Charm 10th
Mexico 2021

Charm in media (theory)

The St Graal Quest

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Adopted viewpoint: broad overview. For more specialized viewpoint: recent plenary talk of Min He at « Strangeness in Quark Matter » or « Heavy-Flavor Transport in QCD Matter » at ECT* (https://indico.ectstar.eu/event/98/overview)

Charm (heavy quark) at $(T, \mu_{B,} \mu_s)=(0,0,0)$

IDENTIFICATION CARD

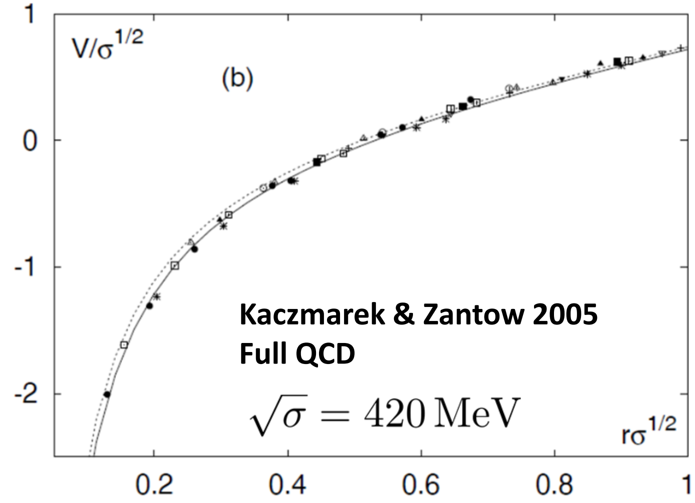
Name: charm
Residence : D, J/ψ, Λ_c
Mass: 1.272 GeV (constit.: 1.6)
Charge : 2/3
Lifetime : $\approx 10^{-12}$ s

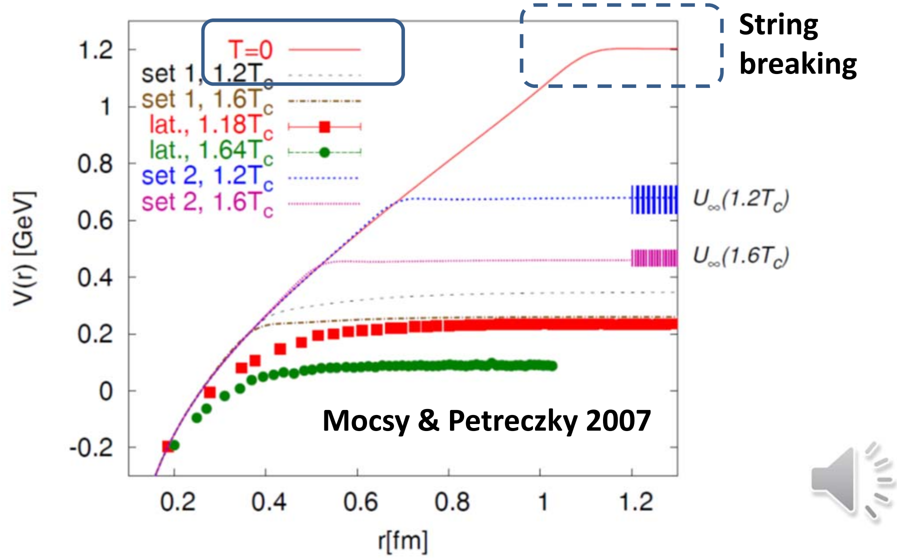
Particle World

- Effective theories (HQET, NRQCD, pNRQCD)
- Cornell potential

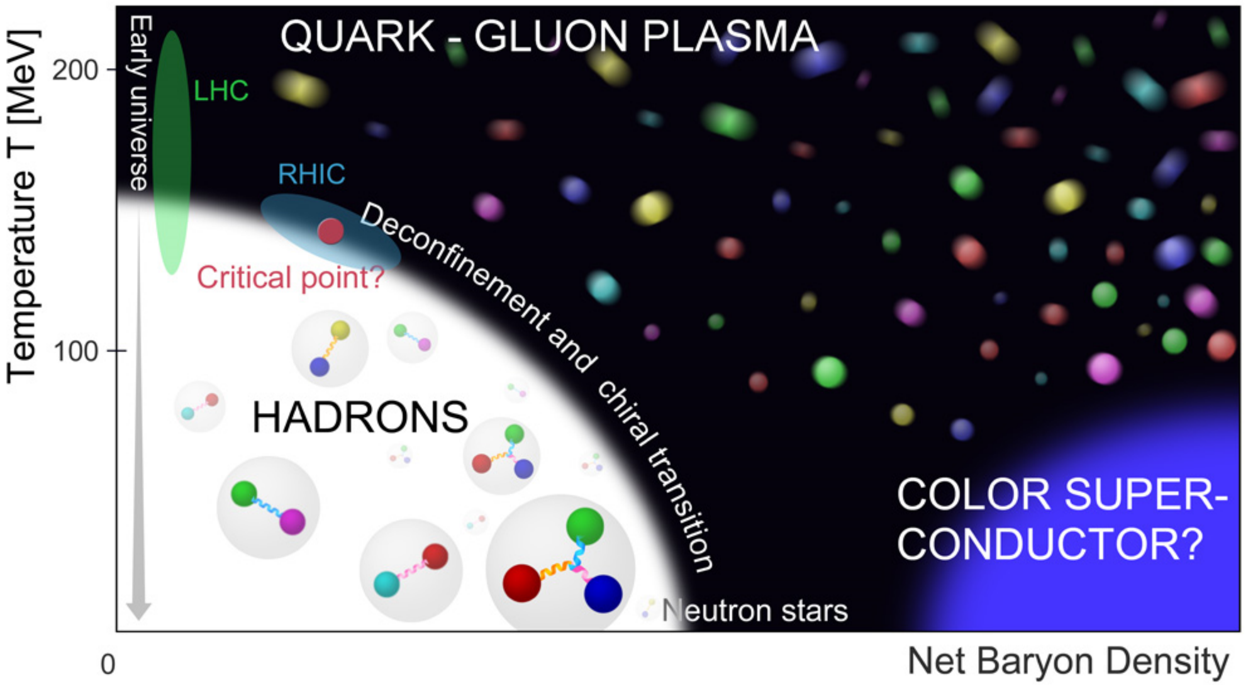
$$V(r) = \underbrace{-\frac{\alpha(r)}{r}}_{\text{Perturbative, Coulomb-like}} + \underbrace{\sigma r}_{\text{Non-perturbative, string-like}}$$

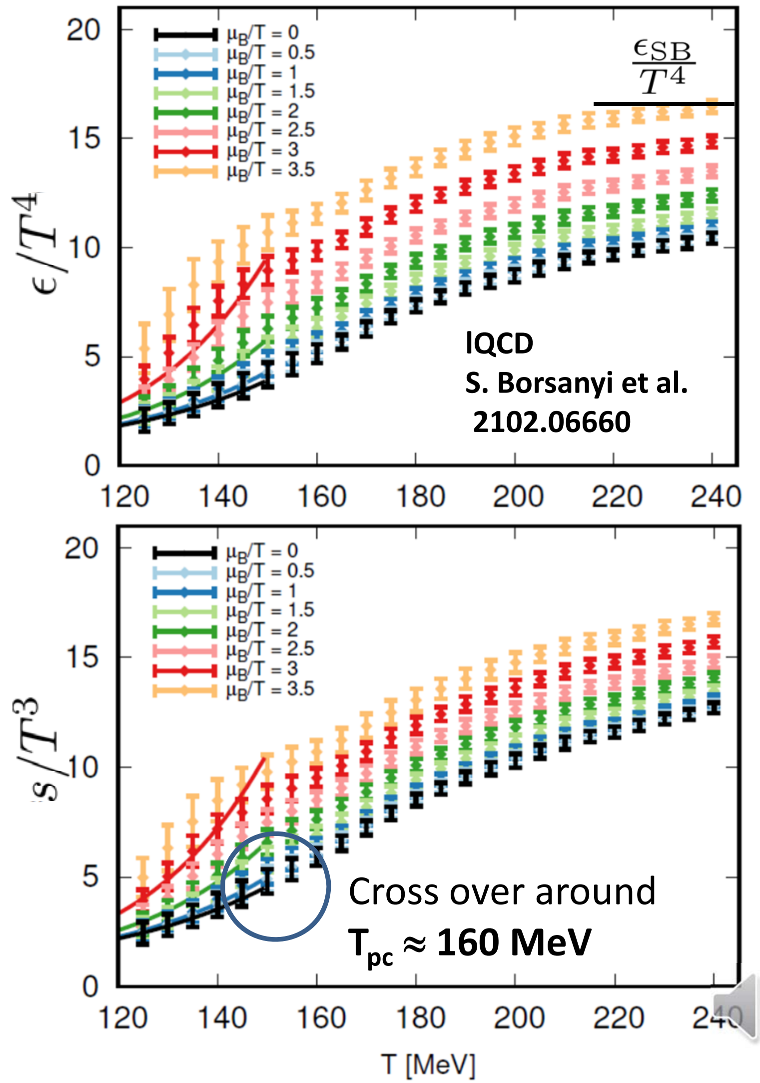
- … supported by lQCD calculations





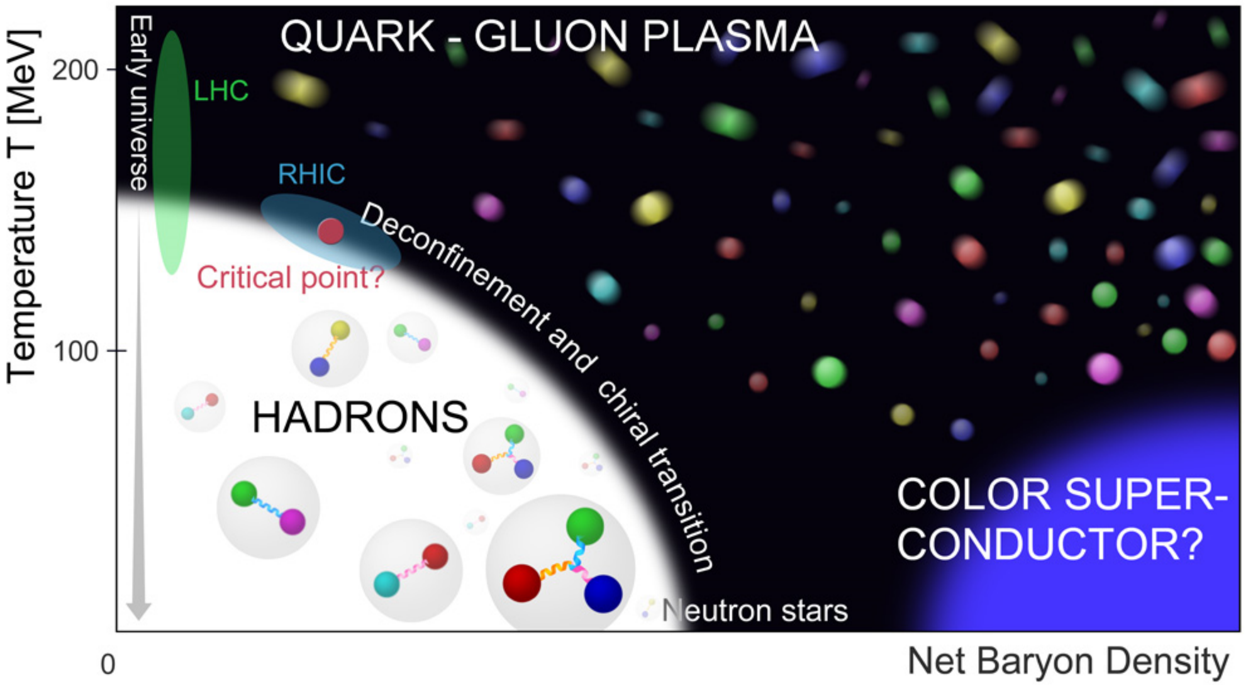
QCD Phase diagram





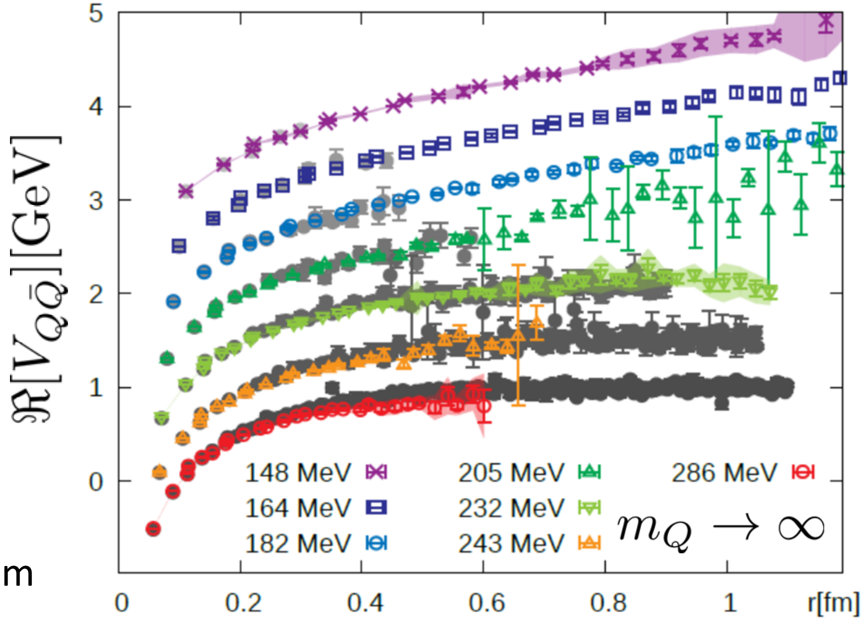
- Around $T_{pc} \approx$ **160 MeV** :
  - o Strong modification of the Polyakov Loop (order parameter for deconfinment)
  - o *gradual* increase of the effective degrees of freedom
- **Challenge : understand the properties of charm quark in this QGP medium** (in this talk: mainly at μ_B=0).

QCD Phase diagram



$$V(r) = \lim_{t\to\infty} \frac{i\partial_t W(t,r)}{W(t,r)}$$

Burnier et al. Phys. Rev. Lett. 114, 082001 (2015)



Grey symbols : free energy

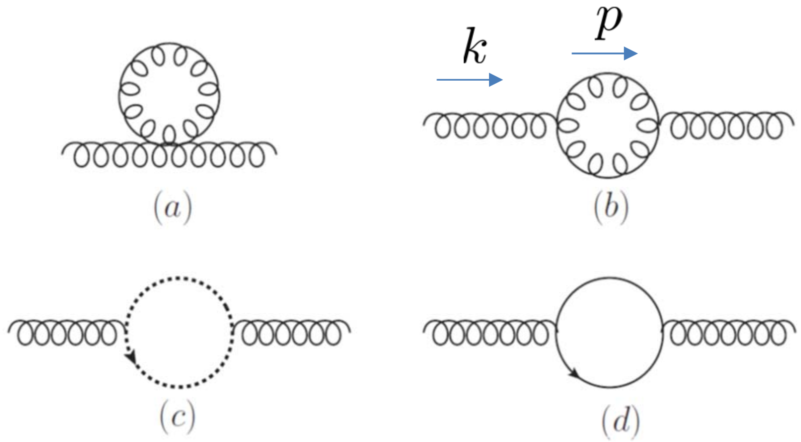
- Challenge : understand the properties of charm quark in this medium (in this talk: mainly at μ_B=0).
- A first answer <- the analysis of the static $Q - \bar{Q}$ potential on the lattice.
- Gradual disappearance of the « long range » force, while the r<0.3 fm « Coulomb-like » core survives at higher temperature.

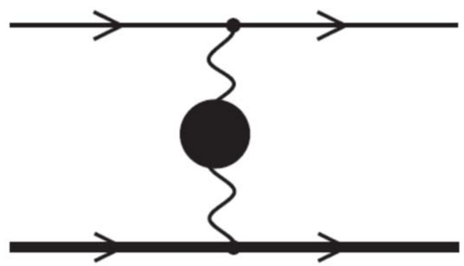
Physical Picture at large Temperature : HTL

- Hard thermal loops approximation
- Simple expression of the gluon propagator based on the HTL self energy when external momentum $|k| \approx m_{Deb} \approx g(T)\, T \ll p \approx T$ ⇔ weak coupling $g(T) \ll 1$ and perturbative schemes
- If energy transfer is small (ok is at least one of the quark is heavy ./. m_{Deb}) => Interaction reduces to a simple Debye-screened potential

$$V_{\rm HTL}(r,t) \approx -\frac{\alpha}{r}\, e^{-m_D r}$$

- Light partons acquire thermal mass α gT as well as collisional width (spectral function)





Masses:

$$M^2_{q(\bar q)}(T,\mu_B) = \frac{N_c^2-1}{8N_c} g^2(T,\mu_B)\left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$$

$$M^2_g(T,\mu_B) = \frac{g^2(T,\mu_B)}{6}\left(\left(N_c + \frac{1}{2}N_f\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

Widths:

$$\gamma_{q(\bar q)}(T,\mu_B) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2(T,\mu_B)T}{8\pi}\ln\left(\frac{2c}{g^2(T,\mu_B)}+1\right)$$

$$\gamma_g(T,\mu_B) = \frac{1}{3}N_c\frac{g^2(T,\mu_B)T}{8\pi}\ln\left(\frac{2c}{g^2(T,\mu_B)}+1\right)$$

Some nice reviews : **Iancu & Blaizot (2000), Ghiglieri et al. (2020),…**

Physical Picture at large Temperature : HTL

Beraudo et al : Nuclear Physics A 846 (2010) 104–142

- Heavy quarks, on the contrary : **reduction of the mass** : For static quark, the dominant effect is the quenching of field over distance α $1/m_D$) …
- …. and still thermal width α g^2T

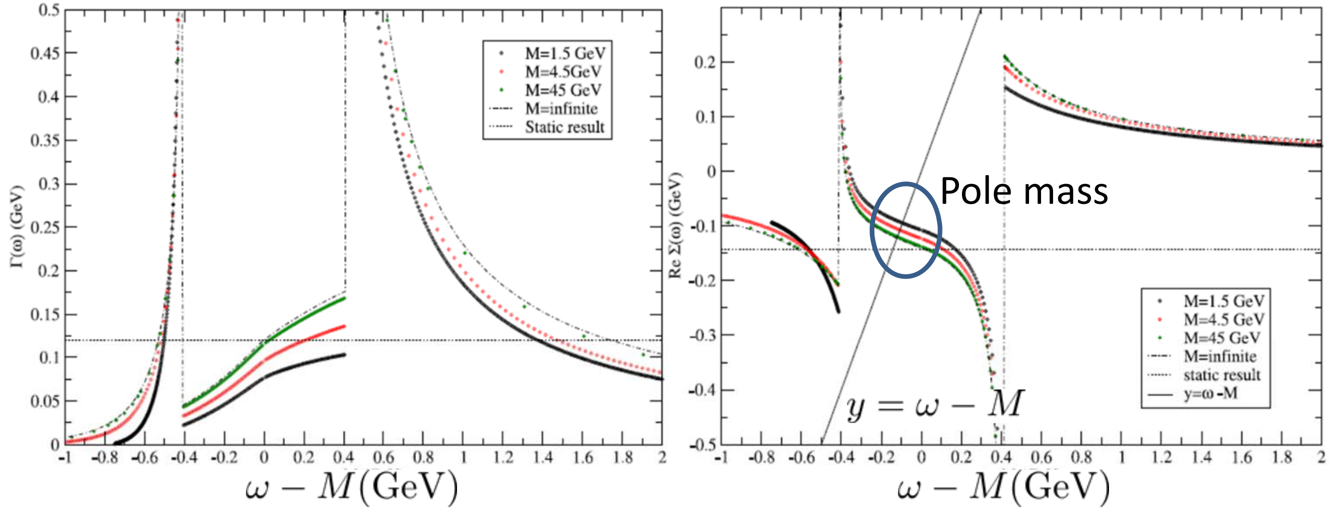


Fig. 6. (Color on-line.) Imaginary part (left) and real part (right) of the self-energy Σ. The horizontal lines, labelled “static limit”, indicate the values of $\Gamma(M \to \infty)$ and $\mathrm{Re}\,\Sigma(M \to \infty)$. With the parameters $\alpha = 0.4$ and $T = 300$ MeV, these are respectively 120 MeV and -143 MeV. Within the gap $\pm\omega_{\mathrm{pl}}$, Γ is an increasing function of M, while $\mathrm{Re}\,\Sigma$ is a decreasing function of M. Both functions nearly reach the infinite mass limit when $M = 45$ GeV.

$$\mathrm{Re}\Sigma(M\to\infty) = -\frac{g^2}{2}\int\frac{d\boldsymbol{k}}{(2\pi)^3}\int_{-\infty}^{+\infty}\frac{dk^0}{2\pi}\frac{\rho_L(k^0,k)}{k^0} = -\frac{\alpha m_D}{2}$$

$$\mathrm{Im}\Sigma^R(M\to\infty) = -\frac{g^2}{2}\lim_{k^0\to 0}\int\frac{d\boldsymbol{k}}{(2\pi)^3}N(k^0)\rho_L(k^0,k) = -\frac{\alpha}{2}T$$

$$\Rightarrow \Gamma(m_Q\to\infty) = \alpha T$$

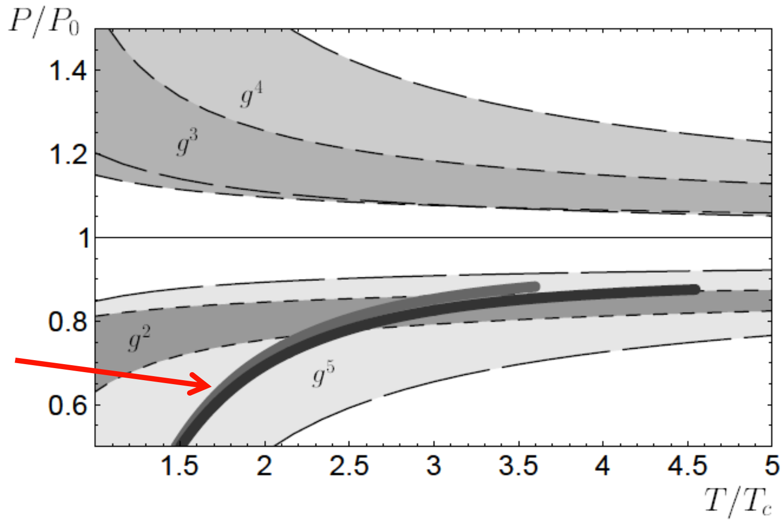
T/M	0	0.0067	0.067	0.133	0.200	0.333
$\delta M/T$	-0.407	-0.4	-0.357	-0.335	-0317	-0.288
$\Delta F_Q/T$	-0.416	-0.409	-0.362	-0.336	-0.318	-0.274
$\mathrm{Re}\Sigma(M)/T$	-0.476	-0.457	-0.41	-0.38	-0.357	-0.326

Physical Picture at large Temperature : HTL

- However, lessons from the past (EOS) : naive HTL approach does not converge uniformly;
- Need clever ressumation and interpretation, as well as extra prescription for fixing m_D (HTL perturbation theory)
- => what about remnants of the confining force ?
- Answer about the applicability might also depend on the considered quantity
- Usually better suited for short range description $r \lesssim m_D^{-1}$

For values of the T achievable nowadays on earth, adding more and more terms simply leads to larger theoretical error bands !!!

lQCD



Kraemmer & Rebhan (2004)

Figure 6. Strictly perturbative results for the thermal pressure of pure glue QCD as a function of T/T_c (assuming $T_c/\Lambda_{\overline{\rm MS}} = 1.14$). The various gray bands bounded by differently dashed lines show the perturbative results to order g^2, g^3, g^4, and g^5, using a 2-loop running coupling with $\overline{\rm MS}$ renormalization point $\bar{\mu}$ varied between πT and $4\pi T$. The thick dark-grey line shows the continuum-extrapolated lattice results from reference [154]; the lighter one behind that of a lattice calculation using an RG-improved action [155].

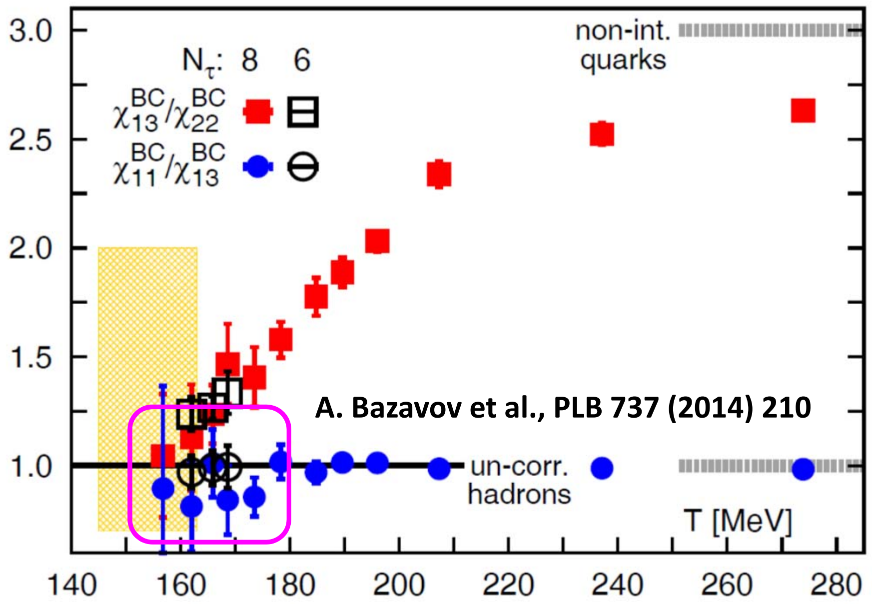
Need for further ressummations **(early 2000's, fi: Blaizot, Iancu & Rebhan)**

Physical Picture around T_{pc}

- Several indications that charm is not weakly interacting around T_{pc} (screening masses, correlators,…)
- Quark susceptibilities on the lattice :

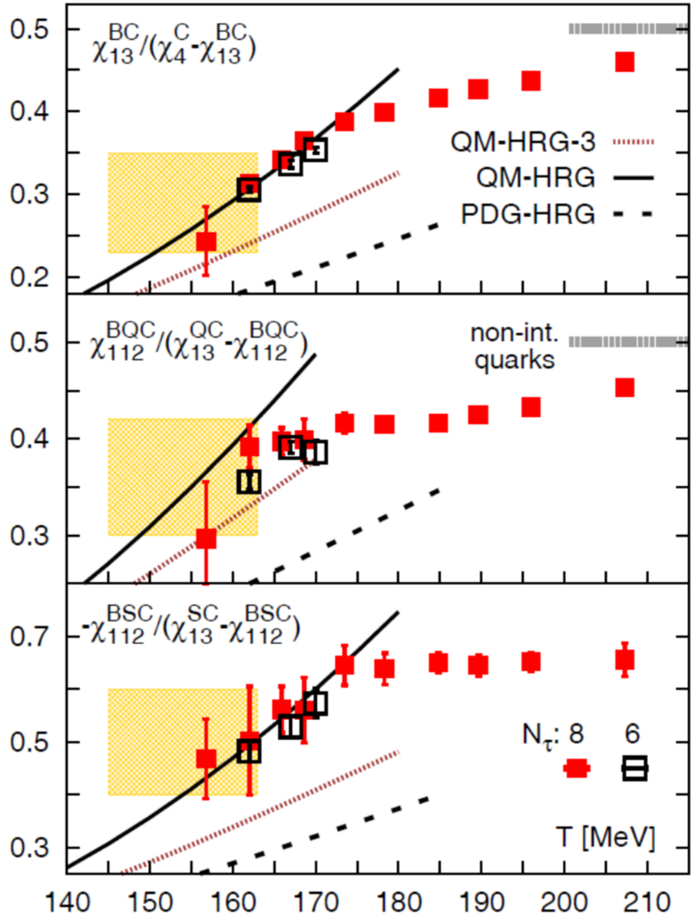
$$\chi_{mn}^{BC} = \frac{\partial^{m+n} p(T,\mu_B,\mu_C)}{\partial \hat{\mu}_B^m \partial \hat{\mu}_C^n}\Big|_{\mu_B=\mu_C=0}$$

where $\hat{\mu} = \mu/T$



All susceptibilities nearly equal, as μ_B and μ_C appear jointly in the charmed-baryonic pressure

Charm baryon to meson pressure



Hadronic nature of charm is confirmed, provided one considers extra charmed-baryonic states from quark models

Physical Picture around T_{pc}

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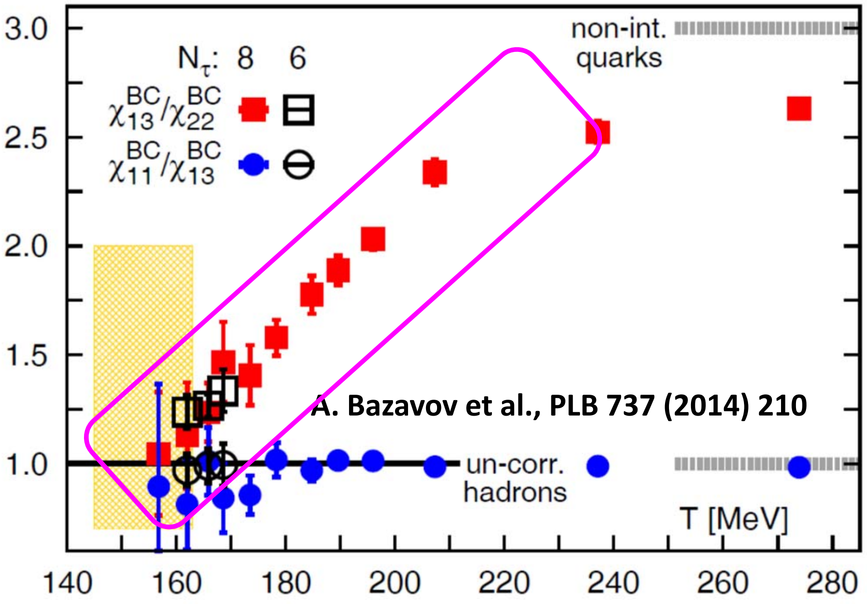
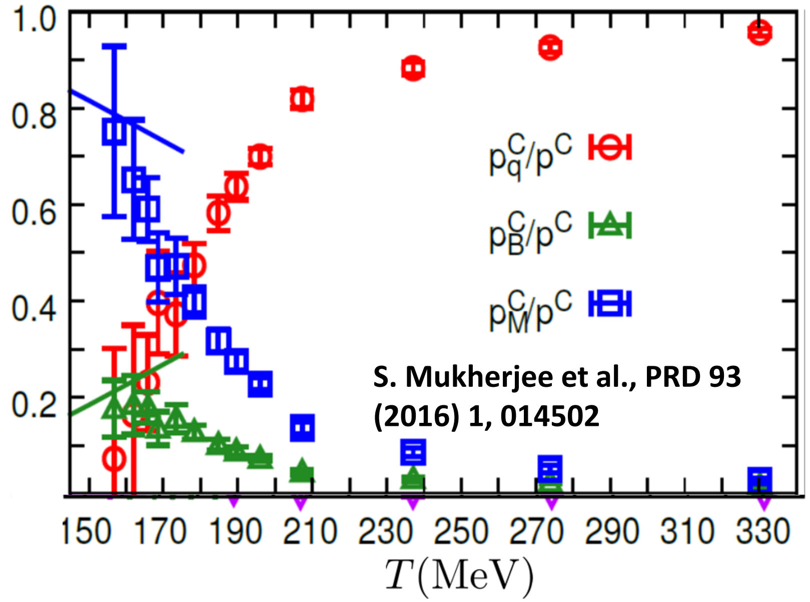
Minimalistic model :

$$P^C = P_q^C(T)\cosh(\hat{\mu}_C + \frac{\hat{\mu}_B}{3}) + P_M^C(T)\cosh(\hat{\mu}_C) + P_B^C(T)\cosh(\hat{\mu}_C + \hat{\mu}_B) + \underbrace{\cdots}_{C>1\ \text{(small)}}$$

fractional contributions of partial pressures (PP)



Gradual transition from hadronic-like -> non interacting quark values



PP drop: hadronic resonances become broad at high T and do not contribute

Jakovác, PRD88 (2013), 065012, Biró, Jakovác, PRD(2014)065012

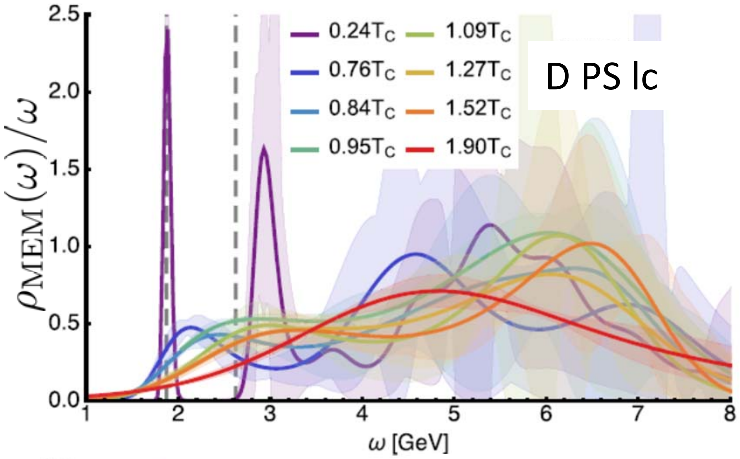
Confirms the resonance picture of Ravagli and Rapp

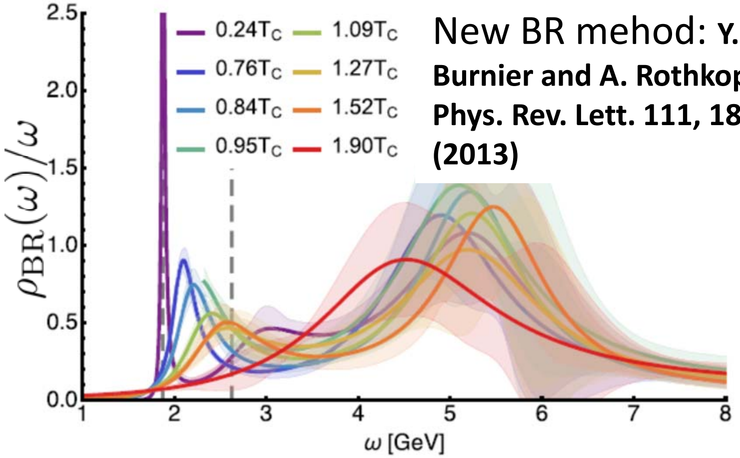
L. Ravagli and R. Rapp, Phys. Lett. B 655 (2007)

Physical Picture around T_{pc}

- Euclidean correlator $G(\tau,T)=\int\rho(\omega,T)K(\tau,\omega,T)d\omega$ with $K(\tau,\omega,T)=\frac{\cosh[\omega(\tau-1/2T)]}{\sinh(\omega/2T)}$

A. Kelly et al, Phys. Rev. D 97(2018), 114509 (2018)



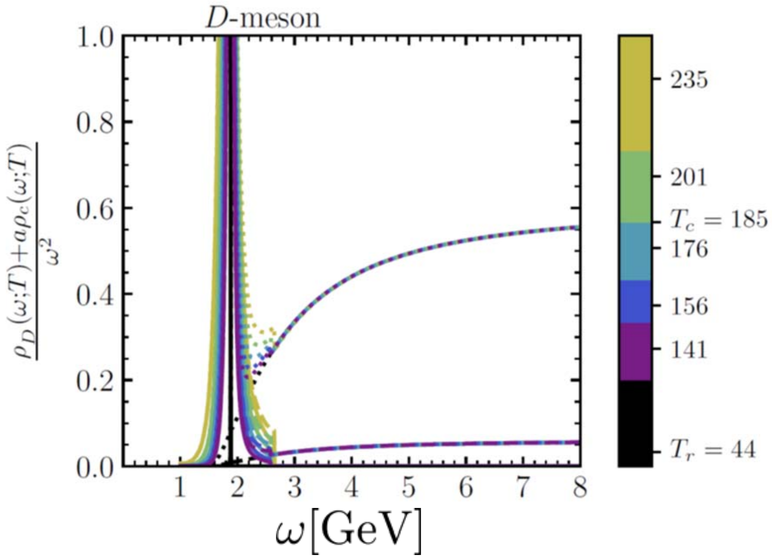


New BR mehod: **Y. Burnier and A. Rothkopf Phys. Rev. Lett. 111, 182003 (2013)**

- Quite challenging inversion problem
- below T_{pc}, the D mesons exhibit consistently more pronounced structures, compared to their D* cousins.
- The BR (inversion) method exhibits remnant peak structures up to T≈ 1.5 T_{pc}
- "The MEM, on the other hand, shows overall more washed out structures, so that at T > T_{pc}, one is hard pressed to identify a genuine peak."

Need further investigation

Glòria Montaña et al, The EPJA56, 294 (2020) … see also talk at SQM 2021



- Effective hadronic theory; spectral function based on GS + continuuum

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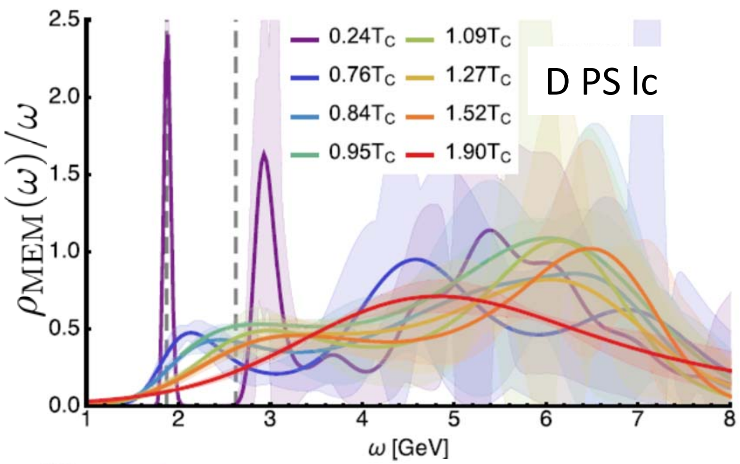

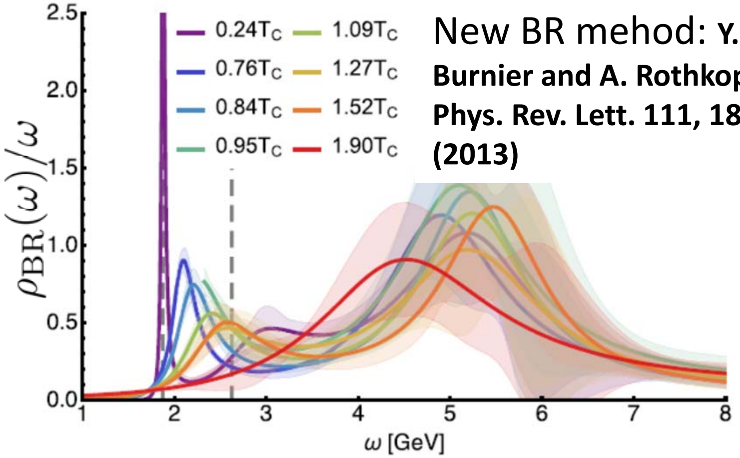

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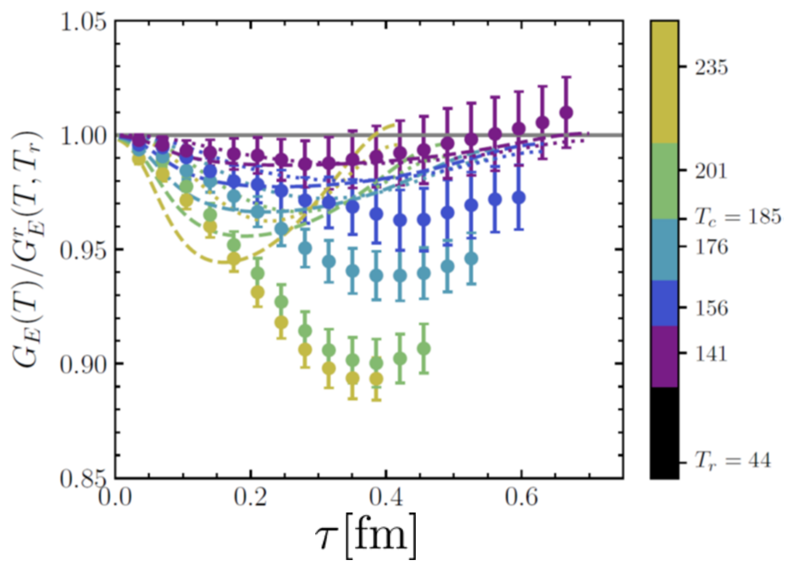
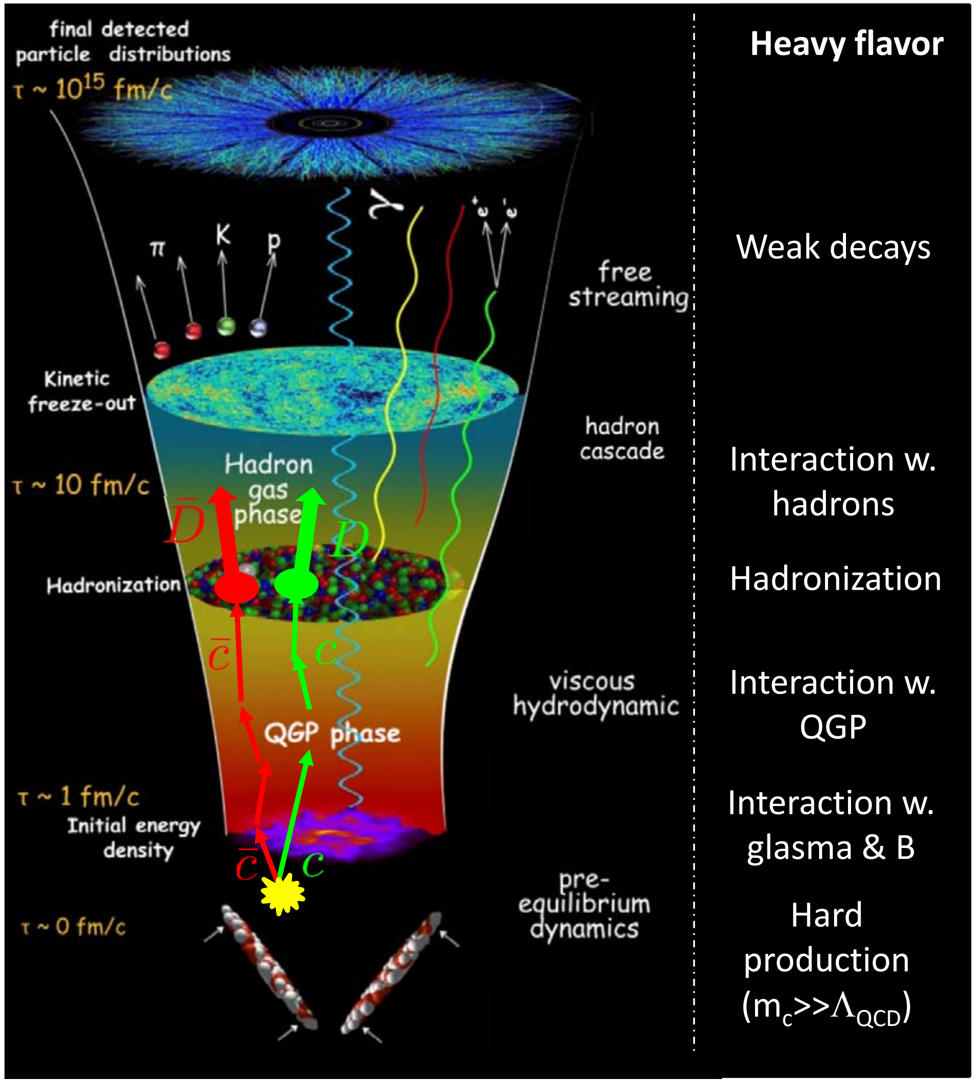


- Effective hadronic theory; spectral function based on GS + continuuum
- Good agreement for low temperature, but large (expected) deviations for $T>T_{pc}$. (higher states, but also deviation from BW shape).

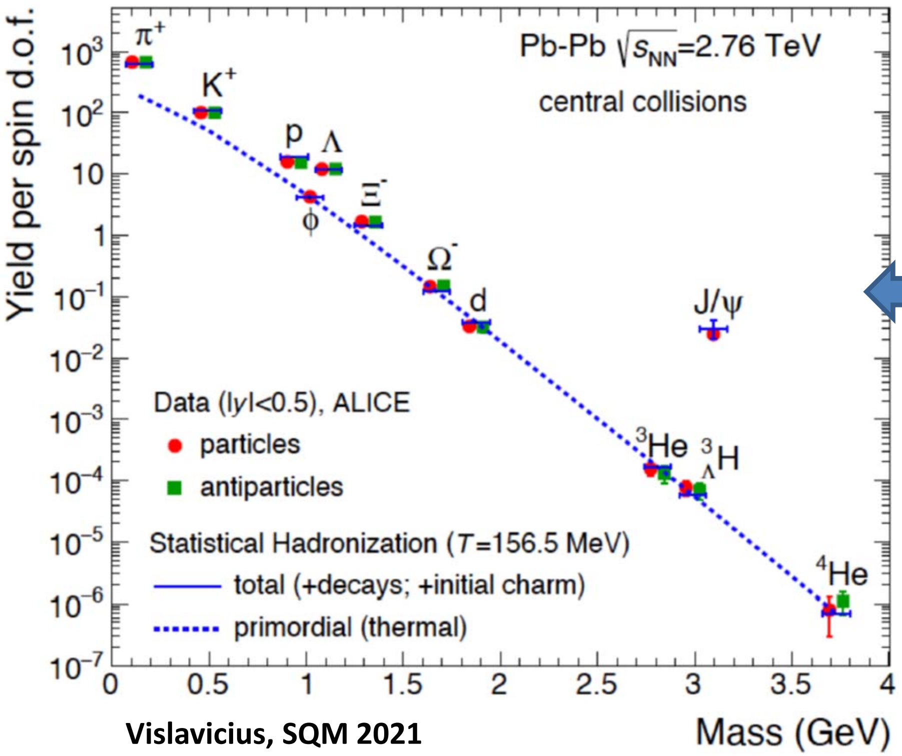
AA collisions as a playground for testing charm in media



- Produced early ($t \approx 1/m_c$)
  - => No further c-cbar generation in ensuing QGP
  - Initial production well controled (advantage of $m_Q >> \Lambda_{QCD}$)
  - But early phase might not be so innocent (magnetic field, CGC-glasma,…)
- => experience the full deconfined phase + hadronic phase
  - probes « deeper » than most of the other hadronic observables *while not fully thermalized* ($t_{relax} \alpha\ m_Q/T^2$)
  - accumulates several effects => need to compare different systems to better differentiate them
- Produced over a wide range of rapidities and p_T
  - increased richness in scrutinizing the interaction of HQ with medium…
  - but also sets more challenges (interactions for $p_T << m_c$, $p_T \approx m_c$, $p_T >> m_c$, appropriate transport theory ?).
- => Several models have emerged that aim at describing OHF production in AA collisions
- All together, a comprehensive understanding of the microscopic properties will only stem from combining deep theory & AA phenomenology.

QGP in AA from c-quark perspective… opaque or transparent ?

- Historical (< 2000) claims of weakly coupled QGP – HQ (suppression of elastic energy loss, small radiative Eloss).
- Most agnostic approach to HF production in AA collisions : **Statistical Hadronization Model**



Vislavicius, SQM 2021

- Based on simple (not simplistic !) generic hypothesis: all correlations lost in QGP, production at freeze out according to statistical weights
- Core – corona decomposition of the domain
- Charm quarks number is fixed at t=0 and conserved
- Predictive power for a large number of hadrons and resonances

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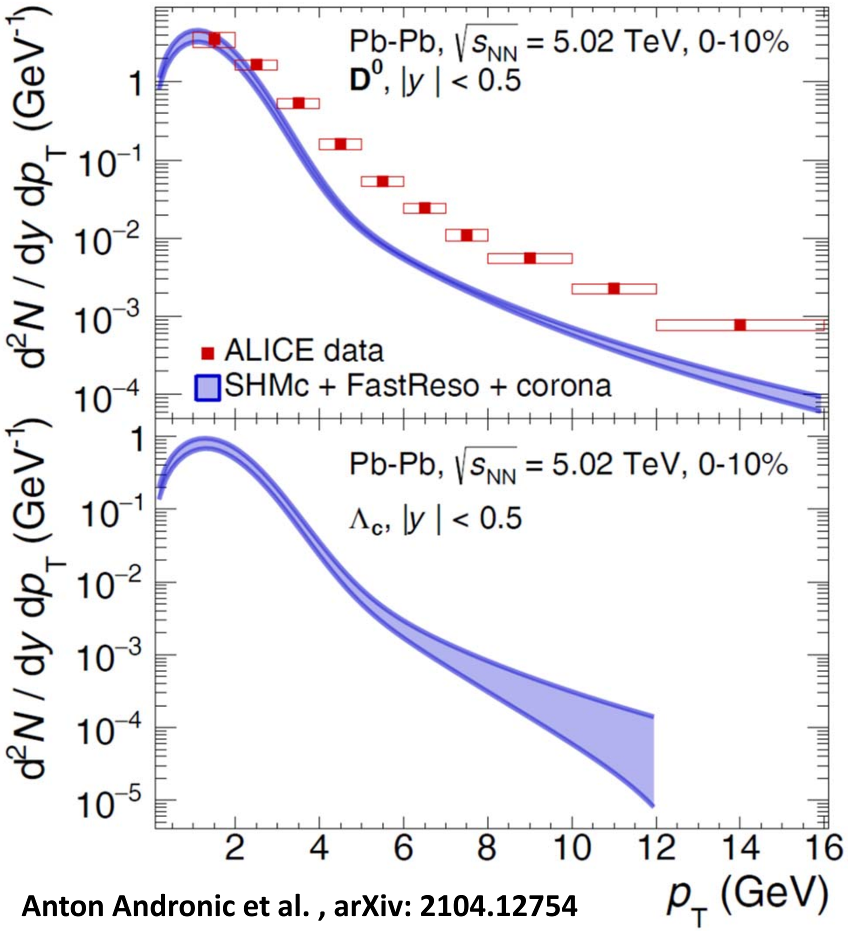

Anton Andronic et al. , arXiv: 2104.12754

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  - o full thermalization in core, differential production according to Cooper-Frye with QGP distributed according to blastwave model + resonance decay.
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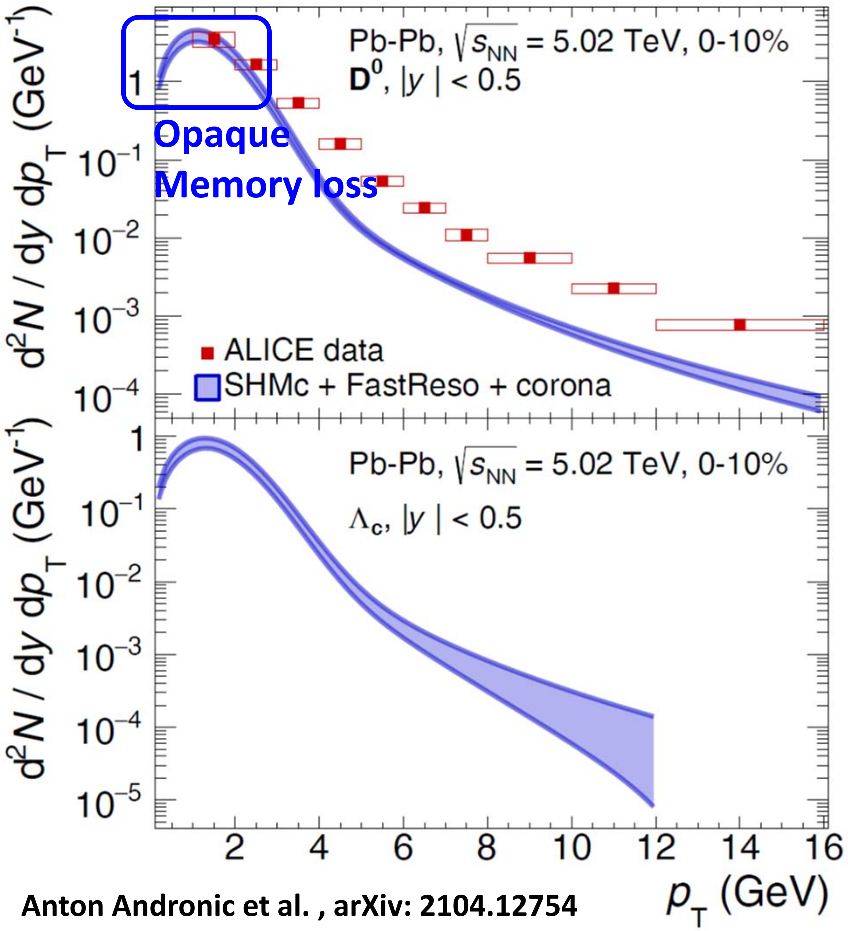

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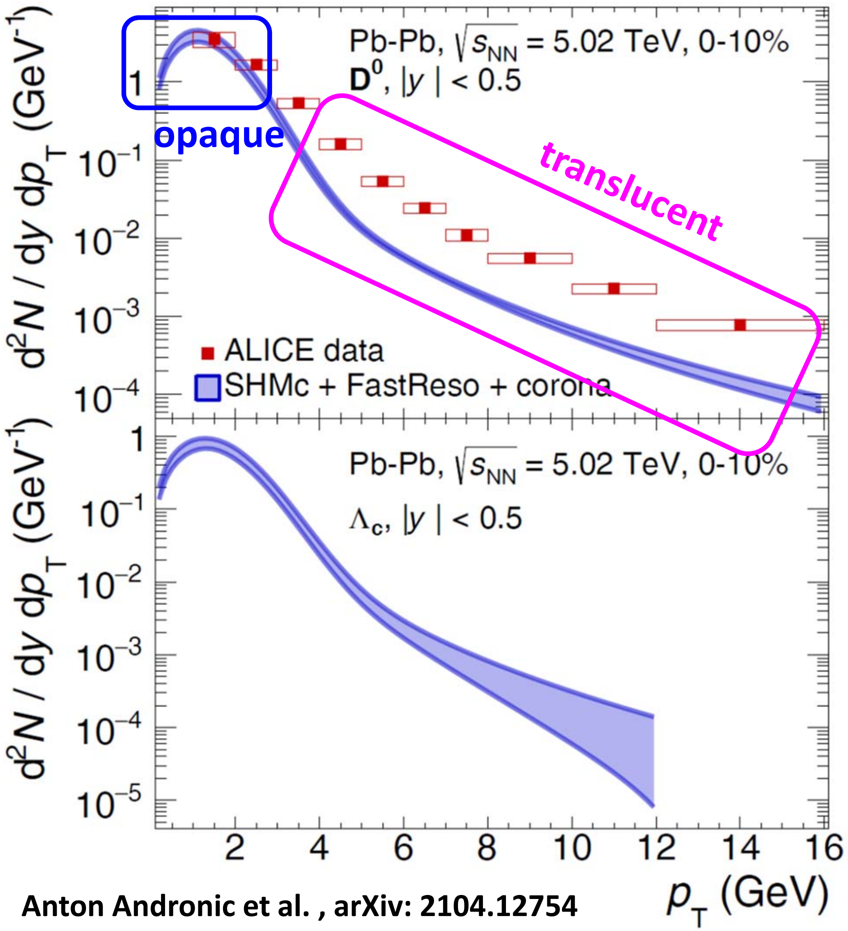

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- Agreement with experiment at low p_T for open charm hadrons demonstrates that the hadronization of open and hidden charm takes place at or close to the QCD phase boundary
- Disagreement at intermediate p_T leaves the room open for incomplete thermalization during evolution ($t_{relax}\ \alpha\ m_Q/T^2$) => indeed probing QGP properties

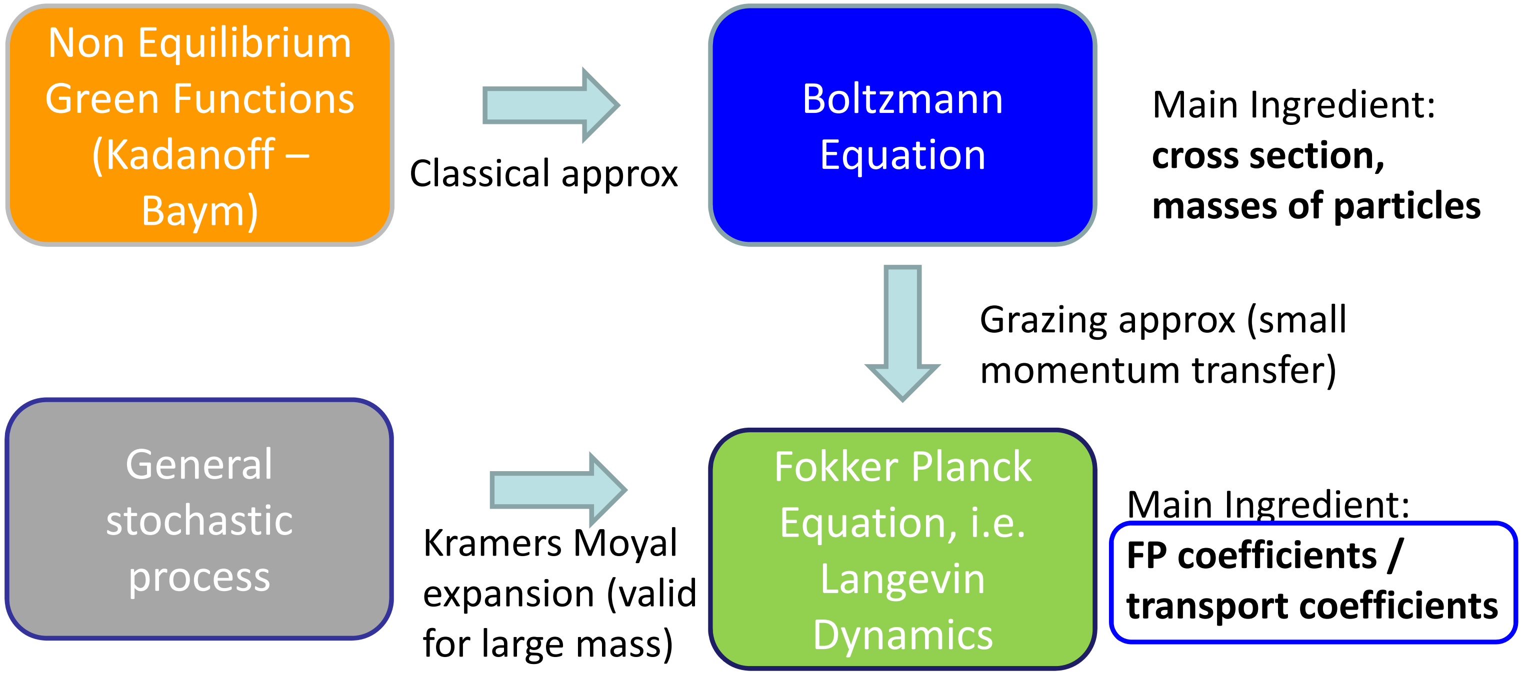
(own interpretation !)

Various approaches to HQ transport

Bottom-up schemes (microscopic -> mesoscopic):

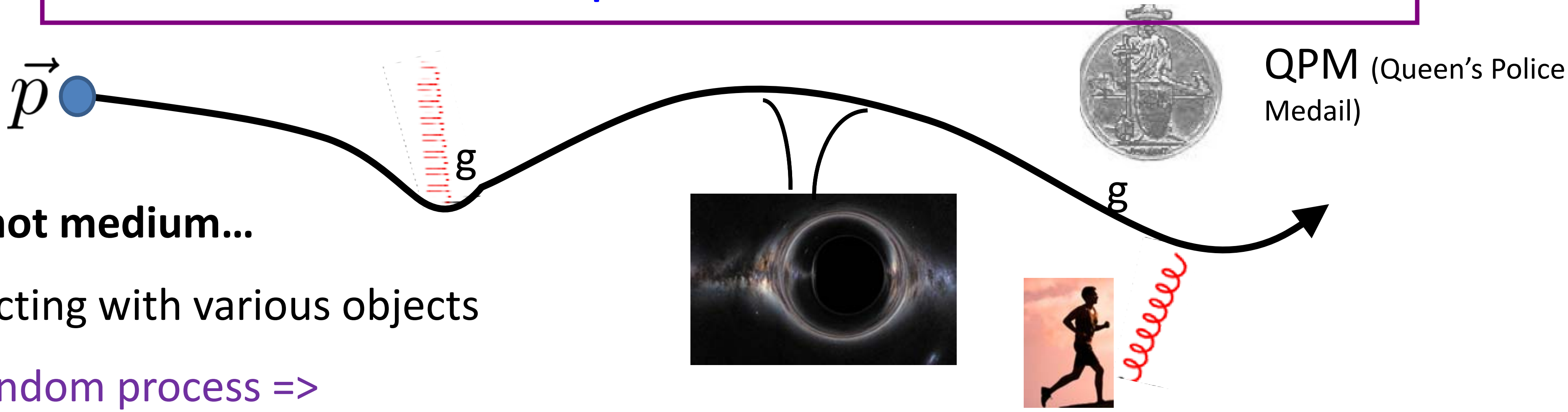
- Assume (effective) degrees of freedom and (effective) interactions
- Take insights and constrains from the fundamental QCD theory, but often inhold some free parameter
- Rely on more or less sophisticated realizations of the transport theory

+ background from fluid dynamics :T(x),u(x), or from transport equations in the light sector



Minimalistic ingredients / quantities to be inferred from the medium.

Transport coefficients



HQ in hot medium…

… interacting with various objects

Quasi random process =>

$$-\frac{d}{dt}\langle\vec{p}\rangle = \vec{A}(\vec{p},T) = \eta_D(\vec{p},T)\times\vec{p}$$ $\eta_D[\mathrm{fm}^{-1}]$: Relaxation rate

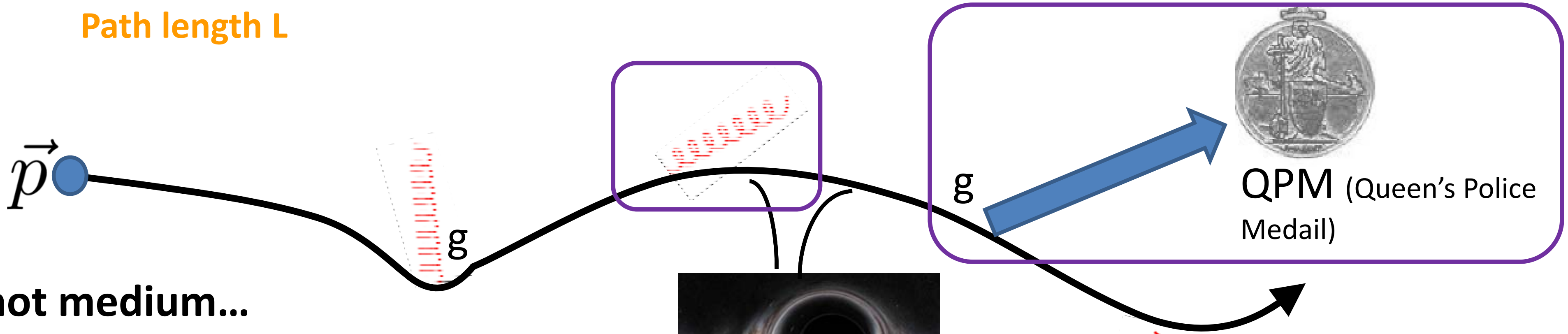
$$\frac{d}{dt}\langle\vec{p}_{T,i}\vec{p}_{T,j}\rangle = \kappa_T(\vec{p},T)\delta_{i,j}$$ $\kappa_T[\mathrm{GeV}^2\mathrm{fm}^{-1}]$: Transverse diffusion coef. (p space) ; $\hat{q} = 2\kappa_T = 4B_0$

Similar in longitudinal direction $\kappa_L[\mathrm{GeV}^2\mathrm{fm}^{-1}]$: Longitudinal diffusion coef.

In general, no relation between these coefficients except $\kappa_T = \kappa_L$ for p=0.

Transport coefficients and inelastic processes

Path length L



HQ in hot medium…

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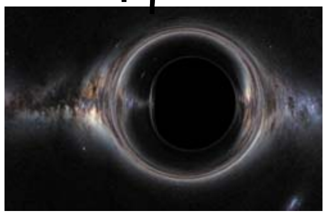
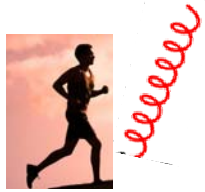


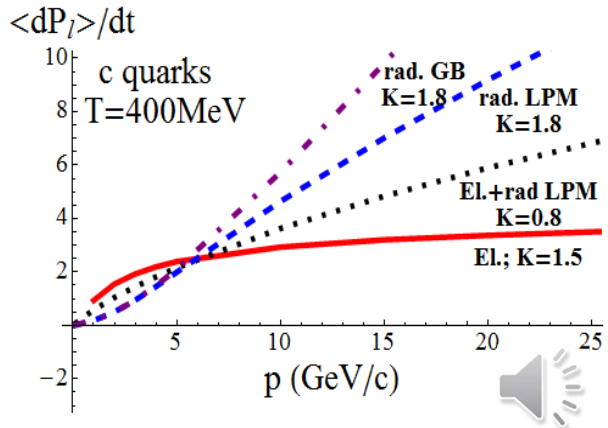


… and emitting some objects

$$\Delta\langle\vec{p}\rangle = \vec{A}(\vec{p},T)\times L + \underbrace{(\Delta\vec{p})_{\rm rad}}$$

- contribution from « radiated » part
- In most of existing schemes: $(\Delta\vec{p})_{\rm rad} = \mathcal{F}(\underbrace{\eta_D,\kappa_T,\kappa_L},p,L)$

Seeked ransport coeff.



!!! In this case, the relaxation rate < (<<) η_D

Transport coefficients at low momentum p≈m_Q

Langevin regime => Einstein relation: $\kappa = 2 T E_Q \eta_D$

$$D_s = \left(= \frac{1}{6} \lim_{t\to\infty} \frac{\langle (\mathbf{x}(t)-\mathbf{x}(0))^2 \rangle}{t} \right)$$

For historical reasons, physics displayed as a function of 2πT x the spatial diffusion coefficient

$$(2\pi T) D_s = \frac{4\pi T^3}{\kappa} = \frac{2\pi T^2}{E_Q \eta_D} \Rightarrow \tau_{\text{relax}} = \eta_D^{-1} = (2\pi T) D_s \times \frac{E_Q}{2\pi T^2}$$

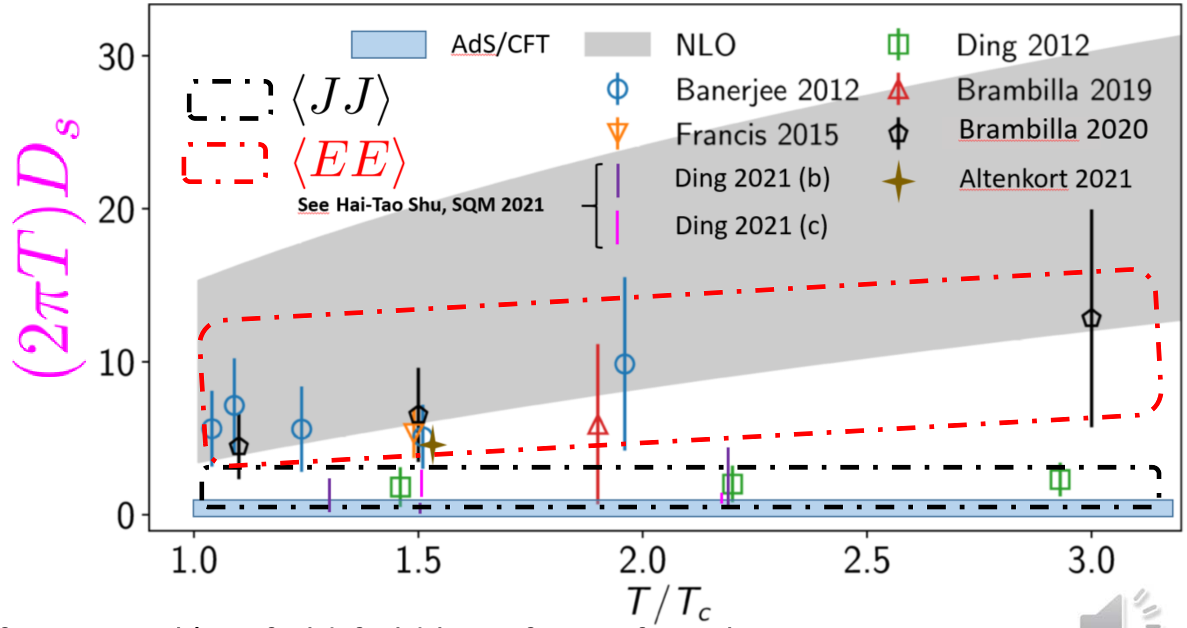
Gauge for the coupling strength

lQCD results

The sole direct rigorous calculation of the transport coeff to my knowledge

$$\tau_{\text{relax}}(T_c) \approx m_Q[\text{GeV}] \times (3 \pm 1.5)\ \text{fm}$$

Still not conclusive



2 possible methods : direct current – current correlator (diffusion peak) or field-field benefitting from large m_Q. Tension between the two approaches ?

Transport coefficients at low momentum $p \approx m_Q$

Langevin regime => Einstein relation: $\kappa = 2TE_Q\eta_D$

$$D_s = \left(= \frac{1}{6} \lim_{t\to\infty} \frac{\langle(\mathbf{x}(t)-\mathbf{x}(0))^2\rangle}{t} \right)$$

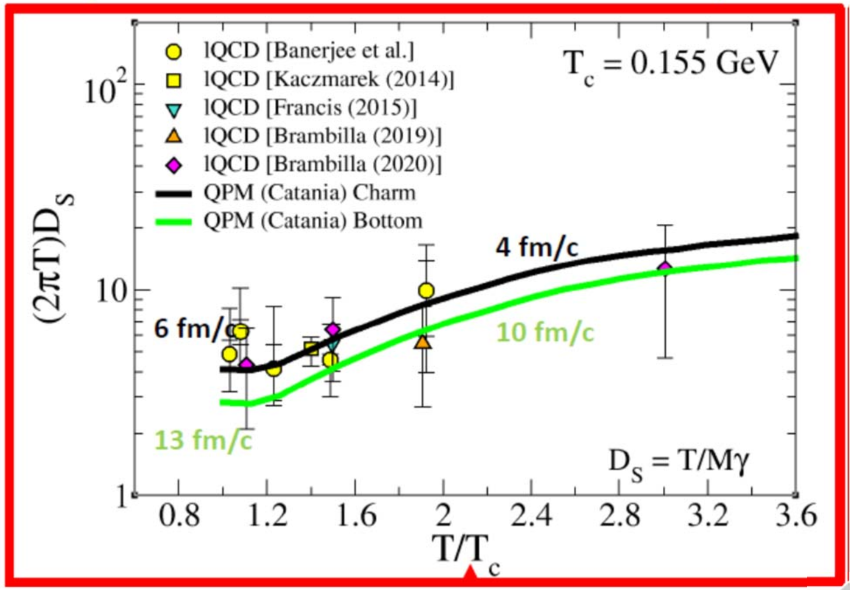
For historical reasons, physics displayed as a function of 2πT x the spatial diffusion coefficient

$$\underbrace{(2\pi T)D_s}_{} = \frac{4\pi T^3}{\kappa} = \frac{2\pi T^2}{E_Q\eta_D} \Rightarrow \tau_{\text{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{E_Q}{2\pi T^2}$$

Gauge for the coupling strength… should be independent of the mass in the large mass limit.

Study of Catania group (with a quasi particle model) shows that this is still not realized for cham mass (30% - 40% difference wrt bottom).

Spatial diffusion coefficient of bottom quark



ML Sambataro, SQM 2021

Transport coefficients at low momentum p≈m_Q

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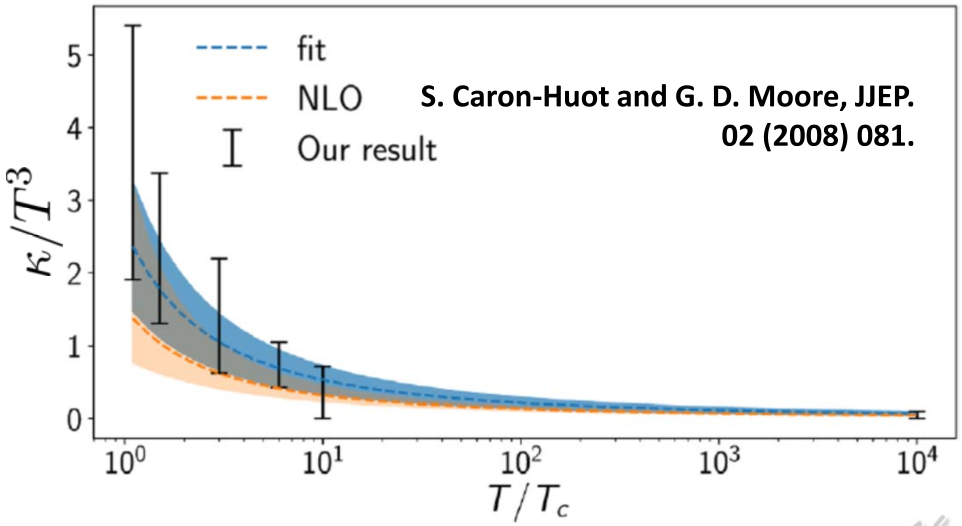
Gauge for the coupling strength

- Large corrections observed from LO -> NLO calculation of κ
- NLO calculation appears to be nearly compatible with lQCD calculations
- The T dependence appears to be in quite good agreement and even serves to design optimal fits

Brambilla et al, PRDD 102, 074503 (2020)

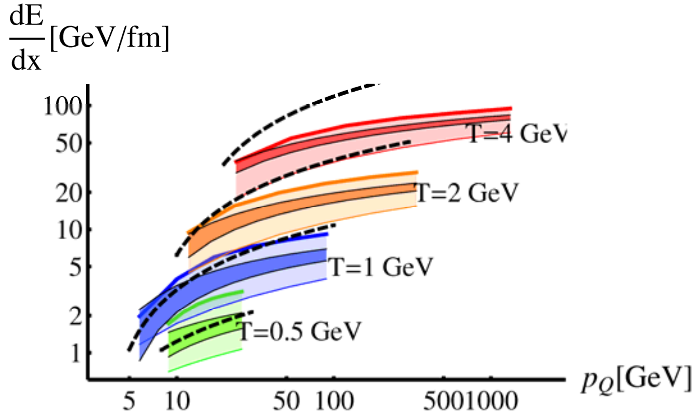


pQCD inspired models (f.i. Nantes)

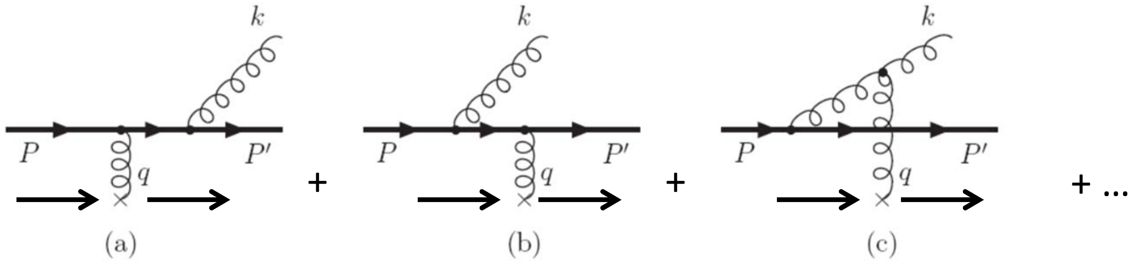
Colisional component

- One-gluon exchange model: reduced IR regulator $\lambda\, m^2_D$ in the hard propagator, fixed on HTL Energy loss at intermediate p_T
- Running coupling α_{eff} (t) and self consistent Debye mass

$$m_{Dself}^2\,(T) = (1+n_f/6)\; 4\pi\alpha_{eff}(m_{Dself}^2)T^2$$



Radiative component



- Extention of Gunion-Bertsch approximation beyond mid-rapidity and to finite mass m_Q) distribution of induced gluon radiation per collision ($\Delta E_{rad}\ \alpha$ E L):

$$P_g(x,\mathbf{k}_\perp,\mathbf{q}_\perp,m_Q) = \frac{3\alpha_s}{\pi^2}\frac{1-x}{x}\left(\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2+xm_Q^2} - \frac{\mathbf{k}_\perp-\mathbf{q}_\perp}{(\mathbf{k}_\perp-\mathbf{q}_\perp)^2+xm_Q^2}\right)^2$$

- LPM effect for moderate gluon energy

Implemented in MC@HQ + EPOS2(3) through Boltzmann dynamics

But also BAMPS, LBL-CCNU, Duke,…

Quasi particle models (f.i DQPM)

- Non perturbative effects near Tc are captured by α_s(T), leading to thermal masses/widths, determined from fits to lQCD EoS.

A. Peshier et al. PLB 337 (1994), PRD 70 (2004); M. Bluhm et al. EPJC 49 (2007); W. Cassing et al. NPA 795 (2007)

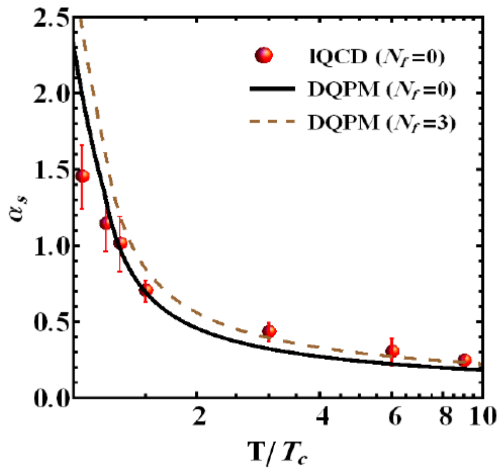
- Relaxation rates larger then in pQCD for all T relevant for QGP, slightly smaller than the ones from TAMU

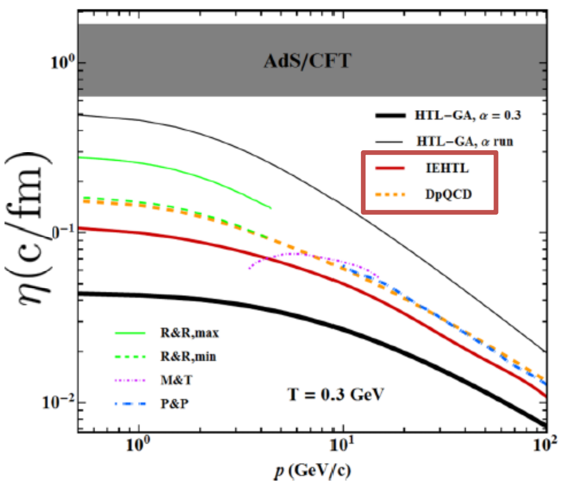
H. Berrehrah et al, PHYSICAL REVIEW C 90, 064906 (2014)

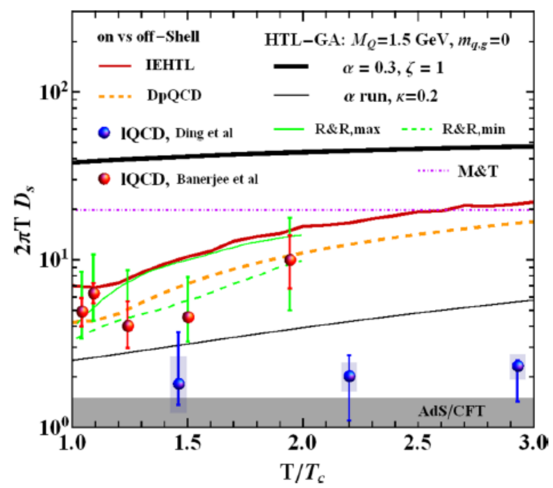
- Implemented for HF dynamics in e.g. PHSD (full off-shell, off-equilirium transport).

T. Song et al. PRC 92 (2015), PRC 93 (2016)

But also CATANIA







Potential models (TAMU)

- Thermodynamic T-matrix approach, T = V +VGT, given by a two-body driving kernel V, estimated from the lQCD internal/free energy for a static Q-Qbar pair; increase of coupling with QGP at small momentum

D. Cabrera, R. Rapp PRD 76 (2007); H. van Hees, M. Mannarelli, V. Greco, R. Rapp PRL 100 (2008)

- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion (many body theory).

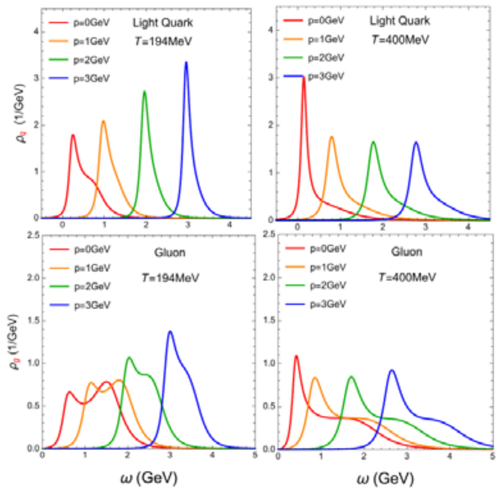
F. Riek, R. Rapp PRC 82 (2010); S. Liu, R. Rapp arxiv:1612.09138

- Resonance correlations in the T-matrix naturally lead to recombination (resonance recombination model) near T_c from the same underlying interactions => amplifies HQ-coupling with QGP

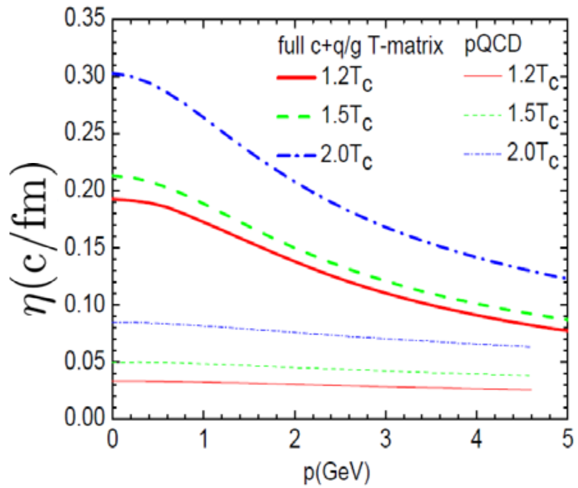
M. He, R. Fries, R. Rapp PRC 82 (2010), PRC 86 (2012)

- Implemented through Langevin dynamics in hydro evolution or in URQMD

- Full quantum treatment of the light quarks (spectral functions)



No good q-particle at low p



Large coupling at small p_Q

Models & Effective Theories

	elastic	Elastic + radiative	radiative	Other
Transport coefficient based (LV,…)	TAMU POWLANG HTL Catania LV	Duke, TAMU w rad.	ASW	ADS/CFT POWLANG lQCD *DABMOD* *S. Li et al, arXiv:1803.01508*
Cross section (or$\|M\|^2$) based (Boltzmann,…)	AMPT MC@sHQ el URQMD PHSD Catania BM	DREENA MC@sHQ el + rad BAMPS CUJET3 HYDJET++ Abir and Mustafa LBL-CCNU VNI/BMS LIDO	$SCET_{G,M}$	

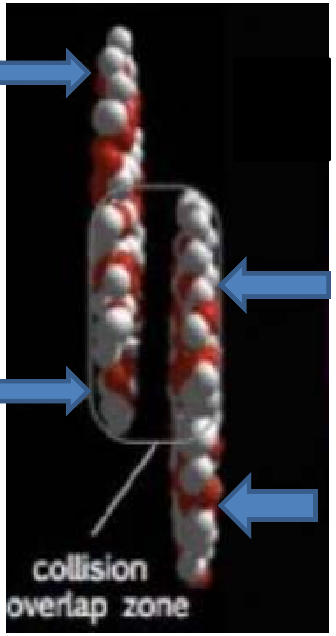
Red: Transport models

Disclaimer : If your model does not appear here, please forgive me and contact me for completion

Observable 1: Nuclear modification factor

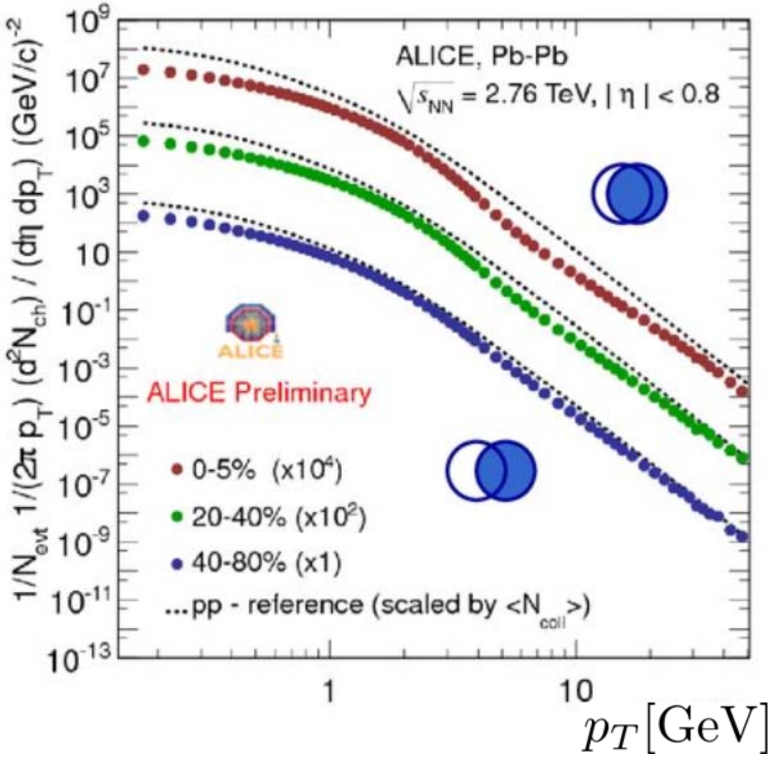
p_T

Beam axis



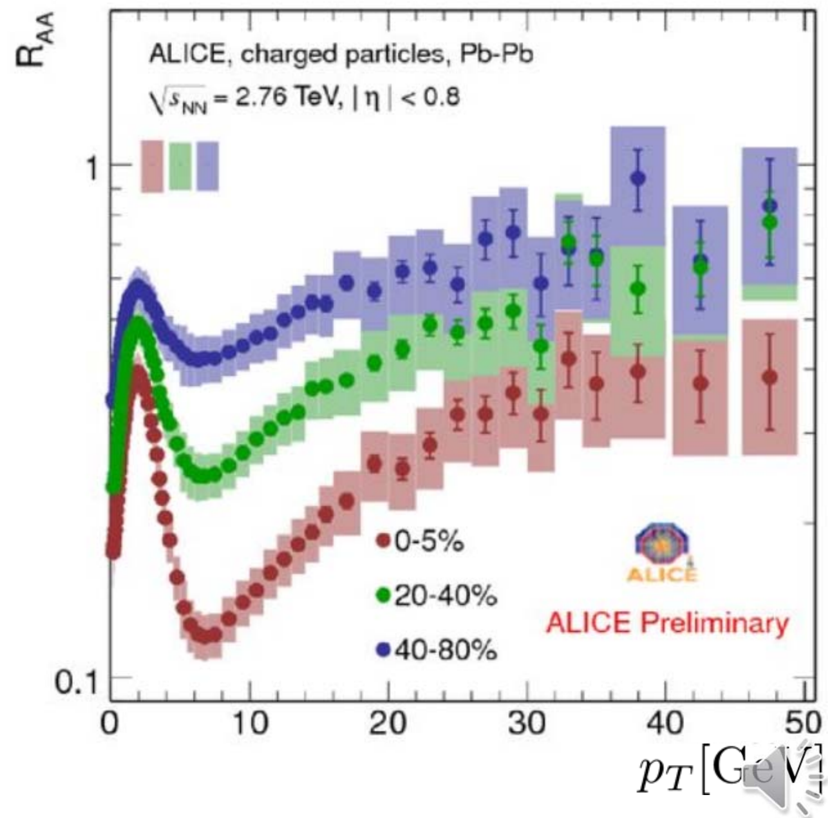
Equivalent number of pp collisions in the overlap: N_{coll}

Charged hadrons p_T spectra



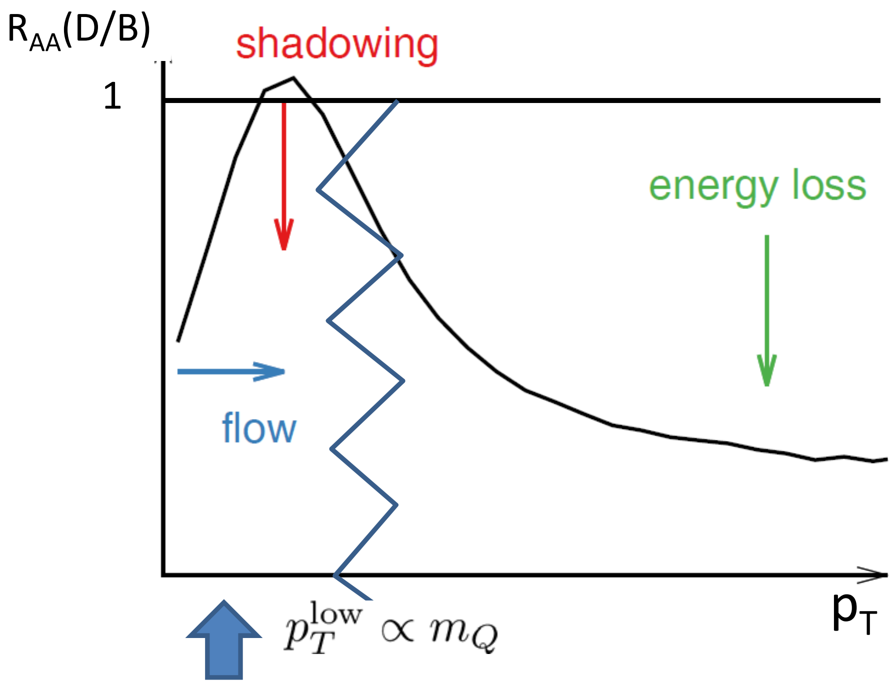
Nuclear modification factor

$$R_{AA}(X) = \frac{\left.\frac{dN^X}{dp_T}\right|_{AA}}{N_{\rm coll}\left.\frac{dN^X}{dp_T}\right|_{pp}}$$



Basic Consequences of HQ interaction with QGP for the R_{AA}

The pattern seen in the data



- Dominated by elastic interactions
- m_Q >> T => needs « many » collisions to equilibrate
- Physics close to « Langevin »

The acknowledged effects

Flow bump: due to

- *(radial) flow of the medium* and coupling at small p_T
- *recombination with light quarks*

shadowing: due to *initial state nuclear effects*

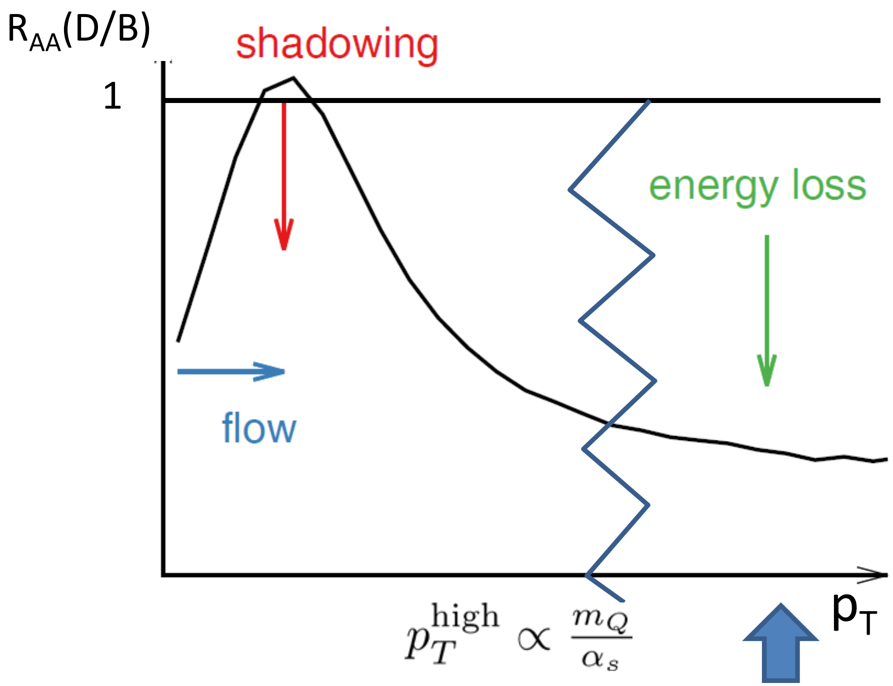
Quenching & energy loss: due to

- elastic and *inelastic* scatterings
- *opacity of the medium*

Italic: extrinsinc to the HF coupling with QGP AKA « energy loss model»

Basic Consequences of HQ interaction with QGP for the R_{AA}

The pattern seen in the data



The acknowledged effects

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- *recombination with light quarks*

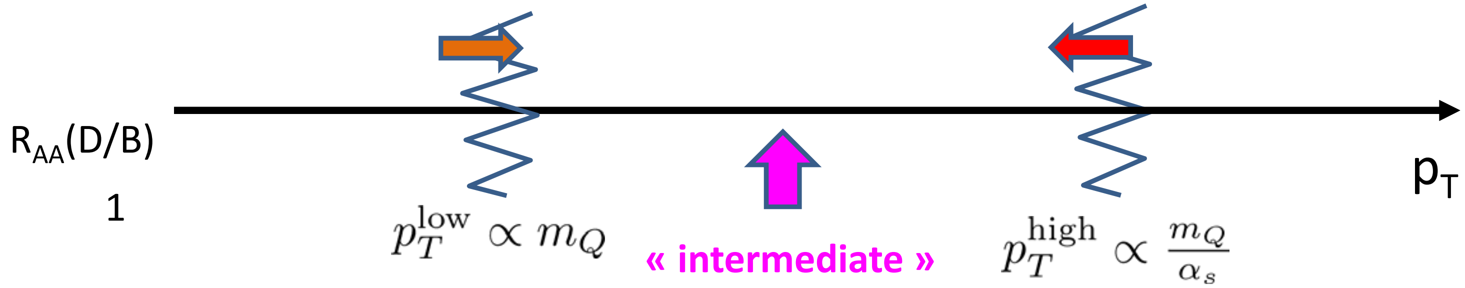
shadowing: due to *initial state nuclear effects*

Quenching & energy loss: due to

- elastic and *inelastic* scatterings
- *opacity of the medium*

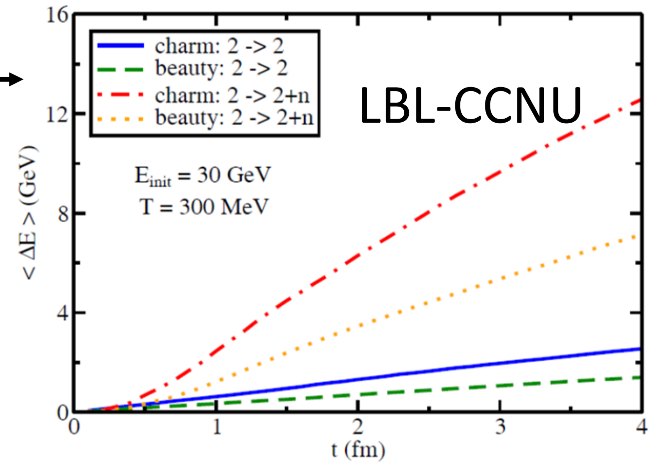
- Dominated by radiative energy loss (with important coherence effects: $\Delta E_{\text{rad}} \propto C_A \hat{q} L^2$)
- Eikonal regime (propagation along straight lines)
- 1 single transport coefficient dominates the whole physics: $\hat{q} \propto \kappa_T$
- HQ do not equilibrate with the medium
- m_Q becomes a subscale of the physics ($m_Q \ll p_T$)

Basic Consequences of HQ interaction with QGP for the R_{AA}



- Interplay between elastic and radiative interactions…
- … whose dominance depends on the path length
- Fluctuations need to be taken properly into account
- Elastic component: Not clear that Langevin regime still applies (harder and harder collisions)
- 3 transport coefficients in momentum space (η, κ_L, κ_T) are « only » constrained by Fluc. Dissip. Th.
- Radiative component acquires NLO in m_Q/p and starts being sensitive to $\hat{e}$ and $\hat{e}_2$

$$\frac{dN_g}{dy\, dl_\perp^2\, d\tau} = 2\,\frac{\alpha}{\pi}\,P(y)\,\frac{1}{l_\perp^4}\left(\frac{1}{1+\chi}\right)^4 \sin^2\left(\frac{l_\perp^2}{4l^-(1-y)}(1+\chi)\,\tau\right) \times \left[\left\{\left(1-\frac{y}{2}\right)-\chi+\left(1-\frac{y}{2}\right)\chi^2\right\}\hat{q}+\frac{l_\perp^2}{l^-}\chi\,(1+\chi)^2\,\hat{e}+\frac{l_\perp^2}{(l^-)^2}\chi\left(\frac{1}{2}-\frac{11}{4}\chi\right)\hat{e}_2\right]$$



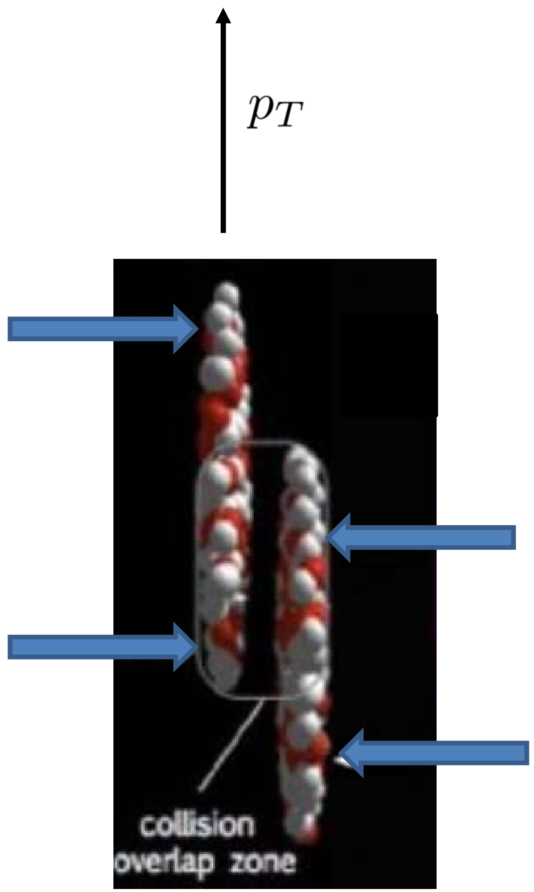
S. Cao et al, Phys. Rev. C 94, 014909 (2016)

Abir and Majumder, Phys. Rev. C 94, 054902 (2016)

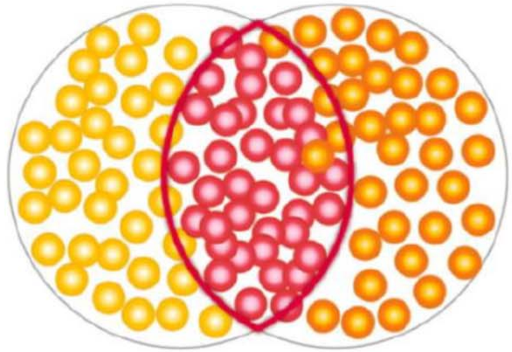
See as well Aichelin, Gossiaux & Gousset, PRD (2013)

Observable 2: azimuthal flows

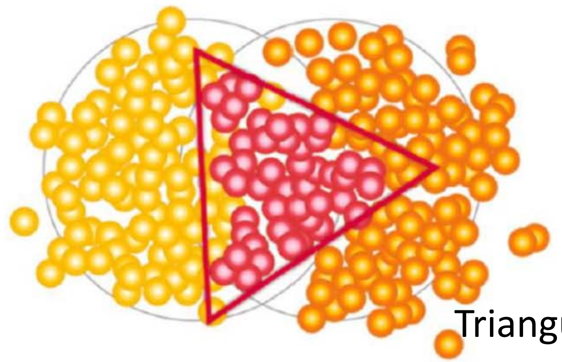
Beam axis (Oz)



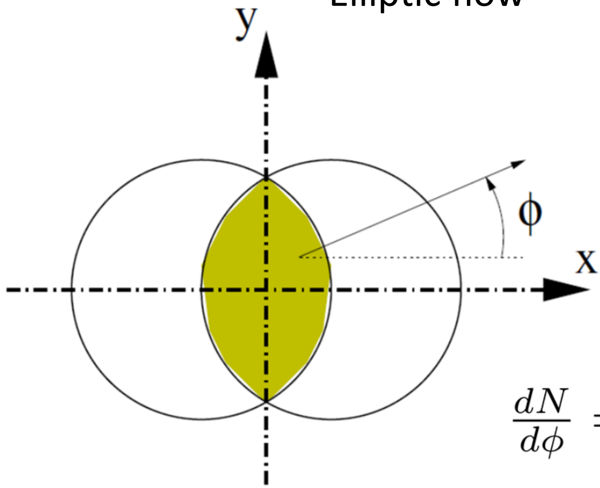
Initial stage of the collisions seen in the transverse plane: Non spherical initial spatial distribution due to eccentricity + fluctuations



Elliptic flow



Triangular flow



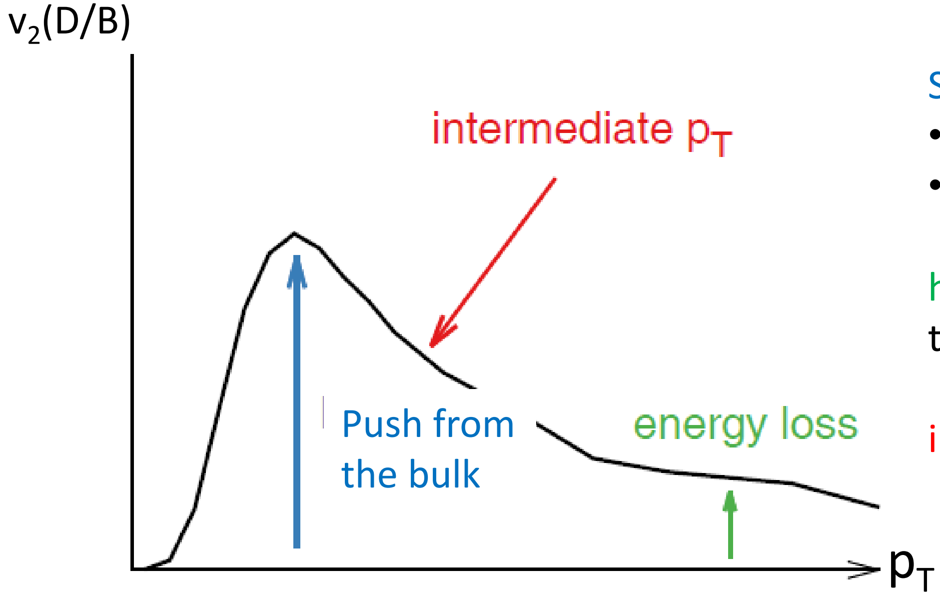
... later on converted in anisotropies due to the fluid dynamics evolution.

anisotropies in the final hadrons azimuthal distributions (Fourier series)

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

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

Basic Consequences of HQ interaction with QGP for the v_2



Small pT: height of v2 at low p_T sensitive to:

- *Bulk anisotropy, mostly at the late times*
- The drag force acting locally on HF

high p_T non-0 v_2 is due to anisotropic Eloss (same ingredients as for the RAA + *geometrical anisotropy of initial distribution of matter*)

intermediate p_T : onset and offset of many competing effects.

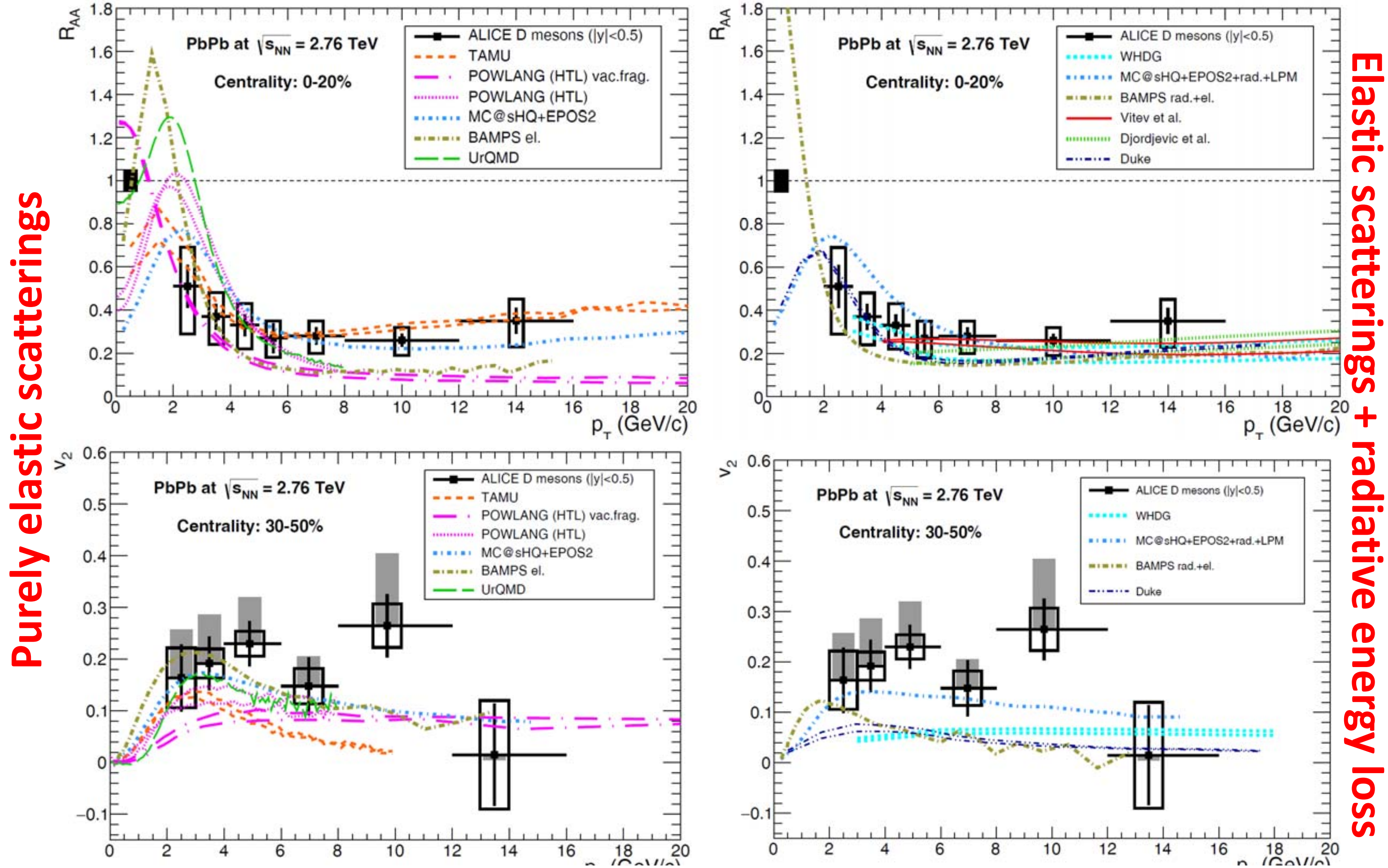
3 Important remarks:

- Any energy loss model, even the crudest one, will generate these typical structures in the R_{AA} and the v_2. Getting a correct **quantitative** agreement is much more involved.
- Quantitative predictions also depends on some « extra ingredients » (bulk, hadronisation,...)
- **While R_{AA} develops early, v_n is sensitive to later stages of the evolution** => quite sensitive to physical mechanisms near Tc.

!!! Alternative pointed out recently within transport model (AMPT & MPC) study: so-called « escape mechanim » characterized by a large v_2 component stemming from $N_{coll} \approx 1$ **L. He et al, Physics Letters B753 (2016) 506**

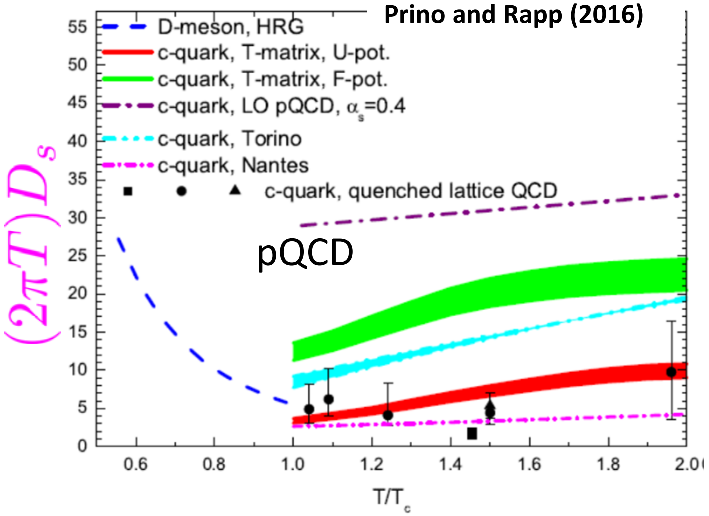
Models vs DATA at LHC (Sapore Gravis Report compilation)

Eur. Phys. J. C (2016) 76



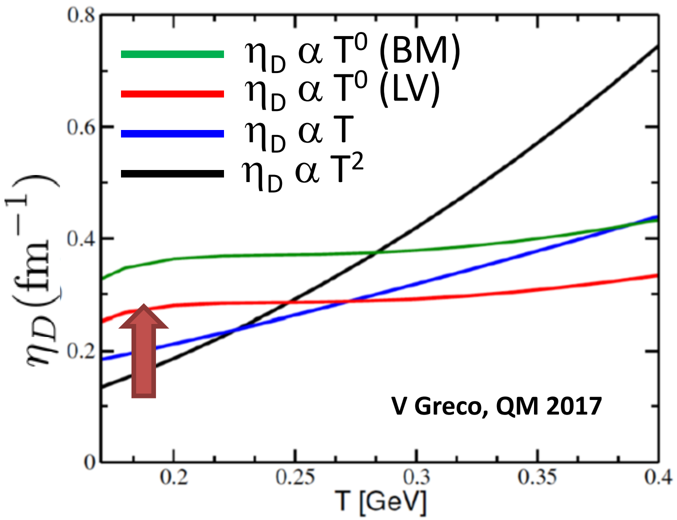
Despite various prescriptions for Energy loss, a lot of models can cope with the data

Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail



$$\tau_{\text{relax}} = \eta_D^{-1} = (2\pi T)D_s \times \frac{m_Q}{2\pi T^2}$$

S.K. Das et al, Physics Letters B747 (2015) 260

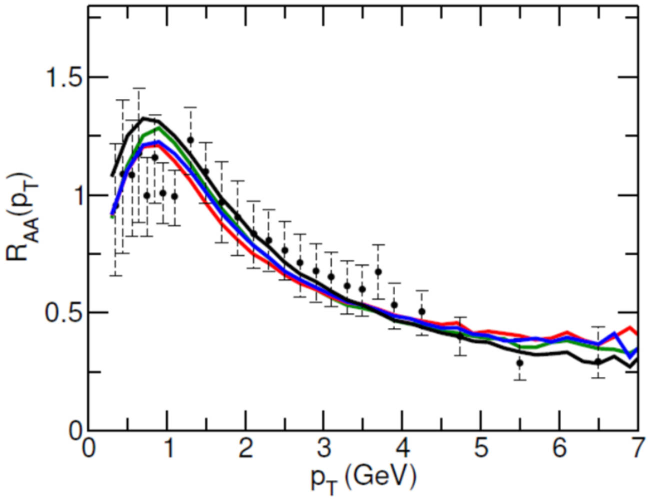


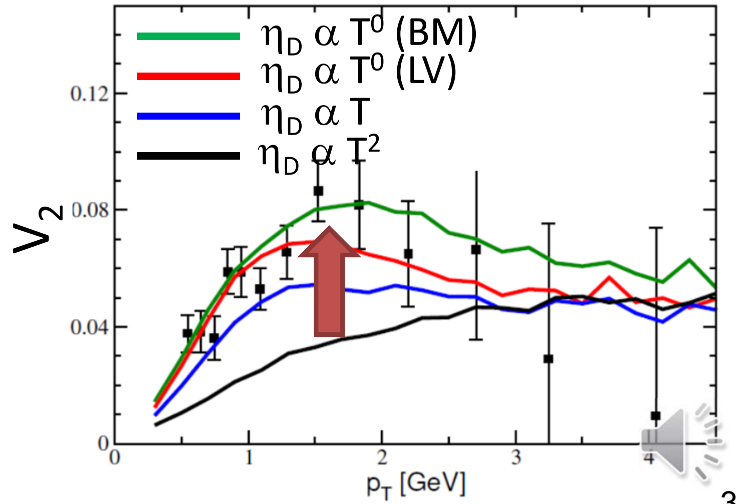
η_D α T^2: pQCD (fixed α_s), AdS/CFT

η_D α T: pQCD (running α_s)

η_D α T^0: QPM, DQPM, U potential (TAMU)

Tuned to reproduce R_{AA} => Larger coupling with the bulk near T_c (when the hydro v_2 has fully developped) => Larger v_2





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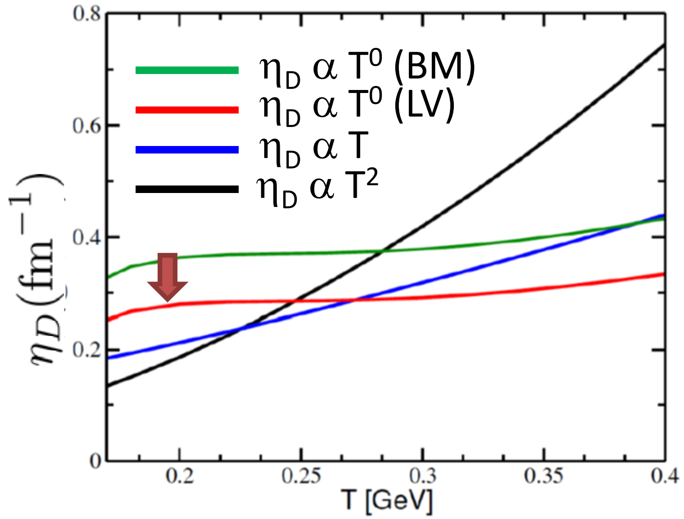
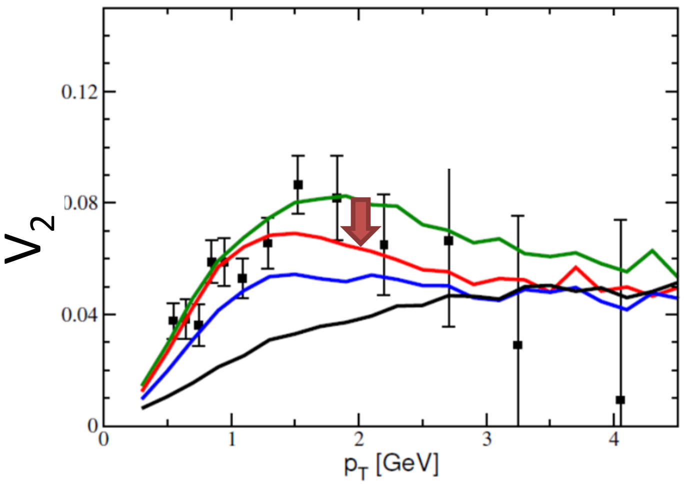




S.K. Das et al, Physics Letters B747 (2015) 260

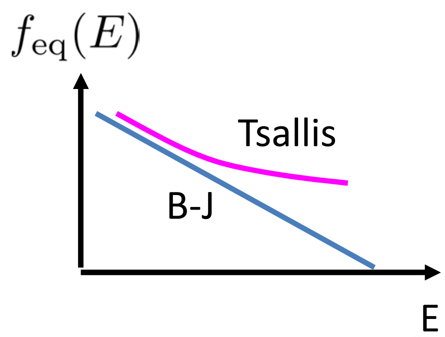
Extra increase from LV => Boltzmann dynamics

Should be seen as a *decrease* passing from Boltzmann =>LV

In models considering $\gamma \propto T^0$ like QPM, DQPM, TAMU: microscopic $d\sigma/d\theta$ generate more diffusion at large angles

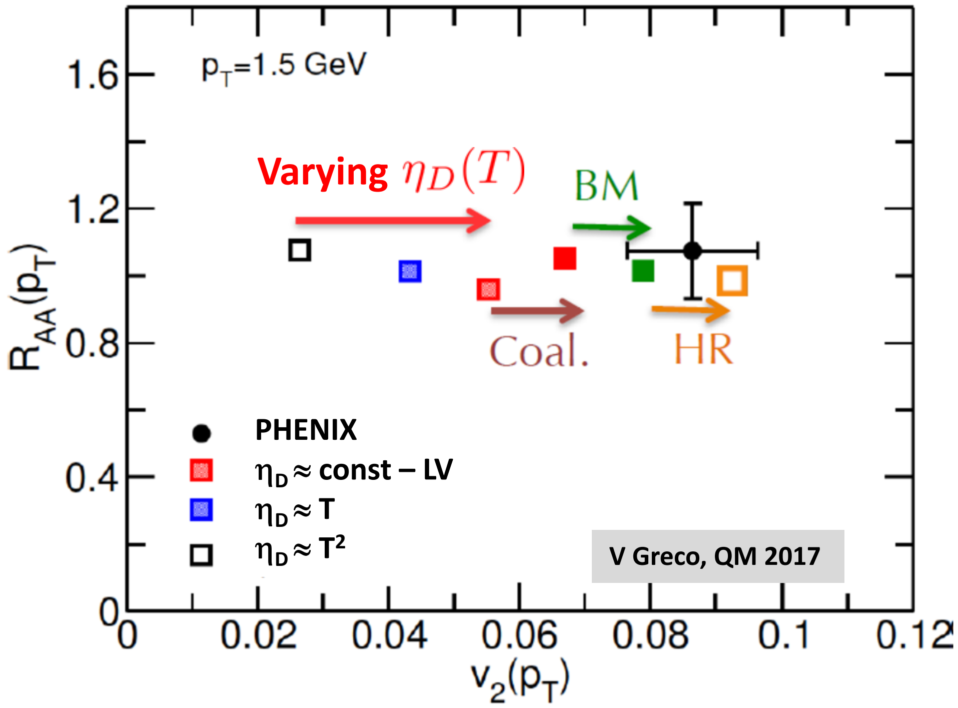
=> Encoding the physics into Langevin scheme, we do not describe properly the fluctuations at large momentum (as seen f.i. in the Tsallis like asymtotic distribution).

=> For dynamical evolution, one needs to cranck down the interaction and the FP coefficients in order to reproduced a « given » R_{AA}



=> Smaller « extracted » coefficients (≈ -20%) & smaller v_2.

Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail



Nice guideline but need:

- To consider extra ingredients (bulk, initial v_2,..)
- To assess the uncertainties on « Coal » and « HR »
- … before one can think of ruling out other trends for η_D.

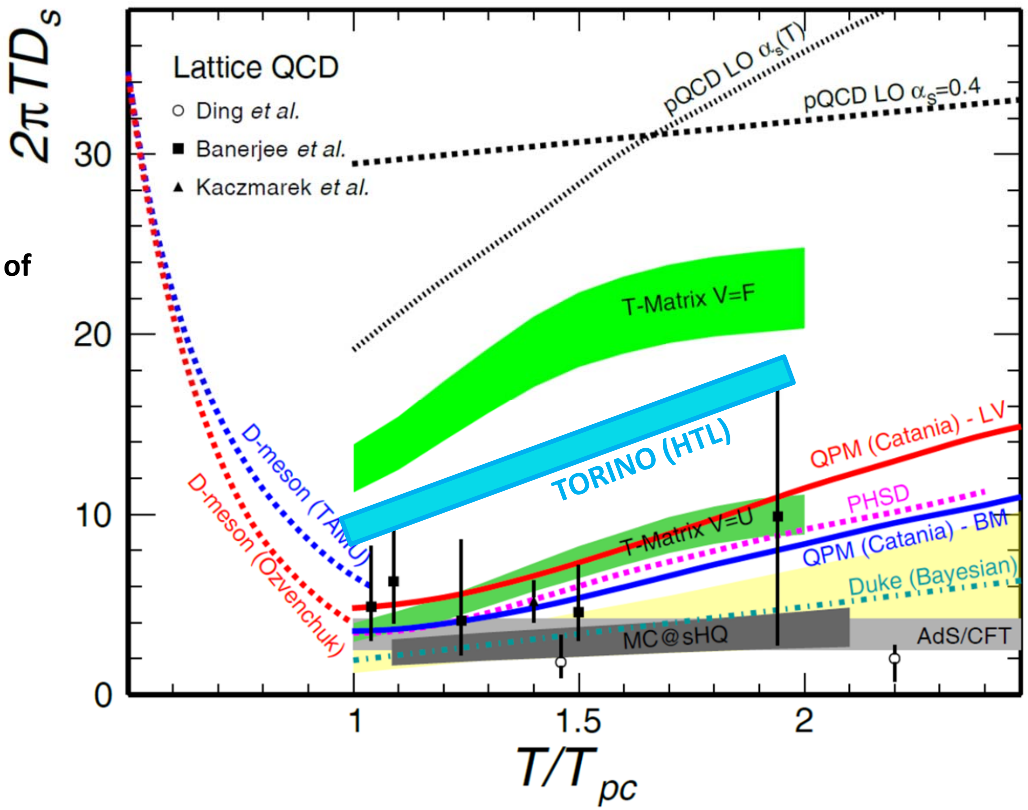
$\eta_D \propto T^2$: pQCD (fixed α_s), AdS/CFT

$\eta_D \propto T$: pQCD (running α_s)

$\eta_D \propto T^0$: QPM, DQPM, U potential (TAMU)

Model summary on $2\pi TD_s$ extraction

X. Dong et al. Annual Review of Nuclear and Particle Science 69:417-445 (2019)



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$$(2\pi T)D_s = \frac{2\pi T^2}{E_Q\,\eta_D}$$

Mild linear increase of $2\pi D_sT$… ⇔ physics beyond pQCD (fixed α_s).

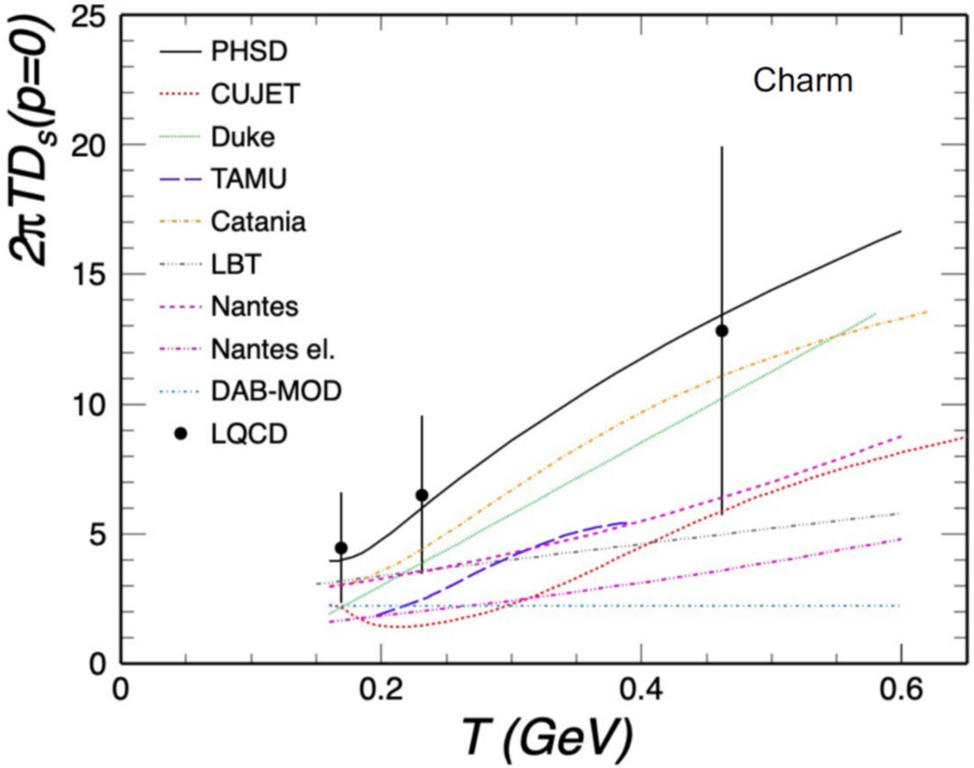
- Most of the values extracted from model comparison with the data are compatible with lQCD calculations !!!
- All together (lQCD, Bayesian analysis and most recent models) make a strong case for physics beyond « weak pQCD LO » around T_c » and at «low» p_T
- However, the question whether one needs to include strong non-perturbative features is still debated … needs to be further addressed in the future.

Model summary on $2\pi TD_s$ extraction

X. Dong et al. Annual Review of Nuclear and Particle Science 69:417-445 (2019)

Latest update : https://indico.ectstar.eu/event/98/contributions/1927/

(HF Transport, ECT* 2021)



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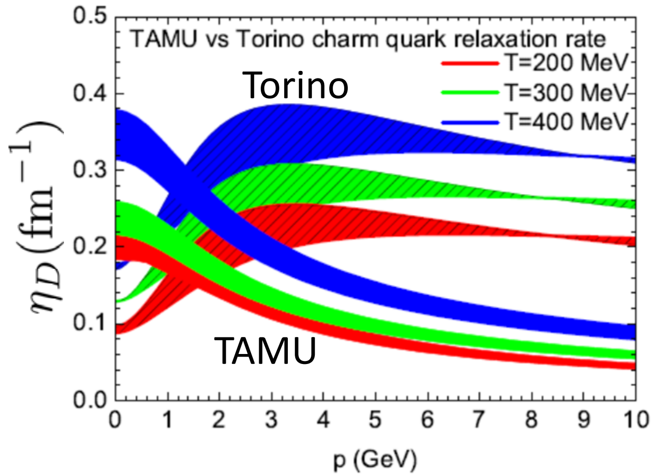
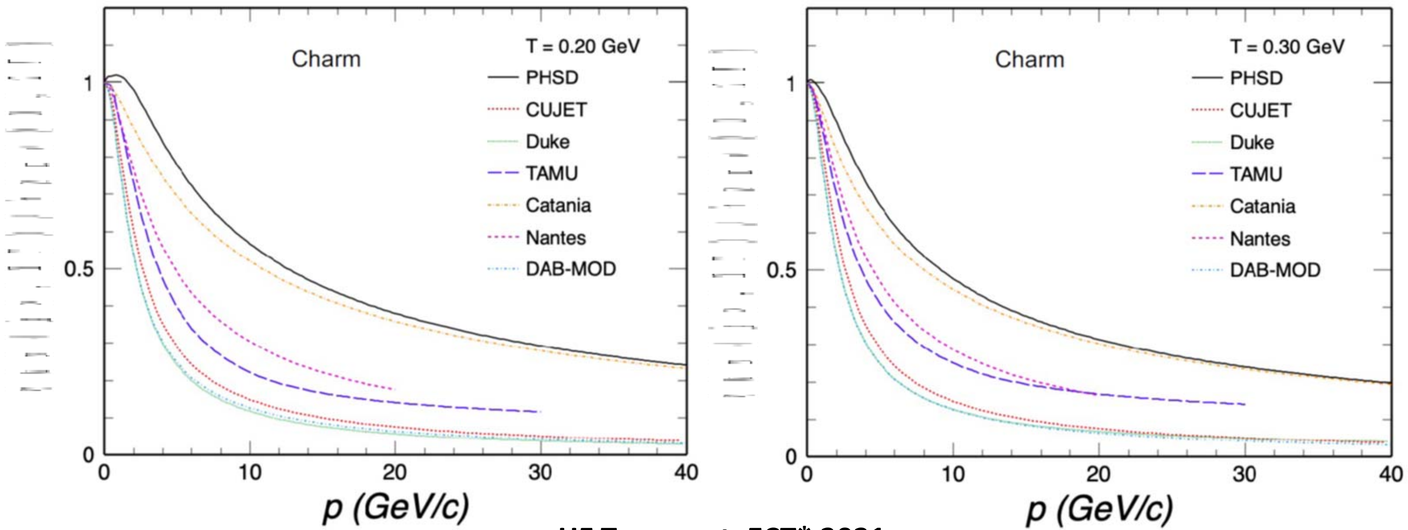
- Most of the values extracted from model comparison with the data are compatible with lQCD calculations !!!
- All together (lQCD, Bayesian analysis and most recent models) make a strong case for physics beyond « weak pQCD LO » around T_c » and at «low» p_T (< 2 GeV/c)
- However, the question whether one needs to include strong non-perturbative features is still debated … needs to be further addressed in the future.

Model summary on $2\pi T D_s$ extraction



Prino and Rapp, J.Phys. G43 (2016), 093002



HF Transport, ECT* 2021
https://indico.ectstar.eu/event/98/contributions/1927/

Further thoughts…

- D_s (p=0) does not represent the full physics (different momentum dependences of η_D) … R_{AA} mostly sensitive to energy loss at *finite* momentum (equilibration at low p_T)
- This momentum dependence is the direct footprint of physical dof and interactions => should be better constrained in the future
- Non trivial role of « extra ingredients » (bulk, hadronisation,…)

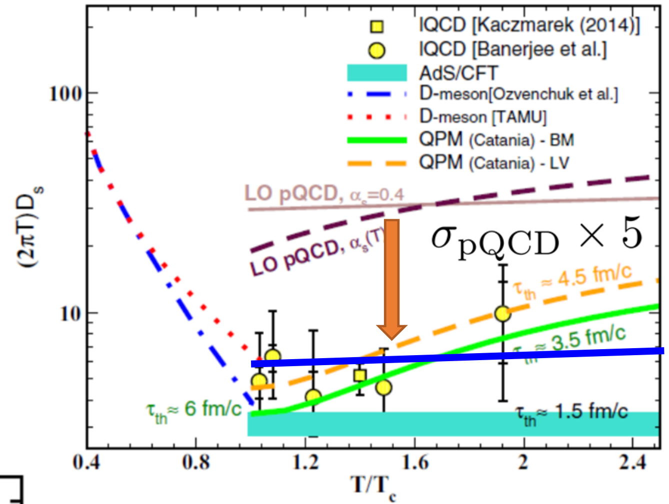
Collective investigation: Consequences from the **bulk choice** (and partly transport)

<u>Question</u>: What is the role of the different medium evolution models, and how do different predictions for the bulk cooling and expansion temperature in the current models manifest themselves in HF observables ?

<u>Method</u>: adopt a common α_s=0.4-pQCD x 5 cross section for thermal light partons acting on c-quarks (or associated FP coefficients for models based on FP) in all frameworks.

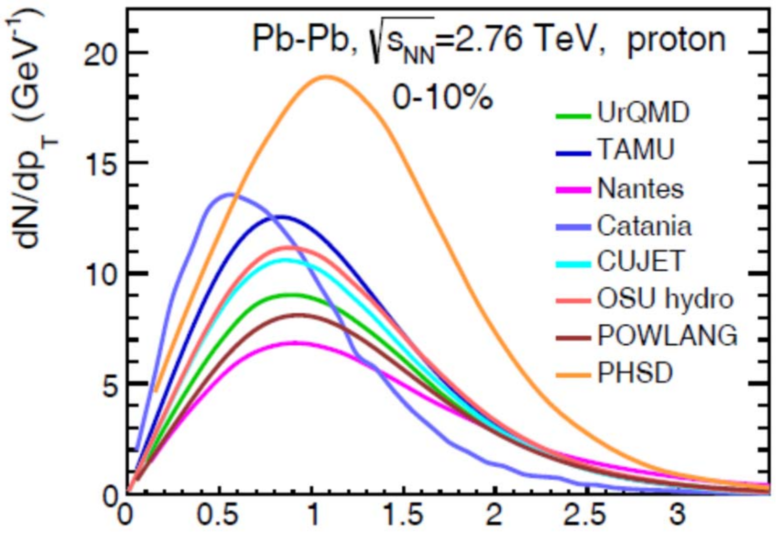
One Interaction for all of them; not aimed at reproducing the data !!!

R. Rapp et al, Nucl. Phys.A 979 (2018) 21-86

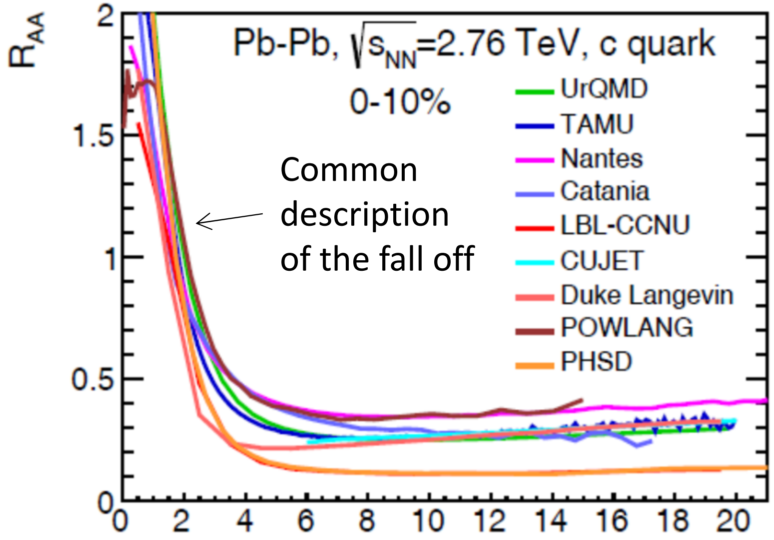


This allows to probe the effect of the bulk with a mechanism that has a D_s roughly similar to the one extracted from lQCD

Protons from the bulk **at FO**



c quarks **at FO**



For most bulks:

$$R_{AA}(c, 10\,\mathrm{GeV}) \approx 0.3 - 0.4$$

For 30%-50%:

$$R_{AA}(c, 10\,\mathrm{GeV}) \approx 0.4 - 0.6$$

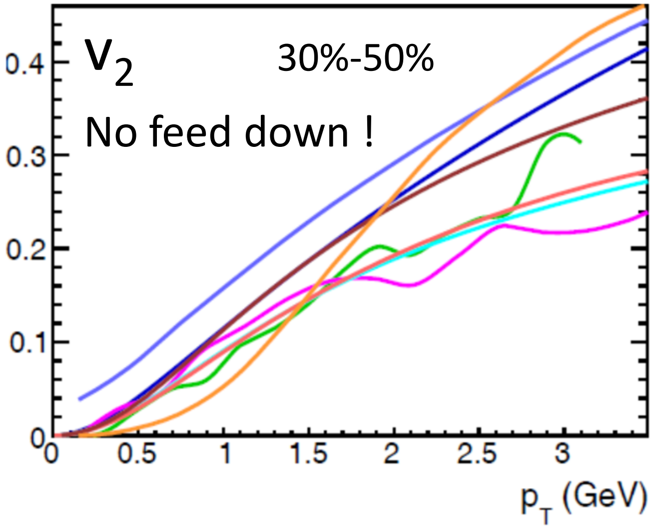
No feed down !

Some correlation between dN(p) and R_{AA}(c) but not systematic

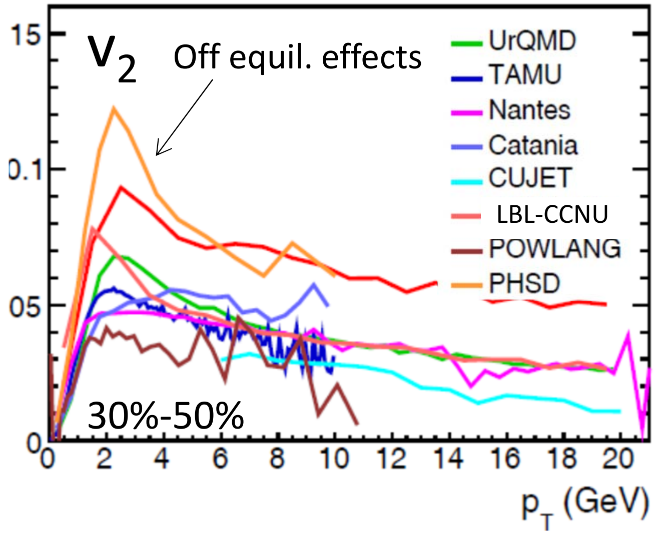
Collective investigation : Consequences from the **bulk choice**

R. Rapp et al, Nucl.Phys.A 979 (2018) 21-86

Protons from the bulk at FO



c quarks at FO

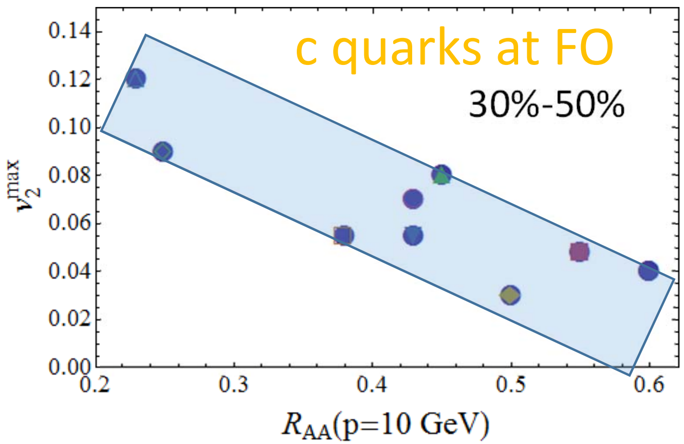


N.B.: LBL-CCNU could not implement scattering on thermal- massive partons

For most bulks:

$$v_2(c, p_T = 4\,\mathrm{GeV}) \approx 0.4 - 0.6$$

Max v_2 reached between 2 and 4 GeV/c



Some correlation between v_2(p) and v_2(c) but not systematic

- Some correlation between R_{AA}(c) and v_2(c) from various bulks, but rather large residuals => Non « scalable » bulkS
- **Adopting a (limited number of) common bulk(s) would permit to shrink the residuals in the « extraction » of the optimal transport coefficients.**

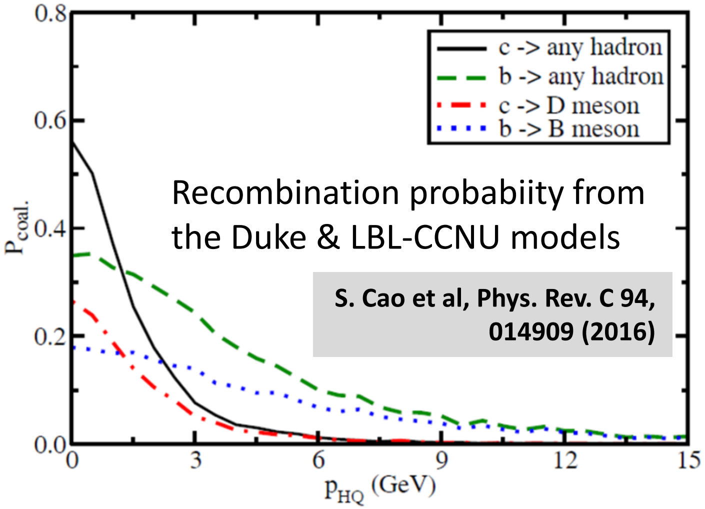
HQ - Hadronization

Acknowledged:

- towards the end of QGP, hadronization of (of equilibrium) HQ can proceed through a dual mechanism:

Low p_T :

- The quark partner(s) are already present in the hot cooling medium
- New specific recombination mechanism; no obvious calibration
- The footprint of reconfinment (?!)
- Crucial to explain the flow bump in R_{AA}(D) and sizable v_2(D) => large impact.



High p_T :

- The quark partner(s) needed to create the HF-hadron have to be generated from the vacuum
- « usual » fragmentation calibrated on p+p and e^++e^- data (Petersen,…)

But also energy density dependent (PHSD) !!!

Uncertain (and not disputed enough):

- Genuine physical recombination process:
  - Instantaneous Parton Coalescence with local (x,p) correlations (Greco, Ko & Levai 2003), Xor in momentum space (Oh et al 2009): known violation of energy-momentum conservation, advocated to have small effects at finite p_T
  - Resonance Recombination Model (Ravagli and Rapp, 2009): kinetic c+qbar -> D; spirit of dynamical recombination around T_c ($P_{recomb} = \Delta\tau \times \Gamma_{res}(p)$; a way to solve the energy-momentum conservation issue
  - In medium Fragmentation (Beraudo et al., 2015) : string from HQ + thermal light
- Differences in the « technical implementations » , e.g. normalisation

HQ - Recombination

Regained interest in Λ_c measurement in view of the recent AA

Acknowledged:

- towards the end of QGP, hadronization of (of equilibrium) HQ can proceed through a dual mechanism:

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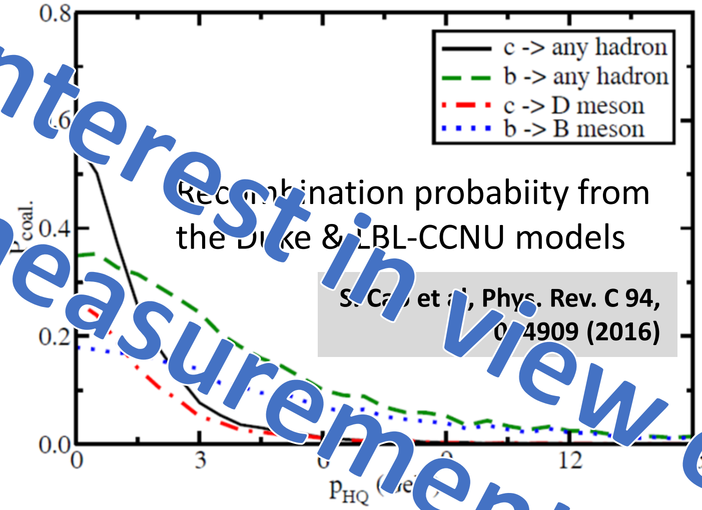

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See Min He, SQM 2021

Jinjoo SEO, charm 2021

Collective investigation : Consequences from various **Hadronization Mechanisms**

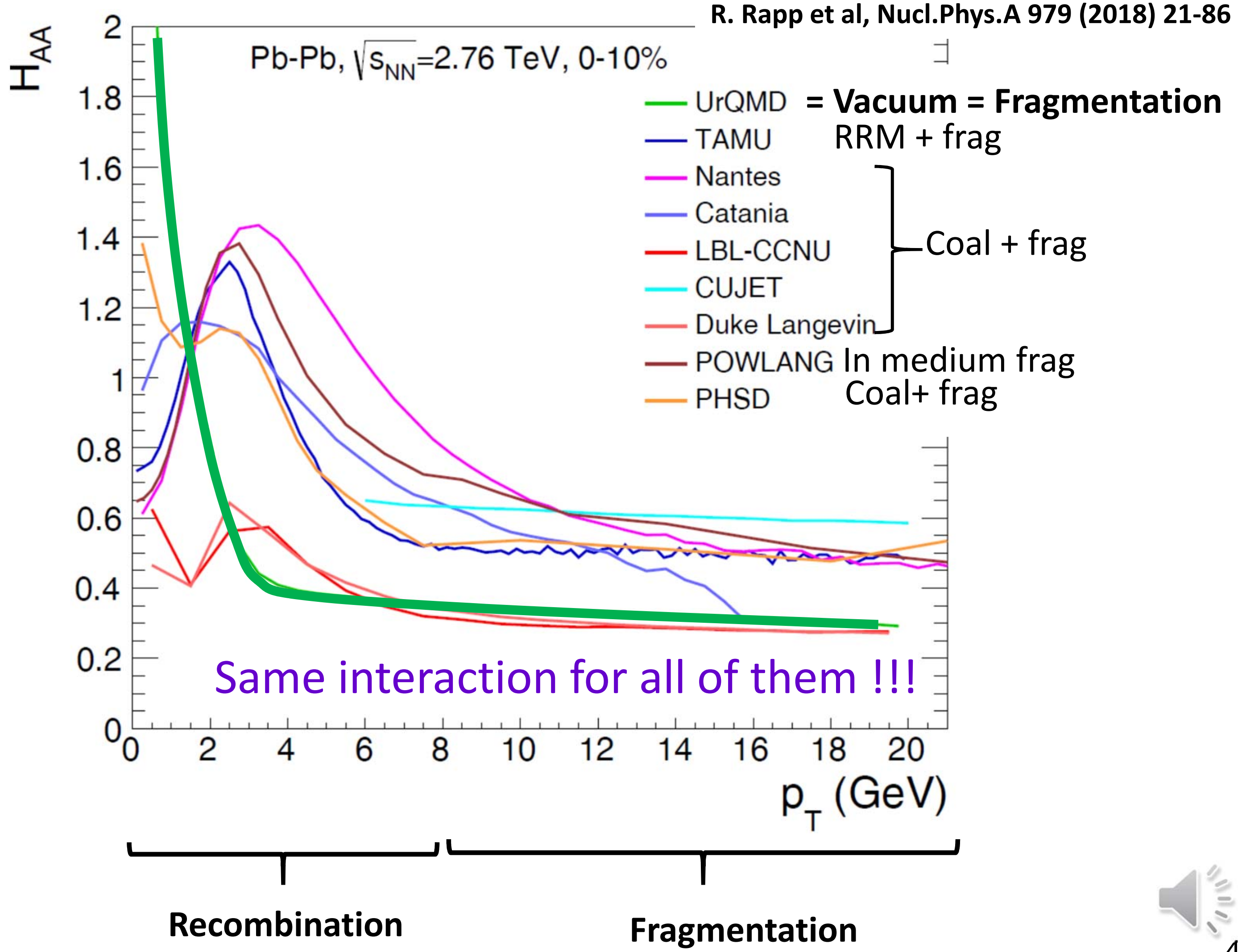
We define and display the H_{AA} quantity

$$H_{AA} = \frac{\frac{dN_D}{dp_T}}{\frac{dN_{c\ \mathrm{final}}}{dp_T}}$$

…which exhibits at best the specific effects of hadronization :

Significant uncertainties !

=> Yes, one can for sure put more constrains with D_s and Λ_c, but probably one has also to converge on more robust schemes for « basic » D mesons



Collective investigation : Study in a QGP brick

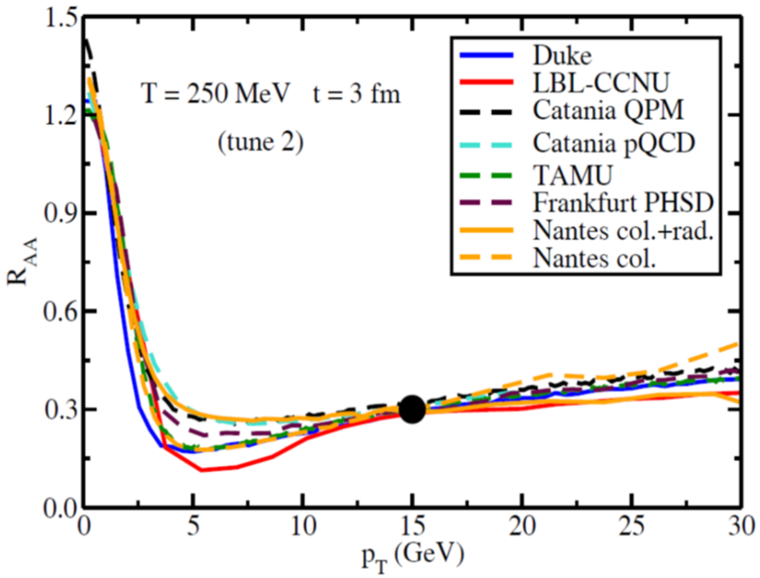
S. Cao et al, Phys.Rev.C 99 (2019) 5, 054907

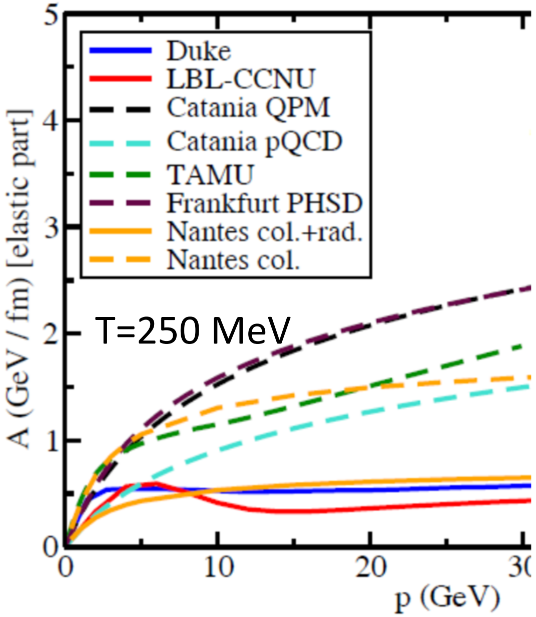
The goal was to :
- Collect and compare the **transport coefficients** from various models,
- Measure and understand their consequences by first studying a simpler brick problem
- Estimate some systematics + uncertainties

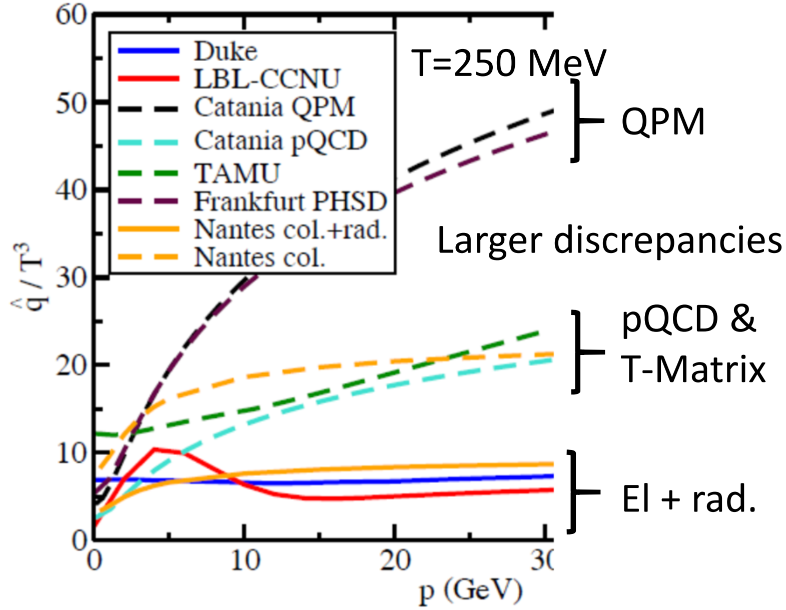
Best controled QGP ever: uniform fixed temperature for all models (with same initial condition FONLL-like @ RHIC)

1) Rescale the coefficients to match R_{AA}=0.3 at p=15 GeV & « final time » 3 fm/c

2) Compare them !







Main result: Nice structuration of the transport coefficients in different classes. For each class, the work illustrates the maximal accuracy reachable once all other ingredients are either fixed or chosen commonly

Recent progresses and future directions

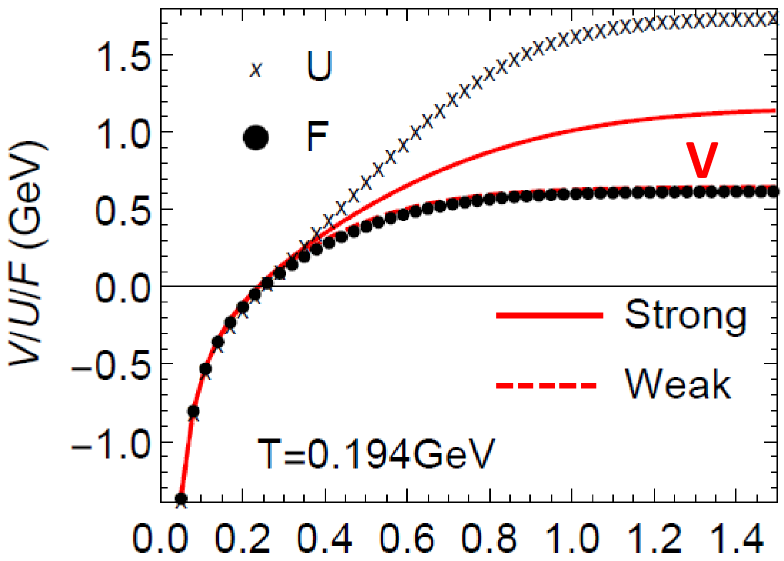
(Selected) Recent trends :

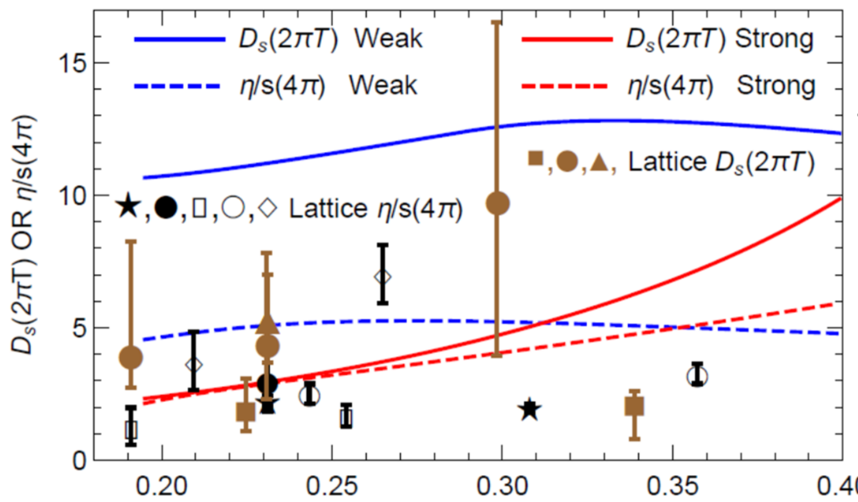
- Generalization of the treatment of (thermal) QGP constituents in the calculation of the transport coefficient :
  - Thermal mass (calibrated on the EOS): **QLBT: https://indico.cern.ch/event/792436/contributions/3548981/, MC@HQ: Nahrgang et al Phys.Rev.C 93 (2016) 4, 044909**
  - Off shell effects (re)considered by the use of spectral function more faithfull to the quantum treatment): **TAMU: Shuai Y.F. Liu et al, Phys. Rev. C 99, 055201 (2019), CATANIA: ML Sambataro et al. Eur. Phys. J. C 80 (2020) 1140**
- Inclusion of radiative energy loss: **TAMU: Shuai Y.F. Liu & R. Rapp JHEP 08 (2020) 168**
- Effect of initial stages on HF evolution (glasma, B field, vorticity): **S. Chatterjee and P. Bozek. PRL120(2018)192301; Y. Sun et al. PLB768(2017) 260-264. PLB 816 (2021) 136271; S. Chen et al Phys.Rev.C 103 (2021) 3; L031902, M. Kurian et al., PRD 101,094024 (2020)**
- …

See as well recent plenary talk of Min He at « Strangeness in Quark Matter » or « Heavy-Flavor Transport in QCD Matter » at ECT* (https://indico.ectstar.eu/event/98/overview)

Recent progresses and future directions

- **Deeper rooting with theory** : TAMU strategy: **S. Y.F. Liu and R. Rapp, PRC97 (2018) 034918**
  - o Hamiltonian formulation of a non relativistic effective theory based on a 2-body potential
  - o Included in the Luttinger-Ward-Baym formalism -> description of the **equation of state** (EoS)
  - o EOS is not enough => evaluation of the **free energy** (./. introduction of Q-Qbar pair) + **quarkonium correlators** ...
  - o Allows to self-consistently derive 2 optimal solutions for the potential by calibration on the equivalent lQCD quantities (one « weak » close to the free energy and one « strong » with remnants of the long range forces… non spectral light quarks and spectral densities





S. Y.F. Liu and R. Rapp Eur. Phys. J. A 56, 44 (2020)

Further comparison with diffusion coefficient favors the « strong » potential

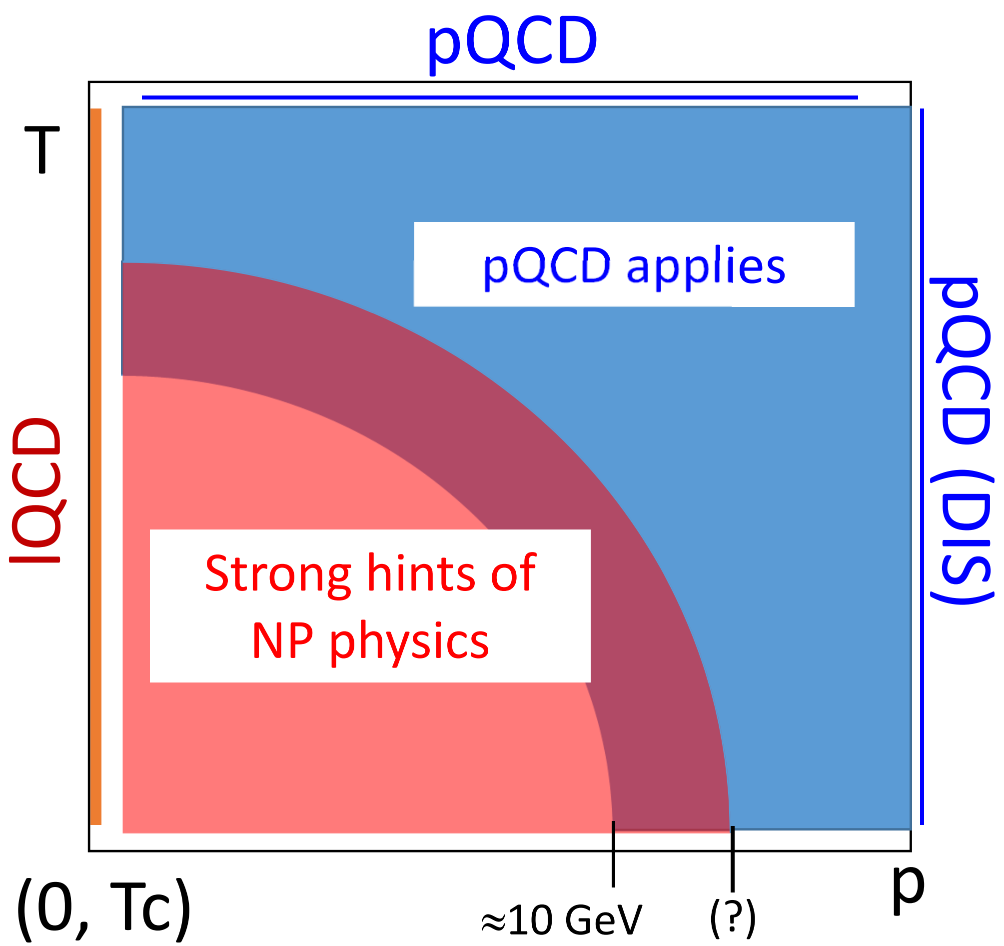
Recent progresses and future directions

Future directions :

- TAMU approach in making the contact with QCD thanks to lQCD calculation and solving of many body theory is a strong incentive for other models to perform an equivalent rooting.
- Calibration on the EOS is a good starting point but other quantities more directly connected to HQ physics should be considered as well (correlators, imaginary potential,…)
- Models based on one (effective) gluon exchange should consider ladder ressummation
- Efforts should be maintained from lQCD community to evaluate quantities as close possible to the Fokker-Planck coefficients at finite momentum (easier contact with phenomenology)
- Need for a better connection between hadronisation of heavy quark at the end of the QGP phase, dynamical models, modern understanding of confinment.
- Need for a systematic reduction of the systematic « errors » affecting the predictions => link with precision data, new observables (correlations)
- Application of the methods to small systems

Conclusions

HF in QGP



- Existing models offer the possibility to describe most of the OHF experimental AA data while being compatible with existing theory constrains…
- … however with unequal precision and no consensus on the physical NP content
- Improvements and quantitative understanding is on their way, but it will still take some time and a lot of efforts => need for ressources, bright (young) people and collective work.
- Open Heavy Flavors are maybe not an ideal probe of QGP yet, but they are quite fascinating and offer bright future for the field, with multiple interconnections (see next slide).

Visual summary