Medium effects on heavy-flavour observables in high-energy nuclear collisions

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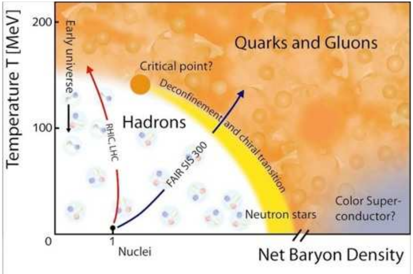
Heavy-ion collisions: exploring the QCD phase-diagram



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

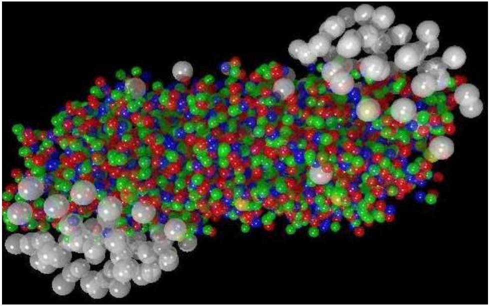
Region explored at LHC: *high-T/low-density* (early universe, $n_B/n_\gamma \sim 10^{-9}$)

- From QGP (color deconfinement, chiral symmetry restored)
- to hadronic phase (confined, chiral symmetry breaking[1])

NB $\langle \overline{q} q \rangle \neq 0$ responsible for most of the baryonic mass of the universe: *only $\sim$35 MeV of the proton mass from $m_{u/d} \neq 0$*

[1] V. Koch, *Aspects of chiral symmetry*, Int.J.Mod.Phys. E6 (1997)

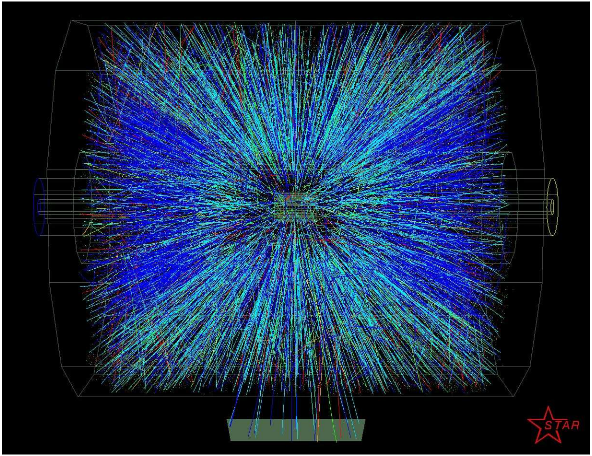
Heavy-ion collisions: a typical event



- Valence quarks of participant nucleons act as sources of strong color fields giving rise to *particle production*
- Spectator nucleons don't participate to the collision;

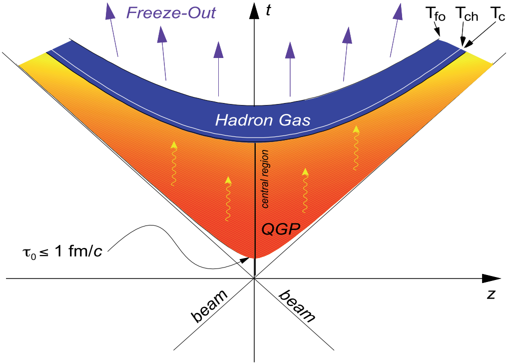
Almost all the energy and baryon number carried away by the remnants

Heavy-ion collisions: a typical event



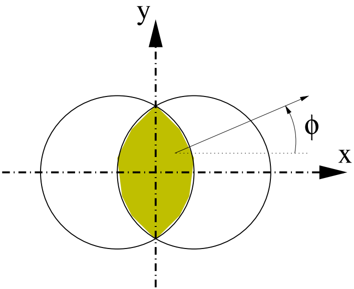
Event display of a Au-Au collision at $\sqrt{s_{\rm NN}} = 200$ GeV

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, quarkonia): produced in *hard pQCD processes* in the initial stage, allow to perform a tomography of the medium

Hydrodynamic behavior: elliptic flow



- In *non-central collisions* particle emission is not azimuthally-symmetric!

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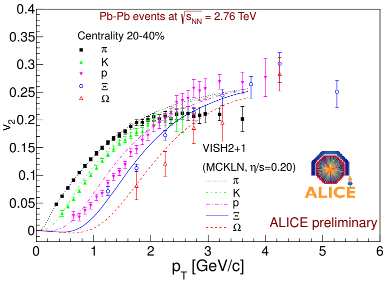


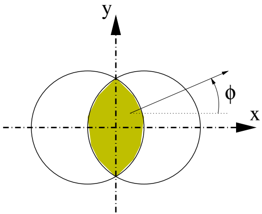
- In *non-central collisions* particle emission is not azimuthally-symmetric!
- The effect can be quantified through the *Fourier coefficient* v_2

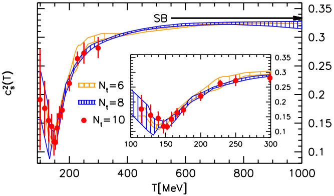
$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2v_2\cos[2(\phi - \psi_{RP})] + \ldots\right)$$

$$v_2 \equiv \langle \cos[2(\phi - \psi_{RP})] \rangle$$

- $v_2(p_T) \sim 0.2$ gives a modulation 1.4 vs 0.6 for in-plane vs out-of-plane particle emission!

Elliptic flow: physical interpretation



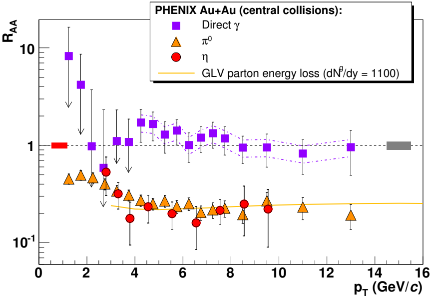


- Matter behaves like a fluid whose *expansion* is *driven by pressure gradients*

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

- Spatial anisotropy is converted into momentum anisotropy;
- At freeze-out *particles* are *mostly emitted along the reaction-plane*.
- It provides information on the EOS of the produced matter (Hadron Gas vs QGP) through the *speed of sound*: $\vec{\nabla} P = c_s^2 \vec{\nabla} \epsilon$

The medium is opaque: jet-quenching



The *nuclear modification factor*

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

quantifies the suppression of high-p_T *hadron spectra*

Hard-photon $R_{AA} \approx 1$

- supports the Glauber picture (binary-collision scaling);
- entails that quenching of inclusive hadron spectra is a *final state effect* due to in-medium energy loss.

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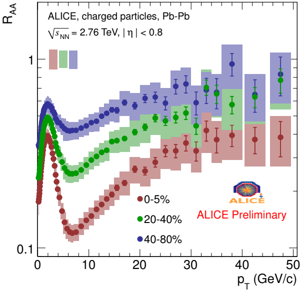

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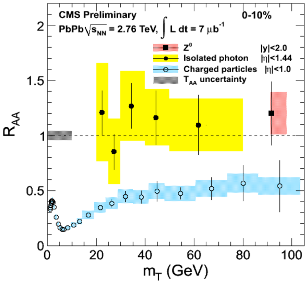

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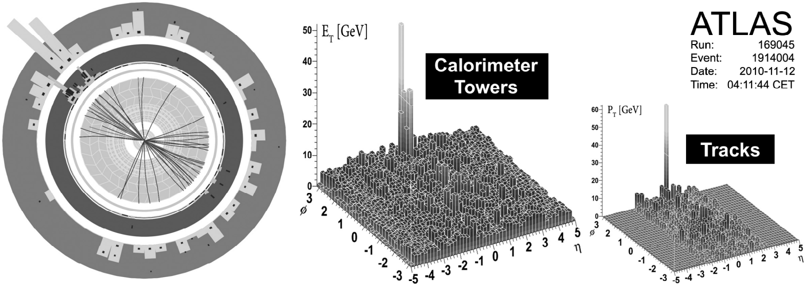
Di-jet imbalance at LHC: looking at the event display

An important fraction of events display a *huge mismatch* in E_T between the leading jet and its away-side partner



Possible to observe event-by-event, without any analysis!

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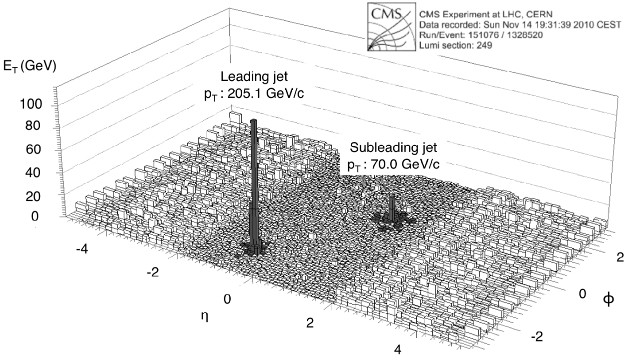

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Heavy Flavour in the QGP: the conceptual setup

- 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);

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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)

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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.

Heavy quarks as probes of the QGP

A realistic study requires developing *a multi-step setup*:

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- Hadronization: not well under control (fragmentation in the vacuum? recombination with light thermal partons?)
  - An item of interest in itself (*change of hadrochemistry* in AA)
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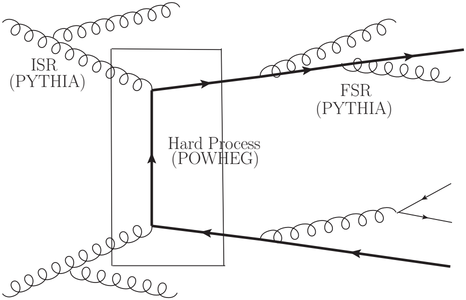
- Final decays ($D \to X\nu e$, $B \to XJ/\psi$...)

HQ production: NLO calculation + Parton Shower



- The tool adopted to simulate the initial $Q\overline{Q}$ production (the POWHEG-BOX package) interfaces the output of a NLO event-generator for the hard process with a parton-shower describing the Initial and Final State Radiation and modeling other *non-perturbative processes* (intrinsic k_T, MPI, hadronizazion)
- This provides a *fully exclusive information on the final state*

Heavy flavour: experimental observables

- D and B mesons
- Non-prompt J/ψ's ($B \to J/\psi\, X$)
- Heavy-flavour electrons, from the decays
  - of charm (e_c)

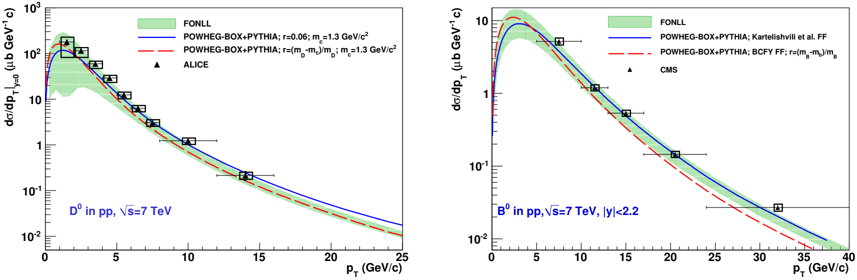
$$D \to X\nu e$$

  - of beauty (e_b)

$$\begin{aligned} B &\to D\nu e \\ B &\to D\nu e \to X\nu e\nu e \\ B &\to DY \to X\nu e Y \end{aligned}$$

- B-tagged jets

HF production in *pp* collisions: results



- Besides reproducing the inclusive D-meson
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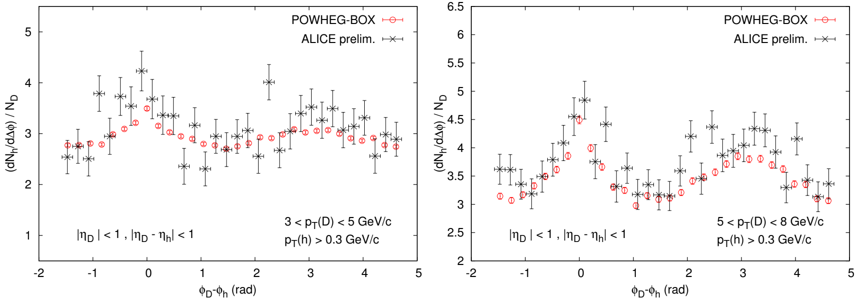

- Besides reproducing the inclusive D-meson
- and B-meson p_T-spectra[2]...
- ...the POWHEG+PYTHIA setup allows also the comparison with $D-h$ correlation data, which start getting available.

[2] W.M. Alberico *et al*, Eur.Phys.J. C73 (2013) 2481

Transport theory: the Boltzmann equation

Time evolution of HQ phase-space distribution $f_Q(t, \mathbf{x}, \mathbf{p})$[3]:

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

- Total derivative along particle trajectory

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + \mathbf{v}\frac{\partial}{\partial \mathbf{x}} + \mathbf{F}\frac{\partial}{\partial \mathbf{p}}$$

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

- Collision integral:

$$C[f_Q] = \int d\mathbf{k} [\underbrace{w(\mathbf{p}+\mathbf{k}, \mathbf{k}) f_Q(\mathbf{p}+\mathbf{k})}_{\text{gain term}} - \underbrace{w(\mathbf{p}, \mathbf{k}) f_Q(\mathbf{p})}_{\text{loss term}}]$$

  $w(\mathbf{p}, \mathbf{k})$: HQ transition rate $\mathbf{p} \to \mathbf{p} - \mathbf{k}$

[3] For results based on BE see e.g. Catania-group papers

From Boltzmann to Fokker-Planck

Expanding the collision integral for *small momentum exchange*[4] (Landau)

$$C[f_Q] \approx \int d\mathbf{k} \left[k^i \frac{\partial}{\partial p^i} + \frac{1}{2} k^i k^j \frac{\partial^2}{\partial p^i \partial p^j} \right] [w(\mathbf{p}, \mathbf{k}) f_Q(t, \mathbf{p})]$$

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The Boltzmann equation reduces to the *Fokker-Planck equation*

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

where (verify!)

$$A^i(\mathbf{p}) = \int d\mathbf{k}\, k^i w(\mathbf{p}, \mathbf{k}) \longrightarrow \underbrace{A^i(\mathbf{p}) = A(p)\, p^i}_{\text{friction}}$$

$$B^{ij}(\mathbf{p}) = \frac{1}{2} \int d\mathbf{k}\, k^i k^j w(\mathbf{p}, \mathbf{k}) \longrightarrow \underbrace{B^{ij}(\mathbf{p}) = \hat{p}^i \hat{p}^j B_0(p) + (\delta^{ij} - \hat{p}^i \hat{p}^j) B_1(p)}_{\text{momentum broadening}}$$

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Problem reduced to the *evaluation of three transport coefficients*

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The relativistic Langevin equation

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

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

with the properties of the noise encoded in

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

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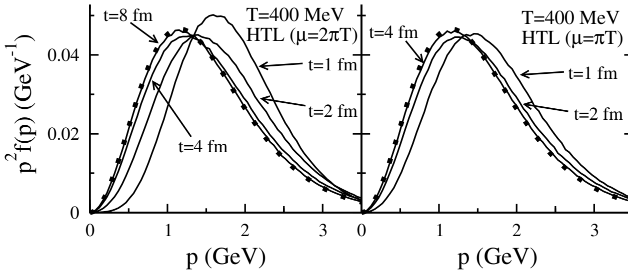
Transport coefficients to calculate:

- *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[5]

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

(Test with a sample of c quarks with $p_0 = 2$ GeV/c)

[5] A.B., A. De Pace, W.M. Alberico and A. Molinari, NPA 831, 59 (2009)

The realistic case: expanding fireball

Within our POWLANG setup (POWHEG+LANGevin) the HQ evolution in heavy-ion collisions is simulated as follows

- $Q\overline{Q}$ pairs initially produced with the POWHEG-BOX package (with nPDFs) and distributed in the transverse plane according to $n_{\rm coll}(\mathbf{x}_\perp)$ from (optical) Glauber model;

[6] P. Romatschke and U.Romatschke, Phys. Rev. Lett. **99** (2007) 172301 and ECHO-QGP, L. Del Zanna *et al.*, Eur.Phys.J. C73 (2013) 2524.

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- 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

  with $u^\mu(x)$ and $T(x)$ fields taken from the output of hydro codes[6];
- Procedure iterated until hadronization

[6] P. Romatschke and U.Romatschke, Phys. Rev. Lett. **99** (2007) 172301 and ECHO-QGP, L. Del Zanna *et al.*, Eur.Phys.J. C73 (2013) 2524.

The Langevin equation provides a link between *what is possible to calculate in QCD* (transport coefficients) and *what one actually measures* (final p_T spectra)

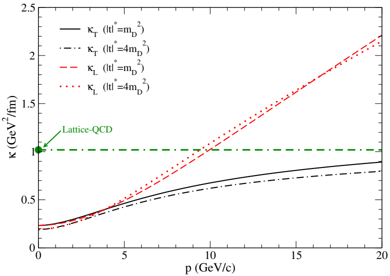
Evaluation of transport coefficients:

- Weak-coupling hot-QCD calculations[7]
- Non perturbative approaches
  - Lattice-QCD
  - AdS/CFT correspondence
  - Resonant scattering

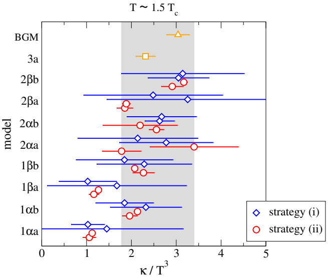
[7] Our approach: W.M. Alberico *et al.*, Eur.Phys.J. C71 (2011) 1666

Transport coefficients: results

Weak-coupling (beauty shown)



Lattice QCD ($M = \infty$)



Obtained accounting for $Qq \to Qq$ and $Qg \to Qg$ scattering, with resummation of medium effects for soft ($|t| < |t|^*$) collisions (Hard Thermal Loop approximation)

$$\kappa = \frac{1}{3}\int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0)\rangle_{\mathrm{HQ}}$$

given by *electric-field correlator*, available only for *imaginary times*

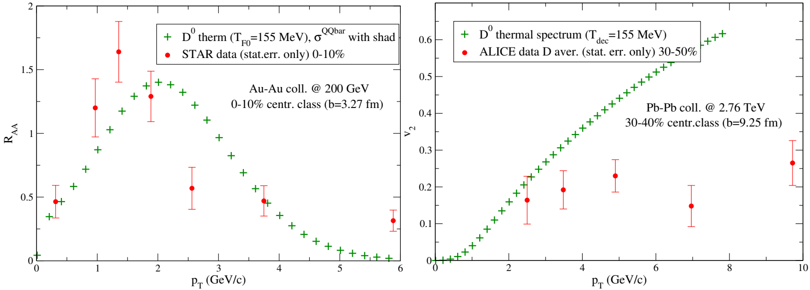
From quarks to hadrons

In the presence of a medium, rather then fragmenting like in the vacuum (e.g. $c \to cg \to c\overline{q}q$), HQ's can hadronize by recombining with light thermal partons from the medium.
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_{dec} c-quarks coupled to light $\overline{q}$'s from a local *thermal distribution*, eventually *boosted* ($u^{\mu}_{\mathrm{fluid}} \neq 0$) to the lab frame;
- Strings are formed and given to PYTHIA 6.4 to simulate their fragmentation and produce the final hadrons ($D + \pi + \dots$)

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* (green crosses: full thermal equilibrium, decoupling from FO hypersurface)



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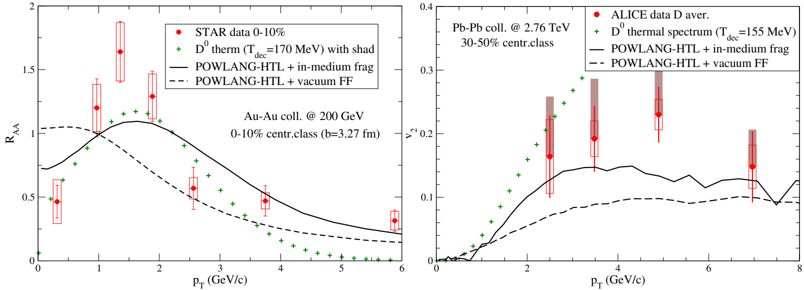
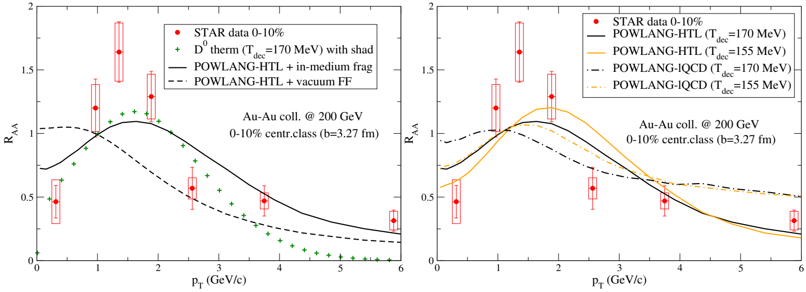


However, *comparing transport results with/without the boost* due to $u^{\mu}_{\rm fluid}$, at least part of the effect might be due to the radial and elliptic flow of the light partons from the medium picked-up at hadronization.

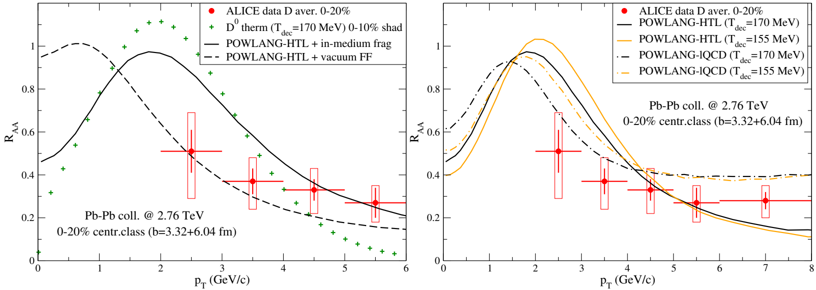
D-meson R_{AA} at RHIC



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)

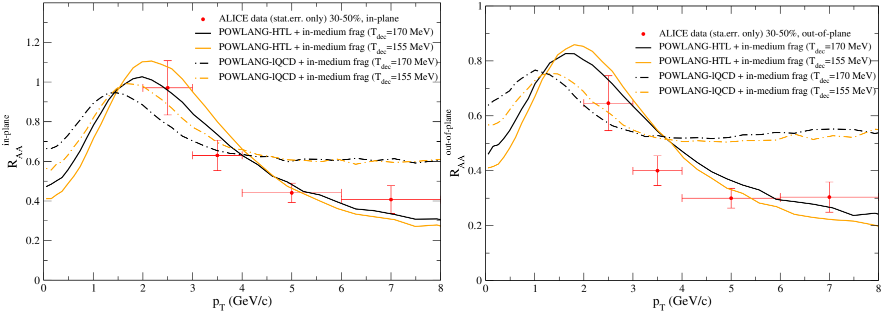
D-meson R_{AA} at LHC



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 + $Q\overline{q}_{\rm therm}$-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:



- Data better described by weak-coupling (pQCD+HTL) transport coefficients;

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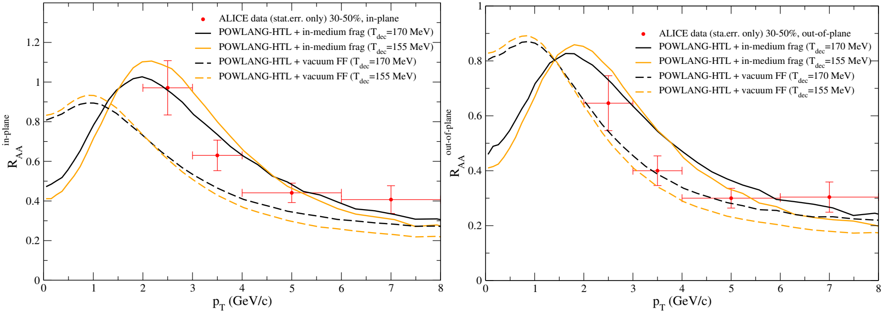
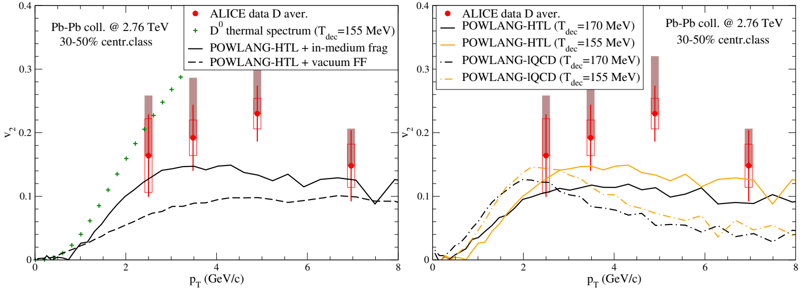


- Data better described by weak-coupling (pQCD+HTL) transport coefficients;
- $Q\overline{q}_{\rm therm}$-string fragmentation describes data slightly better than in-vacuum independent Fragmentation Functions.

D-meson v_2 at LHC



Concerning D-meson v_2 in non-central $(30-50\%)$ Pb-Pb collisions:

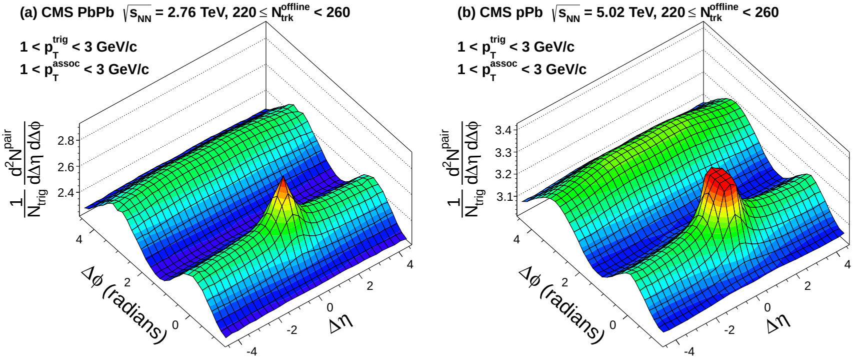
- $Q\overline{q}_{\rm therm}$-string fragmentation routine significantly improves our transport model predictions compared to the data;
- HTL curves with a *lower decoupling temperature* display the best agreement with ALICE data

HF in small systems

(p-Pb and d-Au collisions)

Recent POWLANG results displayed in JHEP 1603 (2016) 123

Hydrodynamic behavior in small systems?



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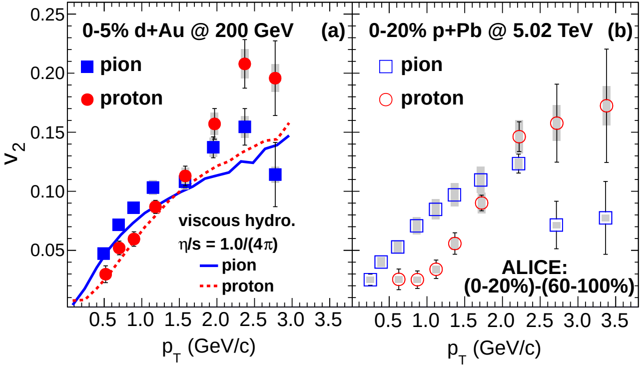
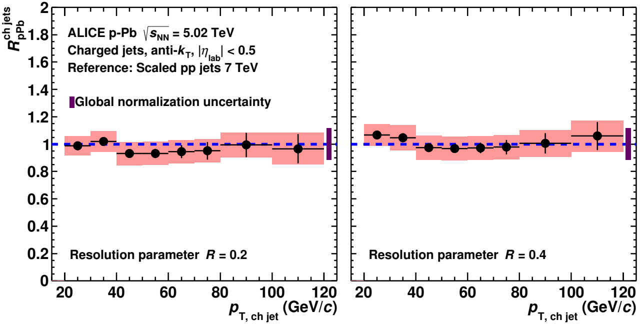


- Long-range rapidity correlations in high-multiplicity p-Pb (and p-p) events: collectiv flow?
- Evidence of non-vanishing elliptic flow v_2 (and mass ordering) in d-Au and p-Pb.

Hard observables in p-A collisions: no medium effect?



No evidence of medium effects in the nuclear modification factor

- neither of jets

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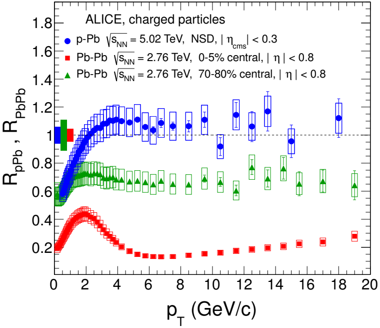

No evidence of medium effects in the nuclear modification factor

- neither of jets
- nor of charged particles

NB Current *lack of a p-p reference* at the same center-of-mass energy source of systematic uncertainty

Hard and soft probes: different sensitivity to the medium

The quenching of a high-energy parton is described by the pocket formula

$$\langle \Delta E \rangle \sim C_R \alpha_s \hat{q} L^2 \sim T^3 L^2$$

with a strong dependence on the temperature and medium thickness.

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with a strong dependence on the temperature and medium thickness.
If one believes that also in p-A collisions soft physics is described by hydrodynamics ($\lambda_{\rm mfp} \ll L$), then starting from an entropy-density profile

$$s(x,y) \sim \exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right]$$

and employing the Euler equation (for $v \ll 1$) and $Tds = d\epsilon$

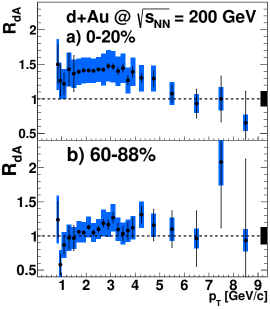
$$(\epsilon + P)\frac{d}{dt}\vec{v} = -\vec{\nabla} P \quad \underset{\vec{\nabla} P = c_s^2 \vec{\nabla}\epsilon}{\longrightarrow} \quad \partial_t \vec{v} = -c_s^2 \vec{\nabla} \ln s$$

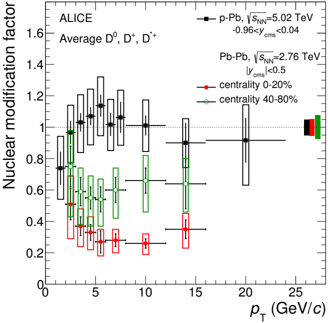
whose solution and mean square value over the transverse plane is

$$v^i = c_s^2 \frac{x^i}{\sigma_i^2} t \quad \longrightarrow \quad \overline{v}^{x/y} = c_s^2 \frac{t}{\sigma_{x/y}}$$

The result has a much milder temperature dependence ($c_s^2 \approx 1/3$) wrt $\hat{q}$ and, although the medium has a ($\approx$3 times) shorter lifetime, radial flow develops earlier, due to the larger pressure gradient

HF in small systems: experimental indications





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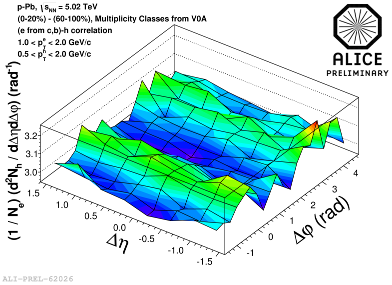

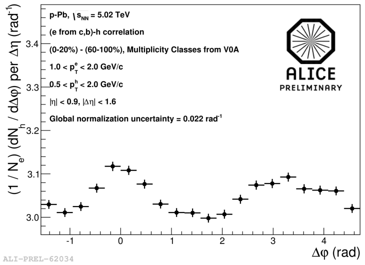

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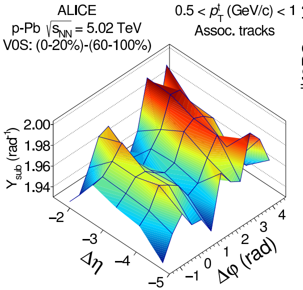

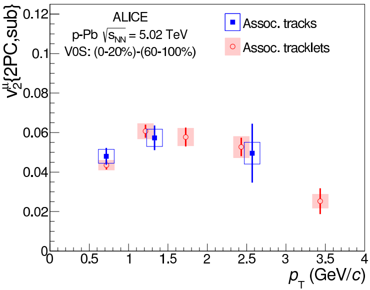

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Medium modeling: event-by-event hydrodynamics

Event-by-event fluctuations (e.g. in the nucleon positions) modeled by Glauber-MC calculation leads to an initial *eccentricity* (responsible for a non-vanishing elliptic flow)

$$s(\mathbf{x}) = \frac{K}{2\pi\sigma^2}\sum_{i=1}^{N_{\rm coll}} \exp\left[-\frac{(\mathbf{x}-\mathbf{x}_i)^2}{2\sigma^2}\right] \quad \longrightarrow \quad \epsilon_2 = \frac{\sqrt{\{y^2-x^2\}^2+4\{xy\}^2}}{\{x^2+y^2\}}$$

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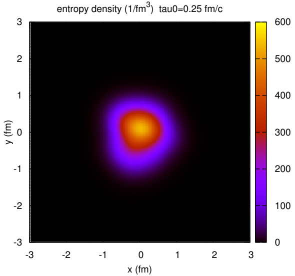

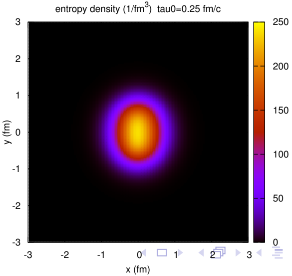

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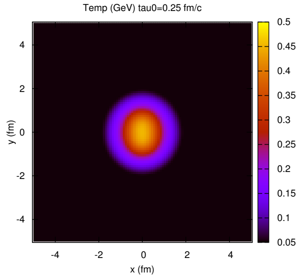
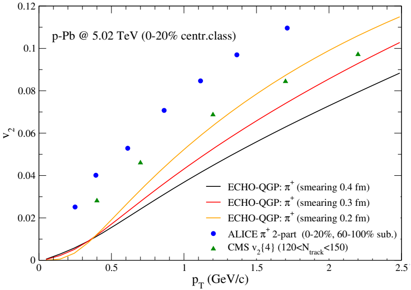
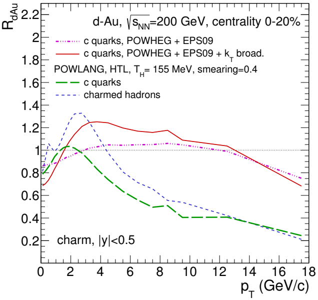
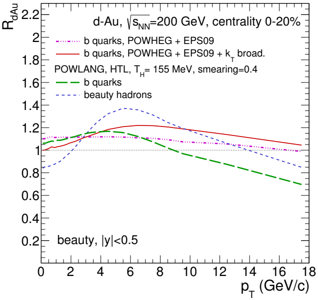




Initial and Final-State effects

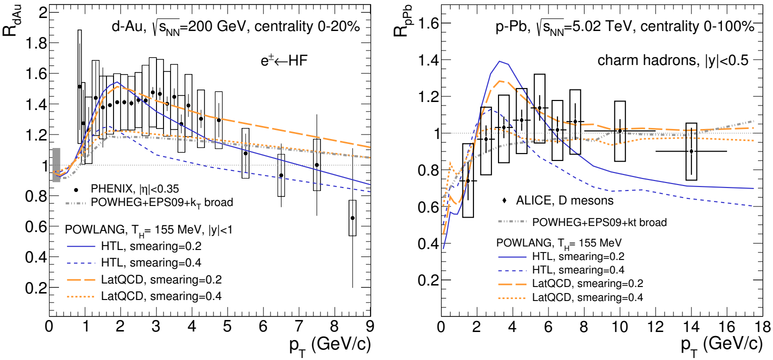




The final result comes from the interplay of initial and final-state effects:

- nPDF's (shadowing and anti-shadowing)
- k_T-broadening in nuclear-matter
- energy-loss in the hot-medium
- in-medium hadronization via recombination

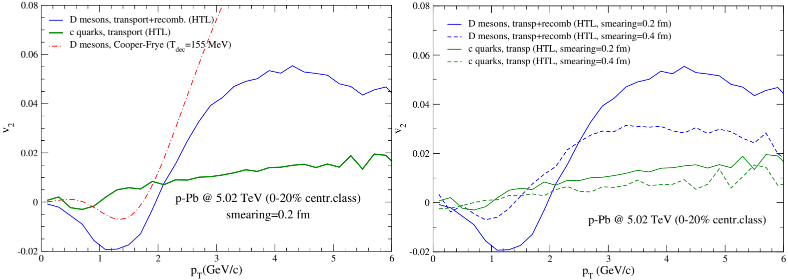
Transport-model predictions



We display our predictions, with different initializations (source smearing) and transport coefficients (HTL vs lQCD), compared to

- HF-electron R_{dAu} by PHENIX at RHIC (left panel)
- D-mesons R_{pPb} by ALICE at the LHC (right panel)

Non-vanishing elliptic flow?



We also predict a non-vanishing v_2 of charmed hadrons, arising mainly from the elliptic flow inherited from the light thermal partons

Future perspectives

A number of experimental challenges or theoretical questions remain to be answered:

- Charm measurements down to $p_T \to 0$: flow/thermalization and total cross-section (of relevance for charmonium supression!)
- D_s and Λ_c measurements: change in hadrochemistry and total cross-section
- Beauty measurements in AA via exclusive hadronic decays: better probe, due to $M \gg \Lambda_{\rm QCD}, T$ (initial production and Langevin dynamics under better control)
- Charm in p-A collisions: which relevance for high-energy atmospheric muons/neutrinos (Auger and IceCube experiments)? Possible initial/final-state nuclear effects?

Back-up material

Transport coefficients: perturbative evaluation

It's the stage where the various models differ!

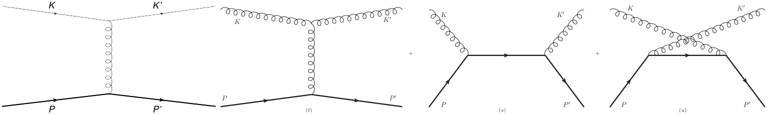
We account for the effect of $2 \to 2$ collisions in the medium

Intermediate cutoff $|t|^* \sim m_D^2$[8] *separating the contributions of*

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

[8] Similar strategy for the evaluation of dE/dx in S. Peigne and A. Peshier, Phys.Rev.D77:114017 (2008).

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



$$\kappa_T^{g/q(\mathrm{hard})} = \frac{1}{2}\frac{1}{2E}\int_k \frac{n_{B/F}(k)}{2k}\int_{k'}\frac{1 \pm n_{B/F}(k')}{2k'}\int_{p'}\frac{1}{2E'}\theta(|t|-|t|^*)\times$$
$$\times\,(2\pi)^4\delta^{(4)}(P+K-P'-K')\left|\overline{\mathcal{M}}_{g/q}(s,t)\right|^2 q_T^2$$

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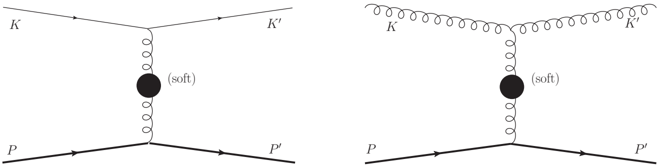
$$\times\,(2\pi)^4\delta^{(4)}(P+K-P'-K')\left|\overline{\mathcal{M}}_{g/q}(s,t)\right|^2 q_L^2$$

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**.

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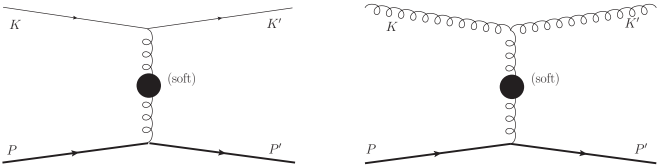

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The *blob* represents the *dressed gluon propagator*, which has longitudinal and transverse components:

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

where *medium effects* are embedded in the HTL gluon self-energy.

Lattice-QCD transport coefficients: setup

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:

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

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In a thermal ensemble $\sigma(\omega) \equiv D^>(\omega) - D^<(\omega) = (1-e^{-\beta\omega})D^>(\omega)$ and

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

Lattice-QCD transport coefficients: results

The spectral function $\sigma(\omega)$ has to be reconstructed starting from the *euclidean electric-field correlator*

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

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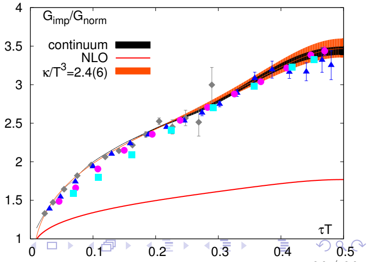
$$\kappa/T^3 \approx 2.4(6) \; (\textit{quenched QCD, cont.lim.})$$

$\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 at QM14)!



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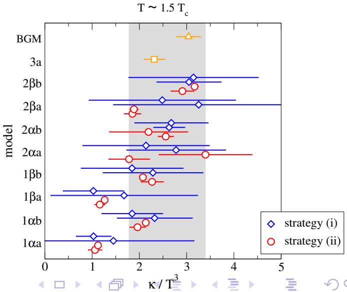

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