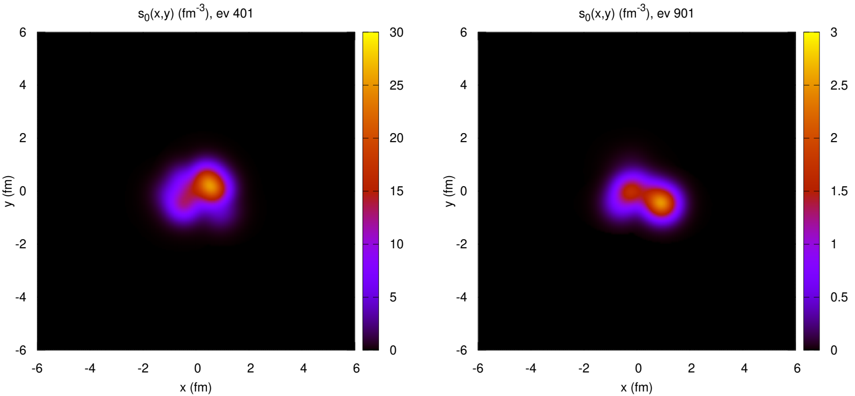
- EBE pp initial conditions generated with TrENTo and evolved with hydro codes (MUSIC and ECHO-QGP);
- Perfect correlation between initial entropy (dS/dy) and final particle multiplicity ($dN_{\rm ch}/d\eta$), $S \approx 7.2 N_{\rm ch}$. $P(N_{\rm ch})$ satisfying KNO scaling nicely reproduced;

Addressing pp collisions...



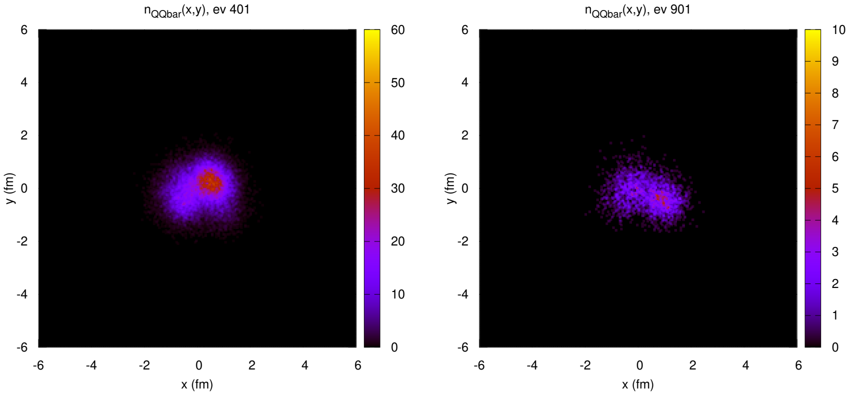
- EBE pp initial conditions generated with TrENTo and evolved with hydro codes (MUSIC and ECHO-QGP);
- Perfect correlation between initial entropy (dS/dy) and final particle multiplicity $(dN_{\rm ch}/d\eta)$, $S \approx 7.2 N_{\rm ch}$. $P(N_{\rm ch})$ satisfying KNO scaling nicely reproduced;
- Samples 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?



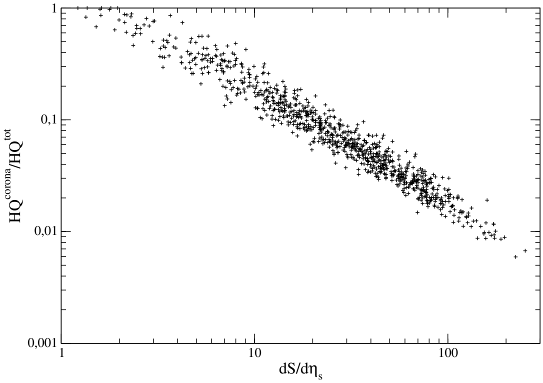
$Q\overline{Q}$ production biased towards hot spots of highest multiplicity events

Why in-medium hadronization also in pp?



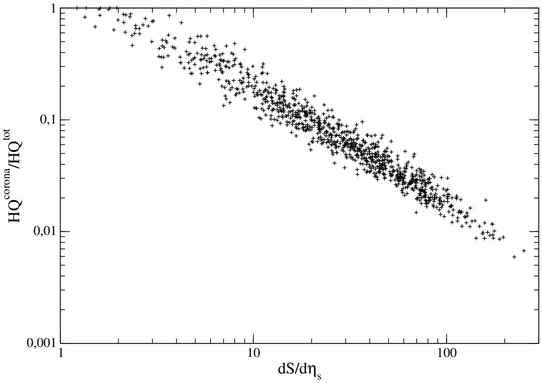
$Q\overline{Q}$ production biased towards hot spots of highest multiplicity events

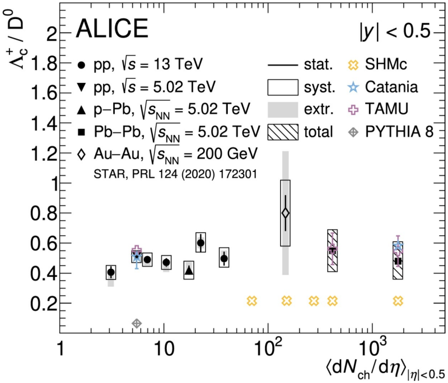
Why in-medium hadronization also in pp?



$Q\overline{Q}$ 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.

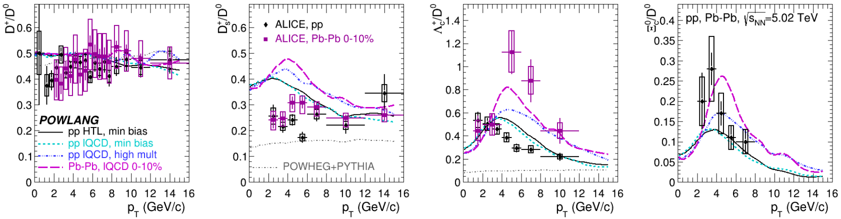
Why in-medium hadronization also in pp?





$Q\overline{Q}$ 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. Studies of charmed-hadron production in *low-multiplicity* pp events of great interest! Would one recover the e^+e^- fragmentation fractions?

Results in pp: particle ratios

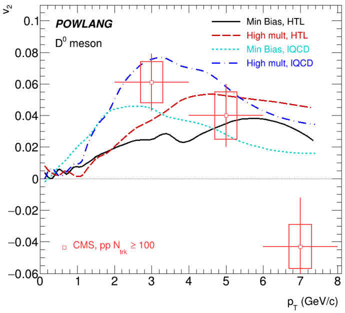


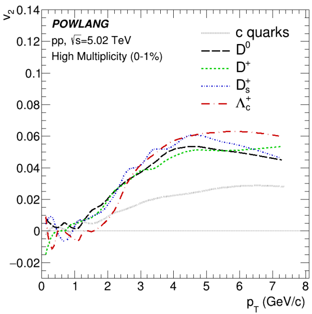
First results for particle ratios[3]:

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

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

Results in pp: elliptic flow

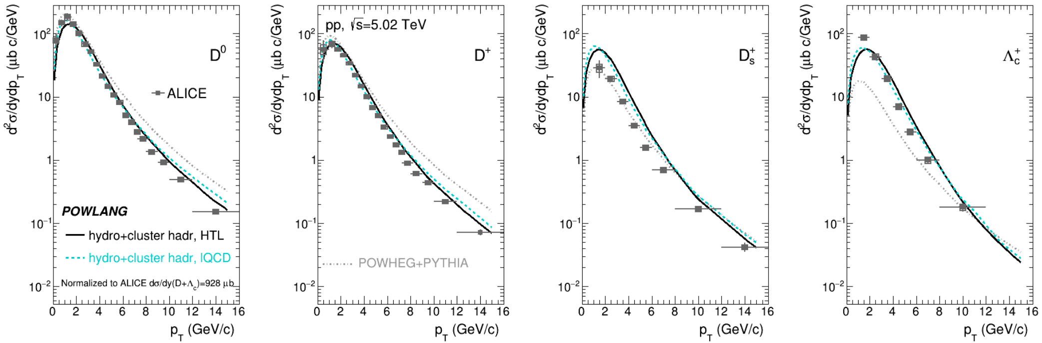




Response to initial elliptic eccentricity ($\langle\epsilon_2\rangle^{\rm mb}\approx\langle\epsilon_2\rangle^{\rm mh}\approx 0.31$) $\longrightarrow$ non-vanishing v_2 coefficient

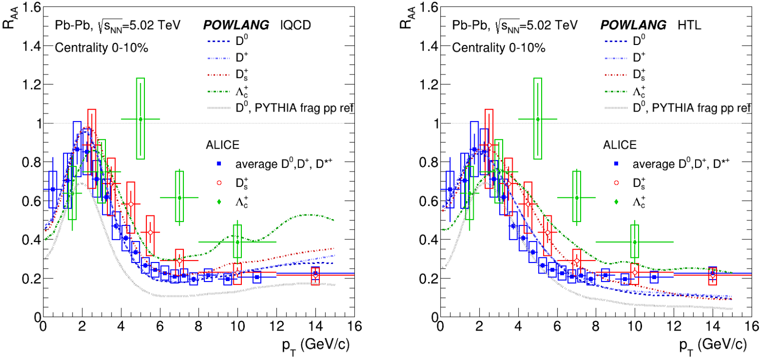
- Differences between minimum-bias and high-multiplicity results only due to longer time spent in the fireball ($\langle\tau_H\rangle^{\rm mb}\approx 1.95$ fm/c vs $\langle\tau_H\rangle^{\rm hm}\approx 2.92$ fm/c)
- Mass ordering at low p_T ($M_{qq} > M_q$)
- Sizable fraction of v_2 acquired at hadronization

Relevance to quantify nuclear effects



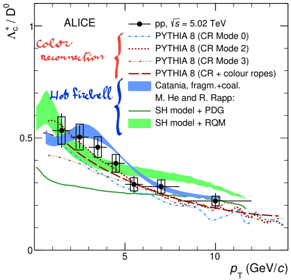
- Slope of the spectra in pp collisions better described including medium effects

Relevance to quantify nuclear effects



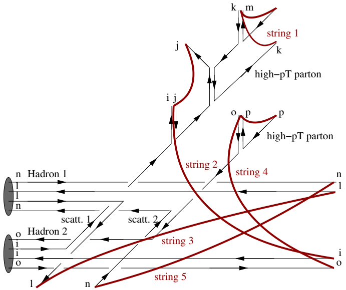
- Slope of the spectra in pp collisions better described including medium effects
- Inclusion of medium effects in minimum-bias pp benchmark fundamental to better describe charmed hadron R_{AA}, both the radial-flow peak and the species dependence

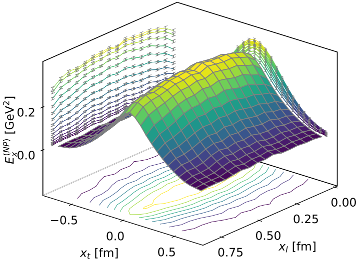
Looking for alternative (?) explanations: Color Reconnection (CR)



Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR).

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

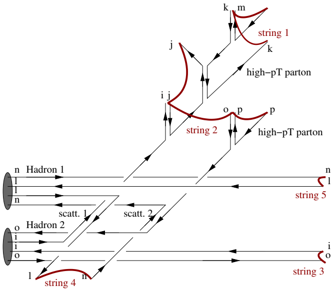


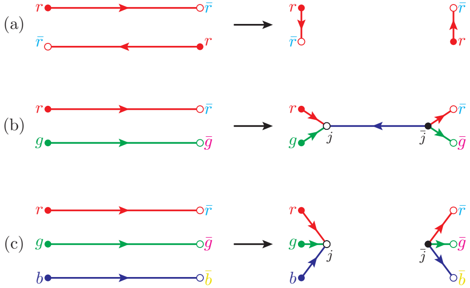


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap[4]

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

Looking for alternative (?) explanations: Color Reconnection (CR)

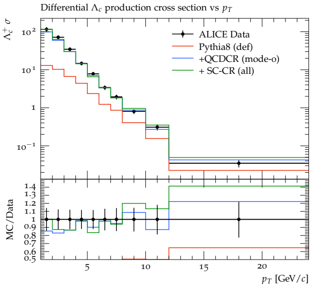


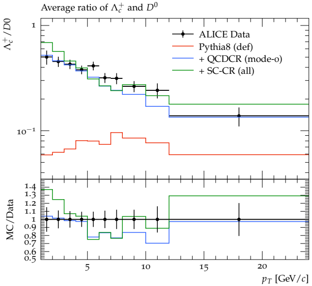


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap[4] and give rise to a rearrangement of color connections to minimize their length (i.e. their invariant mass).

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

Looking for alternative (?) explanations: Color Reconnection (CR)

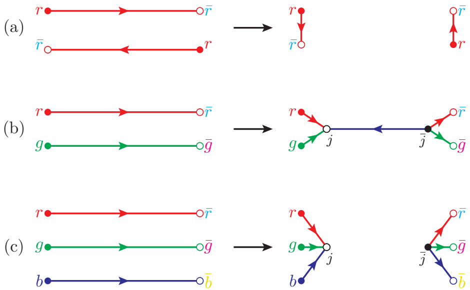


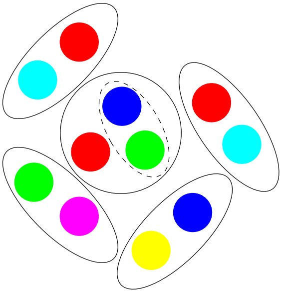


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap[4] and give rise to a rearrangement of color connections to minimize their length (i.e. their invariant mass). Enhanced charmed baryon production correctly reproduced.

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

Looking for alternative (?) explanations: Color Reconnection (CR)

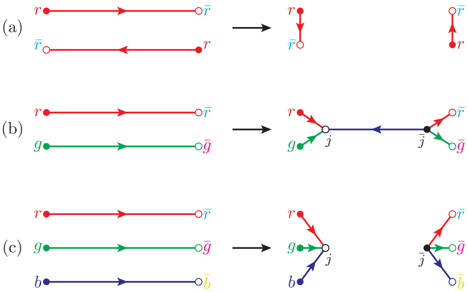


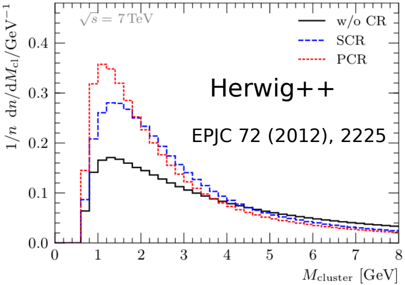


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap[4] and give rise to a rearrangement of color connections to minimize their length (i.e. their invariant mass). Enhanced charmed baryon production correctly reproduced. CR vs LCN in a small fireball: two really different pictures?

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

Looking for alternative (?) explanations: Color Reconnection (CR)

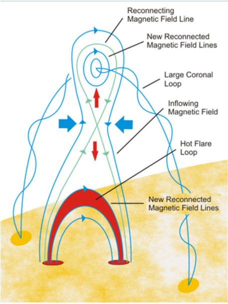


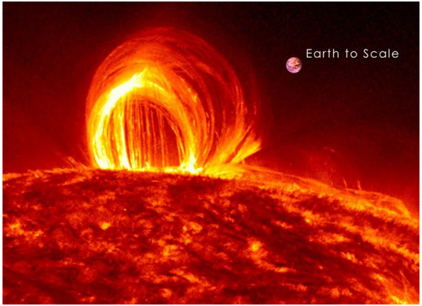


Charmed baryon enhancement in *pp* collisions can be accounted for *either* assuming the formation of a small fireball *or*, in PYTHIA, introducing the possibility of color-reconnection (CR). Strings have a finite thickness, in a dense environment they can overlap[4] and give rise to a rearrangement of color connections to minimize their length (i.e. their invariant mass). Enhanced charmed baryon production correctly reproduced. CR vs LCN in a small fireball: two really different pictures?

[4] M. Baker et al., EPJC 80 (2020) 6, 514; C. Bierlich et al., EPJC 84 (2024) 3, 231

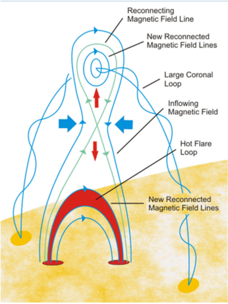
CR = no QGP formation?

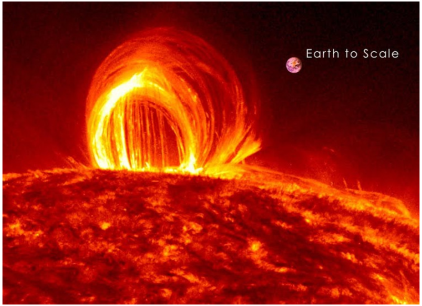




Most violent phenomena astrophysical phenomena associated to magnetic reconnections: sudden conversion of energy stored in the B-field into kinetic energy of the plasma particles

CR = no QGP formation?

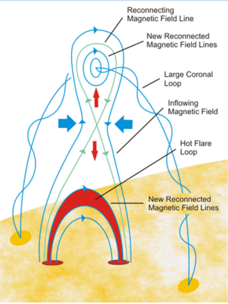


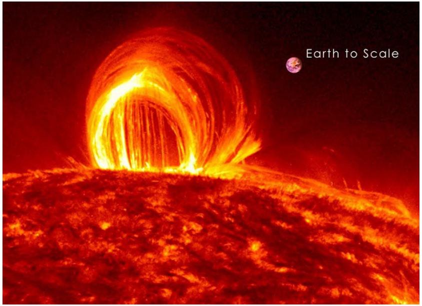


Most violent phenomena astrophysical phenomena associated to magnetic reconnections: sudden conversion of energy stored in the B-field into kinetic energy of the plasma particles

- Still not completely understood in the case of electrodynamic plasmas

CR = no QGP formation?

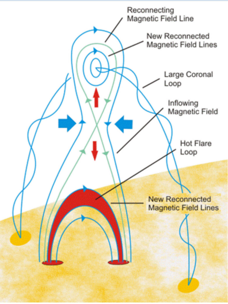


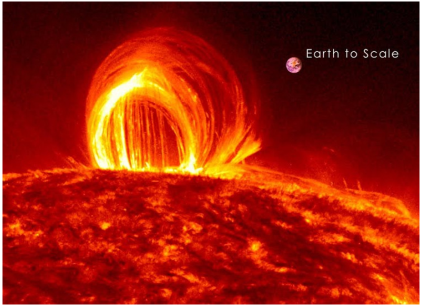


Most violent phenomena astrophysical phenomena associated to magnetic reconnections: sudden conversion of energy stored in the B-field into kinetic energy of the plasma particles

- Still not completely understood in the case of electrodynamic plasmas
- however, the existence of a plasma with *finite electric resistivity* (either from collisions of from a collective flow) looks a *necessary condition* for magnetic reconnection to occur

CR = no QGP formation?



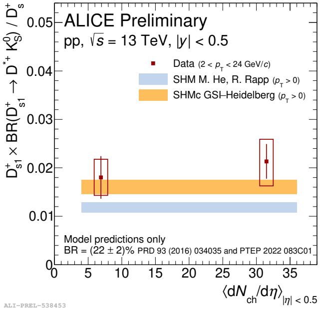


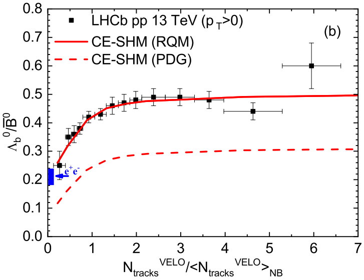
Most violent phenomena astrophysical phenomena associated to magnetic reconnections: sudden conversion of energy stored in the B-field into kinetic energy of the plasma particles

- Still not completely understood in the case of electrodynamic plasmas
- however, the existence of a plasma with *finite electric resistivity* (either from collisions of from a collective flow) looks a *necessary condition* for magnetic reconnection to occur

Is CR possible without the formation of a QGP with *finite color conductivity?*

HF statistical hadronization



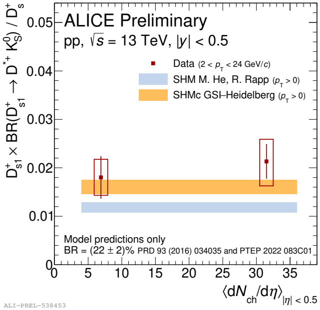


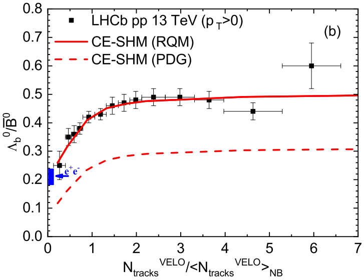
$$Z(\vec{Q}) = \int_0^{2\pi} \frac{d^5\phi}{(2\pi)^5} e^{i\vec{Q}\cdot\vec{\phi}} \exp[\sum_j \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} e^{-i\vec{q}_j\cdot\vec{\phi}} z_j] \,, \quad \text{with} \quad z_j = (2J_j+1)\frac{VT_H}{2\pi^2} m_j^2 K_2(\frac{m_j}{T_H})$$

Statistical description of HF production (Y. Dai, S. Zhao and M. He, 2402.03692) accounting for

- Deviation from chemical equilibrium (quark fugacities)

HF statistical hadronization



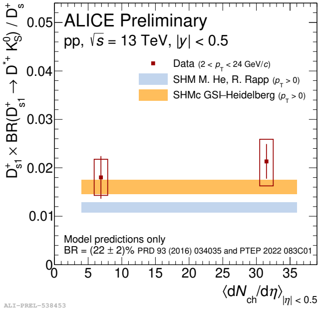


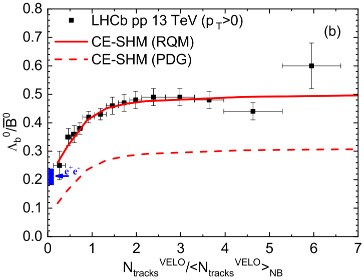
$$Z(\vec{Q}) = \int_0^{2\pi} \frac{d^5\phi}{(2\pi)^5} e^{i\vec{Q}\cdot\vec{\phi}} \exp[\sum_j \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} e^{-i\vec{q}_j\cdot\vec{\phi}} z_j]\,, \quad \text{with} \quad z_j = (2J_j+1)\frac{VT_H}{2\pi^2} m_j^2 K_2(\frac{m_j}{T_H})$$

Statistical description of HF production (Y. Dai, S. Zhao and M. He, 2402.03692) accounting for

- Deviation from chemical equilibrium (quark fugacities)
- Exact charge conservation within correlation volume V

HF statistical hadronization





$$Z(\vec{Q}) = \int_0^{2\pi} \frac{d^5\phi}{(2\pi)^5} e^{i\vec{Q}\cdot\vec{\phi}} \exp[\sum_j \gamma_s^{N_{sj}} \gamma_c^{N_{cj}} \gamma_b^{N_{bj}} e^{-i\vec{q}_j\cdot\vec{\phi}} z_j] , \quad \text{with} \quad z_j = (2J_j+1)\frac{VT_H}{2\pi^2} m_j^2 K_2(\frac{m_j}{T_H})$$

Statistical description of HF production (Y. Dai, S. Zhao and M. He, 2402.03692) accounting for

- Deviation from chemical equilibrium (quark fugacities)
- Exact charge conservation within correlation volume V
- Enlarged set of hadronic resonance wrt PDG

Conclusions and perspectives

- 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;

Conclusions and perspectives

- 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;
- LCN model coupled to transport calculations in a small fireball provides a 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;

Conclusions and perspectives

- 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;
- LCN model coupled to transport calculations in a small fireball provides a 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;
- Occurrence of medium effects on HF observables even in pp collisions justified by the HQ production biased towards hot spots of the highest-multiplicity events

Conclusions and perspectives

- 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;
- LCN model coupled to transport calculations in a small fireball provides a 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;
- Occurrence of medium effects on HF observables even in pp collisions justified by the HQ production biased towards hot spots of the highest-multiplicity events
- Independent, strong indications that the collective phenomena observed in small systems have the same origin as those measured in heavy-ion collisions

Conclusions and perspectives

- 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;
- LCN model coupled to transport calculations in a small fireball provides a 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;
- Occurrence of medium effects on HF observables even in pp collisions justified by the HQ production biased towards hot spots of the highest-multiplicity events
- Independent, strong indications that the collective phenomena observed in small systems have the same origin as those measured in heavy-ion collisions
- Do alternative explanations really exclude the formation of a small deconfined fireball?

Conclusions and perspectives

- 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;
- LCN model coupled to transport calculations in a small fireball provides a 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;
- Occurrence of medium effects on HF observables even in pp collisions justified by the HQ production biased towards hot spots of the highest-multiplicity events
- Independent, strong indications that the collective phenomena observed in small systems have the same origin as those measured in heavy-ion collisions
- Do alternative explanations really exclude the formation of a small deconfined fireball?
- Extension to pA collisions and to beauty production in progress

Conclusions and perspectives

- 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;
- LCN model coupled to transport calculations in a small fireball provides a 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;
- Occurrence of medium effects on HF observables even in pp collisions justified by the HQ production biased towards hot spots of the highest-multiplicity events
- Independent, strong indications that the collective phenomena observed in small systems have the same origin as those measured in heavy-ion collisions
- Do alternative explanations really exclude the formation of a small deconfined fireball?
- Extension to pA collisions and to beauty production in progress
- Hadronization remains a (the?) major source of systematic uncertainty in the extraction of HF transport coefficients