5th International Workshop “QCD challenges from pp to AA collisions”

Münster (Germany), 2-6 September 2024

# Trigger talk : Energy loss and transport in the medium and in small systems

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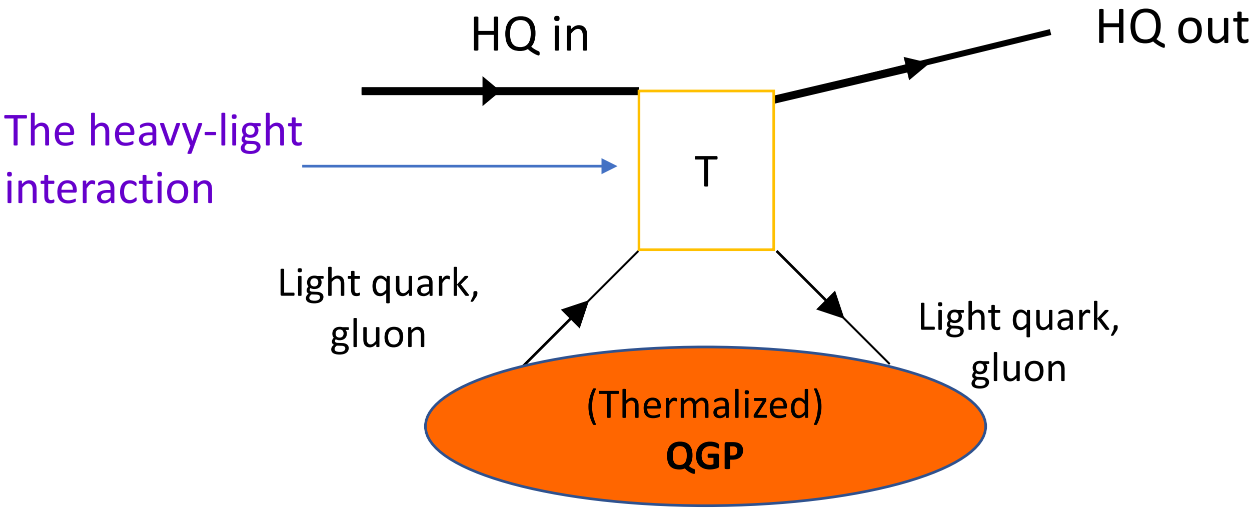
and Pays de la Loire

# Transport and Energy loss of (quasi) particles like heavy quarks ?

**Simple collisional (elastic): 2 → 2**



HQ in

HQ out

The heavy-light interaction

T

Light quark, gluon

Light quark, gluon

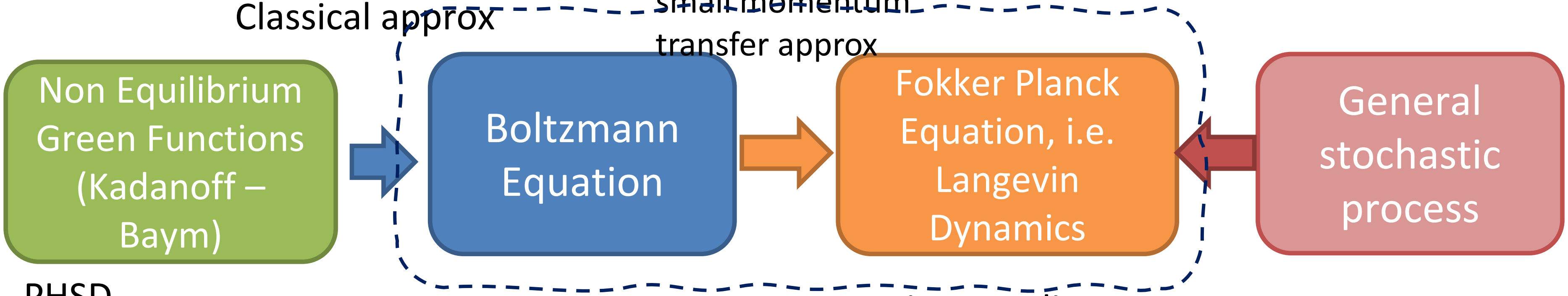
(Thermalized) **QGP**

**Possible schemes**

Mostly used in phenomenology

Classical approx

small momentum transfer approx



Non Equilibrium Green Functions (Kadanoff – Baym)

Boltzmann Equation

Fokker Planck Equation, i.e. Langevin Dynamics

General stochastic process

PHSD

Main Ingredient: **cross section**

Main Ingredient: **FP coefficients / transport coefficients**

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

Relaxation rate

$$\frac{d}{dt}\langle\vec{p}_{T,i}\vec{p}_{T,j}\rangle = \kappa_T(\vec{p},T)\delta_{i,j} \quad \kappa_T[\mathrm{GeV}^2\mathrm{fm}^{-1}]:$$

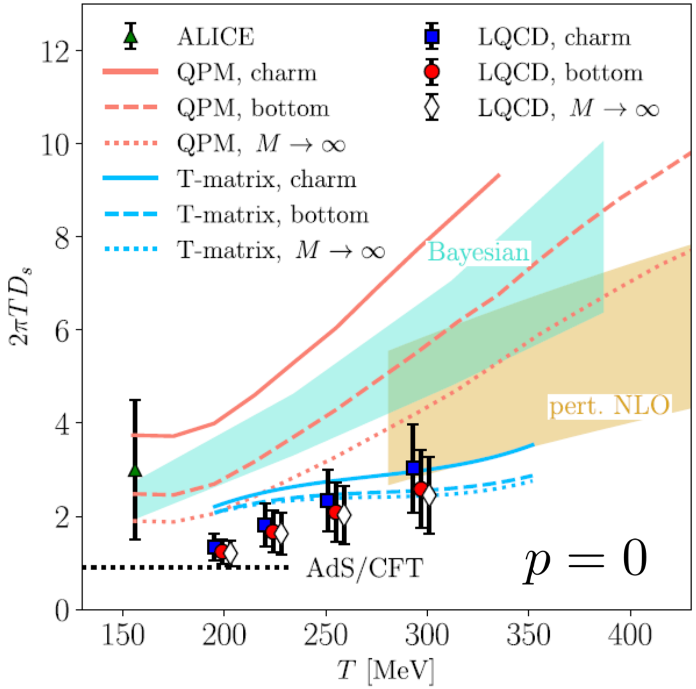
Trans. diffusion coef. (p space) ;

$$\boxed{\hat{q} = 2\kappa_T = 4B_0}$$

Same for Longitudinal diffusion coef. => **3 characteristics** of the Eloss

Not easy to extract from lQCD….Improvement last year year for Ds

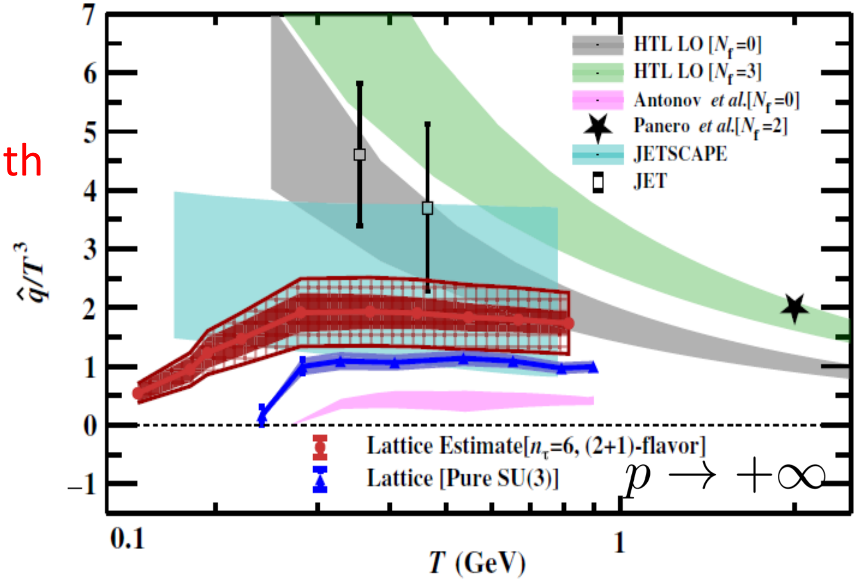
$$(2\pi T)D_s = \frac{4\pi T^3}{\kappa(p{=}0)} = \frac{2\pi T^2}{m_Q\eta_D(p{=}0)}$$



PHYSICAL REVIEW LETTERS 132, 051902 (2024)

Tension with

A. Kumar et al, PHYSICAL REVIEW D 106, 034505 (2022)



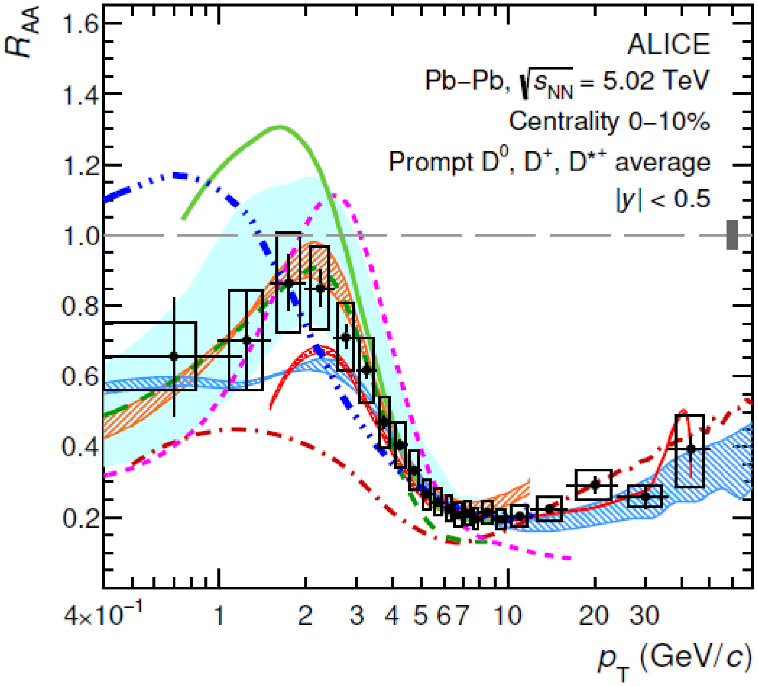
Leading twist expansion

Indeed, no LO pQCD model reproduces the $R_{AA}$ data at pT < 10 GeV/c

# Challenges for the Energy loss

A. For HQ transport at small and intermediate energy, we need both drag and diffusion at finite momentum => not solely Ds.

ALICE, JHEP 01 (2022) 174

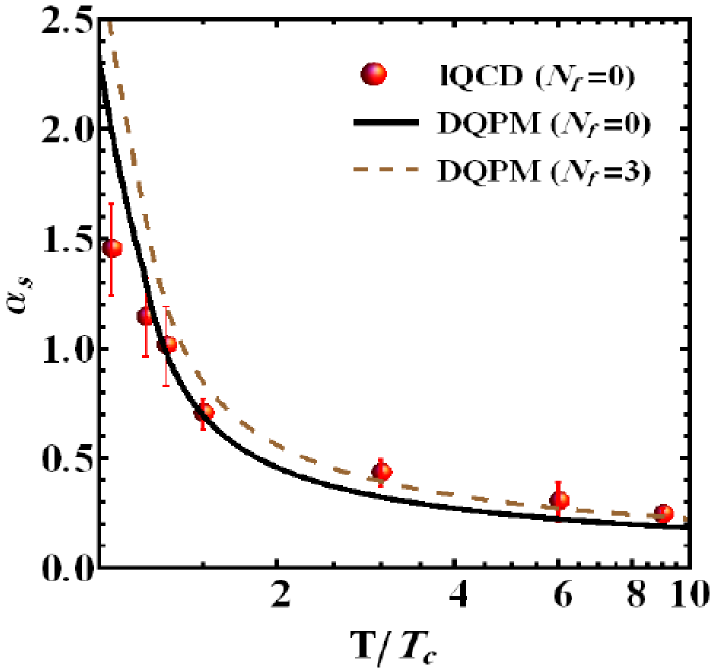


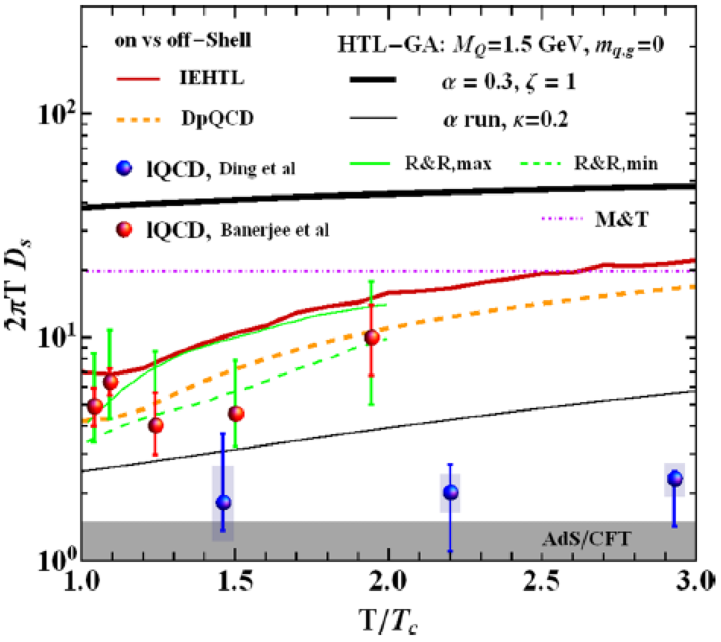
B. Not accessible for lQCD and maybe even not definable (not Gauge invariant) + no guidance from NLO as for the physics => **models**

Several ways to increase the effective coupling with the QGP

# Several ways to increase the effective coupling with the QGP

A. Increase the overall coupling constant but preserves the global Coulombic structure for the interaction (DQPM)





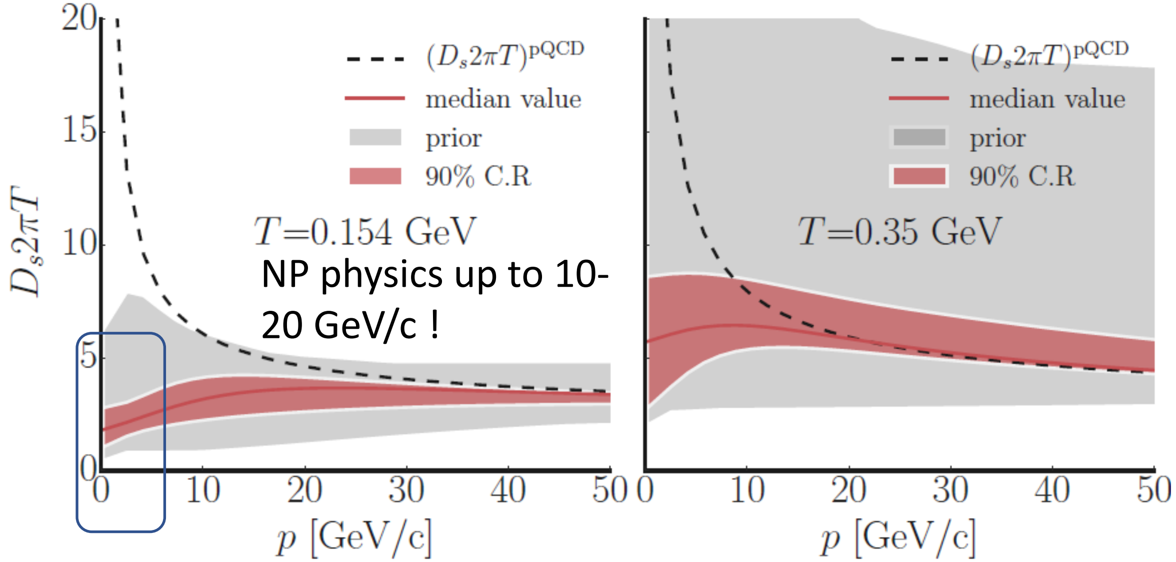
H. Berrehrah et al, PHYSICAL REVIEW C 90, 064906 (2014)

# Several ways to increase the effective coupling with the QGP

B. Be agnostic, start from a generic form of the diffusion coefficient Ds containing NP physics…

$$D_s(T,p) = \frac{1}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\mathrm{lin}}(T;\alpha,\beta) + \frac{(\gamma^2 p)^2}{1+(\gamma^2 p)^2}(D_s 2\pi T)^{\mathrm{pQCD}}(T,p)$$

… and let the data "choose" the optimal parameters (Bayesian analysis)



NP physics up to 10-20 GeV/c !

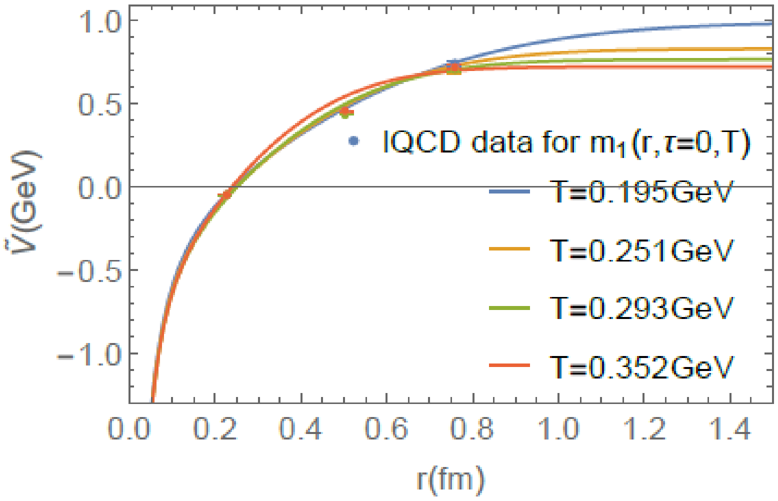
**Y. Xu et al**
**arXiv:1710.00807v1**

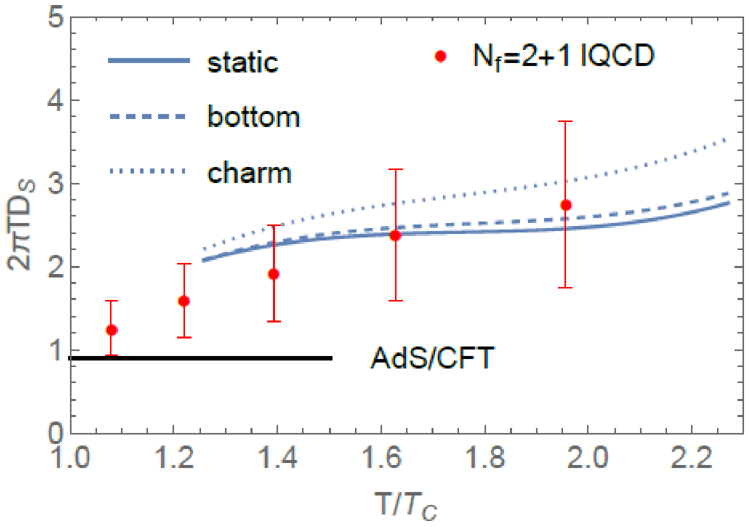
# Several ways to increase the effective coupling with the QGP

C. remnant of NP force at finite distance (TAMU), leading to quasi bound state at not too high T, treated through the non relativistic T Matrix Approach

Z. Tang et al, arXiv:2310.18864v1

In-medium potential



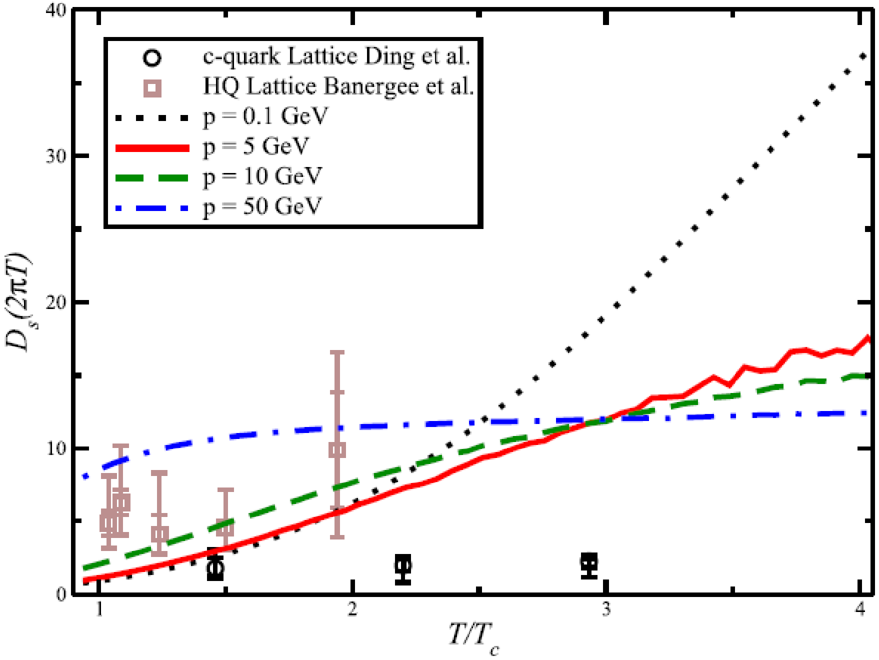


# Several ways to increase the effective coupling with the QGP

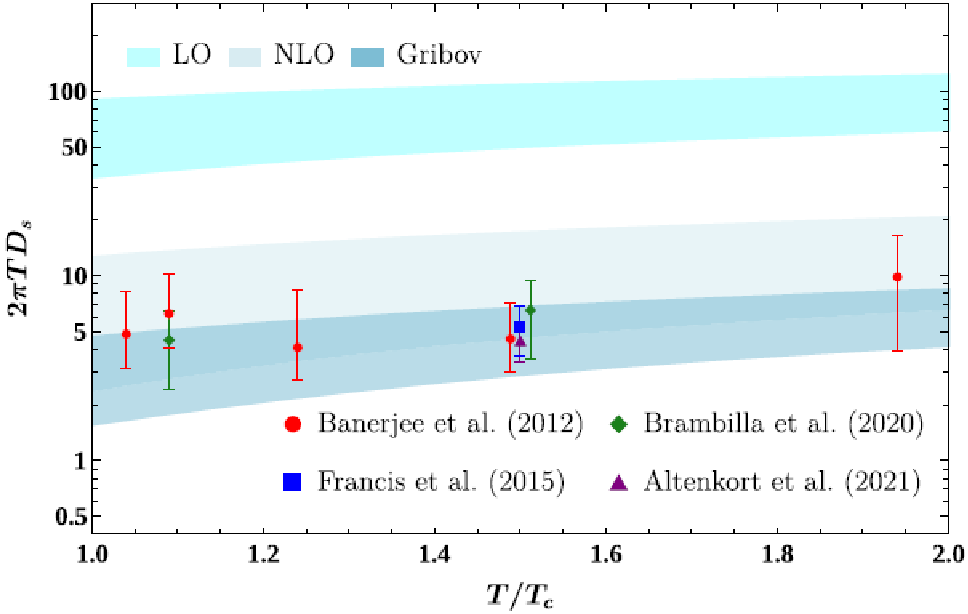
D. remnant of NP force at finite distance using a Gribov-Zwanziger like term in the interaction btwn light q and HQ :

$$V(\vec{q}) = -\frac{4\pi\alpha_s C_F}{m_d^2 + |\vec{q}|^2} - \frac{8\pi\sigma}{(m_s^2 + |\vec{q}|^2)^2}$$

X-J Xing et al, Physics Letters B 838 (2023) 137733

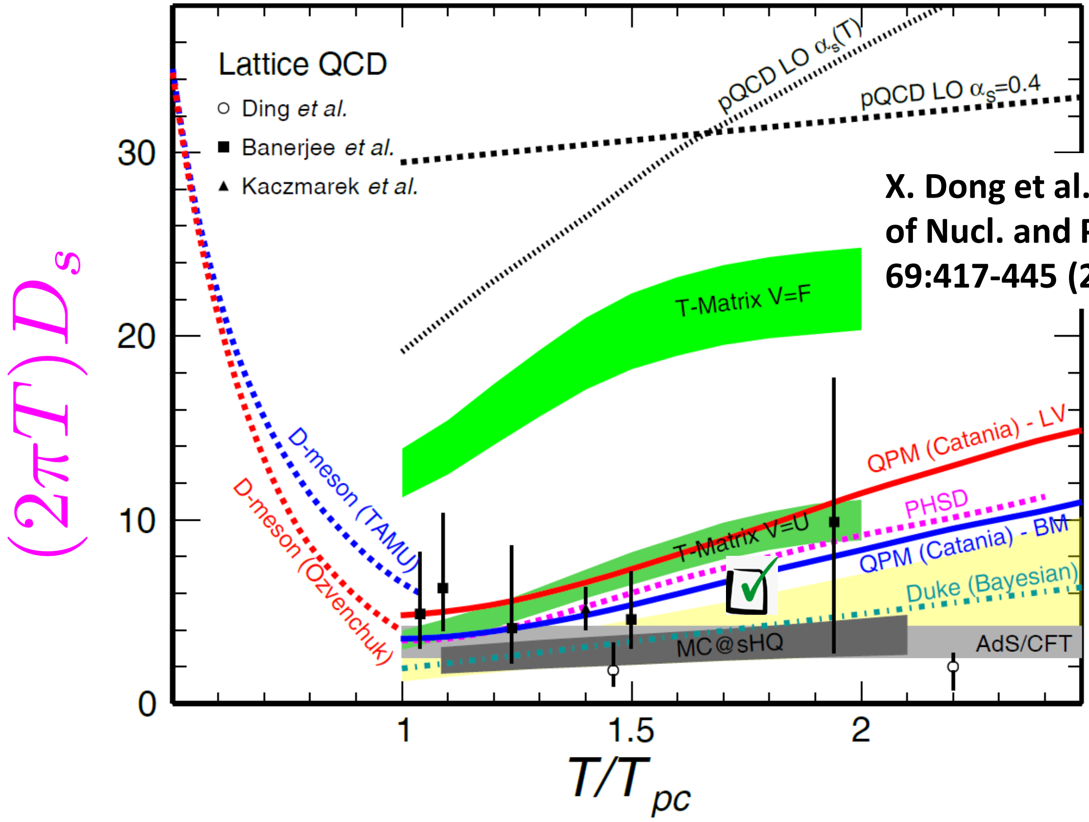


S. Madni et al Physics Letters B 838 (2023) 137714



# HQ Transport coefficients

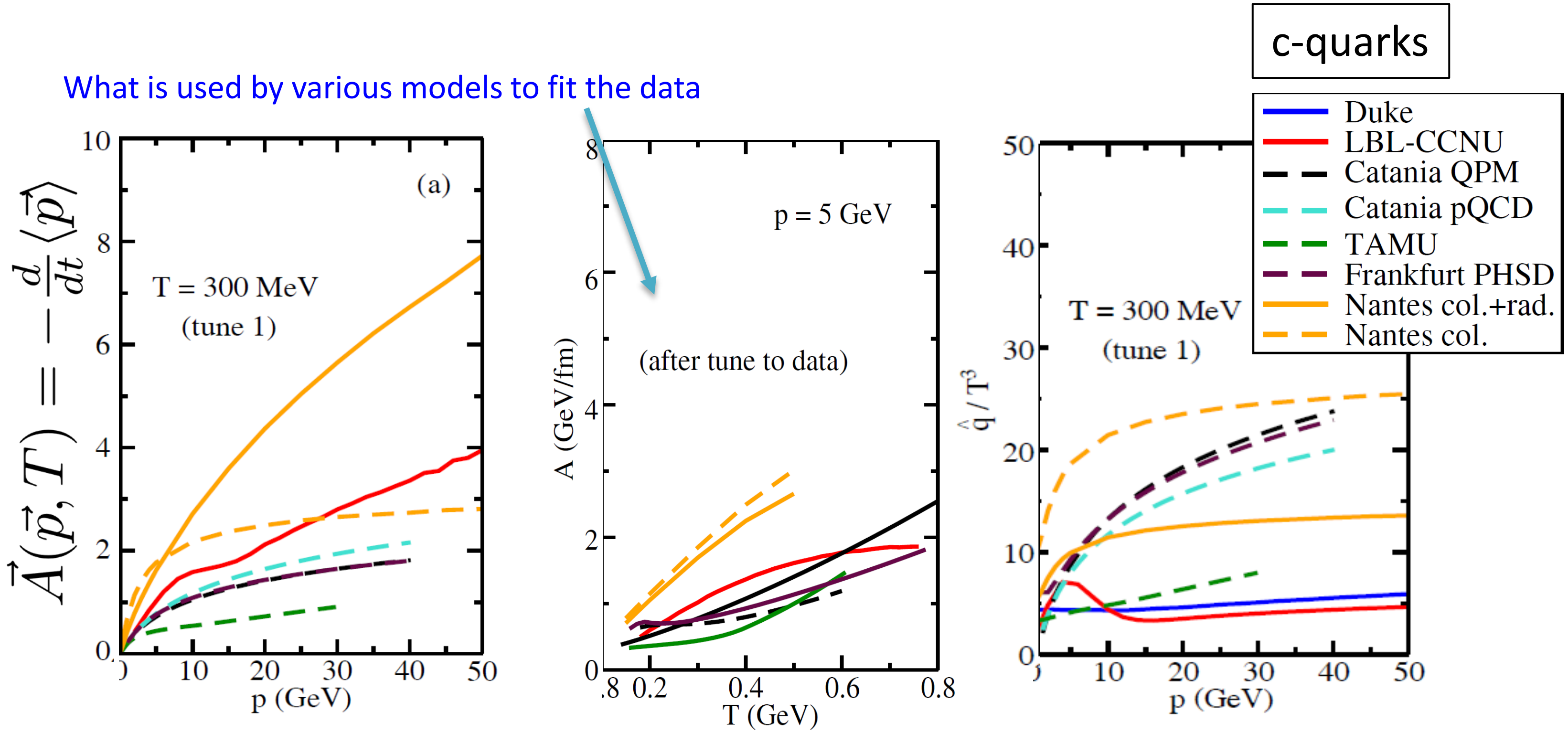
All “recent” models compatible with the experimental data are “close“ to the AdS/CFT limit for Ds



**X. Dong et al. Annual Review of Nucl. and Part. Science 69:417-445 (2019)**

# HQ Transport coefficients

But various models show drastically different momentum dependence !



c-quarks

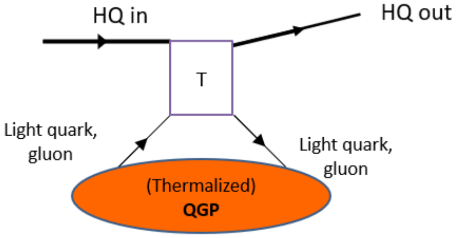
What is used by various models to fit the data

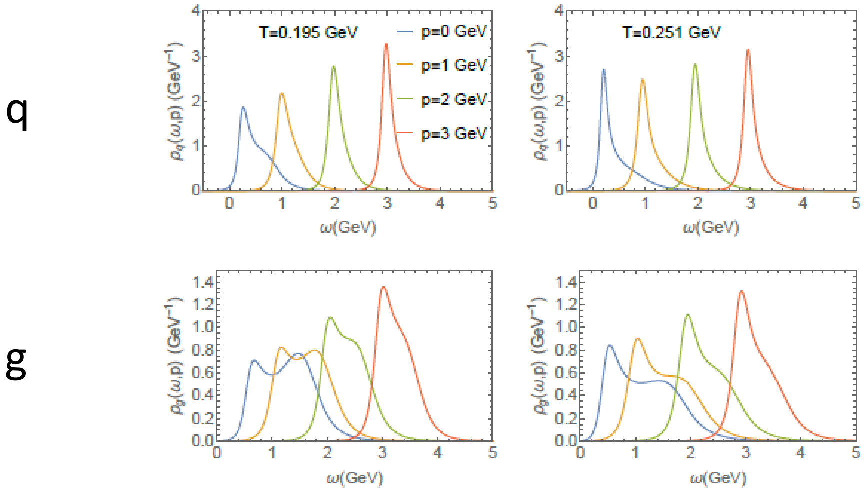
*HQ working group, Phys.Rev.C* 99 (2019) 5, 054907

All models solely based on purely elastic energy loss would be excluded (in their large momentum limit) by the recent lQCD calculation $\hat{q}/T^3 \approx 2$ if taken at face value.

# Challenges and perspectives for the Eloss

- Usefulness and feasibility of NNLO calculations ?
- Nature of the QGP scatterers in model and effective theories; 2 common choices : $m_q=0$ or $m_q=\infty$. However, a) finite thermal mass and b) even finite thermal width !





Z. Tang et al, arXiv:2310.18864v1

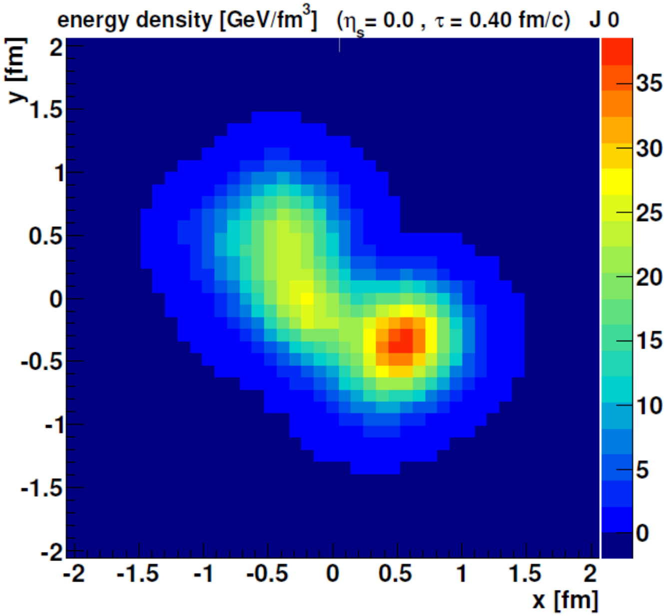
- Some constrains “at finite p” from lQCD
- Using all existing constrains from lQCD (not only EOS)
- Constrains from experiments beyond usual $R_{AA}$ and $v_2$: correlations (hope of probing individual transport coefficients)
- Try to tame the diversity increase by defining generic classes of models
- …

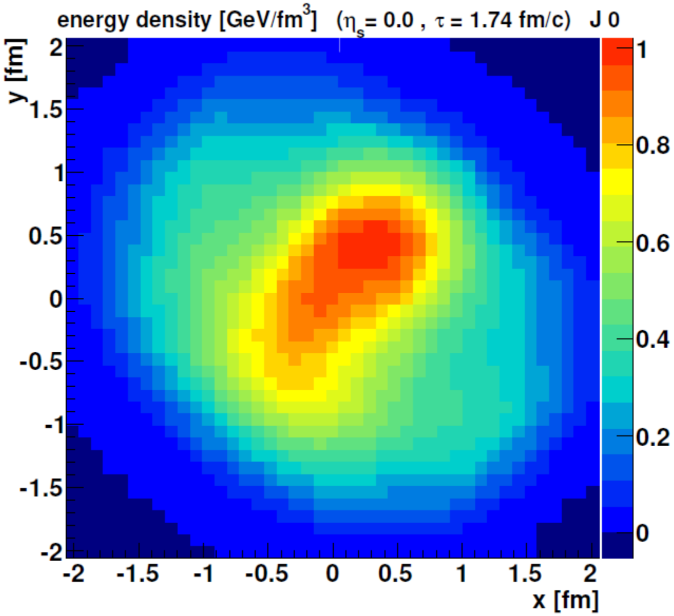
To be discussed this week

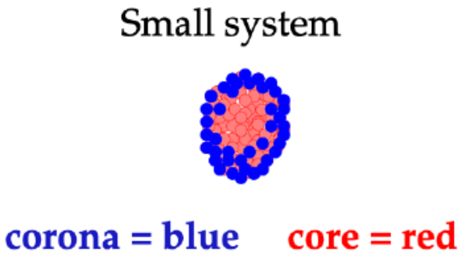
# Eloss in small systems : example with EPOS4-HQ

## EPOS + Hydro : framework that encompass pp, pA and AA collisions

=> Go and look in pp







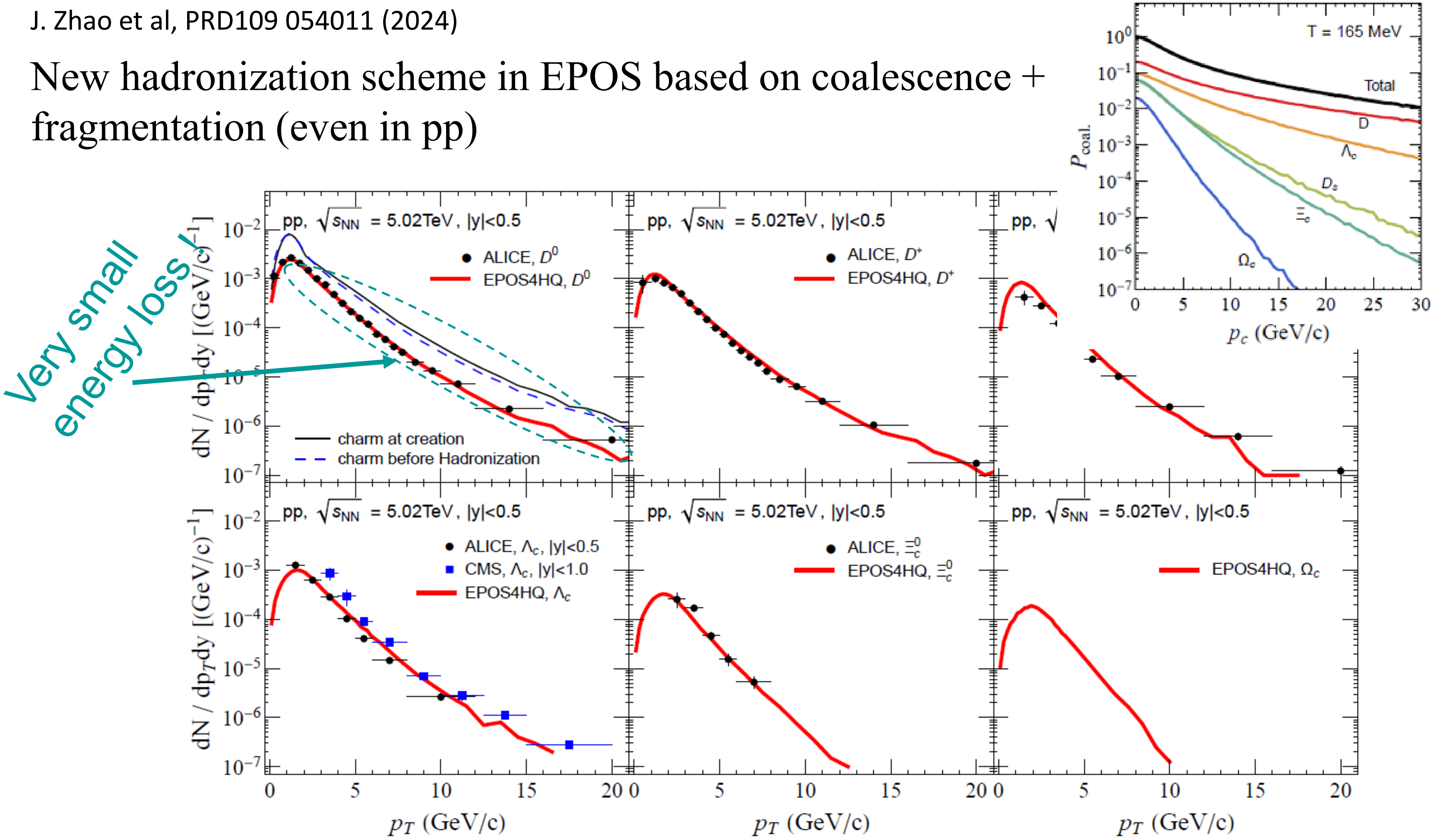
*The energy density is larger than the critical energy density $\epsilon_0$ —> deconfined QCD matter in pp as well !*

*=> In EPOS4, QGP droplet is one of the ingredients of collectivity*

# Eloss in small systems : example with EPOS4-HQ

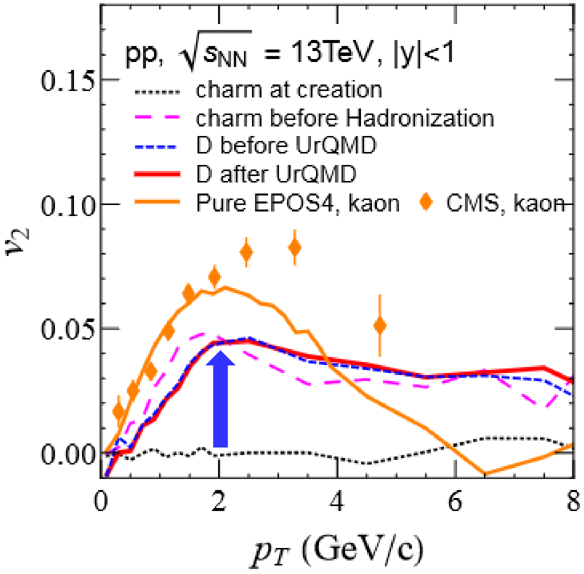
J. Zhao et al, PRD109 054011 (2024)

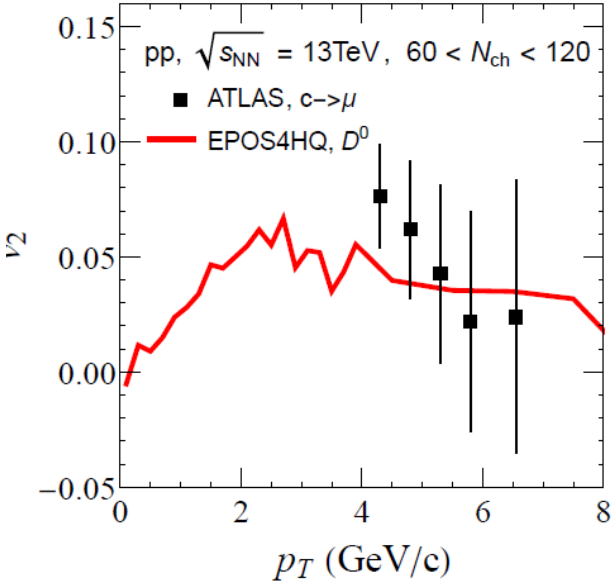
New hadronization scheme in EPOS based on coalescence + fragmentation (even in pp)

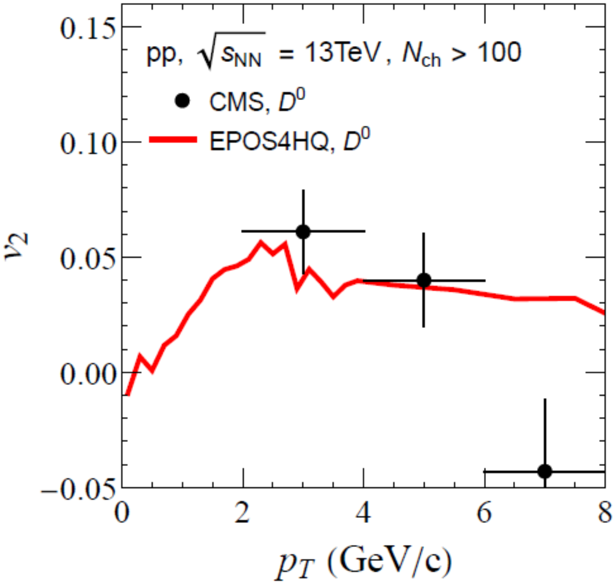


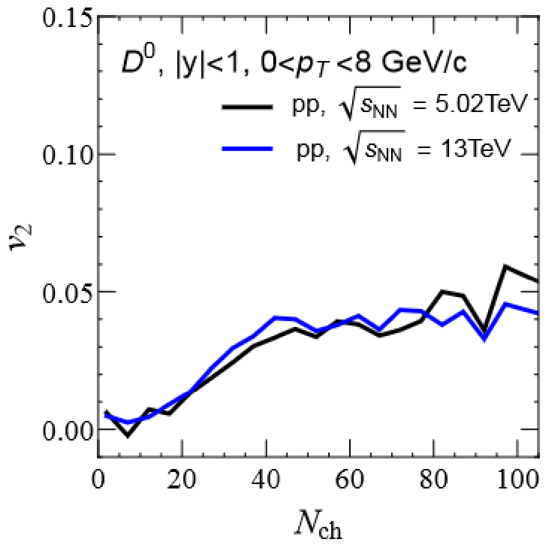
Good agreement in the pp sector for the yield, essentially due to the **coalescence + fragmentation hadronization**

# Eloss in small systems : example with EPOS4-HQ









***EPOS4HQ describes well the elliptic flow of D meson !***

***Clear sign of momentum redistribution during the short evolution (only comes through the $v_2$ in pp)***

***Little effect of the hadronic stage***

See as well : M. He and R. Rapp, Phys. Lett. B 795, 117 (2019), V. Minissale, S. Plumari, and V. Greco, Phys. Lett. B 821, 136622 (2021), H.-h. Li, F.-l. Shao, and J. Song, Chin. Phys. C 45, 113105 (2021), A. Beraudo, A. De Pace, D. Pablos, F. Prino, M. Monteno, and M. Nardi, arXiv:2306.02152

# Eloss in small systems : example with EPOS4-HQ

OHF production in pp and in small systems:  subtle interplay between moderate energy loss and other effects like modified hadronization (as well as CNM effects in pA)

| **observable** | **HQ energy loss in QGP** | **Coalescence in the presence of a QGP droplet** |
|---|---|---|
| Hadron pt spectra | Little effect | **LARGE effect** |
| Hadron yield ratios | Little effect | **LARGE effect** |
| v2 | **LARGE effect** | Little effect |
| Azimuthal correlations | Little effect | Little effect |

**According to EPOS4-HQ: Everything consistent with the production of a short-lived QGP in most active pp collisions at LHC**

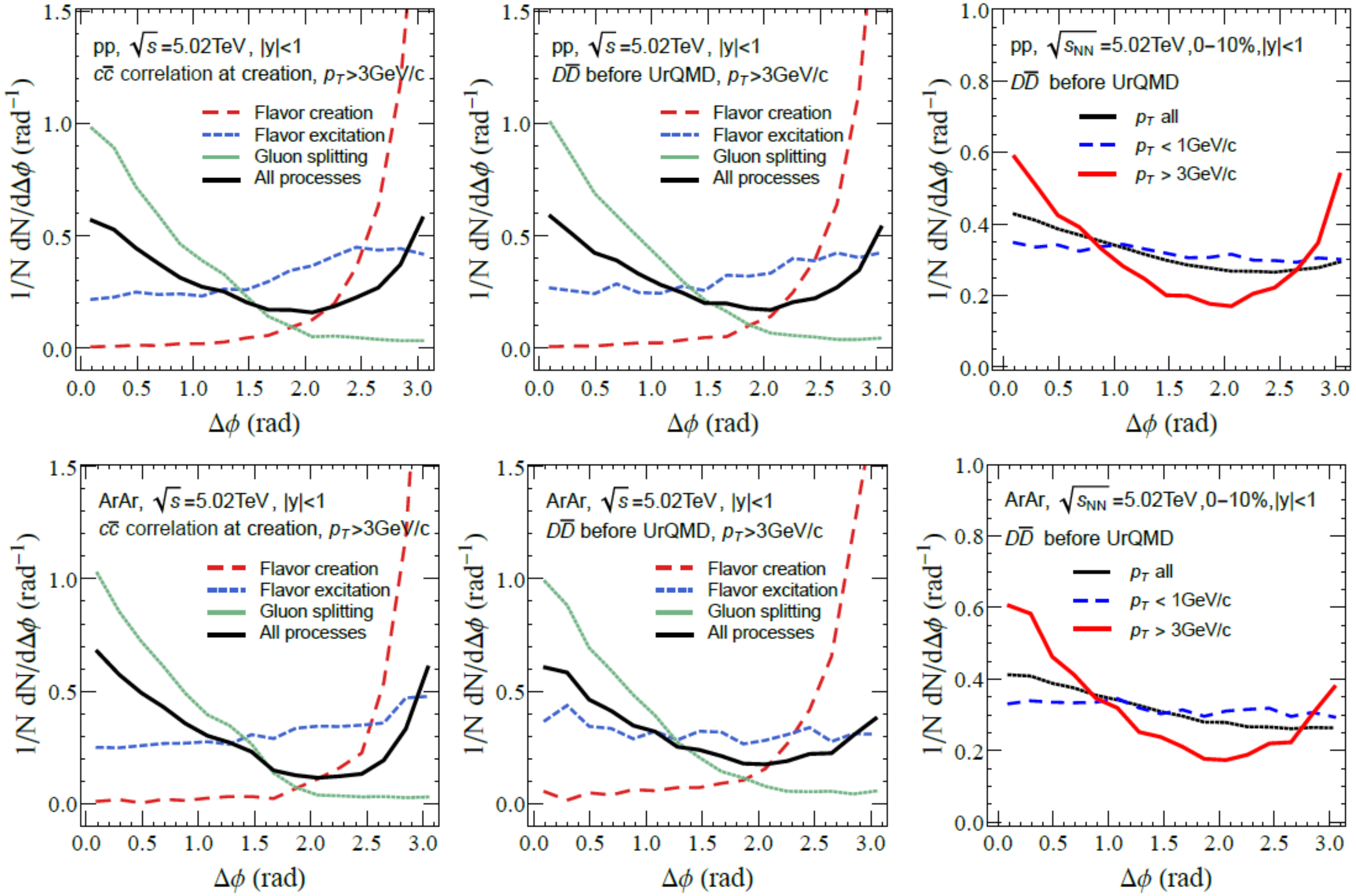
**Challenge : how to falsify this interpretation ?**

# Eloss in small systems : example with EPOS4-HQ

J. Zhao et al, arXiv:2407.20919v1

Azimuthal distributions in AA:

Single pair $|y| < 1,\, p_T > 3\,\mathrm{GeV}/c$



# Eloss in small systems : example with EPOS4-HQ

J. Zhao et al, arXiv:2407.20919v1

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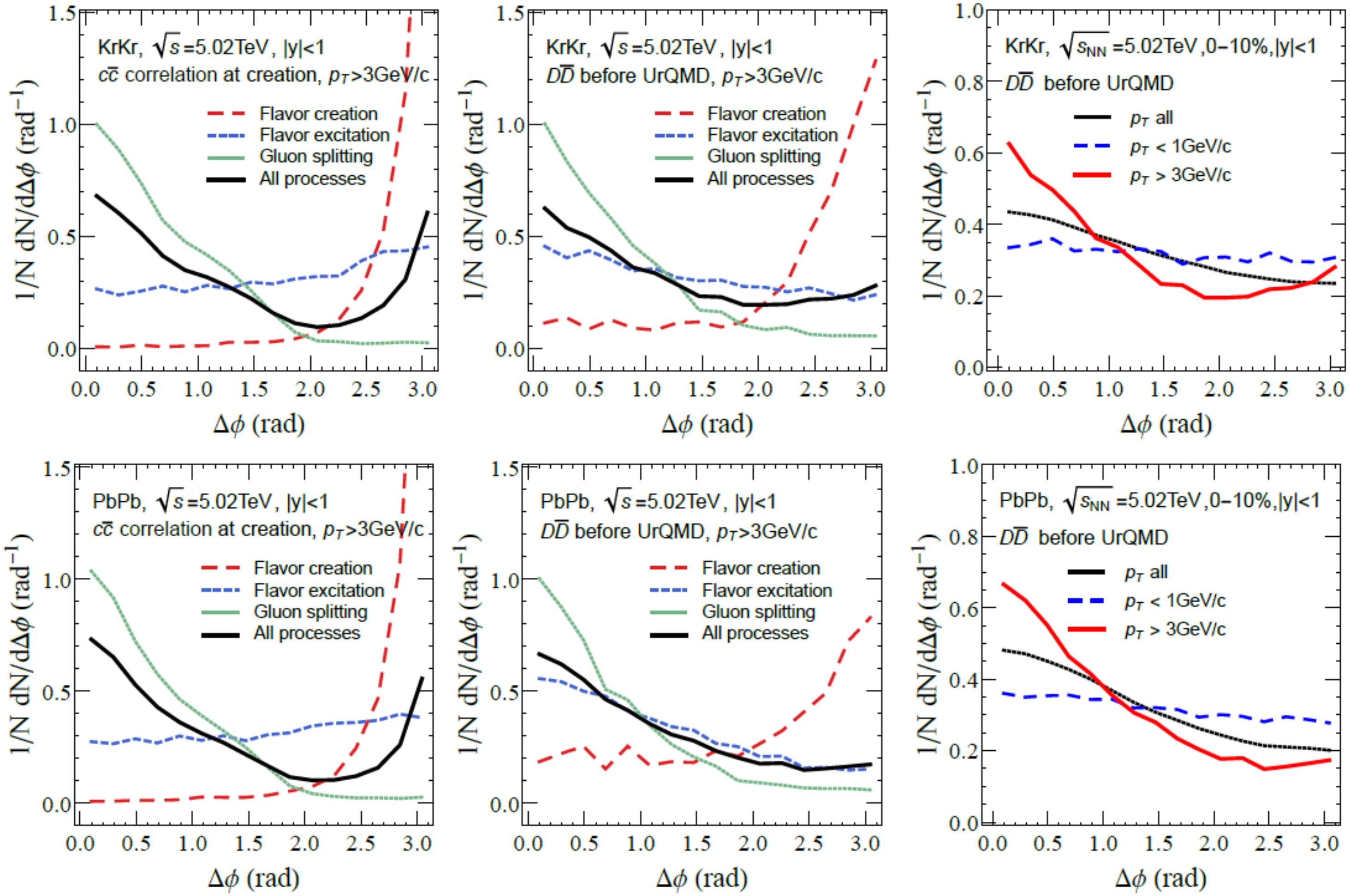


**Progressive weakening of the back to back correlation for larger systems (HQ undergo different histories / QGP velocities when going b2b)**

# From single parton to $Q\bar{Q}$ transport (and quarkonia production)

Complexity

Single parton (Q): $\underbrace{\{\text{Boltzmann or KB , FP}\ \}}_{\text{transport}} \otimes$ models of Q – QGP interaction

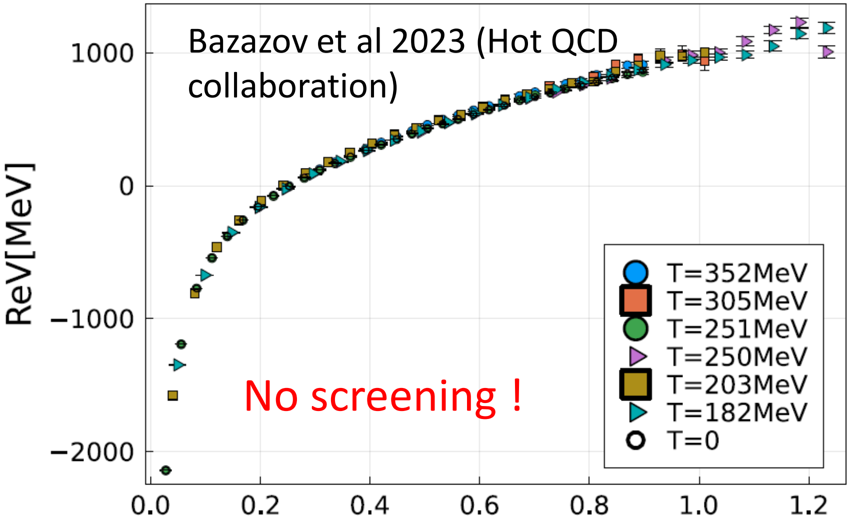
Complex potential, still subject to some uncertainties

$Q\bar{Q}$ transport: Enriched transport ⊗ {Q – QGP interaction , $Q\bar{Q}$ binding at finite T}

2 body, quantum features

Increased diversity among the models

# From single parton to $Q\bar{Q}$ transport (and quarkonia production)



Bazazov et al 2023 (Hot QCD collaboration)

No screening !

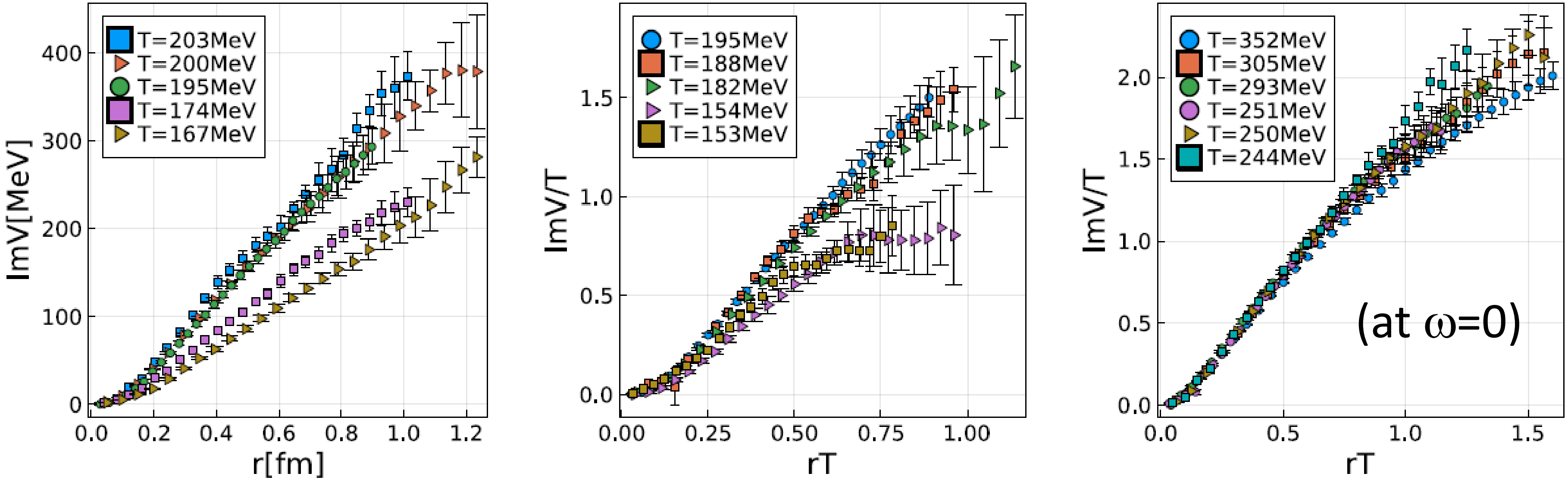
Wilson loop

$$W(\tau,r,T)=\int_{-\infty}^{+\infty} d\omega\, e^{-\omega\tau}\rho_r(\omega,T)$$

⬇

$$\rho_r^{\text{peak}}(\omega,T)=\frac{1}{\pi}\text{Im}\frac{A_r(T)}{\omega-\text{Re}V(r,T)-i\Gamma(\omega,r,T)}$$

Spectral density



(at $\omega$=0)

- Nice r T scaling
- Dipole structure at small r, no saturation seen at “large” r

# Recent collective work (EMMI RRTF) on quarkonia production

Most important issues :

**A. Andronic et al. *Eur.Phys.J.A* 60 (2024) 4, 88**

i) the identification and model comparisons of transport parameters;
ii) the controlled implementation of constraints from lattice QCD;
iii) the significance of quantum transport treatments.

5 key questions

1) To what extent are the currently employed **transport approaches** (mostly carried out in semi-classical approximations) **consistent** in their treatment of quarkonium dissociation and regeneration ?

2) What are the equilibrium limits of the transport approaches and how do the former compare to the results of the statistical hadronization model ?

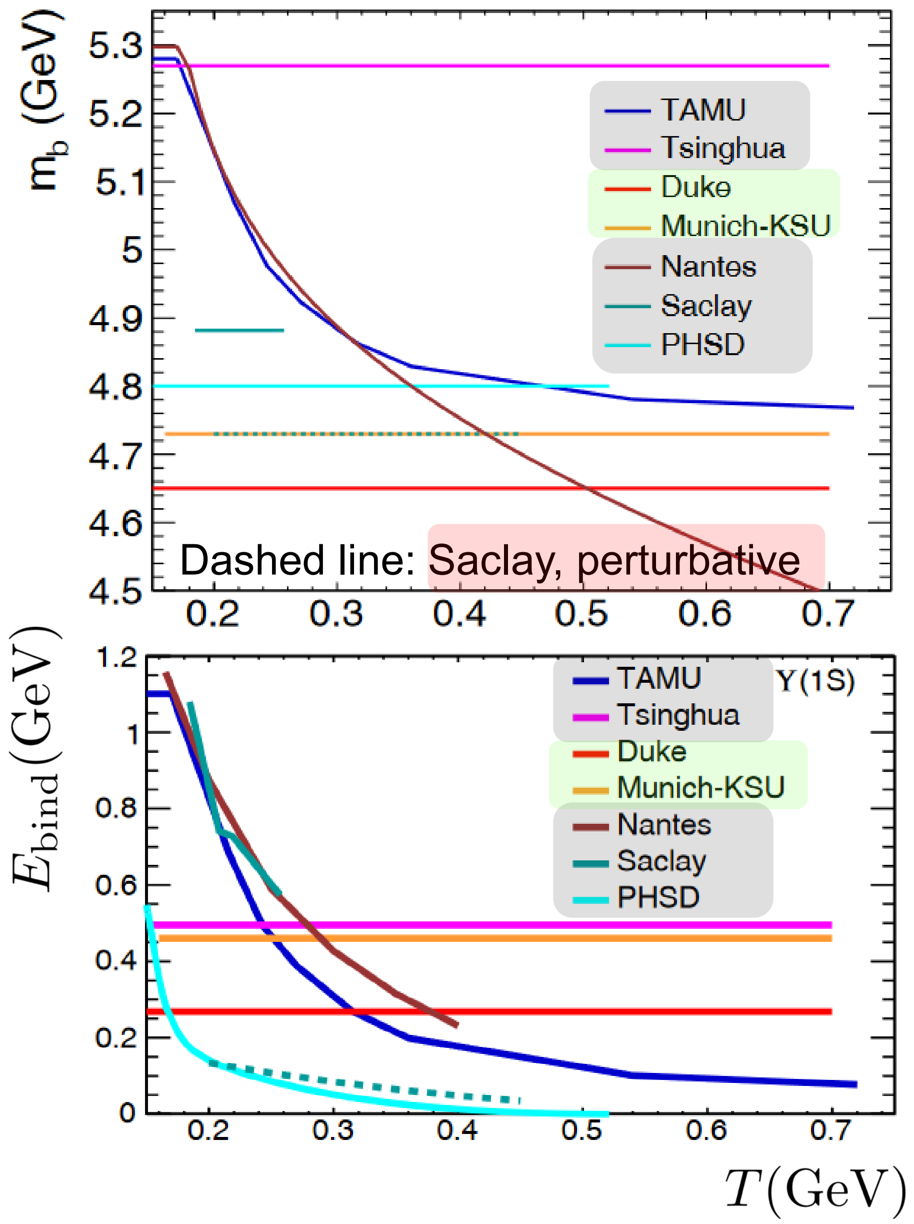
3) What is the significance of the **effects on quantum transport** of the quarkonium wave packets, and what is needed to develop quantum transport into a realistic phenomenology ?

4) How can the abundant information from **lattice QCD** (quarkonium correlation functions, heavy quark free energies and susceptibilities, and the open heavy-flavor sector) be **systematically implemented into transport approaches** ?

5) What are the **ultimate model uncertainties**, and will those allow for conclusions on the fundamental question of the existence of hadronic correlations in a deconfined medium?

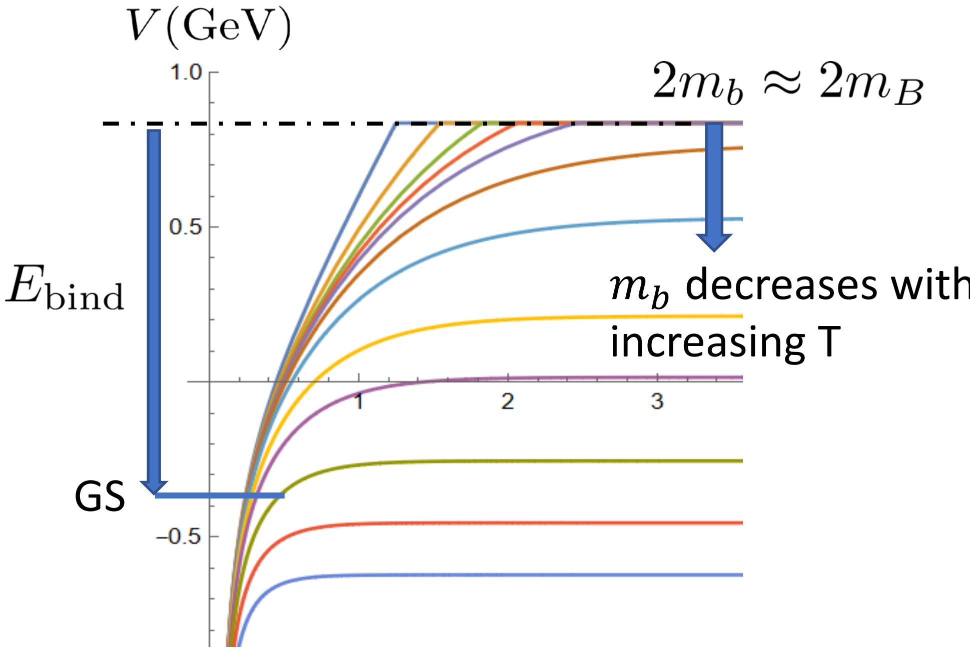
Several tasks and homeworks + 2 in-person meetings + one year of work for the 5 conveners

# Recent collective work (EMMI RRTF) : binding energy



Convention for $m_Q$ and binding energy $E_b$ :

$$m_{Y(1S)} = 2m_b - E_{\mathrm{bind}} = 9.46\,\mathrm{GeV}$$

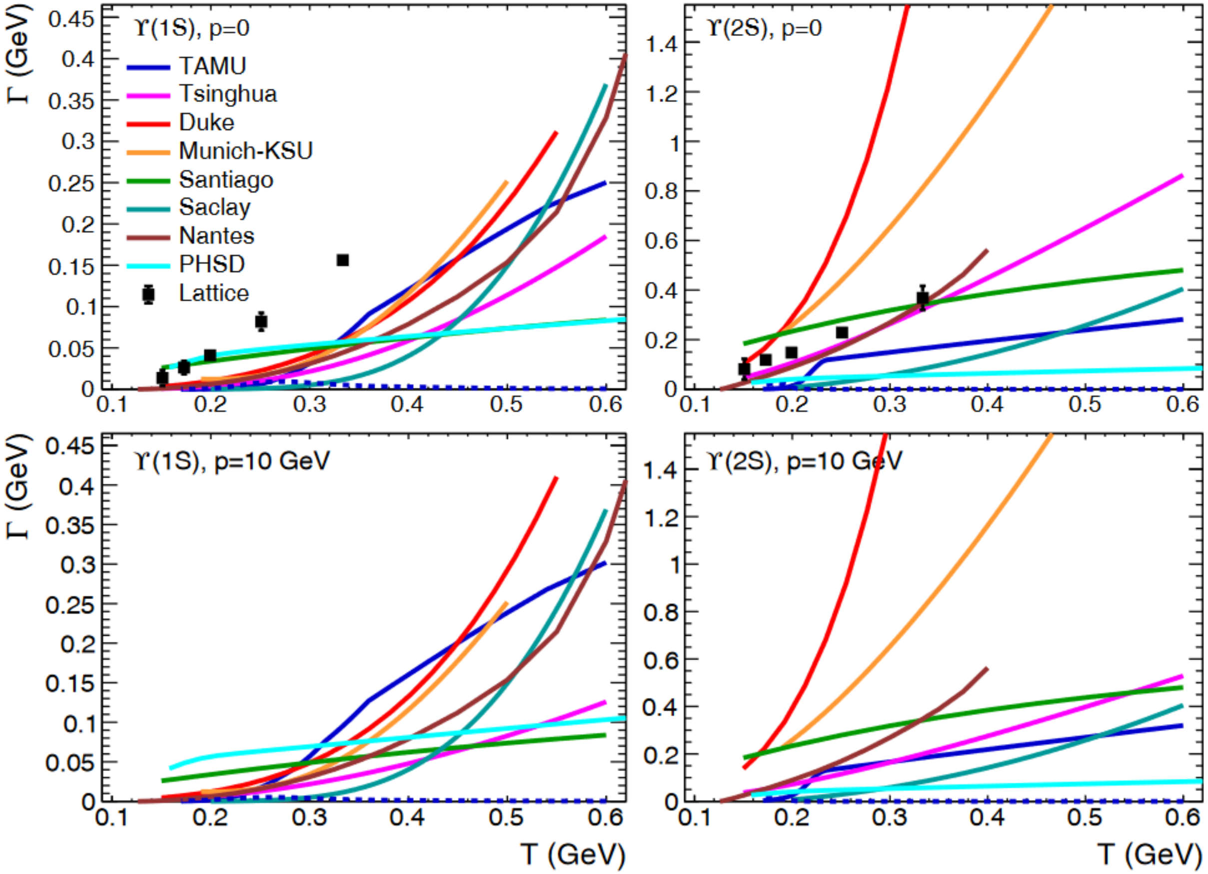


$m_b$ decreases with increasing T

- ➢ Vacuum spectroscopy : Approaches which include long-range forces (TAMU, Tsinghua, Nantes, Saclay –non pert) generate a larger binding energy than approaches relying on Coulomb potential (Duke, Munich-KSU, Saclay pert)
- ➢ Consequence: $m_b$ in the models vary by ± 5%

# Recent collective work (EMMI RRTF) : dissociation rate

Bottomonia family

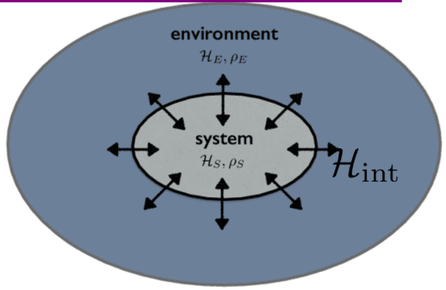


**Insufficient constraints !**

Many more studies in the report… quite useful to grasp the broadness of underlying assumptions about quarkonia modelling … Interesting material for this workshop !

- Large overall spread for both values of p considered; larger for Y(2S).
- Different T-dependences. Models less based on microscopic modelling of Y (Santiago, PHSD) have the most "flatish" one.
- For Y(1S) : some convergence in the relevant T-range [0.3;0.4], apart from Saclay but with different mechanisms.
- Hints of common hierarchy with $E_b(T)$, but some exceptions (f.i. TAMU, which has the largest T-dep. of $E_b$ does not has the fastest increase) => other effects.
- Duke and KSU-Munich (pNRQCD) in good agreement for Y(1S).

# $Q\bar{Q}$ in AA: a case of quantum transport ?



Quite generally, the system builds correlation with the environment thanks to the Hamiltonian $\hat{H} = \hat{H}_S^{(0)} + \hat{H}_E + \hat{H}_{\rm int}$

Von Neumann equation for the total density operator $\hat{\rho}$

**System + environment**

$$\hat{\rho}(t=0) = \hat{\rho}_S(t=0) \otimes \hat{\rho}_E$$

$$\frac{d\hat{\rho}}{dt} = -i[\hat{H}, \hat{\rho}]$$

**Evolution of the total system**

$$\hat{\rho}(t) = \hat{U}(t,0)\,[\hat{\rho}_S(t=0) \otimes \hat{\rho}_E]\,\hat{U}^\dagger(t,0)$$

Trace out environment degrees of freedom =>
Reduced density operator $\hat{\rho}_S^{\rm red}$

**System**

$$\hat{\rho}_S^{\rm red}(t=0) = \hat{\rho}_S(t=0)$$

**Evolution of the system**

$$\hat{\rho}_S^{\rm red}(t) = {\rm tr}_E\left[\hat{U}(t,0)\,[\hat{\rho}_S(t=0) \otimes \hat{\rho}_E]\,\hat{U}^\dagger(t,0)\right]$$

Evol. eq. on the red. Density: $\dfrac{{\rm d}\hat{\rho}_S^{\rm red}}{{\rm d}t} = \mathcal{L}[\hat{\rho}_S^{\rm red}]$ (linear mapping)

However, $\mathcal{L}[\cdot]$ is generically a non local super-operator in time

# Recent OQS implementations (single $Q\bar{Q}$ pair)

(Year > 2015)

Not exhaustive

| regime | SU3 ? | Dissipation ? | 3D / 1D | Num method | year | remark | ref |
|---|---|---|---|---|---|---|---|
| **NRQCD ⇔ QBM** | No | No | 1D | Stoch potential | 2018 | | Kajimotoet al. , Phys. Rev. D 97, 014003 (2018), 1705.03365 |
| | Yes | No | 3D | Stoch potential | 2020 | Small dipole | R. Sharma et al Phys. Rev. D 101, 074004 (2020), 1912.07036 |
| | Yes | No | 3D | Stoch potential | 2021 | | Y. Akamatsu, M. Asakawa, S. Kajimoto (2021), 2108.06921 |
| | No | Yes | 1D | Quantum state diffusion | 2020 | | T. Miura, Y. Akamatsu et al, Phys. Rev. D 101, 034011 (2020), 1908.06293 |
| | Yes ✓ | Yes ✓ | 1D | Quantum state diffusion | **2021** | | Akamatsu & Miura, EPJ Web Conf. 258 (2022) 01006, 2111.15402 |
| | No | Yes | 1D | Direct resolution | **2021** | | O. Ålund, Y. Akamatsu et al, Comput. Phys. 425, 109917 (2021), 2004.04406 |
| | Yes ✓ | Yes ✓ | 1D | Direct resolution | **2022** | | S Delorme et al, https://inspirehep.net /literature/ 2026925 |
| **pNRQCD** (i) | Yes | No | 1D+ | Direct resolution | 2017 | S and P waves | N. Brambilla et al, Phys. Rev. D96, 034021 (2017), 1612.07248 |
| (i) Et (ii) | Yes | No | 1D+ | Direct resolution | 2017 | S and P waves | N. Brambilla et al, Phys. Rev. D 97, 074009 (2018), 1711.04515 |
| (i) | Yes | No | Yes | Quantum jump | **2021** | See SQM 2021 | N. Brambilla et al. , JHEP 05, 136 (2021), 2012.01240 & *Phys.Rev.D* 104 (2021) 9, 094049, 2107.06222 |
| (i) | Yes ✓ | Yes ✓ | Yes ✓ | Quantum jump | **2022** | | N. Brambilla et al. 2205.10289 |
| (iii) | Yes ✓ | Yes ✓ | Yes ✓ | Boltzmann (?) | 2019 | | Yao & Mehen, Phys.Rev.D 99 (2019) 9, 096028, 1811.07027 |
| NRQCD & « pNRQCD » | Yes | Yes | 1D | Quantum state diffusion | **2022** | | Miura et al. http://arxiv.org/abs/2205.15551v1 |
| Other | No | Yes | 1D | Stochastic Langevin Eq. | 2016 | Quadratic W | Katz and Gossiaux |

…

See as well table in 2111.15402v1

# A consistent picture emerging in the bottomia sector

Beauty sector: good overall consistency of the following facts:

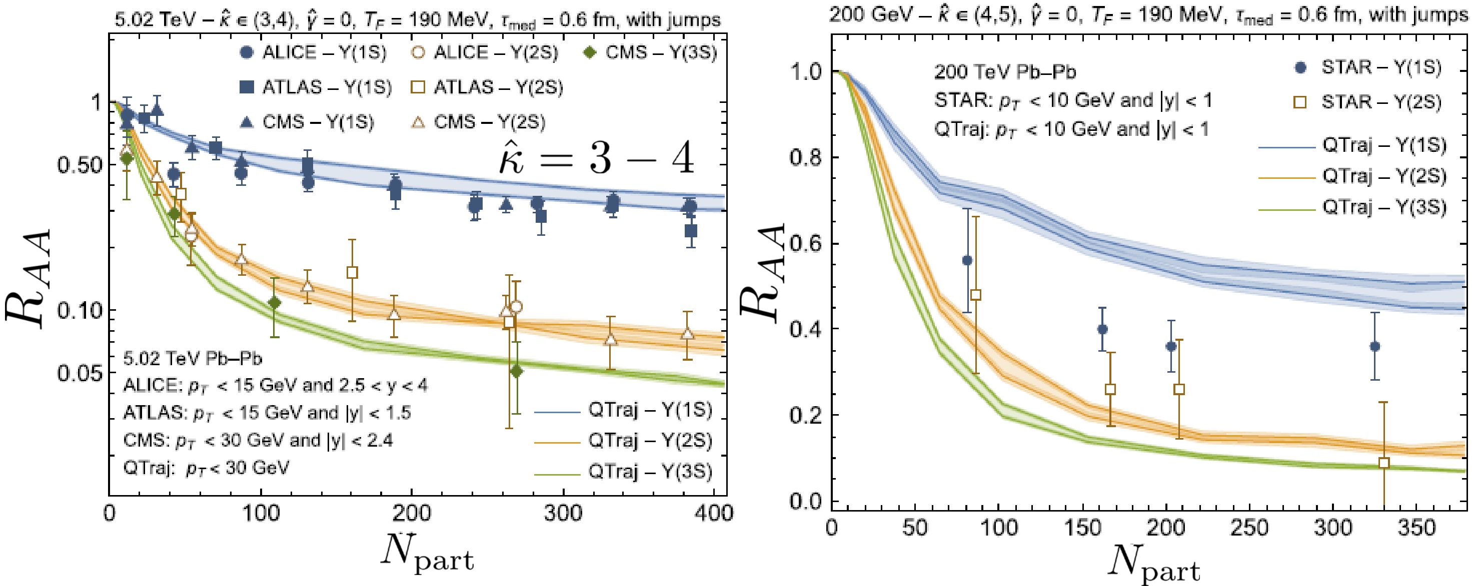
- Similar production of Υ(1S) from RHIC -> LHC
- Higher states strongly suppressed
- Washing out of the spectral function (but the Υ(1S) which survive up to T = 0.45 GeV)

Not paying too much attention at CNM effects

With the interpretation that higher states (which contribute to the prompt Υ(1S)) are suppressed both at RHIC and LHC in the QGP, while the gound state Υ(1S) survive and is thus a genuine hard QGP probe; higher states could be produced (partly) through recombination. Especially true for Υ(3S)

N.B.: No precise $v_2(\Upsilon)$ measured up to now. One would expect very small $v_2(\Upsilon(1S))$ and slightly larger $v_2(\Upsilon(2S))$… but will be hard to measure.

**M. Strickland & S. Thapa, Phys. Rev. D 108, 014031 (2023)**



Good agreement with suppression at LHC but not at RHIC

**Other implementations** : Osaka, Saclay, Nantes, Duke,…

# Two regimes for the dynamical modeling

$m_D \ll E_{\mathrm{bind}}$

Quantum Optical Regime

$m_D \sim E_{\mathrm{bind}}$

$m_D \gg E_{\mathrm{bind}}$

Quantum Brownian Motion

- **Well identified resonances**
- Time long enough wrt quantum decoherence time (once we reach this regime)

**Good description with transport models (TAMU, Tsinghua, Duke)**

Central quantities :
2->2 and 2->3 Cross sections,
decay rates

Equilibrium : exp(-$E_n$/T) (theorem)

SC Approx: rate equations

?

- Correlations growing with cooling QGP
- **Best described in position-momentum space**
- Time short wrt quantum decoherence time ?

Quantum Master Equations for **microscopic dof (QS and Qbars)**

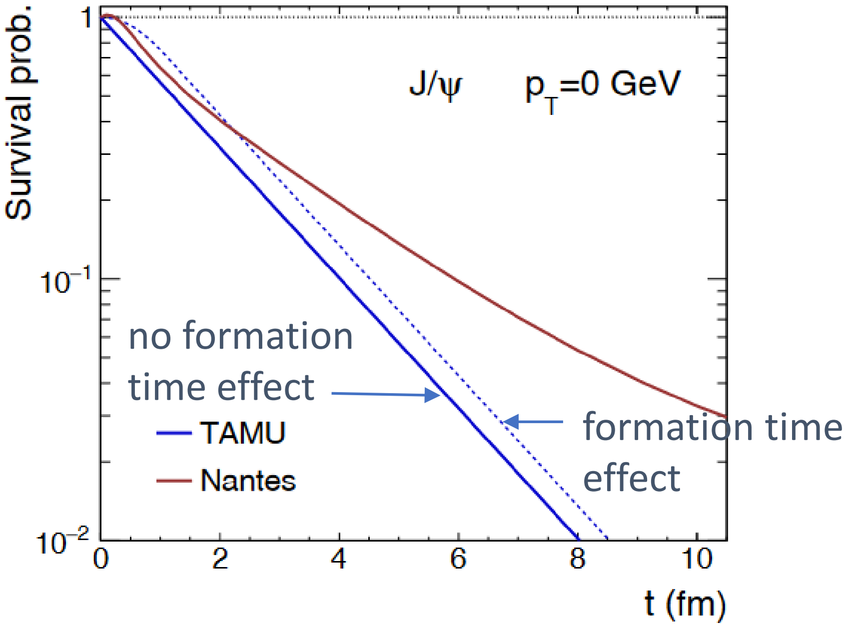
Equilibrium / asympt* : some limiting cases

SC Approx: Fokker-Planck equations in position-momentum space

* Since one is facing both dissociation and recombination, obtaining a correct equilibrium limit of these models is an important prerequisite !!!

# Challenges and perspectives for $Q\bar{Q}$ transport

- Converge towards a more precise estimation of the complex potential
- Be able to design a quantum transport that interpolates / encompass both Quantum optical and Quantum Brownian regimes
- Understand what are the genuine quantum features as well as the validity / accuracy of semi-classical approximations and schemes (especially important for charmonia production)



no formation time effect

formation time effect

A. Andronic et al. *Eur.Phys.J.A* 60 (2024) 4, 88

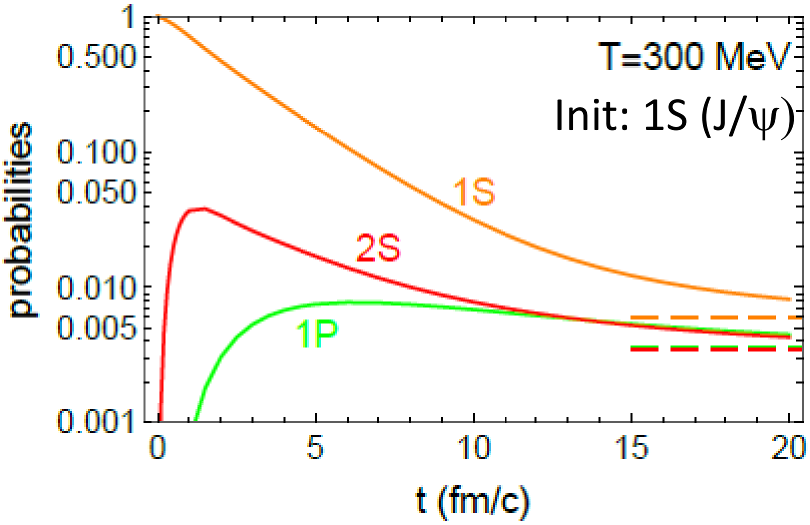
Quantum features expected at the "beginning" of the evolution…

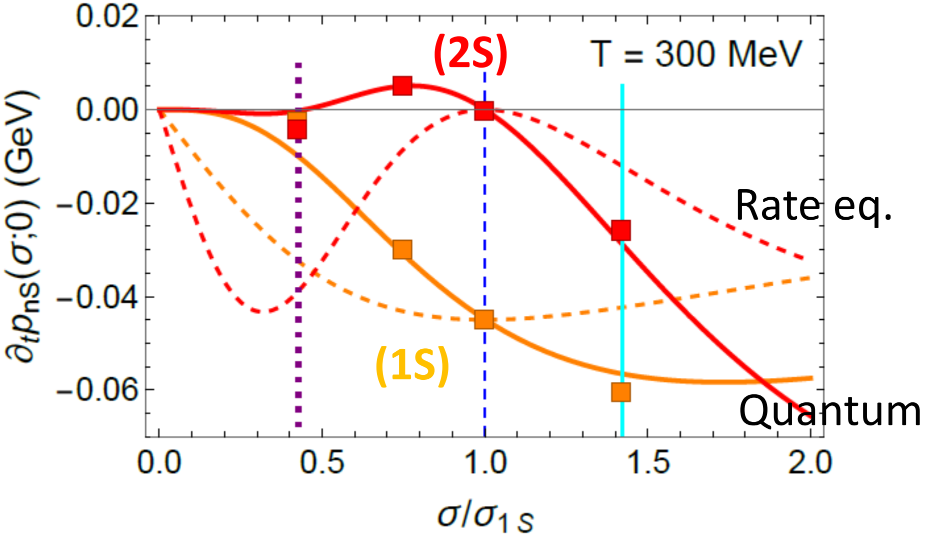
Nantes Quantum evolution starts from a compact state and observes a transient stage lasting for ≈ 0.5 fm/c, then ≈ exponential decay.

The "quantum delay" is implemented in TAMU SC evolution through effective formation time

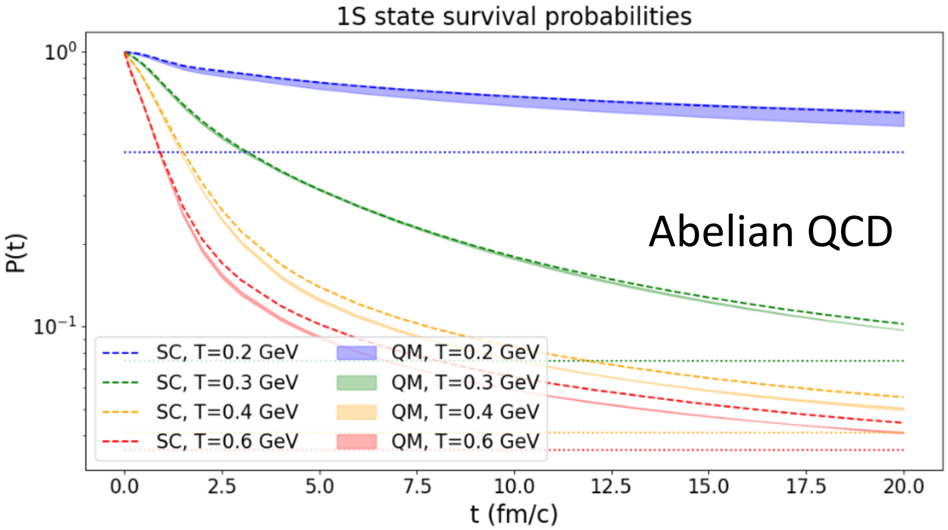
# Quantum vs SC (in the QBM regime)

**S. Delorme et al.,JHEP06(2024)060**



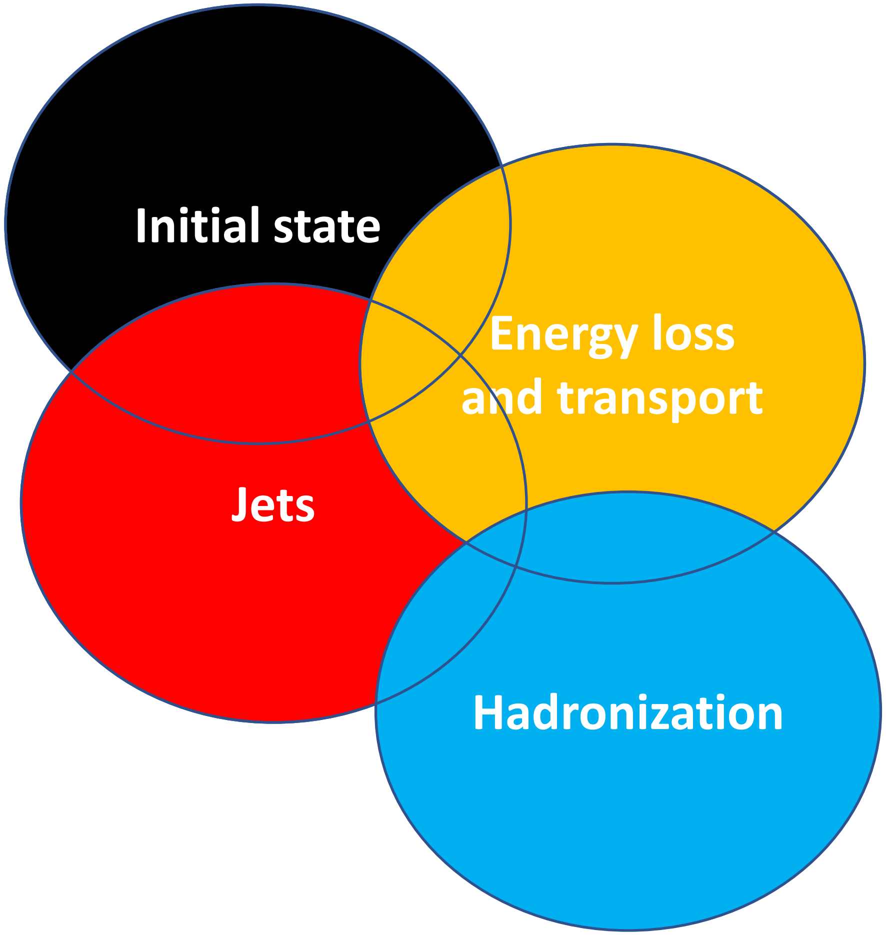


**Aoumeur Daddi Hammou, ICHEP 2024**



- For compact states, the initial slope is not well reproduced using rate equations
- For Abelian QCD, SC approximation leads to very good description of the time evolution of eigenstates probabilities (QBM regime)

# Intertrack Material



Initial state

Energy loss and transport

Jets

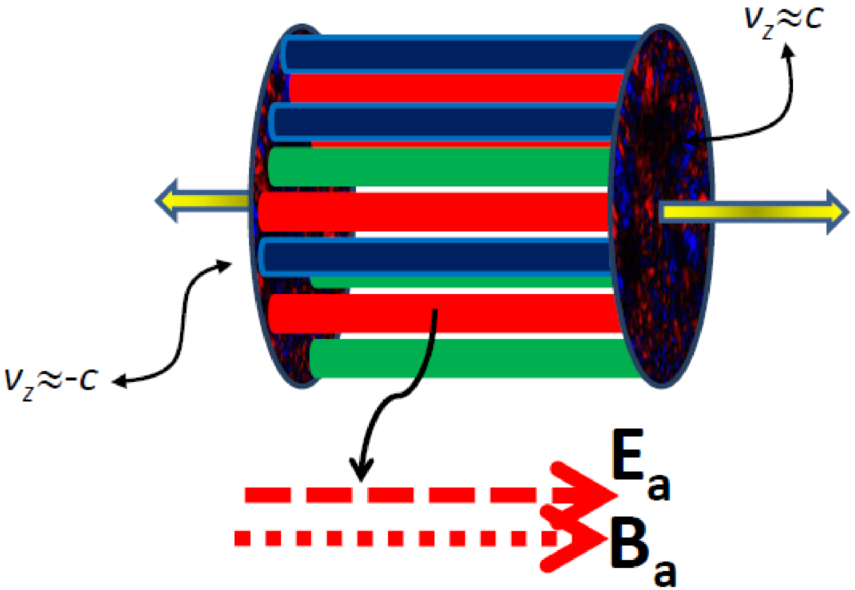
Hadronization

…

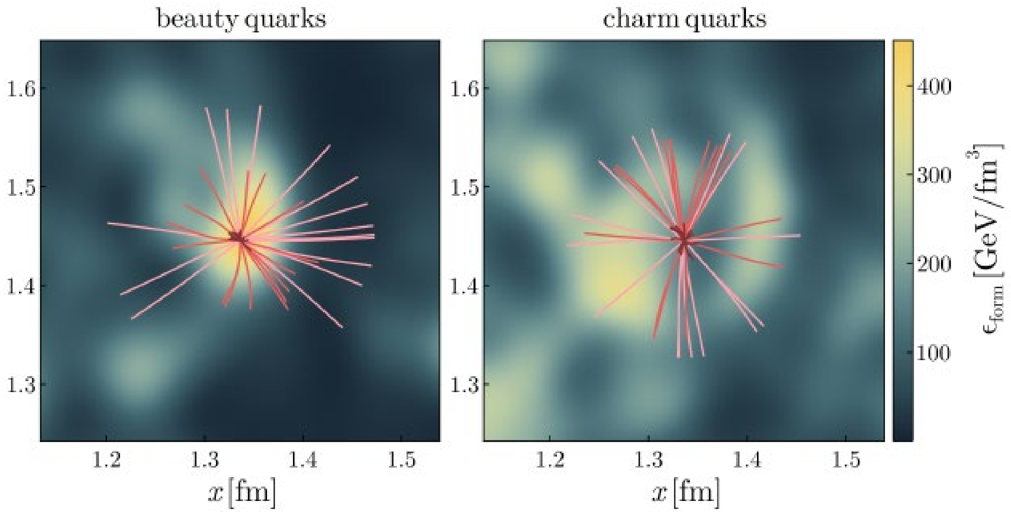
# Early stage evolution of HQ in the Glasma phase (and others)

- Diffusion of heavy quarks in the early stages of high energy nuclear collisions

Early stage : **Glasma**



D. Avramescu et al, Phys. Rev. D 107 (2023), 114021 + refs therein



trajectories of heavy quarks propagating in a single Glasma flux tube

- Diffusion of HQs in the early stage of HIC is affected by the strong fields: coherence memory effects are essential; extra broadening => could affect the final spectra and have consequence on exp. observables.

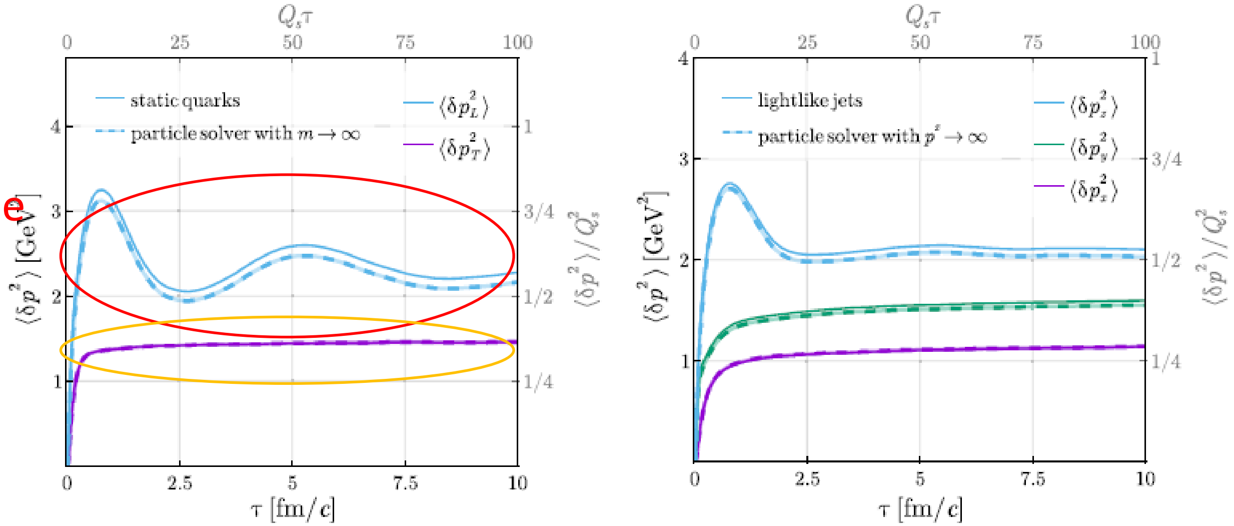
See as well: “Simulating Charm Quarks in IP-Glasma Initial Stage and Quark-Gluon Plasma: A **Hybrid** Approach for charm quark phenomenology”, Manu Kurian @ SQM2024

# Early stage evolution of HQ in the Glasma phase (and others)

- Non trivial effects seen for the broadening, as compared to the "usual" in-QGP evolution ?

Oscillations of the long. component (resulting from the glasma dynamics ? )

Saturation of the transverse component



(a) Infinitely massive heavy quarks

(b) Highly energetic light-like jets

**D. Avramescu et al, Phys. Rev. D 107 (2023), 114021 + refs therein**

- Larger broadening for b quarks (produced earlier)… Some exp. Consequence ?

- But Magnetic fields could influence the production as well : "Heavy flavor production under a strong magnetic field", Shile Chen @ SQM 2024

# The impact of quasi particle on energy loss and jets

Consequence of the Moliere scattering (pQCD scattering on light partons) on some jet observables :

**Z. Hulcher et al,Acta Phys.Polon.Supp. 16 (2023) 1, 57**

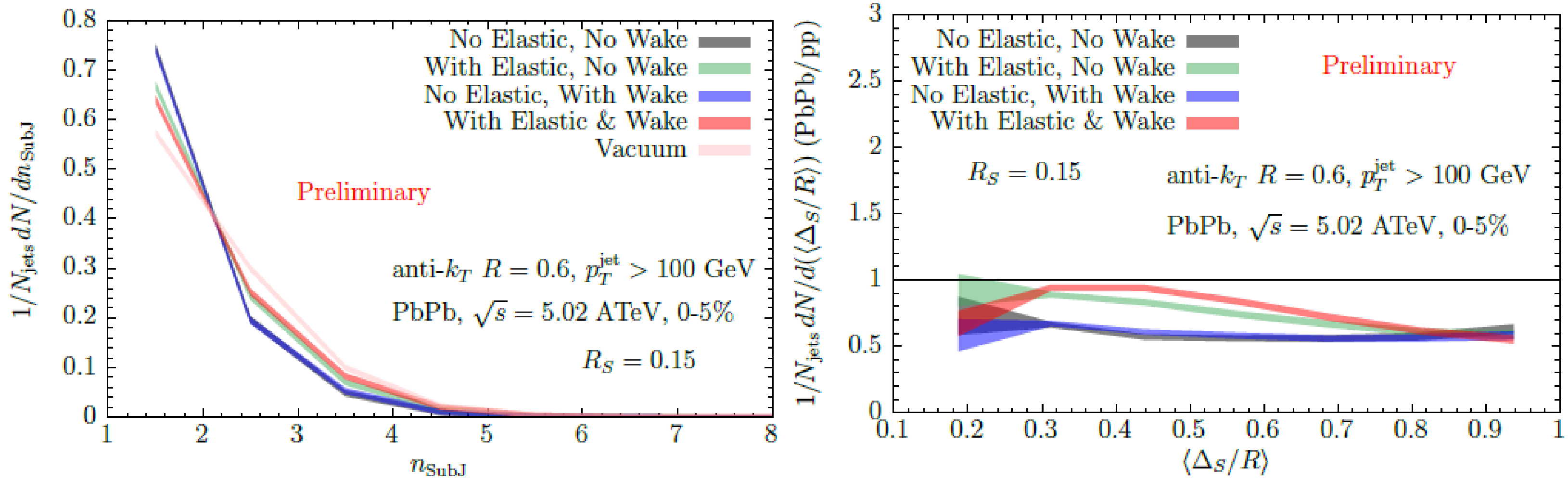
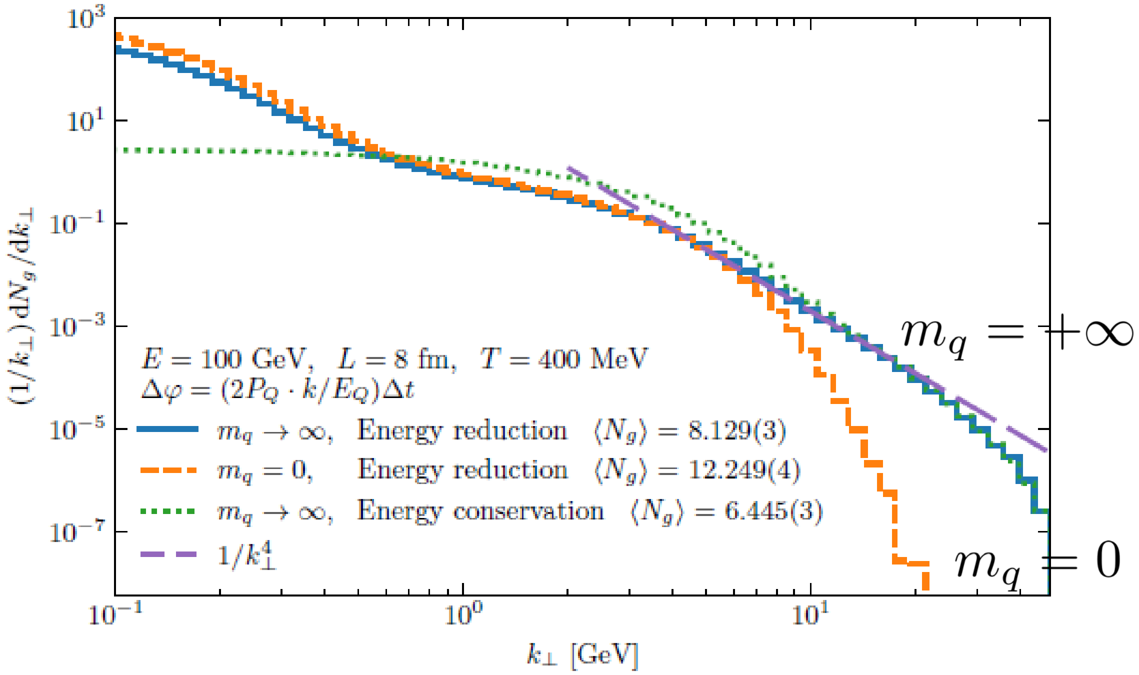


Fig. 3. Results for the properties of the inclusive subjets distributions analyzing the impact of the elastic scatterings separately and in combination, for the subjet multiplicity (left panel) and the average angular distance among them (right panel).

# The impact of quasi particle on energy loss and jets

Effect of the mass of the QGP scatterers on the gluon radiation in the BDMPS-Z regime:

**I. Karpenko et al., 2404.14579v1**

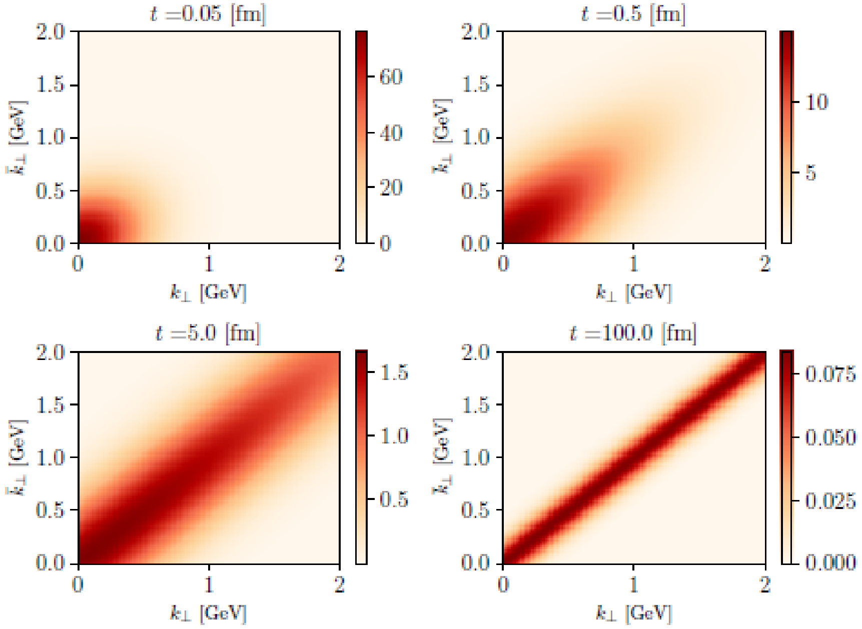


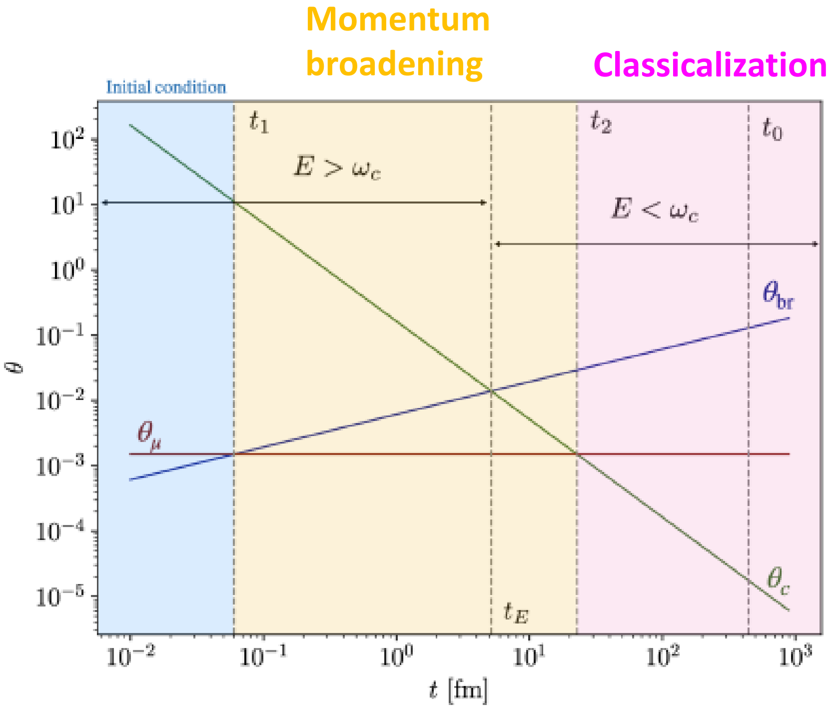
What about the consequences of the “remnant of the NP forces” for the jet evolution ?

# New insights on jet evolution from open quantum systems ?

Quantum evolution of a ultrarelativistic parton interacting with the QGP

**J Barata et al., Phys. Rev. D 108, 014039 (2023)**





$$t_0 = \frac{E}{\mu^2}\,, \quad t_1 = \frac{\mu^2}{\hat{q}}\,, \quad t_2^3 = \frac{E^2}{\hat{q}\mu^2}\,.$$

Momentum broadening happens in the quantum regime. Any consequence for the induced radiation and the jet evolution ?