Dynamics of heavy flavor quarks in high energy nuclear collisions

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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);

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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 (last part of this talk)

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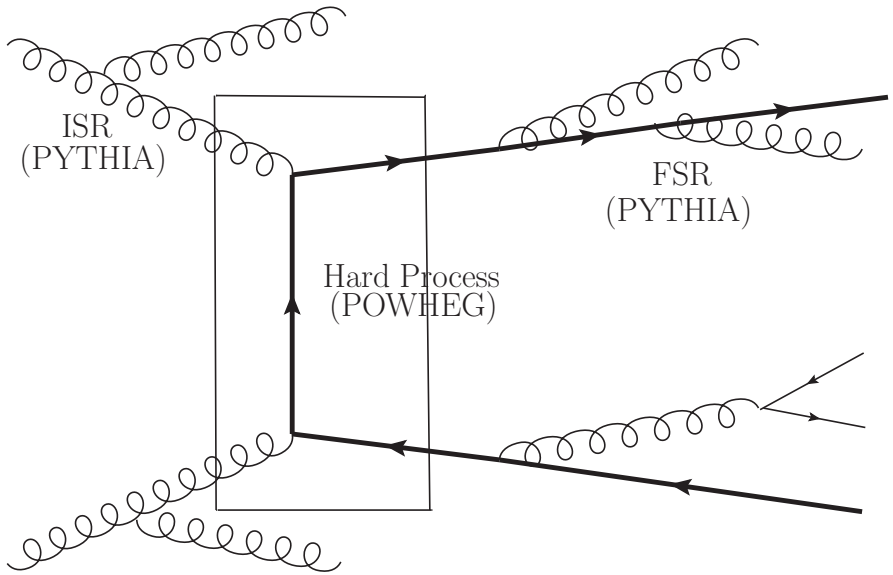
NB for realistic temperatures $g \sim 2$, so that one can wonder *whether a charm is really "heavy"*, at least in the initial stage of the evolution.

Simulating the initial hard production

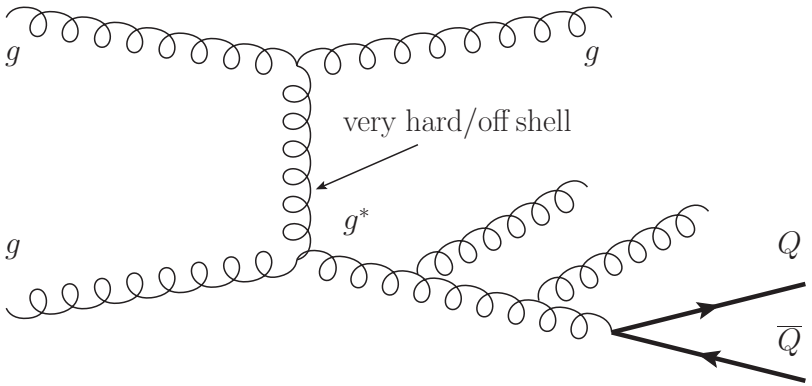


- Powerful pQCD tools[1] are available to simulate the initial $Q\overline{Q}$ production, interfacing the output of a NLO event-generator (POWHEG, MC@NLO) for the hard process with a parton-shower (PYTHIA, HERWIG) describing Initial and Final State Radiation.
- This provides a *fully exclusive information on the final state*

[1] For a systematic comparison (POWHEG vs MC@NLO vs FONLL): M. Cacciari *et al.*, JHEP 1210 (2012) 137.

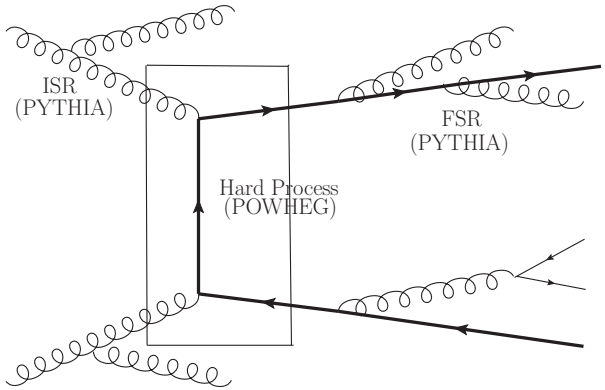
FONLL vs POWHEG+PS

FONLL



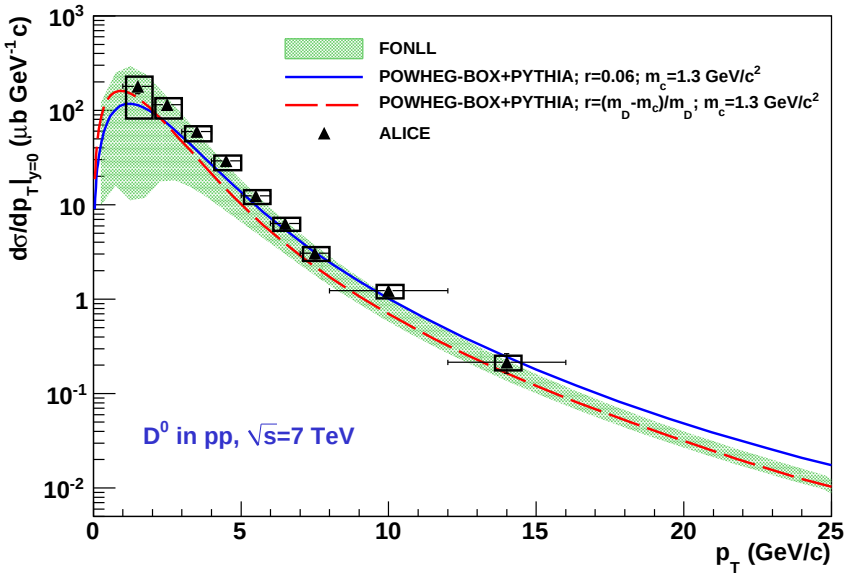
- It is a *calculation*
- It provides NLL accuracy, resumming large $\ln(p_T/M)$
- It includes processes missed by POWHEG (hard events with light partons)

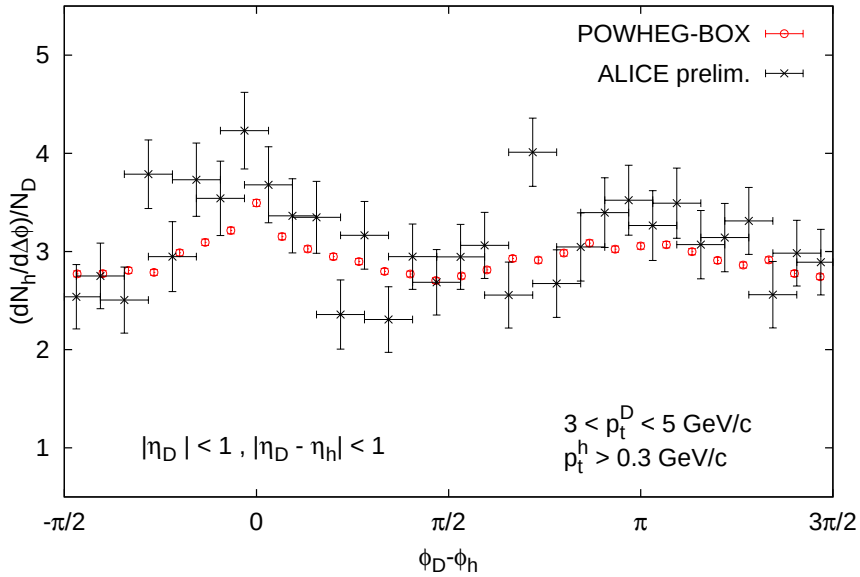
POWHEG+PS



- It is an *event generator*
- Results compatible with FONLL
- It is a more flexible tool, allowing to address more differential observables (e.g. $Q\overline{Q}$ correlations)

HF production in *pp* collisions: results





- Besides reproducing the inclusive p_T-spectra...[2]
- ...the POWHEG+PYTHIA setup allows also the comparison with $D-h$ correlation data, which start getting available (see M. Nardi poster)

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

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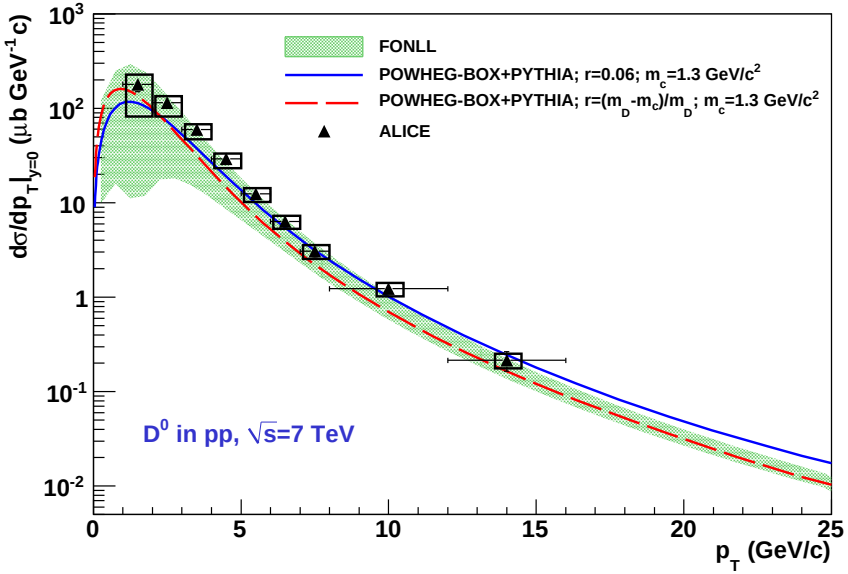

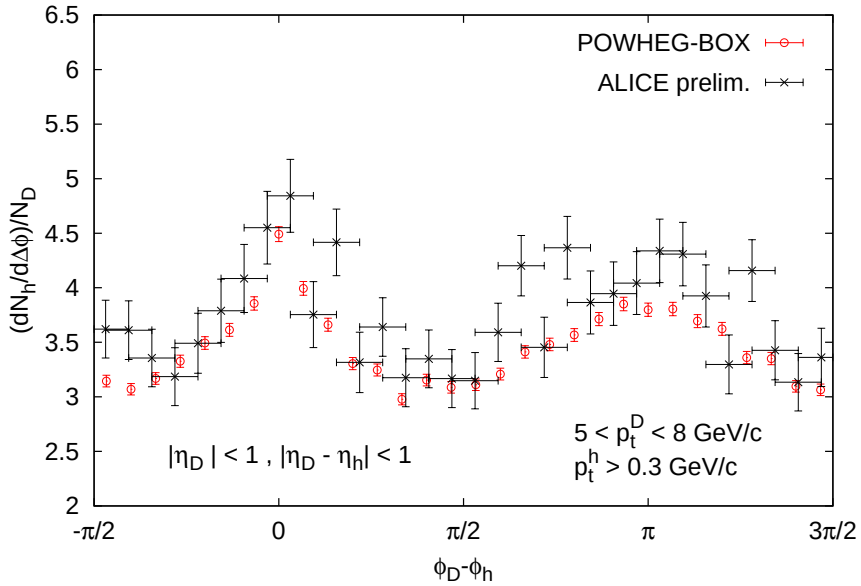

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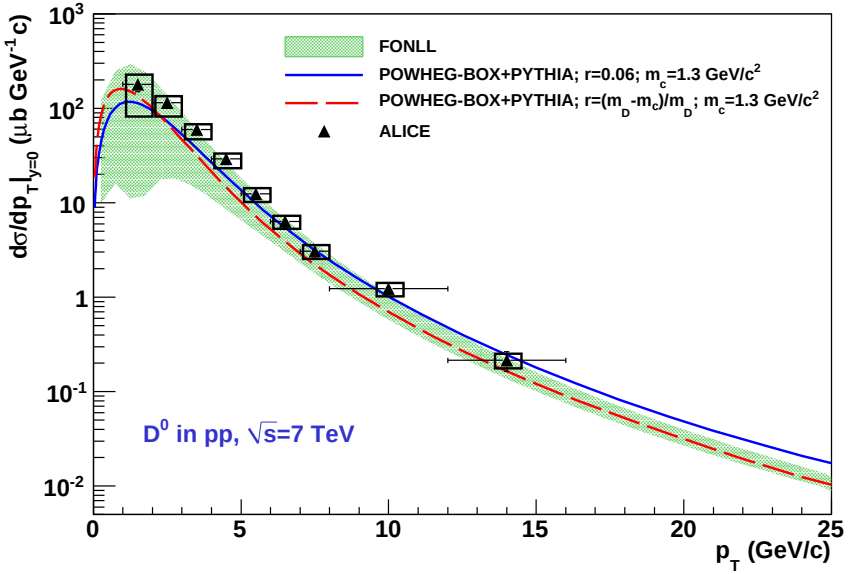

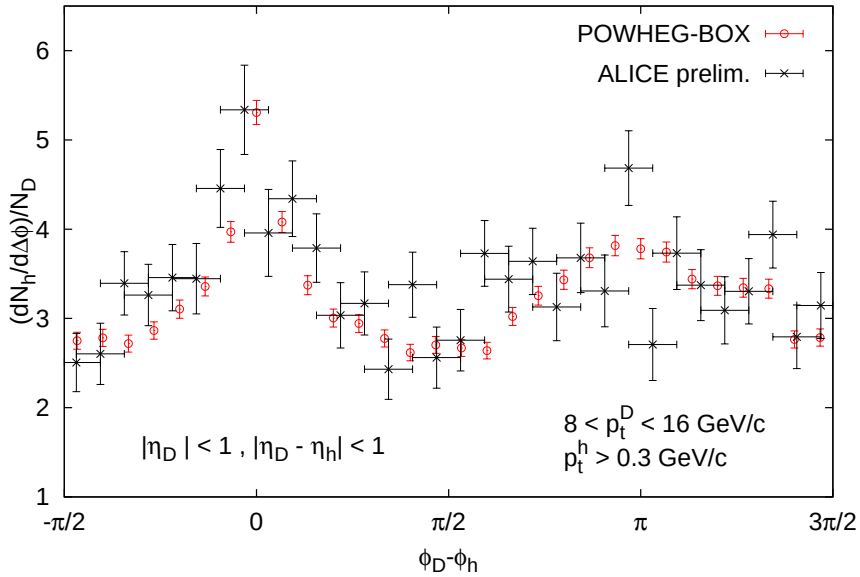

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HF in nucleus-nucleus collisions

- 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 $\sqrt{s_{\mathrm{NN}}}$?

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 $\mathbf{x}$-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] Approach implemented in codes like BAMPS (J. Uphoff talk at this conf.)

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* (approx. to be quantitatively tested!)

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

where

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

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

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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

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

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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!)

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

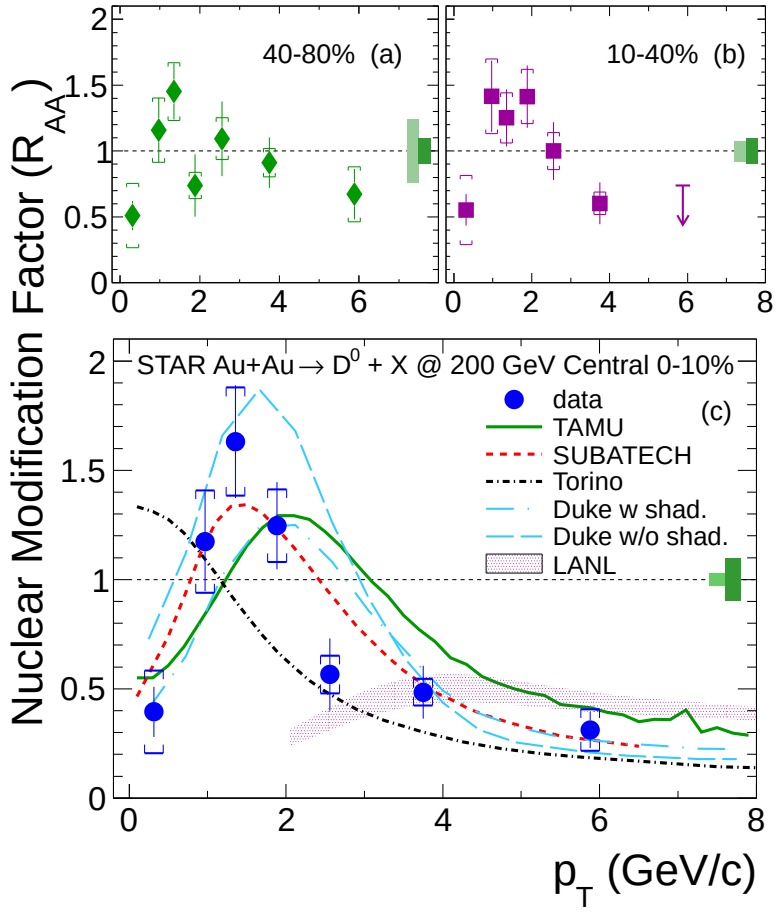
fixed in order to assure approach to equilibrium (Einstein relation):

Results vs experimental data

D-mesons at low-p_T: STAR data compared to various model predictions (see parallel talks).
Sharp peak ≈ 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...



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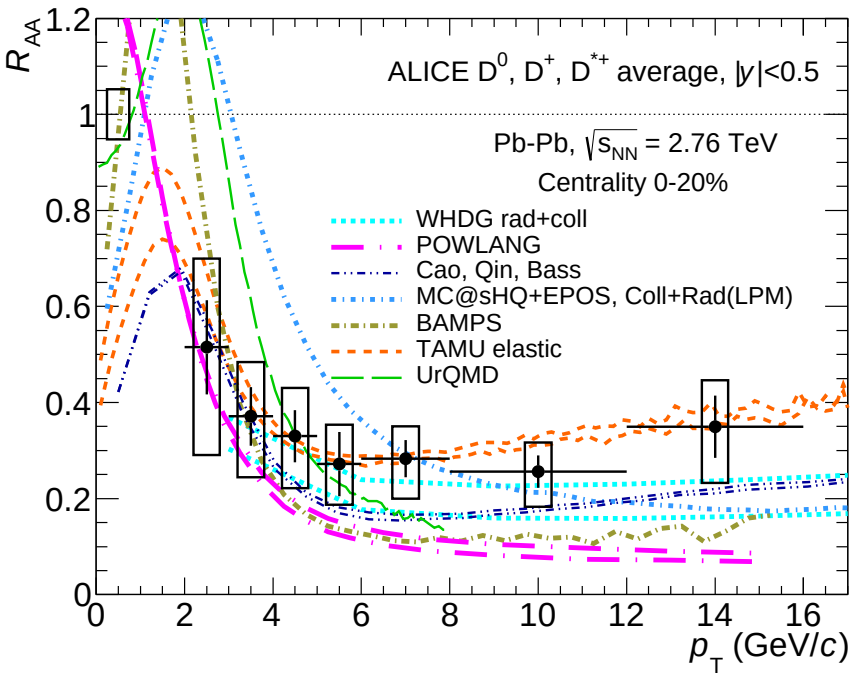

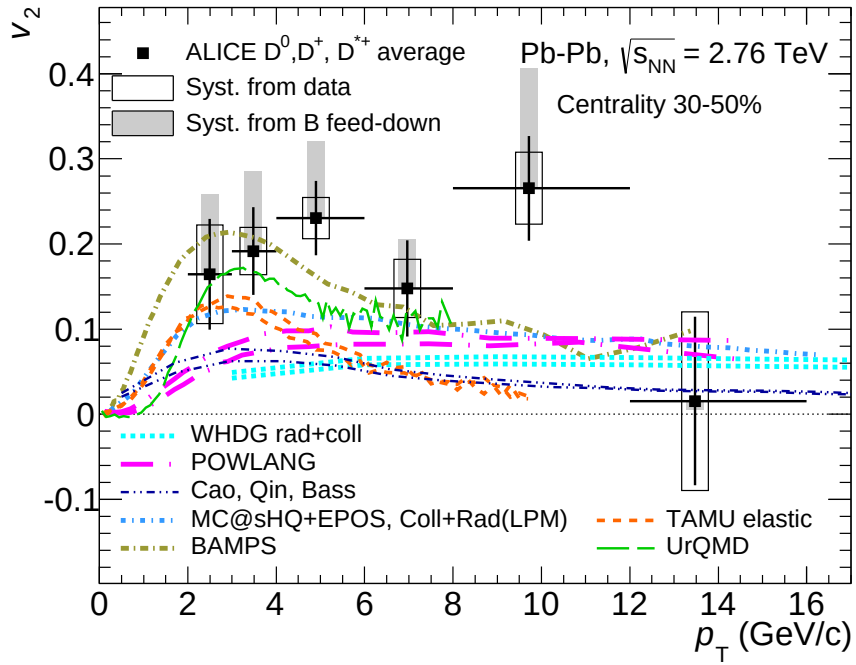

ALICE data so far cover a higher-p_T region

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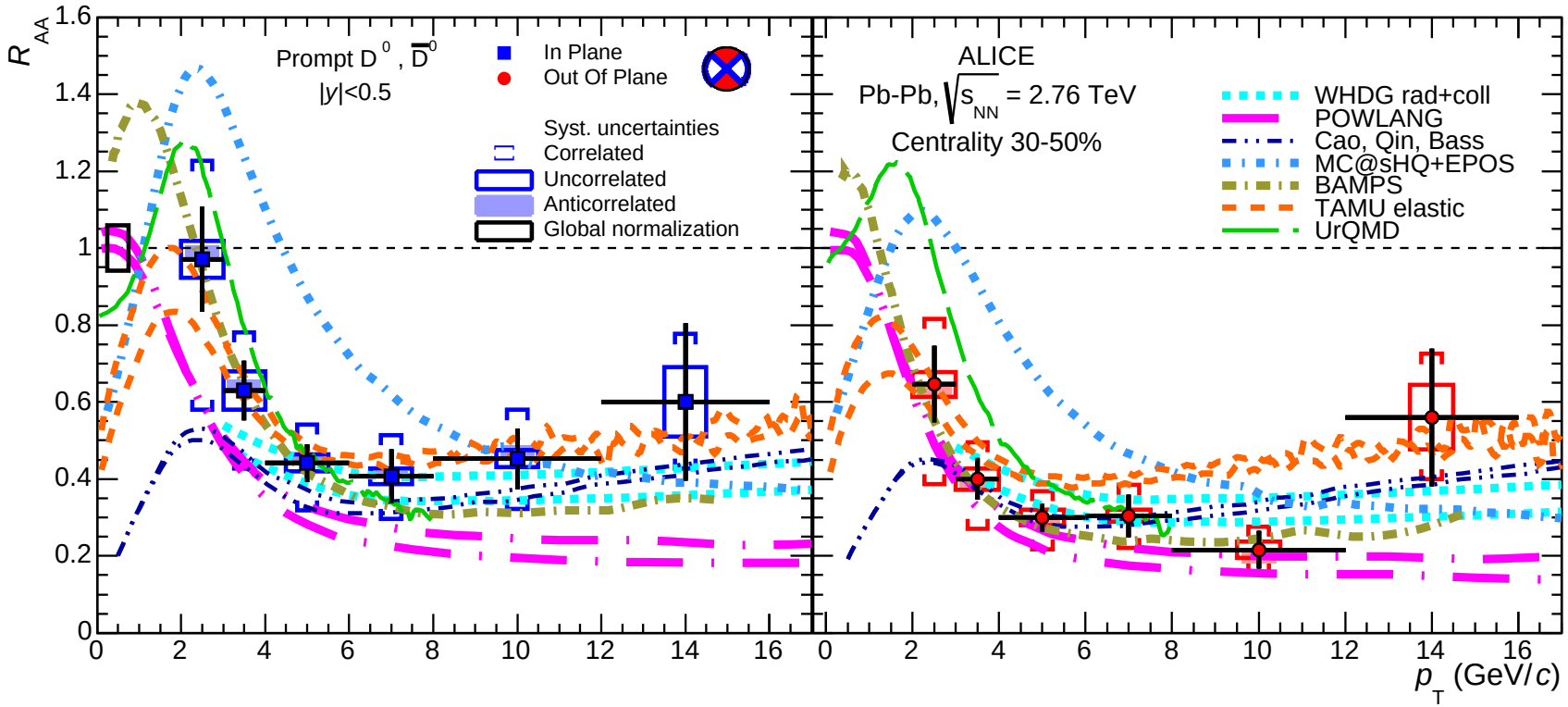

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- Models are challenged to reproduce both R_{AA} and v_2
- R_{AA} vs EP allows the study of *path-length* dependence of energy-loss

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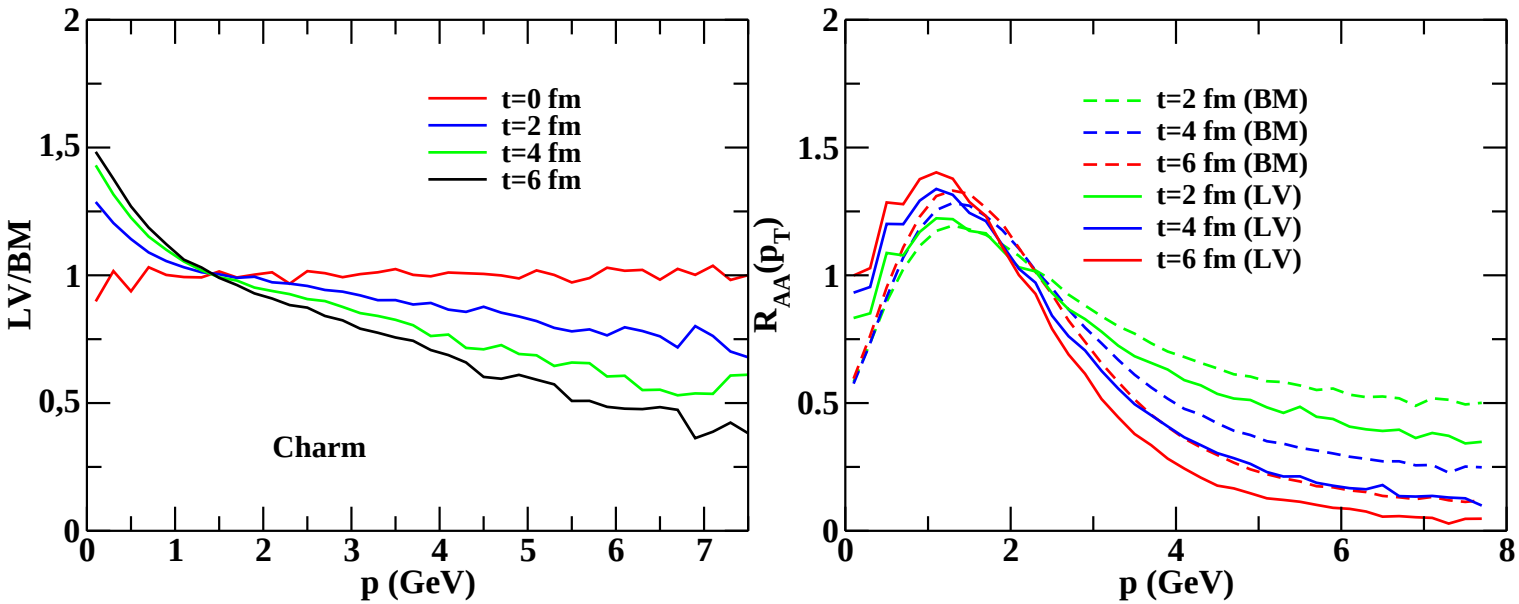

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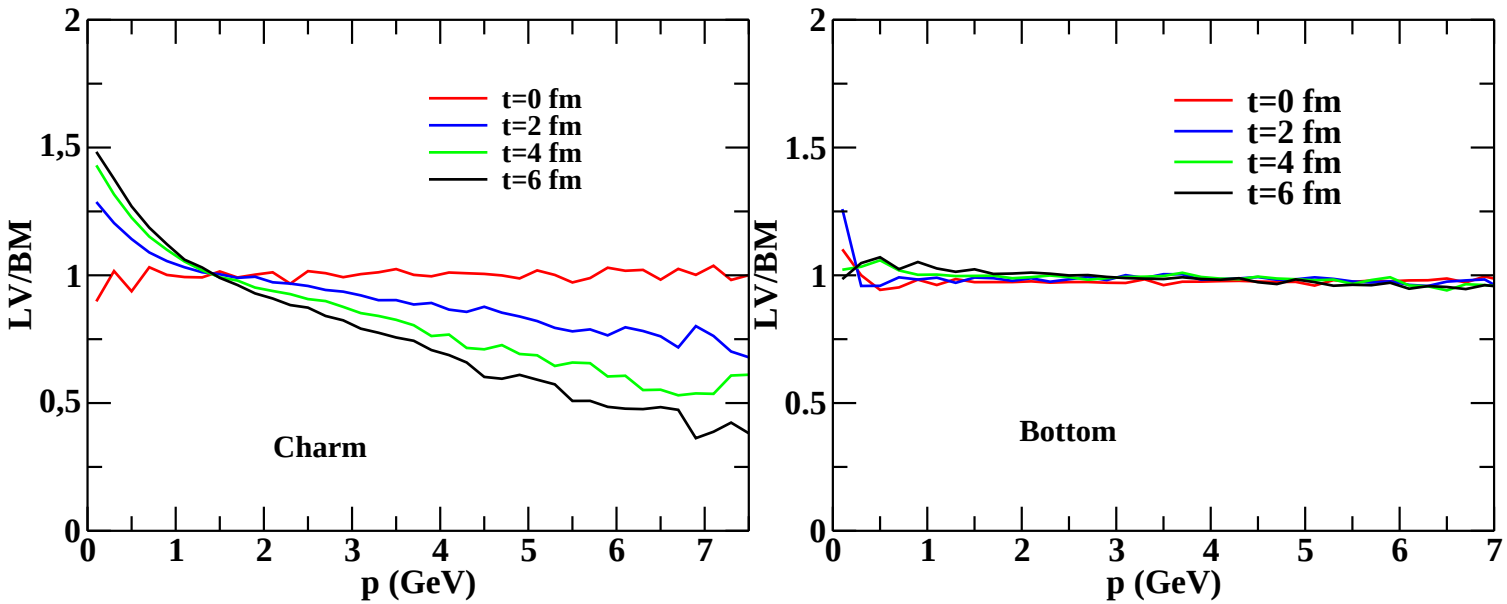

For beauty on the other hand Langevin≡Boltzmann!

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

Hence, in the $p \longrightarrow 0$ 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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κ is then given by the $\omega \to 0$ limit of the *spectral density* $\sigma(\omega)$ of the above E-field correlator

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

Lattice-QCD transport coefficients: results

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

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

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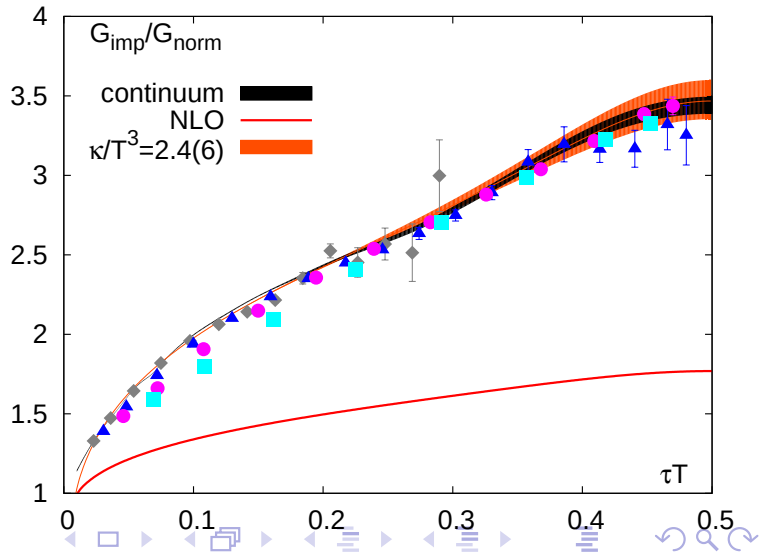
$\kappa/T^3 \approx 2.4(6)$ (*quenched QCD*, *cont.lim.*)

$\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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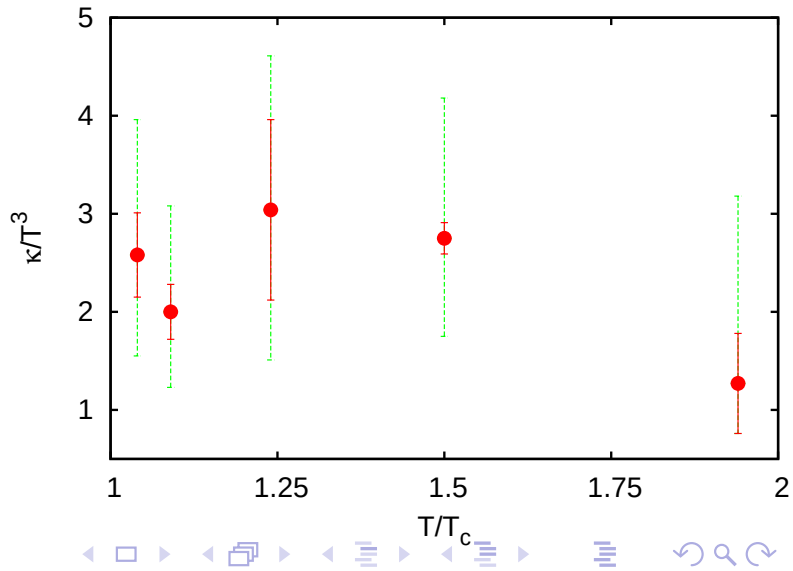

Lattice-QCD transport coefficients: results

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

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

according to

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

One gets (D. Banerjee *et al.*, PRD 85 (2012) 014510; A. Francis *et al.*, PoS LATTICE2011 202 and arXiv:1311.3759 [hep-lat])

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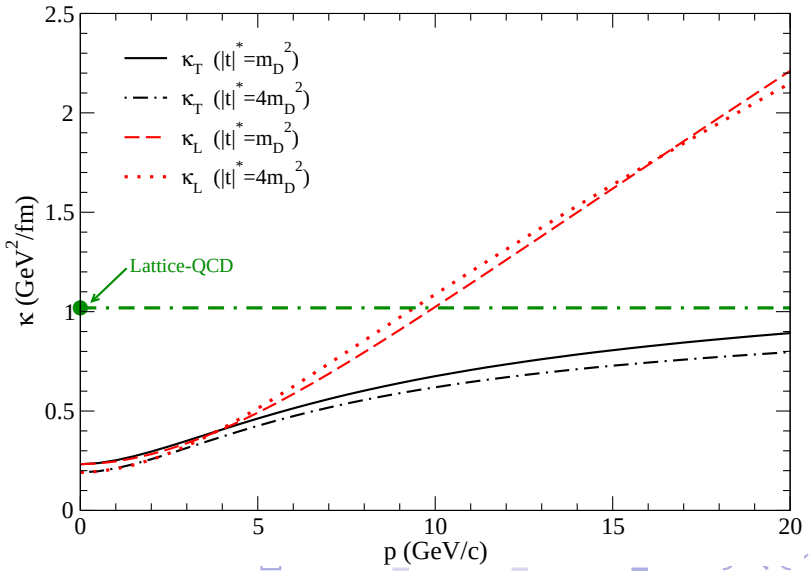

First message: look at beauty!

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:

- $M \gg gT$: Langevin equation equivalent to Boltzmann equation;
- $M \gg T$: static ($M = \infty$) l-QCD results more reliable for beauty

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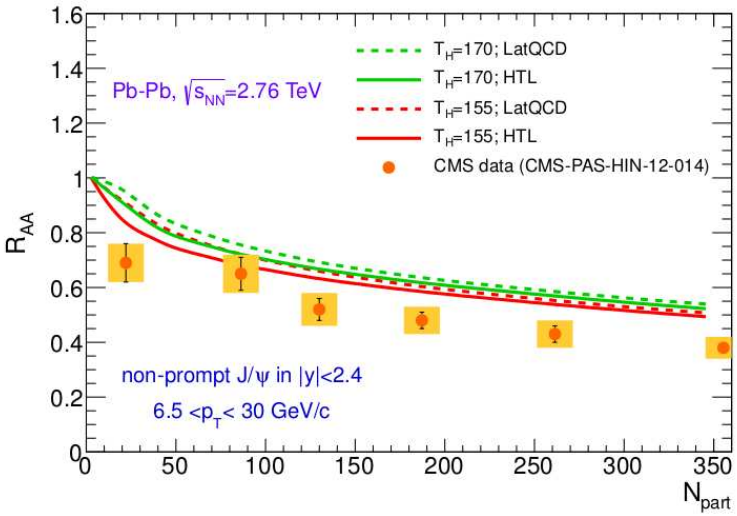

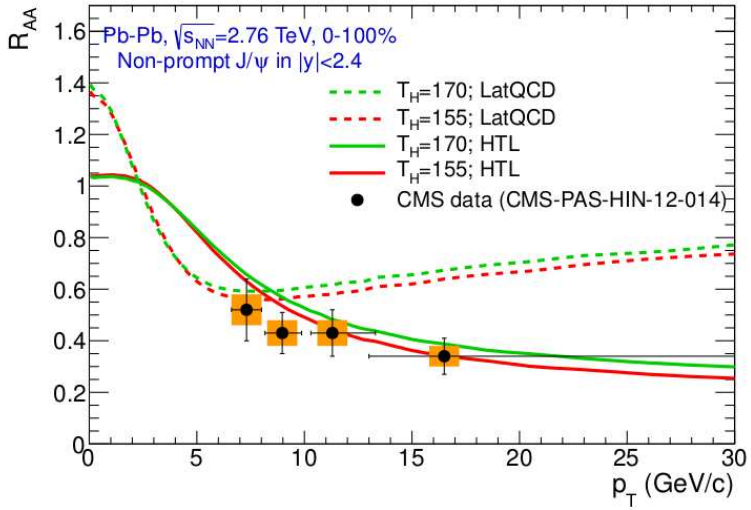

Measurements so far limited to non-prompt J/ψ's at quite high p_T

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?
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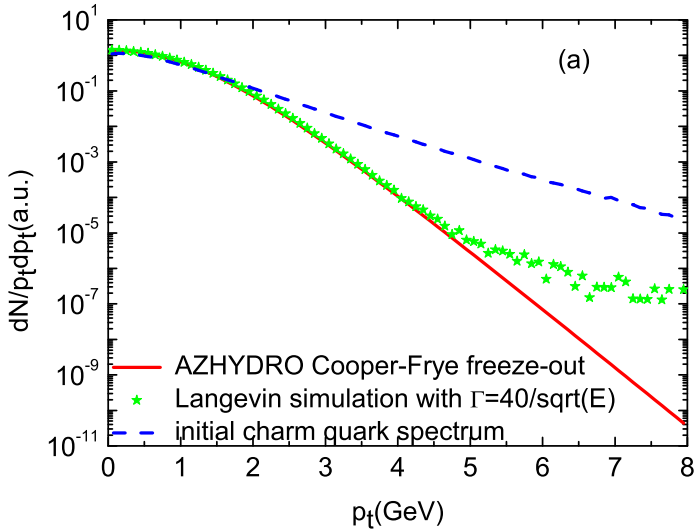
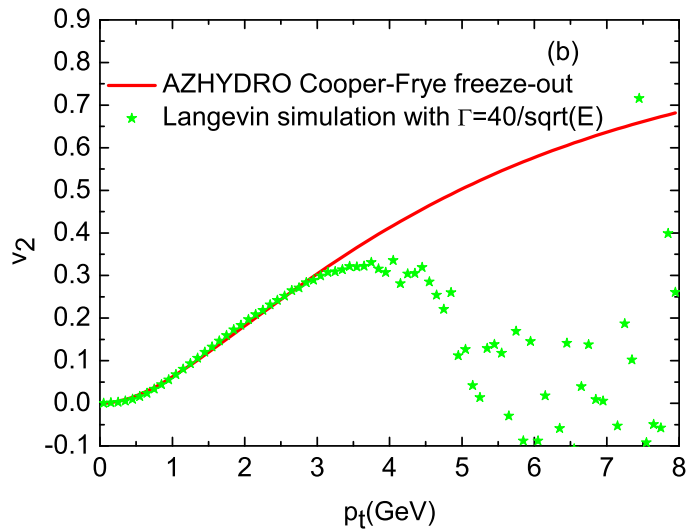
NB thermal equilibrium of HQ's at the end of the QGP phase is assumed in the description of hidden and open charm production within the Statistical Hadronization Model

Validation of the theoretical tools

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:

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





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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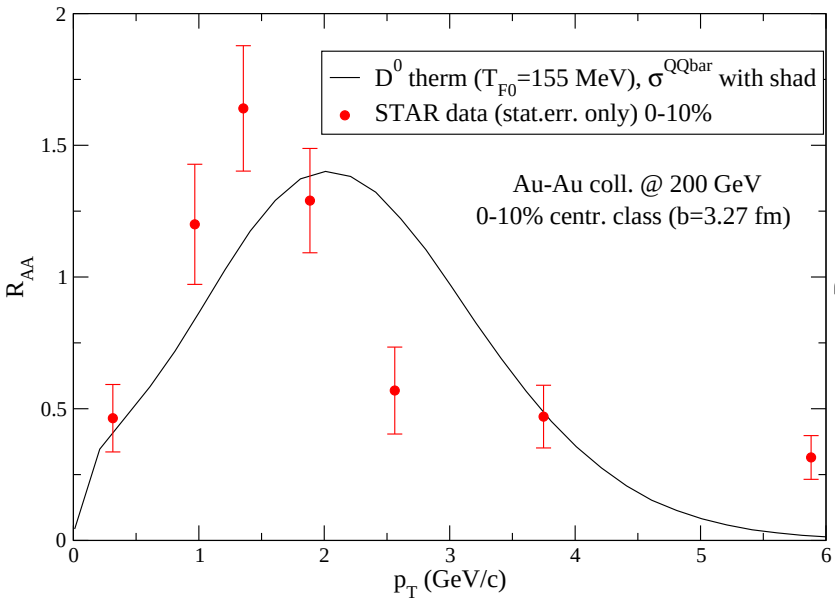

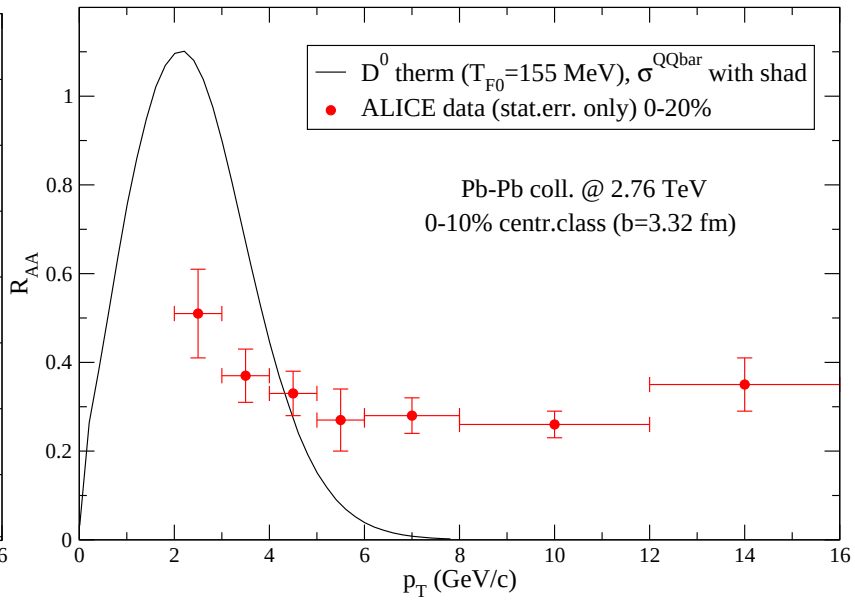

Evidence of peak from radial flow at RHIC, while more data at low-p_T (waiting for ALICE ITS upgrade, S. Siddhanta talk) necessary at LHC; in any case charm at least *partially out of kinetic equilibrium*

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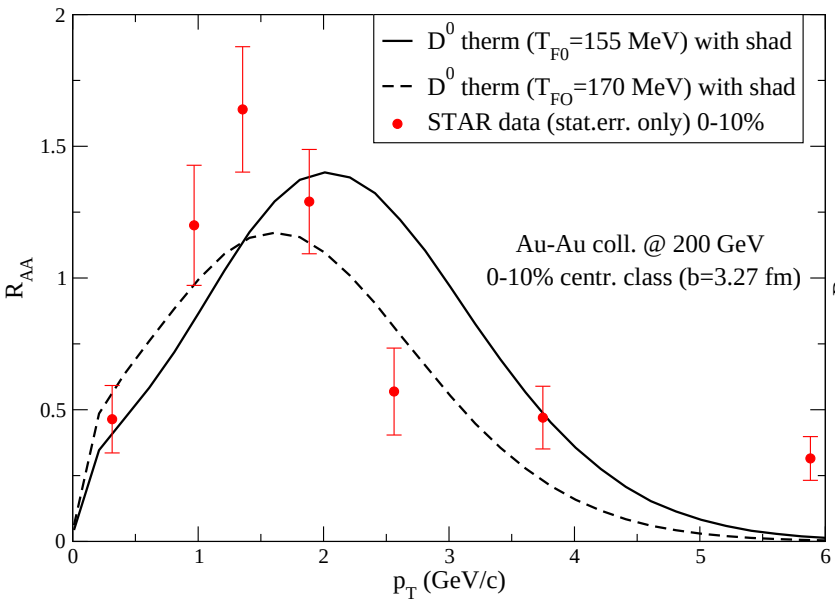

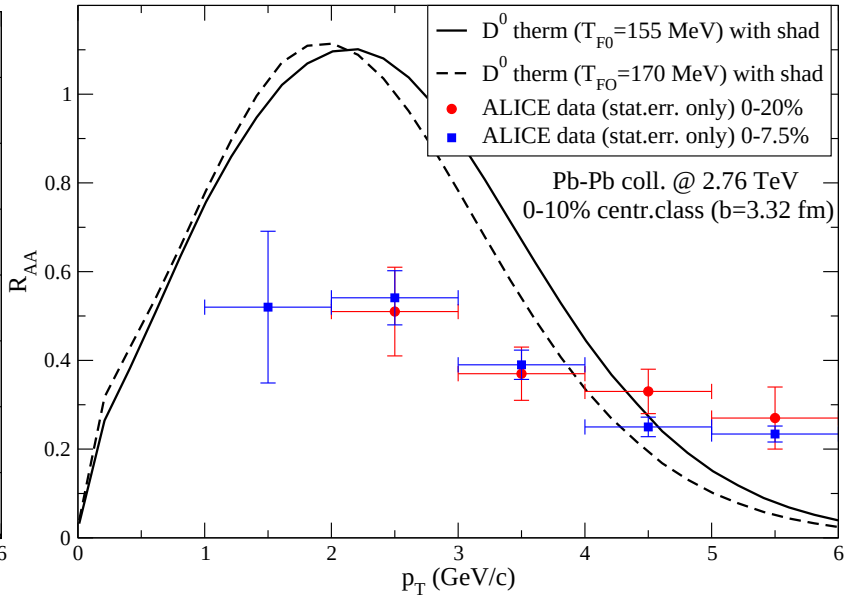

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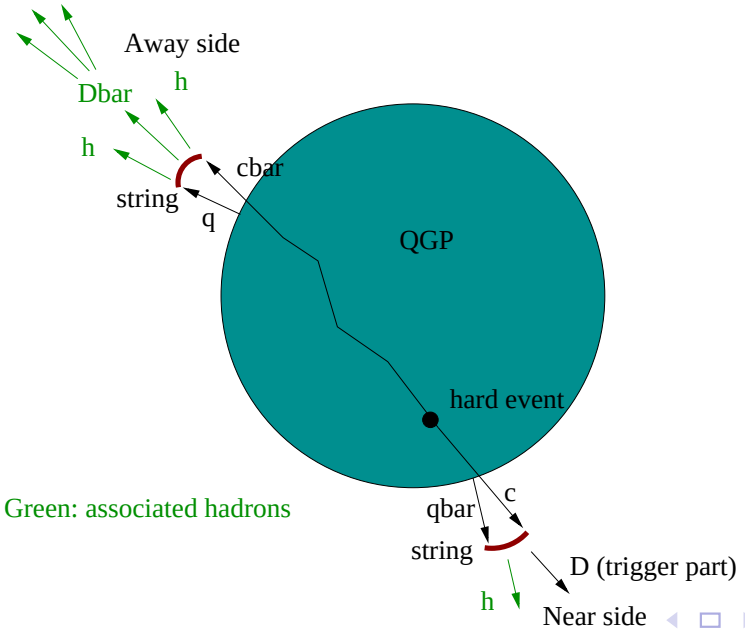
From quarks to hadrons

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:

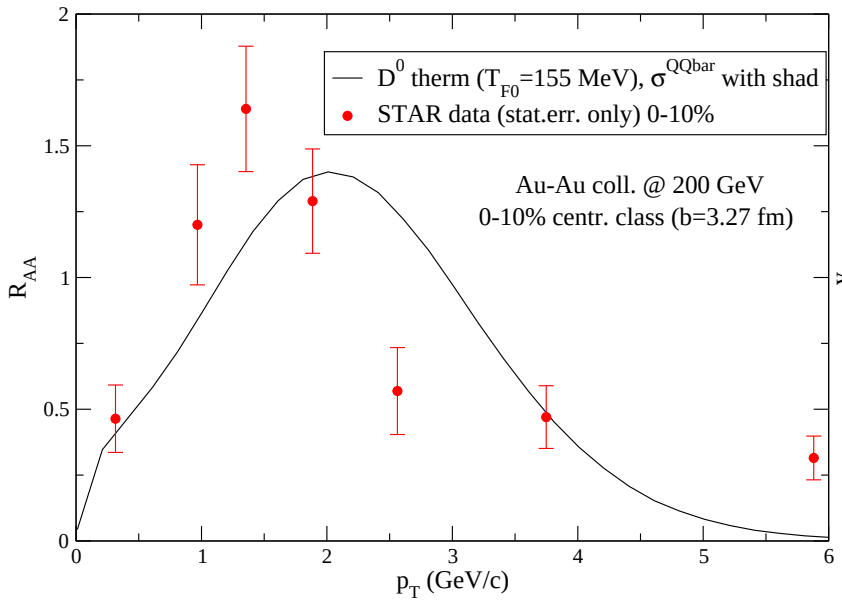
- At $T_{\rm dec}$ c-quarks coupled to light $\overline{q}$'s from a local *thermal distribution*, eventually *boosted* ($u^{\mu}_{\rm fluid} \neq 0$) to the lab frame;
- Strings are formed and given to PYTHIA 6.4 to simulate their fragmentation and produce the final hadrons ($D + \pi + \ldots$)

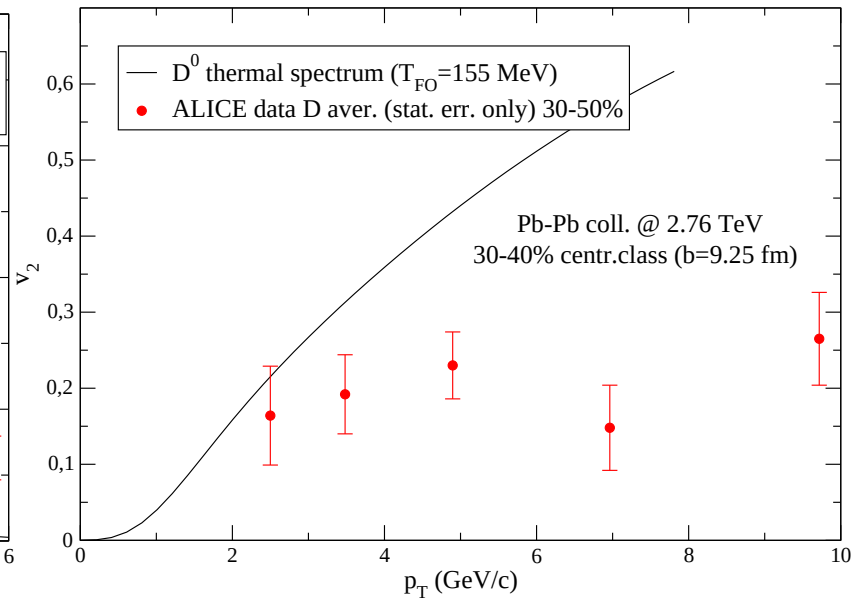
Approach allows also the study of $D - h$ correlations in AA collisions



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*





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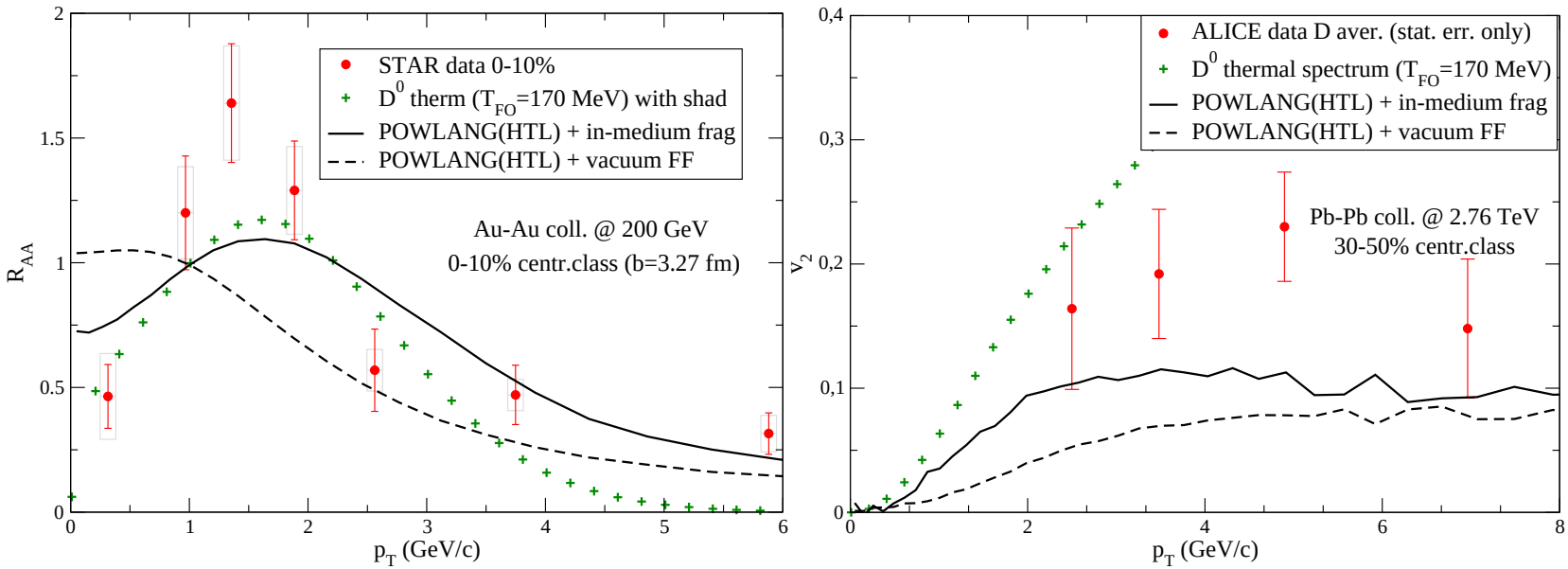

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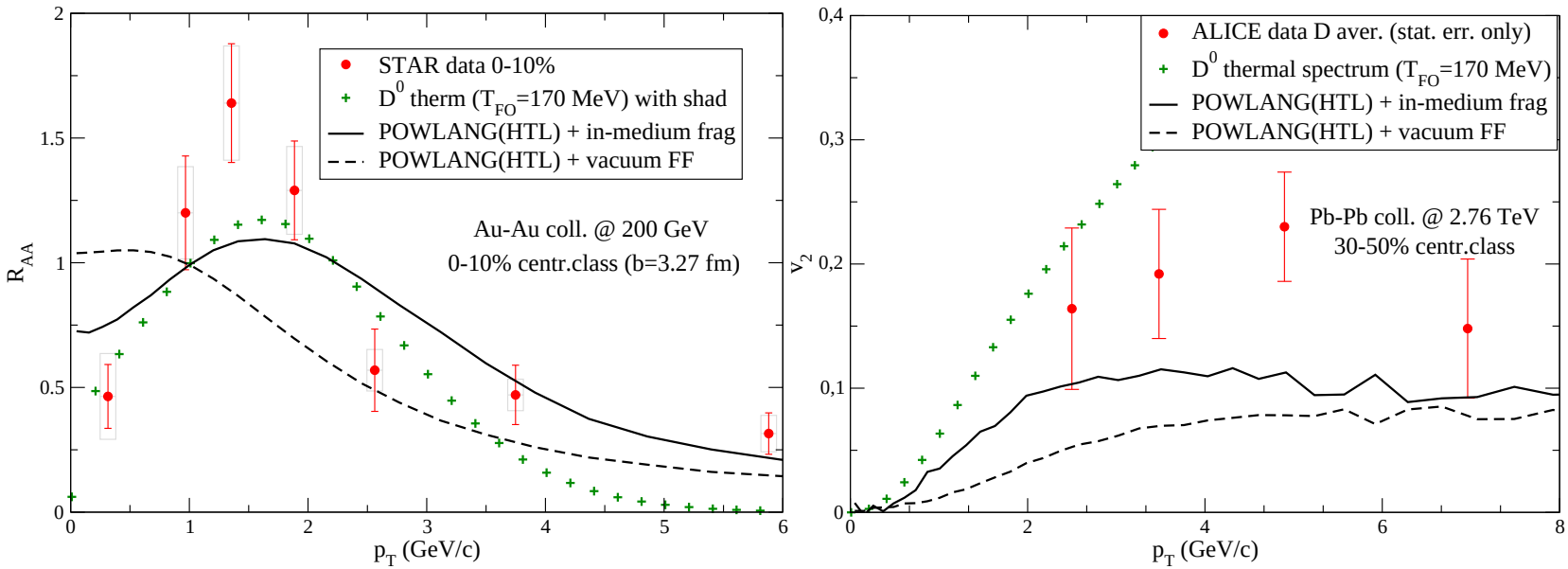

However, *comparing the curves with/without the boost* due to u^{μ}_{fluid}, at least part of the effect might be due to the radial and elliptic flow of the light partons from the medium picked-up at hadronization.

Rescattering in the hadronic phase should be also investigated (see Ozvenchuk and Torres-Rincon posters)!

A new possibility: $D-h$ correlations

Facing $D-h$ correlations in nuclear collisions represents a real challenge for theory calculations, requiring a complete modeling of hadronization in the presence of a hot medium, which introduces *large uncertainties*.

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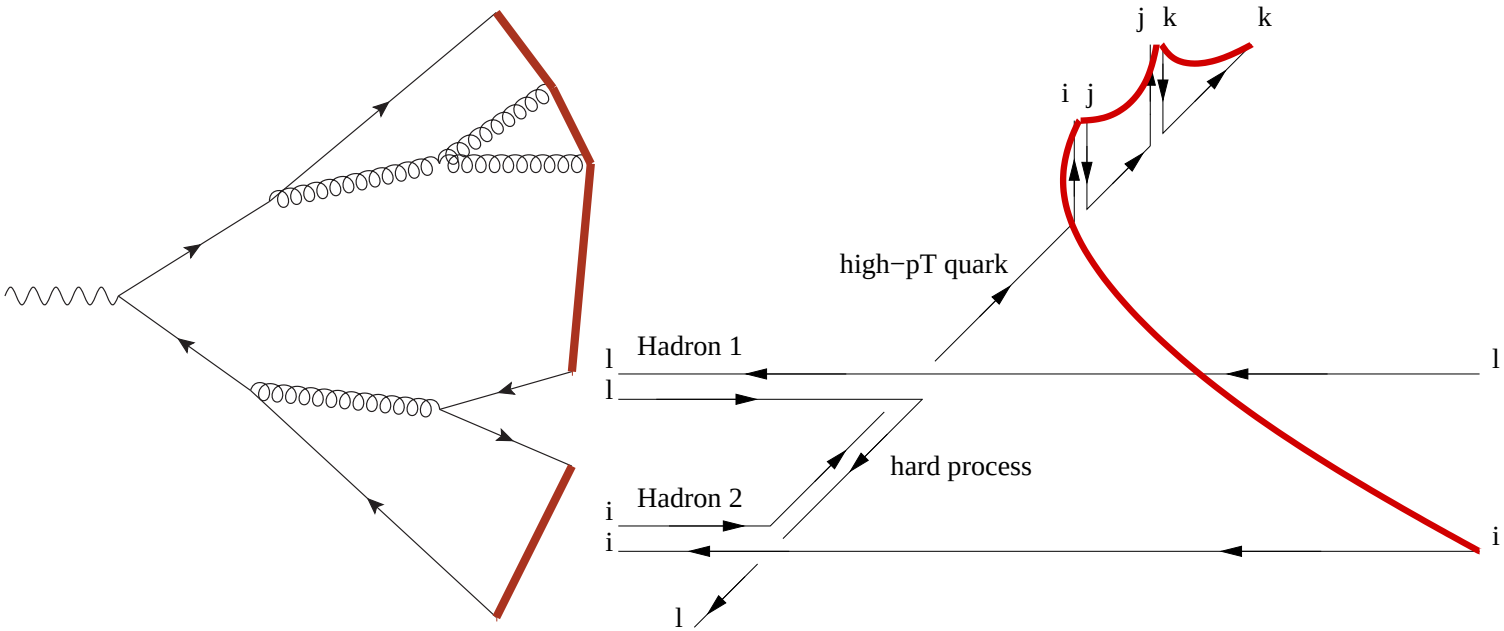

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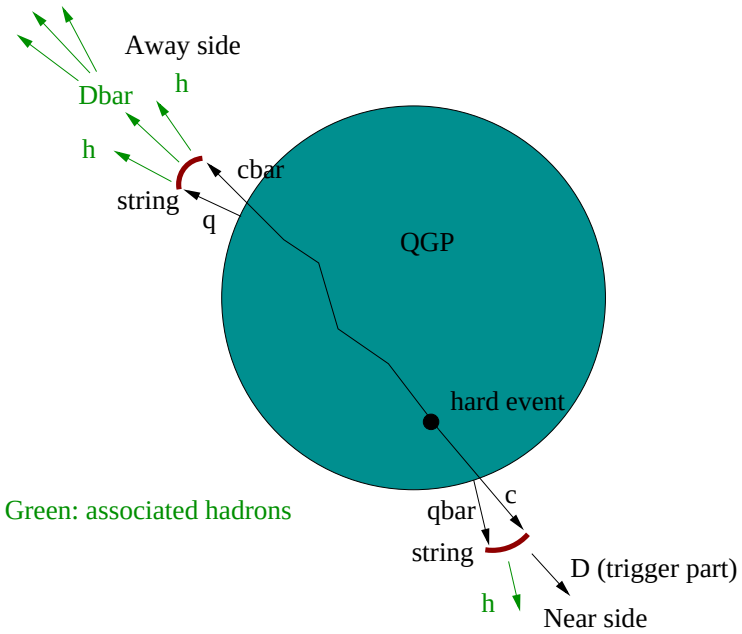

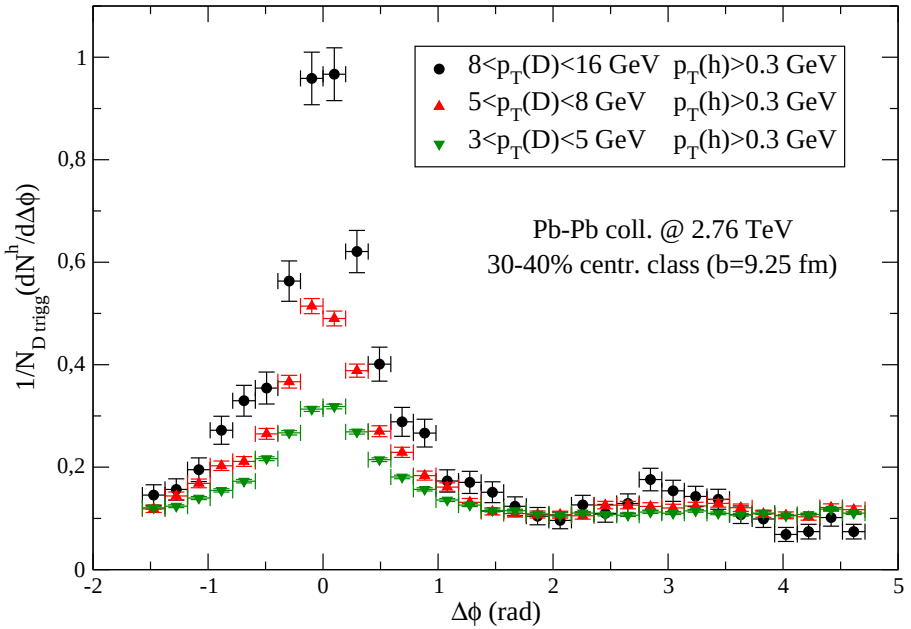

With this grain of salt *preliminary results* with our models can be shown[5]
One observes an almost complete suppression of the away-side peak

[5] See M. Nardi poster

HF correlations: what one can realistically expect

Experimentally accessible signals in AA and pA collisions only *indirectly* related to charm, e.g. $e-h$ or $D-h$ correlations.

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- from the hadronization of the light partons hit/radiated by c-quarks
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$D-\overline{D}$ correlation remaining a dream, *if the purpose is to study the angular decorrelation occurring in the partonic phase* it would be important, in view of a theory/experiment comparison, to choose probes which can only come (in principle) from the charm/beauty decays, e.g. e^+-e^-, $e-\mu$, $D-e$

Chemical equilibrium?

- The possibility of performing future experiments at much larger beam energies ($\sqrt{s_{NN}} = 39$ TeV at FCC) raises the question of the possibility for charm to reach *chemical* equilibrium with the plasma

[6] WB Collaboration, NPA 904-905 (2013) 869c-872c and PLB 730 (2014) 99-104

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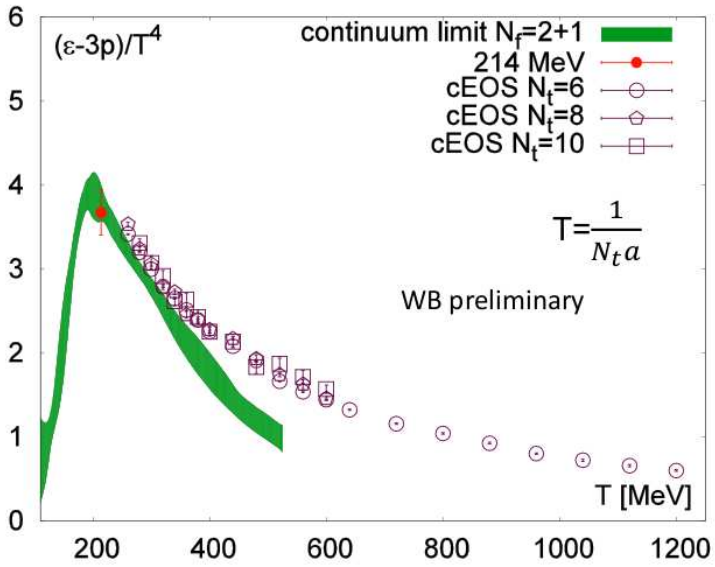
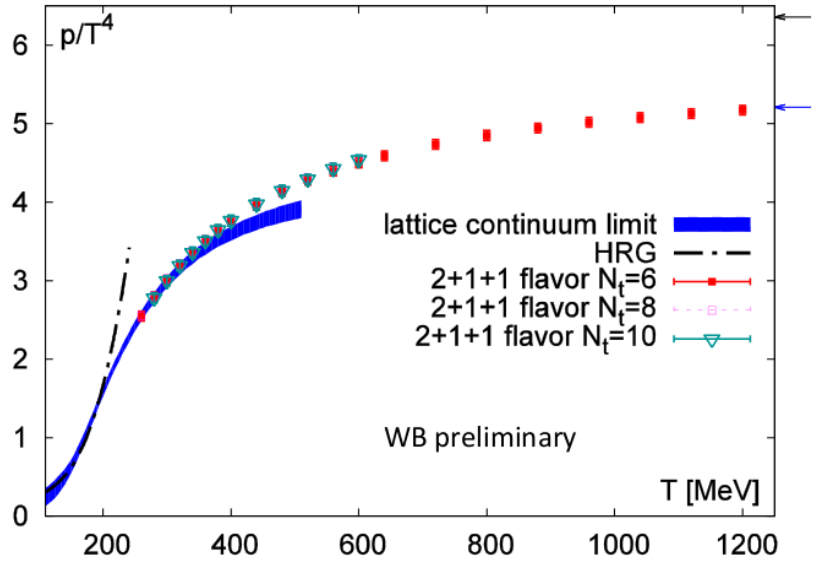
- The possibility of performing future experiments at much larger beam energies ($\sqrt{s_{NN}} = 39$ TeV at FCC) raises the question of the possibility for charm to reach *chemical* equilibrium with the plasma
- if so, charm has to be treated as the other light flavors and its contribution to the EOS has to be taken into account





first results becoming available from lattice-QCD simulations[6]

[6] WB Collaboration, NPA 904-905 (2013) 869c-872c and PLB 730 (2014)

Chemical equilibrium? theoretical setup

- Perturbative calculations (the same as for strangeness) predict

$$\Gamma_{\rm chem} = \frac{g^4 C_F}{8\pi M^2}\left(2C_F - \frac{N_c}{2} + N_f\right)\left(\frac{TM}{2\pi}\right)^{\frac{3}{2}} e^{-M/T}$$

- The result can be recast[7] in a form

$$\Gamma_{\rm chem} = \frac{2\pi\alpha_s^2 T^3}{9M^2}\left(\frac{7}{6} + N_f\right)\frac{\chi_c}{\chi_{\rm light}} \qquad (\chi_i : \text{QN suscept. of flav. } i)$$

  suited to be interfaced to lattice-QCD calculations[8], providing the estimates

$$\Gamma_{\rm chem}^{-1} \sim 60\ \text{fm/c}, \quad \text{for } T \sim 400\ \text{MeV}$$
$$\Gamma_{\rm chem}^{-1} \sim 10\ \text{fm/c}, \quad \text{for } T \sim 600\ \text{MeV}$$

[7] D. Bödeker and M.Laine, JHEP 07 (2012) 130

[8] H.T. Ding *et al*, PoS LATTICE 2010 (2010) 180; S. Borsany *et al*, PoS LATTICE 2011 (2011) 201

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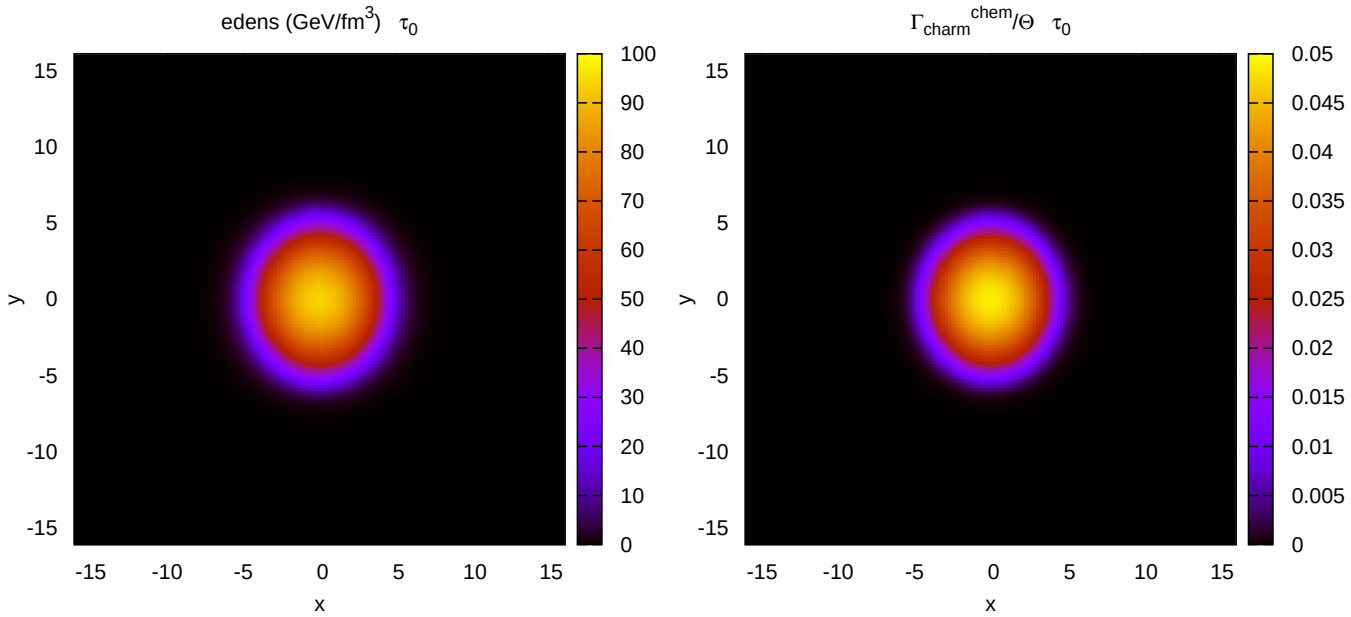

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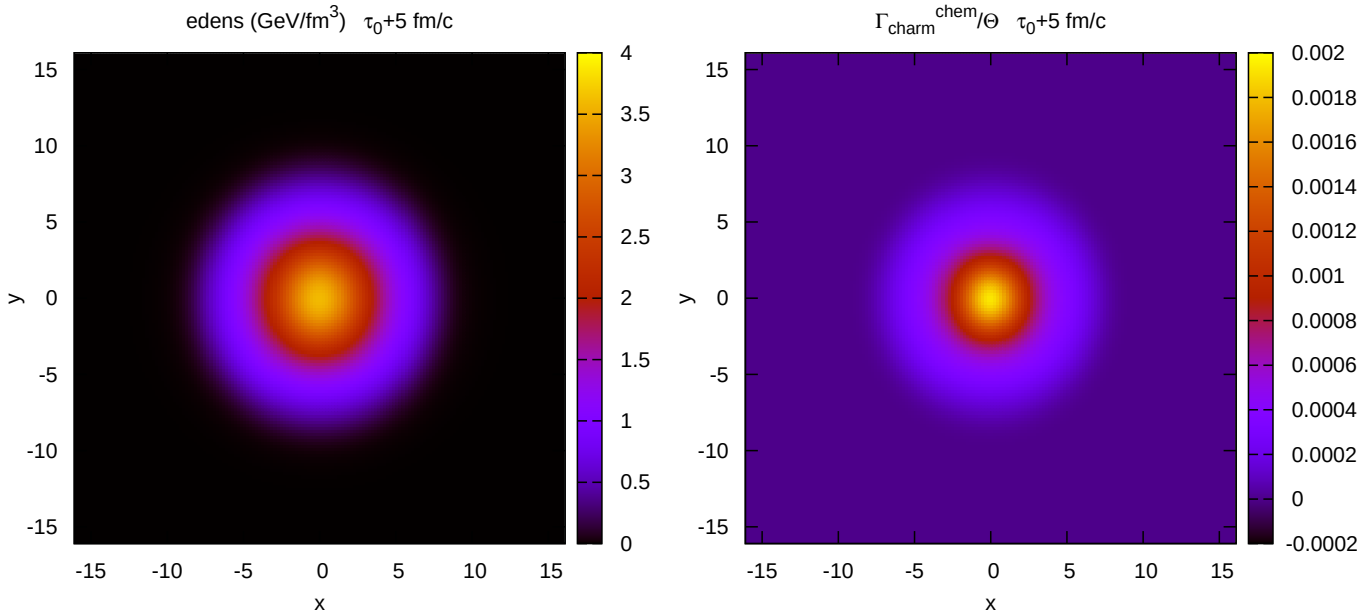

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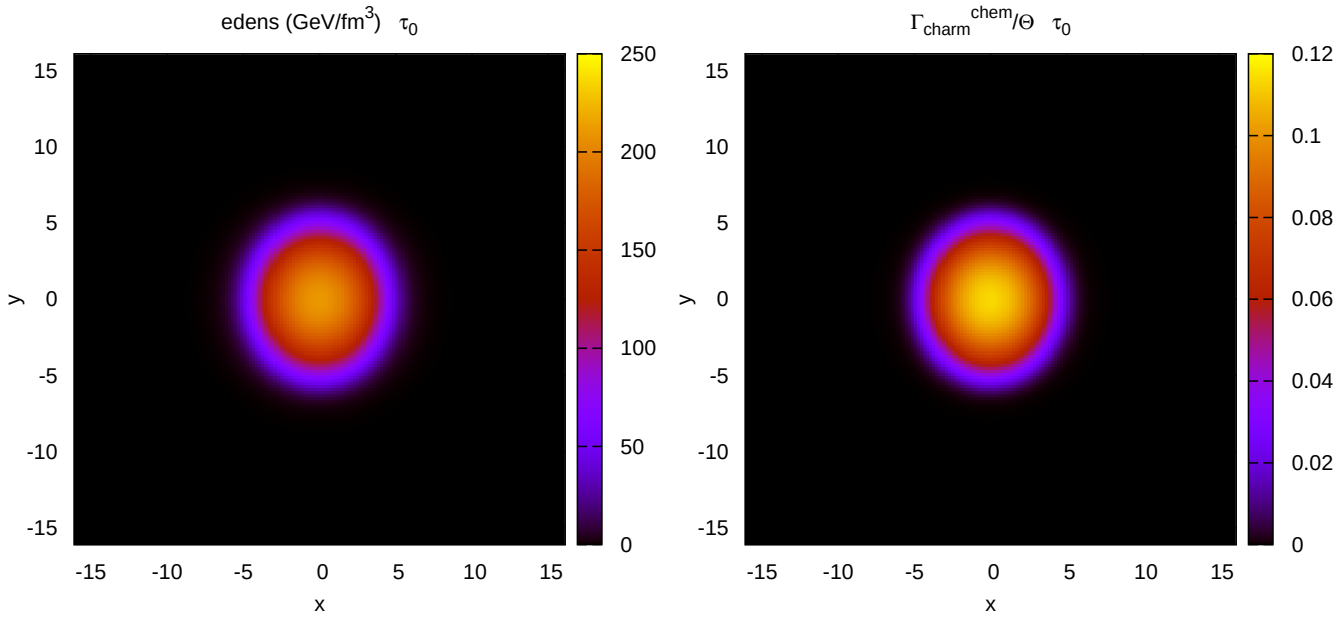

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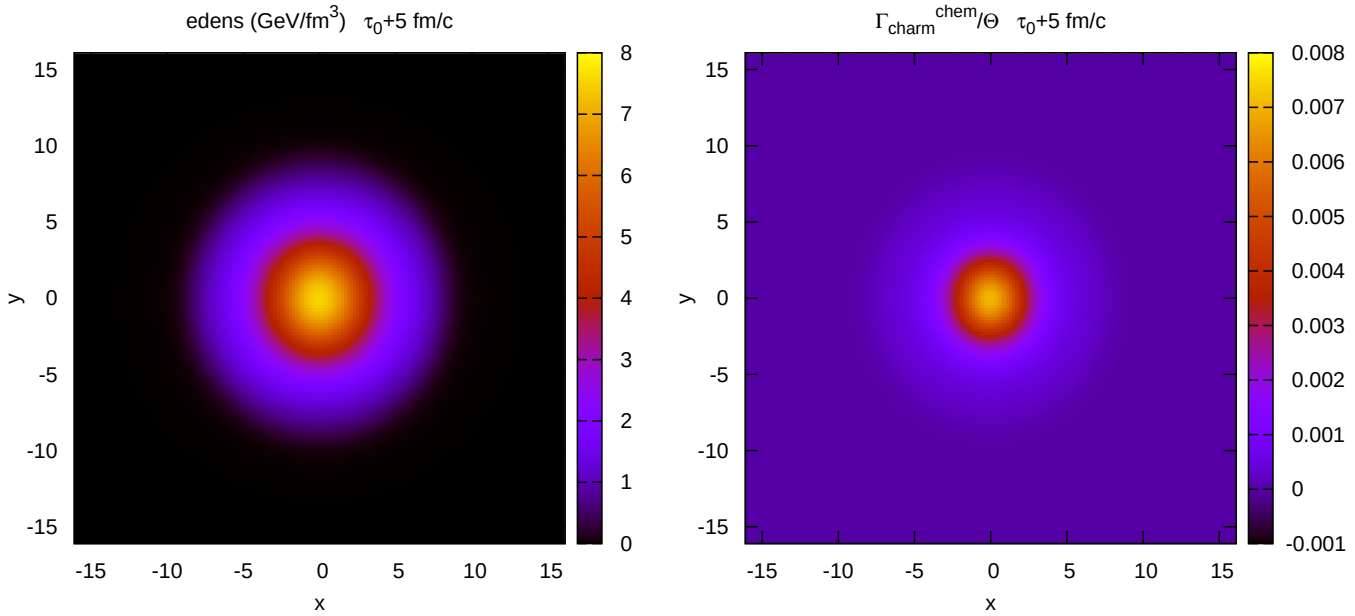

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Heavy Flavor at high-p_T

HF at high-p_T become a tool to study the dependence of jet-quenching on the

- color charge (rate of gluon emission)
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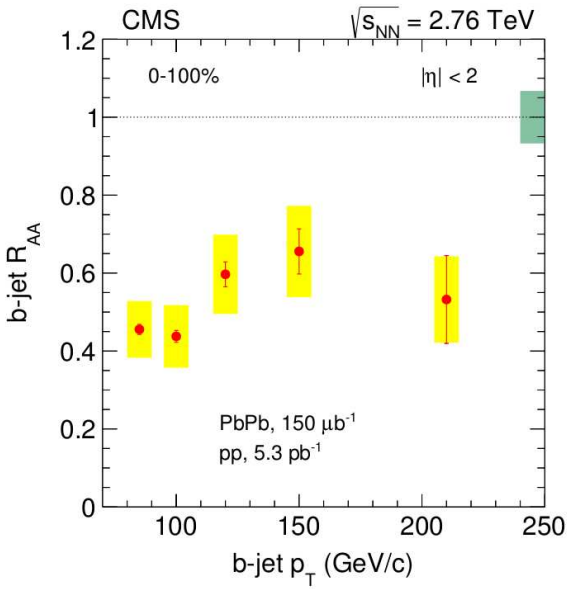
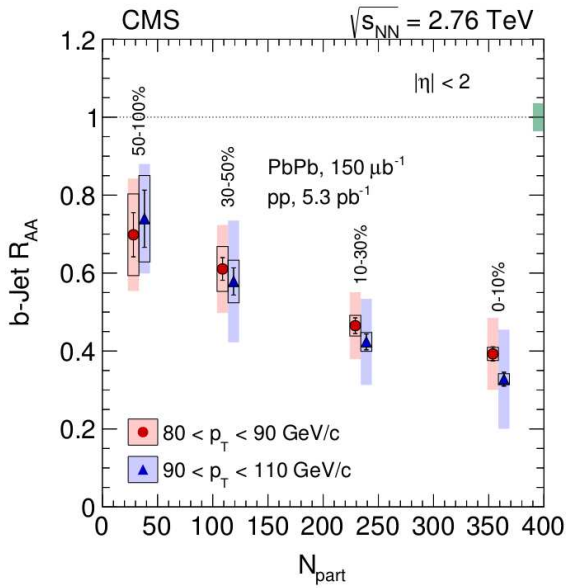




Quenching of *b*-jets compatible with light flavors (see K.E. Jung talk)

HF at high-p_T: theoretical setup (I)

Already in the case of a medium of *static scattering centers* (pure Yukawa-like potentials) the finite quark mass introduces important modification to the spectrum of radiated gluons (DGLV approach)

$$x\frac{dN_g}{dxd\mathbf{k}} = \frac{C_F\alpha_s}{\pi^2}\left(\frac{L}{\lambda_g}\right)\int d\mathbf{q}\frac{\mu^2}{\pi(\mathbf{q}^2+\mu^2)^2}\left[1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2+x^2M^2}{2xE}\Delta z_1\right)\right] \times \frac{-2(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+x^2M^2}\left(\frac{\mathbf{k}}{\mathbf{k}^2+x^2M^2}-\frac{\mathbf{k}-\mathbf{q}}{(\mathbf{k}-\mathbf{q})^2+x^2M^2}\right)$$

affecting ($x=\omega/E$)

- both the formation time $\tau_f \approx 2\omega/[(\mathbf{k}-\mathbf{q})^2+x^2M^2]$
- and the angular distribution of radiation

HF at high-p_T: theoretical setup (II)

The major modification considering a realistic *dynamical medium*[9] of light quarks and gluons is the appearance of *unscreened* magnetic interactions

$$x\frac{dN_g}{dxd\mathbf{k}} = \frac{C_F\alpha_s}{\pi^2}\left(\frac{L}{\lambda_{\rm dyn}}\right)\int d\mathbf{q}\frac{\mu^2}{\pi\,\mathbf{q}^2(\mathbf{q}^2+\mu^2)}\left[1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2+\chi^2}{2xE}\Delta z_1\right)\right] \times\frac{-2(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2}\left(\frac{\mathbf{k}}{\mathbf{k}^2+\chi^2}-\frac{\mathbf{k}-\mathbf{q}}{(\mathbf{k}-\mathbf{q})^2+\chi^2}\right)$$

which (in the above $\chi^2 \equiv x^2M^2 + m_g^2$)

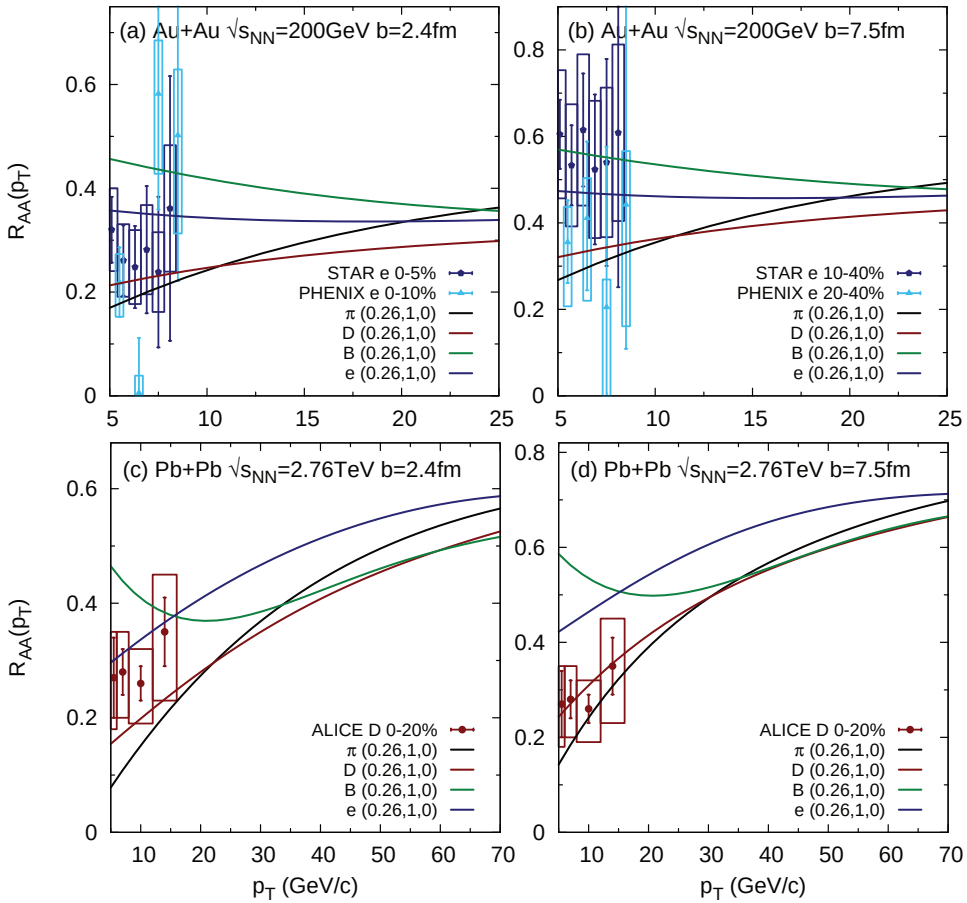
- enhance the cross section for *soft-momentum exchange*
- require the introduction of an "effective" dynamical gluon mean-free-path $\lambda_{\rm dyn}^{-1} \equiv 3\alpha_s T$

Overall, the effect is an enhancement of the radiative energy-loss

[9] M. Djordjevic and U.Heinz, PRC 77 (2008) 024905 and PRL 101 (2008) 022302 and M.D. talk at this conference

HF at high-p_T: theoretical predictions

Formalism recently implemented in a Monte Carlo tool[10], including also a description of the background medium, collisional energy-loss, energy-loss fluctuations...



[10] CUJET 2.0, J.Xu, A. Buzzatti and M. Gyulassy, arXiv:1402.2956 [hep-ph]

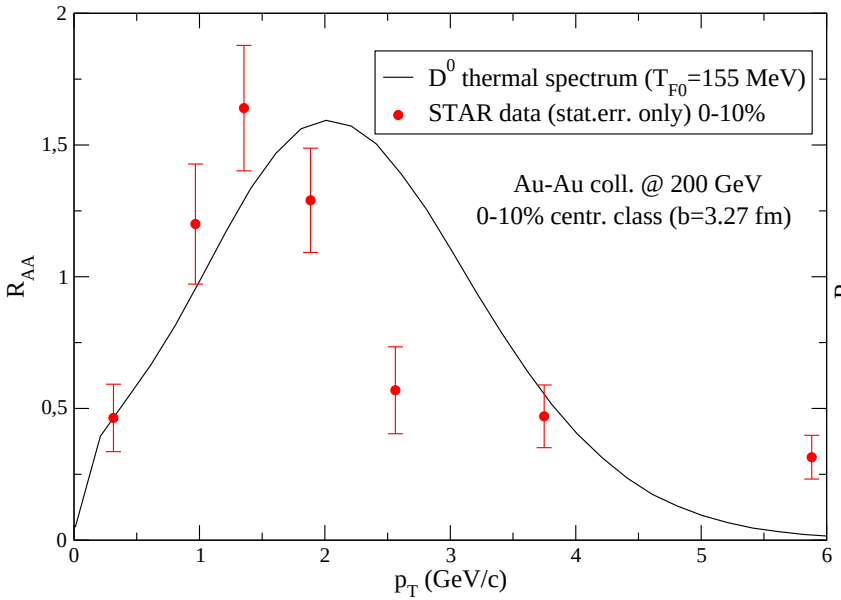
Summary

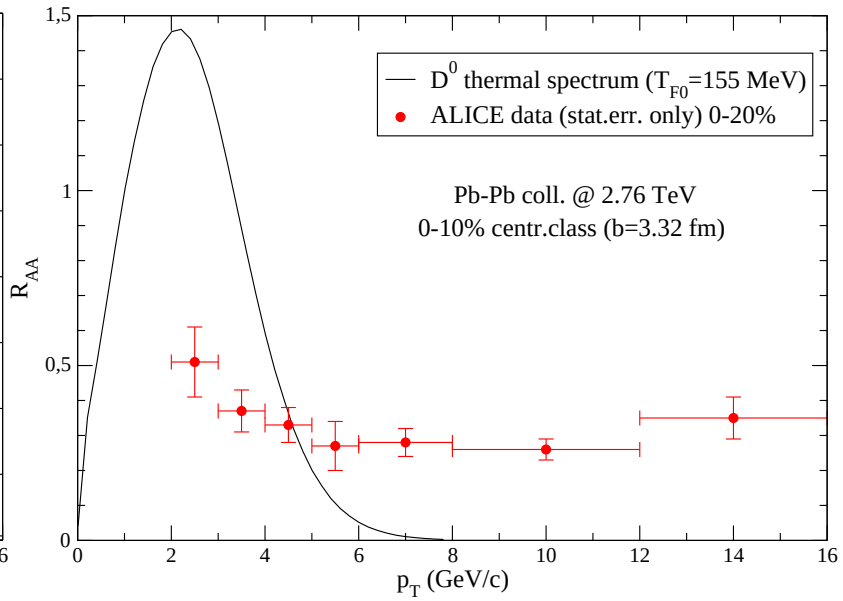
- HF @ low p_T: how close to thermalization?
  - (more) data at low p_T necessary to draw conclusions and constrain transport coefficients
  - future measurements of beauty will allow a comparison with a really robust theoretical setup
- HF @ high p_T:
  - a tool to study flavor (mass and color charge) dependence of parton energy loss
  - theory challenges and open issues: the same as usual jet-quenching studies

Thank you

Back-up slides

Charm thermal spectra without shadowing





Charm thermal spectra without shadowing