Heavy flavours in high energy collisions: quenching, thermalization and correlation

Andrea Beraudo

INFN - Sezione di Torino

Heavy Quark Physics in Heavy-Ion collisions: experiments, phenomenology and theory,
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Description of soft observables based on hydrodynamics, assuming to deal with a system close to local thermal equilibrium (no matter why);

Description of jet-quenching based on energy-degradation of external probes (high-$p_T$ partons);
Heavy Flavor in the QGP: the conceptual setup

- Description of soft observables based on hydrodynamics, assuming to deal with a system close to local thermal equilibrium (no matter why);
- Description of jet-quenching based on energy-degradation of external probes (high-$p_T$ partons);
- Description of heavy-flavor observables requires to employ/develop a setup (transport theory) allowing to deal with more general situations and in particular to describe how particles would (asymptotically) approach equilibrium.
Description of soft observables based on hydrodynamics, assuming to deal with a system close to local thermal equilibrium (no matter why);

Description of jet-quenching based on energy-degradation of external probes (high-$p_T$ partons);

Description of heavy-flavor observables requires to employ/develop a setup (transport theory) allowing to deal with more general situations and in particular to describe how particles would (asymptotically) approach equilibrium.

NB At high-$p_T$ the interest in heavy flavor is no longer related to thermalization, but to the study of the mass and color charge dependence of jet-quenching (not addressed in this talk).
Why are charm and beauty considered heavy?

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- $M \gg gT$, with $gT$ being the typical momentum exchange in the collisions with the plasma particles: many soft scatterings necessary to change significantly the momentum/trajectory of the quark.
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- $M \gg gT$, with $gT$ being the *typical momentum exchange* in the collisions with the plasma particles: many soft scatterings necessary to change significantly the momentum/trajectory of the quark.

NB for realistic temperatures $g \sim 2$, so that one can wonder *whether a charm is really “heavy”*, at least in the initial stage of the evolution.
Simulating the initial hard production

- Powerful pQCD tools\(^1\) are available to simulate the initial $Q\bar{Q}$ production, interfacing the output of a NLO event-generator (POWHEG, MC@NLO) for the hard process with a parton-shower (PYTHIA, HERWIG) describing Initial and Final State Radiation.

- This provides a fully exclusive information on the final state

\(^1\)For a systematic comparison (POWHEG vs MC@NLO vs FONLL): M. Cacciari et al., JHEP 1210 (2012) 137.
FONLL vs POWHEG+PS

FONLL

- It is a calculation
- It provides NLL accuracy, resumming large $\ln(p_T/M)$
- It includes processes missed by POWHEG (hard events with light partons)

POWHEG+PS

- It is an event generator
- Results compatible with FONLL
- It is a more flexible tool, allowing to address more differential observables (e.g. $Q\bar{Q}$ correlations)
Besides reproducing the inclusive $p_T$-spectra...\textsuperscript{2}

...the POWHEG+PYTHIA setup allows also the comparison with $D-h$ correlation data, which start getting available.

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HF in nucleus-nucleus collisions

- Transport calculations: a critical overview
- Towards a precise determination of the transport coefficients from QCD
- How close/far are heavy quarks go to/from thermalization? Are final (hadronic) observables able to answer this question? What could be the role of experiments at increasing $\sqrt{s_{NN}}$?
Transport theory: the Boltzmann equation

Time evolution of HQ phase-space distribution $f_Q(t, x, p)^3$:

$$
\frac{d}{dt} f_Q(t, x, p) = C[f_Q]
$$

- **Total derivative** along particle trajectory
  $$
  \frac{d}{dt} \equiv \frac{\partial}{\partial t} + v \frac{\partial}{\partial x} + F \frac{\partial}{\partial p}
  $$

Neglecting $x$-dependence and mean fields: $\partial_t f_Q(t, p) = C[f_Q]

- **Collision integral**:
  $$
  C[f_Q] = \int d\mathbf{k} \left[ w(p + k, k)f_Q(p + k) - w(p, k)f_Q(p) \right]
  $$
  \text{gain term - loss term}

  $w(p, k)$: HQ transition rate $p \rightarrow p - k$

\(^3\text{Approach adopted for HQs by Greco et al, Gossiaux et al. and for the whole medium in codes like BAMPS}\)
Expanding the collision integral for *small momentum exchange*\(^4\) (Landau)

\[
C[f_Q] \approx \int d\mathbf{k} \left[ k^i \frac{\partial}{\partial p^i} + \frac{1}{2} k^i k^j \frac{\partial^2}{\partial p^i \partial p^j} \right] [w(p, k)f_Q(t, p)]
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\(^4\)B. Svetitsky, PRD 37, 2484 (1988)
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The Boltzmann equation reduces to the *Fokker-Planck equation* (approx. to be quantitatively tested!)

\[
\frac{\partial}{\partial t} f_Q(t, p) = \frac{\partial}{\partial p^i} \left\{ A^i(p) f_Q(t, p) + \frac{\partial}{\partial p^j} [B^{ij}(p) f_Q(t, p)] \right\}
\]

where

\[
A^i(p) = \int d\mathbf{k} \ k^i w(p, k) \quad \rightarrow \quad A^i(p) = A(p) \ p^i
\]

\[
B^{ij}(p) = \frac{1}{2} \int d\mathbf{k} \ k^i k^j w(p, k) \quad \rightarrow \quad B^{ij}(p) = \hat{p}^i \hat{p}^j B_0(p) + (\delta^{ij} - \hat{p}^i \hat{p}^j) B_1(p)
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---

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From Boltzmann to Fokker-Planck

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A^i(p) = \int d\mathbf{k} k^i w(p, \mathbf{k}) \quad \rightarrow \quad A^i(p) = A(p) p^i \quad \text{friction}
\]

\[
B^{ij}(p) = \frac{1}{2} \int d\mathbf{k} k^i k^j w(p, \mathbf{k}) \quad \rightarrow \quad B^{ij}(p) = \hat{p}^i \hat{p}^j B_0(p) + (\delta^{ij} - \hat{p}^i \hat{p}^j) B_1(p) \quad \text{momentum broadening}
\]

Problem reduced to the **evaluation of three transport coefficients**

\(^4\)B. Svetitsky, PRD 37, 2484 (1988)
The relativistic Langevin equation

The Fokker-Planck equation can be recast into a form suitable to follow the dynamics of each individual quark: the \textbf{Langevin equation}

\[
\frac{\Delta p^i}{\Delta t} = -\eta_D(p)p^i + \xi^i(t),
\]

with the properties of the noise encoded in

\[
\langle \xi^i(p_t)\xi^j(p_{t'}) \rangle = b^{ij}(p_t) \frac{\delta_{tt'}}{\Delta t} \hspace{1cm} b^{ij}(p) \equiv \kappa_{\parallel}(p) \hat{p}^i \hat{p}^j + \kappa_{\perp}(p)(\delta^{ij} - \hat{p}^i \hat{p}^j)
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**Transport coefficients** (to derive from theory):

- **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**):
A first check: thermalization in a static medium

For $t \gg 1/\eta_D$ one approaches a relativistic Maxwell-Jüttner distribution

$$f_{MJ}(p) \equiv \frac{e^{-E_p/T}}{4\pi M^2 T K_2(M/T)}, \quad \text{with} \quad \int d^3p \, f_{MJ}(p) = 1$$

(Test with a sample of $c$ quarks with $p_0 = 2$ GeV/c and weak-coupling HTL transport coefficients)

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A.B., A. De Pace, W.M. Alberico and A. Molinari, NPA 831, 59 (2009)
Within our **POWLANG** setup (**POWHEG**+**LANG**evin) the HQ evolution in heavy-ion collisions is simulated as follows

- $Q\bar{Q}$ pairs initially **produced with** the **POWHEG-BOX** package (with nPDFs) and **distributed** in the transverse plane **according to** $n_{\text{coll}}(x_\perp)$ from (optical) Glauber model;

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The realistic case: expanding fireball

Within our **POWL** setup (**POW**HEG+**LAN**Gevin) the HQ evolution in heavy-ion collisions is simulated as follows

- $Q\bar{Q}$ pairs initially produced with the **POW**HEG-**BOX** package (with nPDFs) and distributed in the transverse plane according to $n_{\text{coll}}(x_\perp)$ from (optical) Glauber model;
- update of the HQ momentum and position to be done at each step in the local fluid rest-frame
  - $u^\mu(x)$ used to perform the boost to the fluid rest-frame;
  - $T(x)$ used to set the value of the transport coefficients
- Procedure iterated until hadronization

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$D$-mesons at low-$p_T$: STAR data compared to various model predictions (see the various talks).

Sharp peak $\approx 1.5$ GeV in central (0 – 10\%) collisions:

- from charm radial flow?
- from coalescence with light quarks (included in some of the models)?

More in the following...
Although the Langevin approach is a very convenient numerical tool and allows one to establish a link between observables and transport coefficients derived from QCD...
The Langevin/FP approach: a critical perspective

Although the Langevin approach is a very convenient numerical tool and allows one to establish a link between observables and transport coefficients derived from QCD... it was nevertheless derived starting from a soft-scattering expansion of the collision integral $C[f]$ truncated at second order (friction and diffusion terms), which may be not always justified, in particular for charm, possibly affecting the final $R_{AA}$ (V. Greco et al., Phys.Rev. C90 (2014) 4, 044901 and F. Scardina talk)
The Langevin/FP approach: a critical perspective

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For beauty on the other hand Langevin$\equiv$Boltzmann!
At the same time the Langevin/FP approach, although formally derived as a soft-scattering limit of the Boltzmann equation, can be considered more general than the latter, requiring simply the knowledge of a few transport coefficients (friction and diffusion) meaningful even in a non-perturbative framework and not relying on quasi-particle picture of the medium.
The Langevin/FP approach: a critical perspective

At the same time the Langevin/FP approach, although formally derived as a soft-scattering limit of the Boltzmann equation, can be considered more general than the latter, requiring simply the knowledge of a few transport coefficients (friction and diffusion) meaningful even in a non-perturbative framework and not relying on quasi-particle picture of the medium.

Notice that, for the light quarks/gluons of the medium one has

- Thermal de Broglie wavelength: $\lambda_{\text{th}} \sim 1/T$
- Mean free path: $\lambda_{\text{mfp}} \sim 1/g^2 T$

In the weak-coupling regime one has $\lambda_{\text{th}} \ll \lambda_{\text{mfp}}$, so that between the relatively rare scatterings one has the propagation of localized on-shell particles. However as the coupling gets large $\lambda_{\text{th}} \sim \lambda_{\text{mfp}}$, the two scales are no longer well separated and a picture based on on-shell distribution function may be no longer valid.
HF transport coefficients

- Weak-coupling calculation (pQCD+HTL)
- Non-perturbative calculation (lattice-QCD)
Transport coefficients: perturbative evaluation

It’s the stage where the various models differ!

We account for the effect of $2 \rightarrow 2$ collisions in the medium

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Intermediate cutoff $|t^*| \sim m_D^2$ separating the contributions of

- hard collisions ($|t| > |t^*|$): kinetic pQCD calculation
- soft collisions ($|t| < |t^*|$): Hard Thermal Loop approximation (resummation of medium effects)

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Transport coefficients $\kappa_{T/L}(p)$: hard contribution

where: $|t| \equiv q^2 - \omega^2$
Transport coefficients $\kappa_{T/L}(p)$: soft contribution

When the exchanged 4-momentum is soft the t-channel gluon feels the presence of the medium and requires resummation.
Transport coefficients $\kappa_{T/L}(p)$: soft contribution

When the exchanged 4-momentum is **soft** the t-channel gluon feels the presence of the medium and requires **resummation**. The **blob** represents the **dressed gluon propagator**, which has longitudinal and transverse components:

$$
\Delta_L(z, q) = \frac{-1}{q^2 + \Pi_L(z, q)}, \quad \Delta_T(z, q) = \frac{-1}{z^2 - q^2 - \Pi_T(z, q)},
$$

where **medium effects** are embedded in the HTL gluon self-energy.
Combining together the hard and soft contributions...

...the dependence on the intermediate cutoff $|t|^*$ is very mild!
Transport coefficients: numerical results

Combining together the hard and soft contributions...

Andrea Beraudo
Heavy flavours in high energy collisions: quenching, thermalization
Non perturbative information on HF transport coefficients can be obtained from lattice-QCD simulations, so far treating the HQ’s as static ($M=\infty$) color sources placed in a thermal bath.
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One consider the non-relativistic limit of the Langevin equation:

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

Hence, in the \(p \to 0\) limit:

\[
\kappa = \frac{1}{3} \int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0) \rangle_{\text{HQ}} \approx \frac{1}{3} \int_{-\infty}^{+\infty} dt \frac{\langle F^i(t)F^i(0) \rangle_{\text{HQ}}}{D(t)}
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In the static limit the force is due to the color-electric field:

$$\mathbf{F}(t) = g \int d\mathbf{x} Q^\dagger(t, \mathbf{x}) t^a Q(t, \mathbf{x}) \mathbf{E}^a(t, \mathbf{x})$$
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$$F(t) = g \int dx Q^\dagger(t, x)t^a Q(t, x)E^a(t, x)$$

$\kappa$ is then given by the $\omega \to 0$ limit of the spectral density $\sigma(\omega)$ of the above E-field correlator

$$\kappa \equiv \lim_{\omega \to 0} \frac{D^>(\omega)}{3} \equiv \lim_{\omega \to 0} \frac{1}{3} \frac{\sigma(\omega)}{1 - e^{-\beta\omega}} \approx \lim_{\omega \to 0} \frac{1}{3} \frac{T}{\omega} \sigma(\omega)$$
The spectral function $\sigma(\omega)$ has to be reconstructed starting from the euclidean electric-field correlator

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

according to

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

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$$\kappa/T^3 \approx 2.4(6) \ (\text{quenched QCD, cont.lim.})$$

$\sim$3-5 times larger then the perturbative result (W.M. Alberico et al, EPJC 73 (2013) 2481). Challenge: approaching the continuum limit in full QCD (see Kaczmarek talk)!
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Measurements of beauty in AA collisions (with future detector upgrades) in the next years will allow one to establish a link between first-principle theoretical predictions (continuum-extrapolated lattice-QCD calculations) and experimental observables:

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- $M \gg T$: static ($M = \infty$) l-QCD results more reliable for beauty
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Measurements so far limited to non-prompt $J/\psi$'s at quite high $p_T$
Heavy Quark thermalization?
Wondering whether heavy quarks thermalize entails a number of related questions...

- Are theoretical tools able to describe their approach to thermal equilibrium in a evolving medium?
- What are the indications coming from experiment? Are final hadronic/leptonic observables able to provide an unambiguous answer on what happens in the partonic stage?
- What could be the role of experiments at larger $\sqrt{s_{NN}}$? Higher temperature and radial flow, but also much harder initial $Q\bar{Q}$ spectrum...
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NB thermal equilibrium of HQ’s at the end of the QGP phase is assumed in the description of hidden and open charm production within the Statistical Hadronization Model: answering this question may support or rule out such an hypothesis.
In the limit of large transport coefficients heavy quarks should reach local thermal equilibrium and decouple from the medium as the other light particles, according to the Cooper-Frye formula:

\[ E(dN/d^3 p) = \int_{\Sigma_{fo}} \frac{p^\mu \cdot d\Sigma^\mu}{(2\pi)^3} \exp[-p \cdot u / T_{fo}] \]

This was verified to be actually the case (M. He, R.J. Fries and R. Rapp, PRC 86, 014903).
Experimental indications

It is possible to compare the *experimental* D-meson $R_{AA}$ with the *theoretical expectation* in the case of *kinetic equilibrium*

- Spectrum in $pp$ given by POWHEG+PYTHIA setup
- Final spectrum in $AA$ given by hydro + Cooper-Frye
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Evidence of a bump from radial flow at RHIC, while more data at low-$p_T$ (waiting for ALICE ITS upgrade) necessary at LHC; in any case charm partially out of kinetic equilibrium, at least at LHC.
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HF in the POWLANG setup: recent developments
(arXiv:1410.6082)

The major novelty concerns the simulation of heavy-quark hadronization, which now can be performed via

- standard vacuum Fragmentation Functions
- recombination with thermal light partons
From quarks to hadrons

In-medium hadronization may affect the $R_{AA}$ and $v_2$ of final D-mesons due to the collective flow of light quarks. We tried to estimate the effect through this model interfaced to our POWLANG transport code:

- At $T_{\text{dec}}$ c-quarks coupled to light $\bar{q}$'s from a local thermal distribution, eventually boosted ($u^t_{\text{fluid}} \neq 0$) to the lab frame;
- Strings are formed and given to PYTHIA 6.4 to simulate their fragmentation and produce the final hadrons ($D + \pi + \ldots$)

One can address the study of $D-h$ and $e-h$ correlations in AA collisions
Experimental data display a peak in the $R_{AA}$ and a sizable $v_2$ one would like to interpret as a signal of *charm radial flow and thermalization*.
From quarks to hadrons: effect on $R_{AA}$ and $v_2$

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However, comparing transport results with/without the boost due to $u_\mu^{\text{fluid}}$, at least part of the effect might be due to the radial and elliptic flow of the light partons from the medium picked-up at hadronization.
From quarks to hadrons: effect on $R_{AA}$ and $v_2$

Experimental data display a peak in the $R_{AA}$ and a sizable $v_2$ one would like to interpret as a signal of *charm radial flow and thermalization*

![Graphs showing $R_{AA}$ and $v_2$ vs. $p_T$](image)

However, *comparing transport results with/without the boost due to $u_\text{fluid}$*, at least part of the effect might be due to the radial and elliptic flow of the light partons from the medium picked-up at hadronization. *Rescattering in the hadronic phase and its effect on $v_2$ should be also investigated (in progress)!*

Andrea Beraudo

Heavy flavours in high energy collisions: quenching, thermalization
It is possible to perform a systematic study of different choices of

- **Hadronization scheme** (left panel)
- **Transport coefficients** (weak-coupling pQCD+HTL vs non-perturbative l-QCD) and **decoupling temperature** (right panel)
Experimental data for central (0–20%) Pb-Pb collisions at LHC display a strong quenching, but – at least with the present bins and $p_T$ range – don’t show strong signatures of the bump from radial flow predicted by “thermal” and “transport + $Q\bar{q}_{\text{therm}}$-string fragmentation” curves.
**$D$ meson $R_{AA}$: in-plane vs out-of-plane**

One can study di $R_{AA}$ in- and out-of-plane in non-central (30–50%) Pb-Pb collisions at LHC:

![Graphs showing $R_{AA}$ vs $p_T$ for in-plane and out-of-plane studies.](image)

- **Data better described by weak-coupling (pQCD+HTL) transport coefficients;**
$D$ meson $R_{AA}$: in-plane vs out-of-plane

One can study di $R_{AA}$ in- and out-of-plane in non-central (30–50%) Pb-Pb collisions at LHC:

- Data better described by weak-coupling (pQCD+HTL) transport coefficients;
- $Q\bar{q}_{\text{therm}}$-string fragmentation describes data slightly better than in-vacuum independent Fragmentation Functions.
Concerning $D$-meson $v_2$ in non-central (30–50%) Pb-Pb collisions:

- $Q\bar{q}_{\text{therm}}$-string fragmentation routine significantly improves our transport model predictions compared to the data;

- HTL curves with a lower decoupling temperature display the best agreement with ALICE data.
Azimuthal correlations: $D - h$

Away-side peak strongly suppressed both in central and semi-central collisions

Andrea Beraudo

Heavy flavours in high energy collisions: quenching, thermalization
Azimuthal correlations: $e - h$

We plot the separate $e_c$ (left) and $e_b$ (right) contributions from charm and beauty decays.

- **charm away-side peak always strongly suppressed** for any centrality and $p_T^{ass}$ cut;
- **beauty always-side peak suppressed but still visible**, providing in principle a richer information.

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Heavy flavours in high energy collisions: quenching, thermalization
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Andrea Beraudo
Heavy flavours in high energy collisions: quenching, thermalization.
We have tried to answer the question of kinetic equilibration of charm in heavy-ion collisions. We have shown how predictions of two different scenarios (hydro and transport+recombination) can be hardly distinguished within the current kinematic range covered by the experiment and they can both describe some qualitative features of the data at low-moderate $p_T$. 
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We have presented a new hadronization routine (recombination followed by string fragmentation) interfaced to our partonic transport code, which improves the agreement of the latter with experimental data ($R_{AA}$, $v_2$, $R_{AA}^{in}$ and $R_{AA}^{out}$).
Summary and perspectives

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- Work in progress:
  - Rescattering in the hadronic phase
  - Transport in small systems (p-A and d-A)