Heavy-flavour (open and hidden) transport and energy loss: open questions and what to do in 2030+

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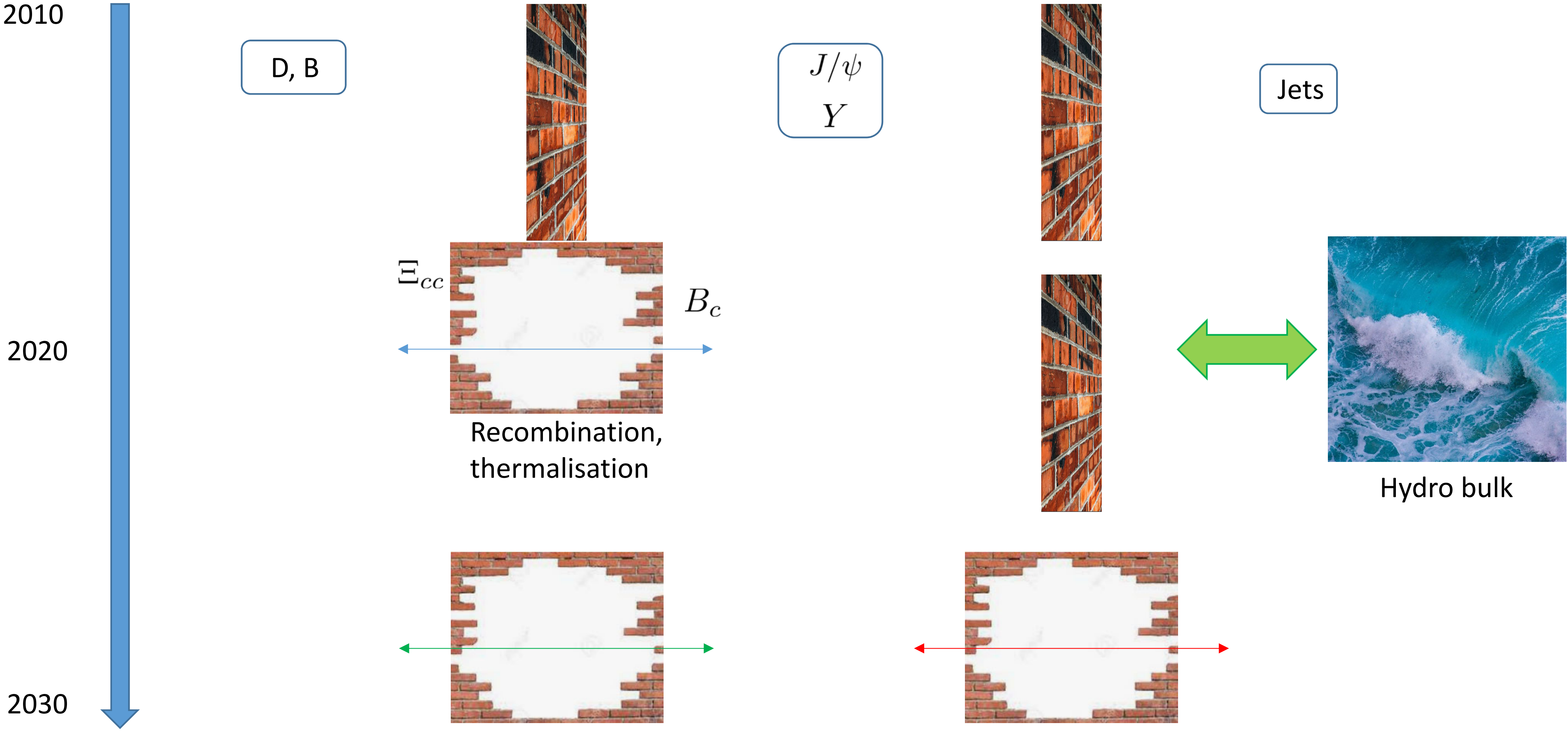
Caution : Not aimed to be an exhaustive review… just a couple of topics that I more or less master

QGP Hard probes



Beyond scientific « unification » issues : sociological impact towards working in theory collaborations

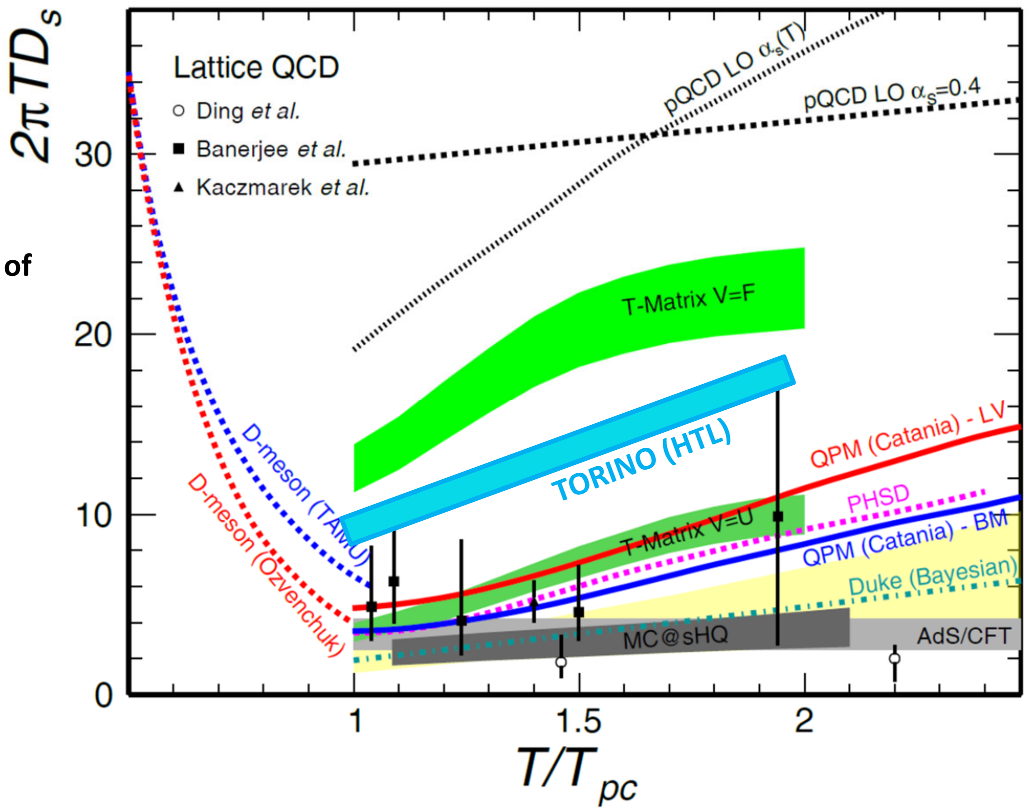
Dominant OHF schemes

- « simple » hard probes :
  - Produced rather early (mind the gluon splitting contribution, though)
  - Well defined color representation

- Main phenomenological frames :
  - transport theory (from Baym-Kadanov to classical Fokker-Planck)
  - 2 different types of energy loss (elastic and radiative), some of them relying on « universal » transport coefficient, for instance the average momentum loss (at any momentum) : $\frac{d\langle\vec{p}_L\rangle}{dt} = \eta_D(p_L)\vec{p}_L$
  - Late hadronisation of single HF quarks (instantaneous coalescence around freeze-out hypersurface)

Model summary on $2\pi TD_s$ extraction

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



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

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

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

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

Mild linear increase of $2\pi D_s T$… ⇔ 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.

Some Challenges on the transport

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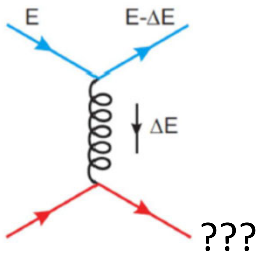
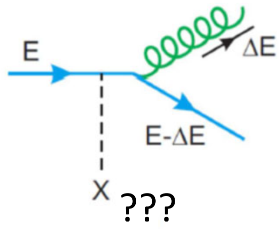
Deux types de pertes d'énergie

BDMPS-Z, etc.





Pro and counts of Fokker Planck vs Boltzmann – like, as the 2nd type of approach requires knowledge of the « light » constituents of the QGP

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**

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- « simple » hard probes :
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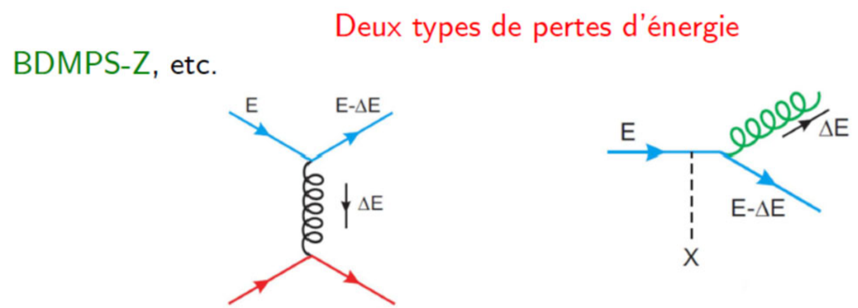
- Main phenomenological frames :
  - Energy loss : In view of the uncertainties affecting the HQ – energy loss, direct lQCD calculation of quantities like $\frac{d\langle \vec{p}_L \rangle}{dt}$ at finite momentum would be desirable …

However, energy loss of a single color charge appears not to be gauge invariant => cannot be easily computed resorting to lQCD techniques; See Eur. Phys. J. A (2017) **53**: 93 (https://doi.org/10.1140/epja/i2017-12282-9) for interesting discussion.

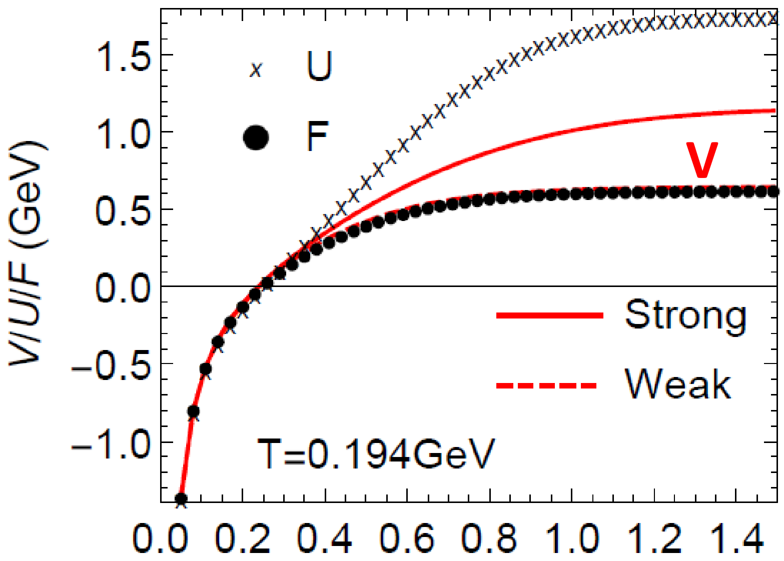
=> Indirect method : rely on QCD-inspired phenomenological models (of Q – QGP interaction)… and use as much inputs from lQCD calculations as possible

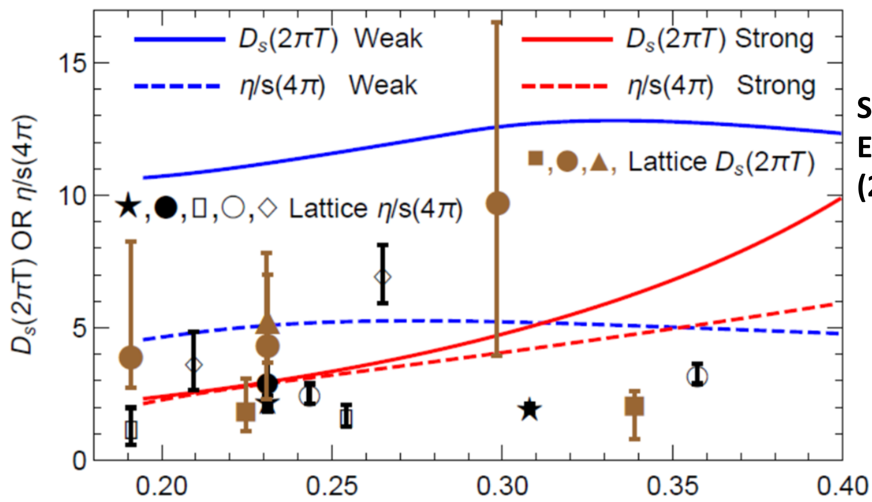


Natural model parameters : thermal polarizations, couplings,…

Recent progresses and future directions

- **Deeper rooting with theory** : TAMU strategy: **S. Y.F. Liu and R. Rapp, PRC97 (2018) 034918**
  - Hamiltonian formulation of a non relativistic effective theory based on a 2-body potential
  - Included in the Luttinger-Ward-Baym formalism -> description of the **equation of state** (EoS)
  - EOS is not enough => evaluation of the **free energy** (./. introduction of Q-Qbar pair) + **quarkonium correlators** ...
  - 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

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Prospect for 2030 :

- all models used for interpretation of Open Heavy Flavor propagation in hot QGP medium are properly calibrated on lQCD quantities af finite T… and interpolate to pQCD at large momentum exchange.
- Possible new methods (f.i. Schwinger – Dyson equations at finite T)

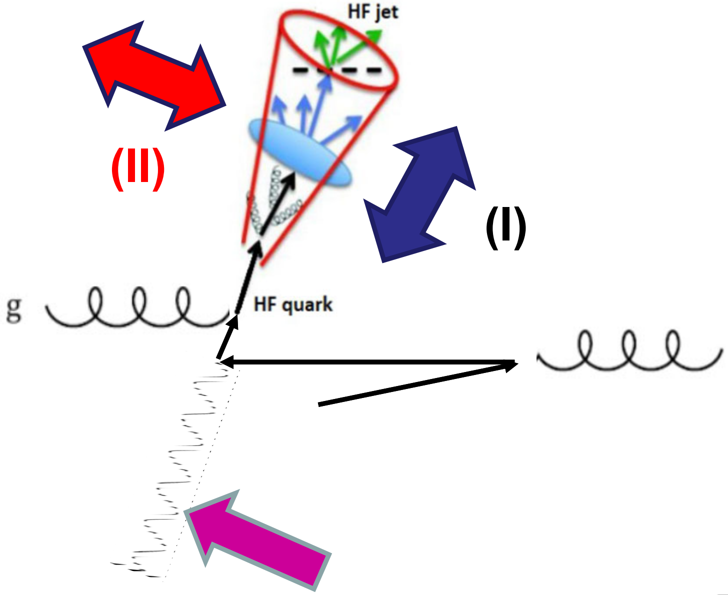
"Future" Observables

What	Good for ?	Caviat
Event shape engineering	Strength and T dependence of the interaction	Might be sensitive to the bulk and initial stage => play collective
Heavy light - correlations	b/c-jet substruture, nature of the interaction	Might be sensitive to various HF creation in pp, to be calibrated
Λ_c, D_s, B_s,…	Understanding hadronization esp. Recombination (if generic enough not to require 1 new free parameter per state) or limits of statistical models	Dynamical treatment of confinement ? Inputs from lQCD probably needed
$v_1(y)$	Constrain (E,B), vorticity, initial tilt of matter initial distribution of HQ in transverse plane	Isn't it a bit too much for this poor observable ?
Correlations	Distinguish between the various facets of energy loss	Requires a very good experimental accuracy
Mass dependence	Distinguish between radiative vs elastic energy loss	Requires D and B measurements with similar acceptance

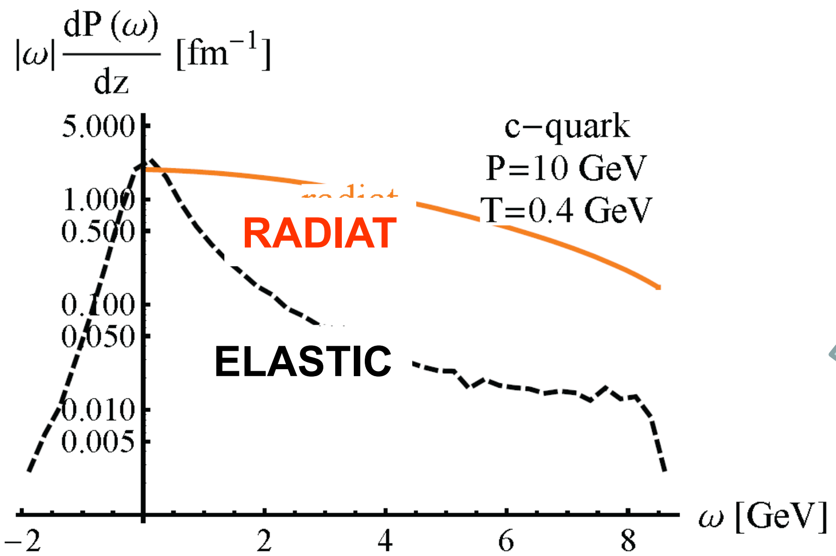
Alternate observable: momentum imbalance

- γ – D/B/c jet /b jet:

In QGP: **Longitudinal fluctuations** of the HQ energy loss crucially depend on the precise mechanism and cannot be measured easily in usual observables like R_{AA} or v_2



No E loss => perfect probe of initial $\vec{P}_{HQ}$

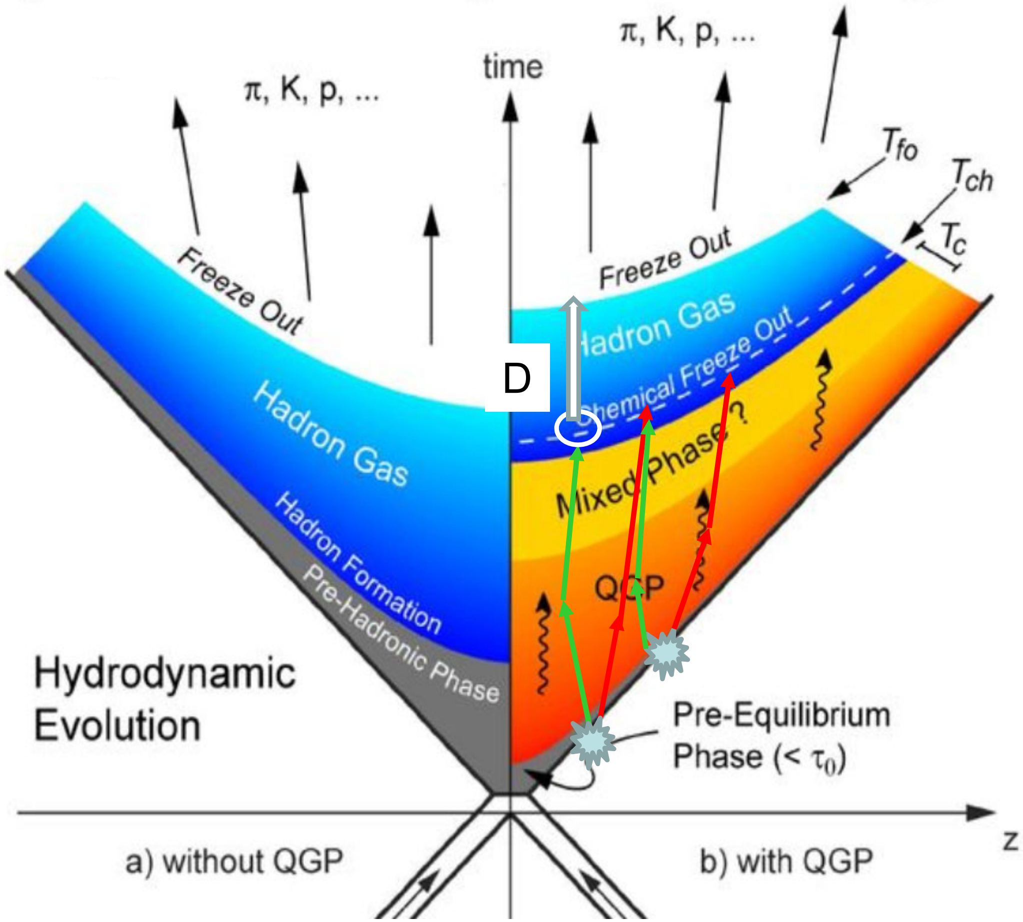


differential probability to loose energy ω per unit time

- Of course: NLO effect in the production mechanisms makes it not so trivial (not to speak about exp. Issues… RUN3 ? RUN4 ?)

Hadronisation : the ultimate quest ?

- Present c/b hadronisation scheme differ quite a lot between various models/groups, especially the « recombination » component



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

Define and display the H_{AA} quantity

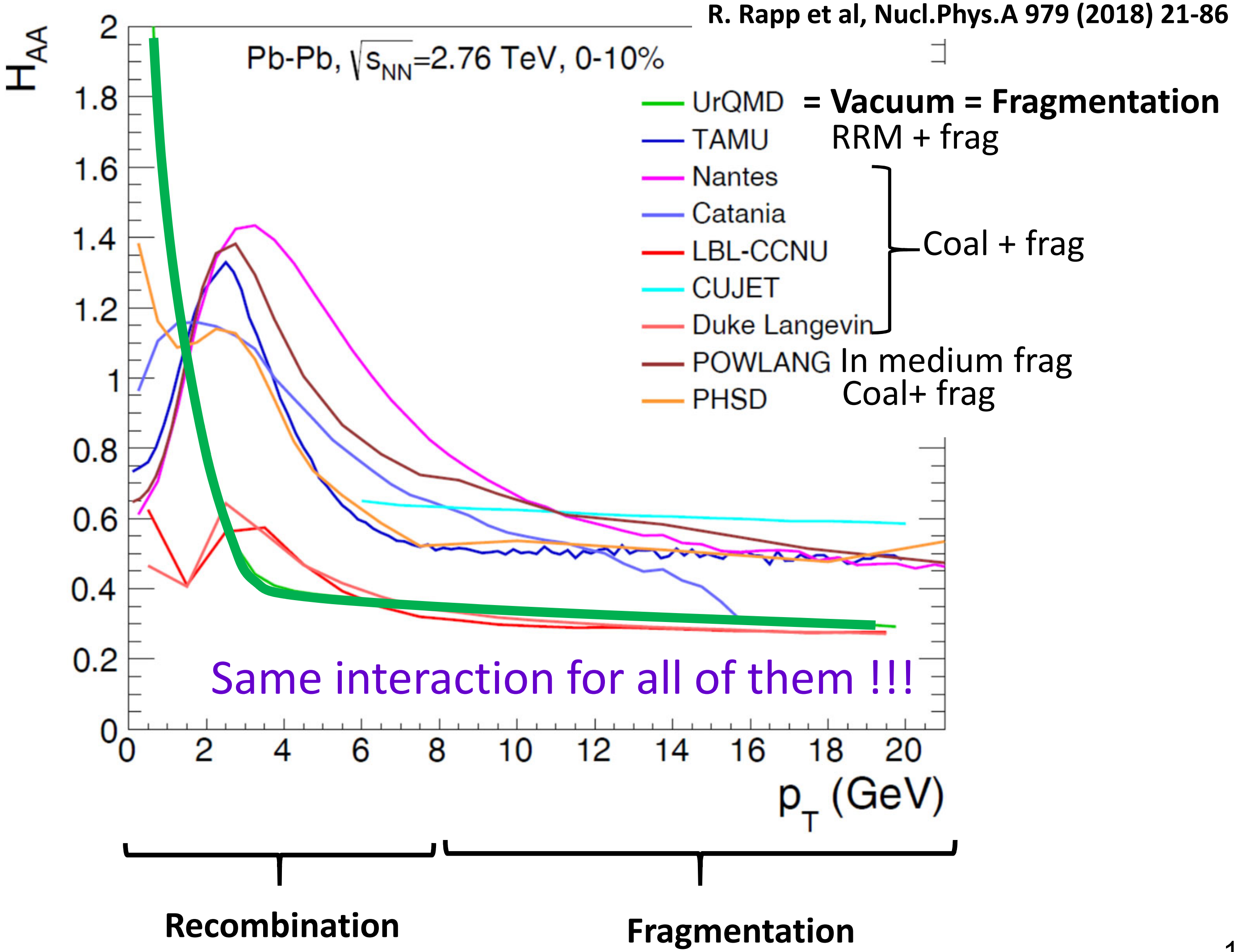
$$H_{AA} = \frac{\frac{dN_D}{dp_T}}{\frac{dN_{c\ \mathrm{final}}}{dp_T}}$$

…which exhibits at best the specific effects of hadronisation :

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

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



Hadronisation : the ultimate quest ?

- Present c/b hadronisation scheme differ quite a lot between various models/groups

- Dedicated study with same background for c-quarks and freeze out hypersurface… shows significant dispersion, especially for Ds and Λc.

+ : Instantaneous coalescence leads to predictions that are in good overall agreement with experimental data

\- : Instantaneous coalescence violates energy-momentum conservation.

\- : recent studies for heavy systems show that the correlation between Q and Qbar is not established « instantaneously »

- **Prospect for 2030 : « I had a dream… »**
  - Dynamical treatment of c + light recombination (inspired from c + cbar systems => charmonia formation).
  - Other ingredients under control => comparison btwn AA data and theory will allow to better understand the fundamental hadronisation mechanisms of heavy quarks,… the ultimate quest.

Some essential ingredients

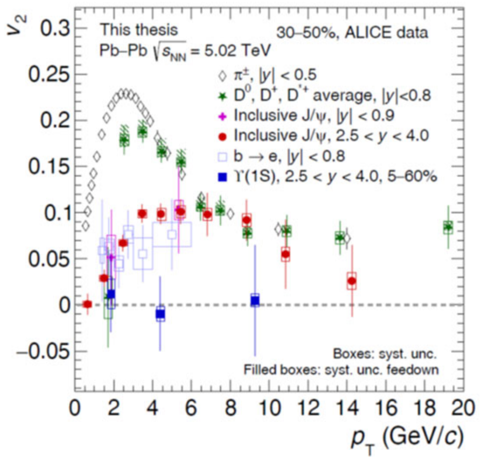
~~Dominant scheme~~ for quarkonia production in AA (low and moderate p_T)

- Suppression
  - Mean field potential screened at high temperature
  - Interactions with QGP dof => thermal excitation (dissociation)

- Increase from off-diagonal production
  - In medium (through resonant states)
  - Statistical recombination

?

Crucial question: Role of Quantumness for quarkonia production ?



Crucial for **charmonia**, which show clear signs from collectivity

Pretty late « formation »

Strictly speaking, no hard probe

Various quarkonia transport approaches

- Usual transport (since mid 2000)
  - Initial « primordial quarkonia », formed as (quantum) decoupled from other components
  - Suppression according to rate equation $\frac{dN_\Phi^{\rm prim}}{dt} = -\Gamma N_\Phi^{\rm prim}$
  - Local recombination -> « re »generation $\frac{dN_\Phi^{\rm reg}}{dt} \propto N_Q N_{\bar{Q}}$
  - Decay rate Γ encodes « *local* » dissociation processes (g + Φ -> Q + Qbar, q/g+ Φ –> q/g+ Q + Qbar)

Both rates equilibrate when statistical equilibrium is reached

Encodes collectivity gained by Q & Qbar

Dominates at large T (quasi free scattering)

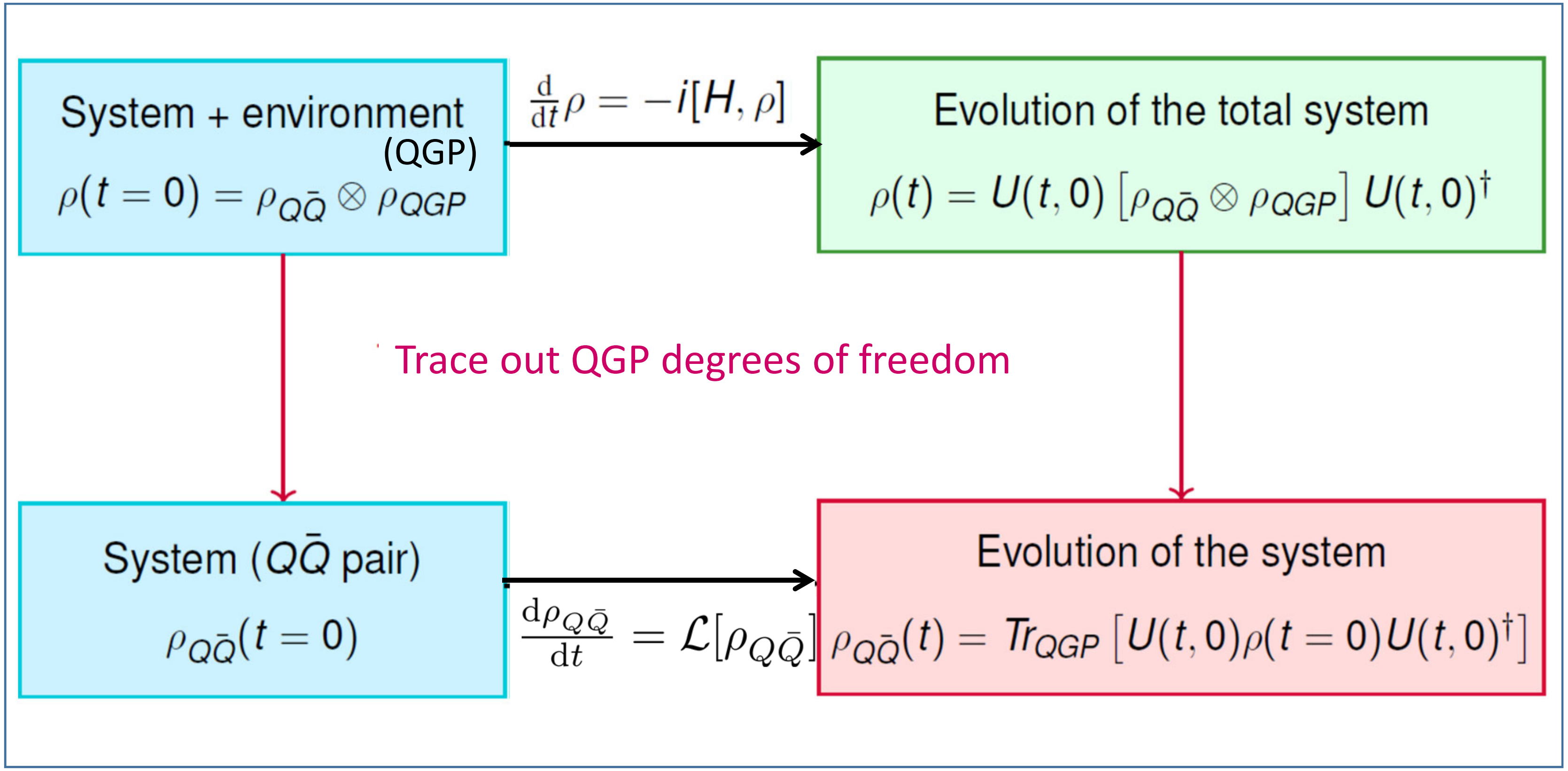
+ : Rather transparent physical processes
Easy for numerical implementation
Rich phenomenology (f.i. v_2 of excited states)

- : Neglect the initial quantum coherence (although Γ is small for close pairs)
Rates are evaluated between bound states of mean-field potential (no transient dynamics for resonances)

Various quarkonia transport approaches

- Since 2015 : Open Quantum System approach, mostly for bottomonia
  - Initial « primordial quarkonia », or compact $b\bar{b}$ state
  - Evolution according to Linblad equation

Open Quantum System Formalism



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

Linblad Equation

Case of a Markovian time-evolution (τ_E smallest scale) => Lindblad equation (local in time)

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{Q\bar{Q}}(t) = -i\left[H_{Q\bar{Q}}, \rho_{Q\bar{Q}}(t)\right] + \sum_i \gamma_i \left[L_i \rho_{Q\bar{Q}}(t) L_i^\dagger - \frac{1}{2}\left\{L_i L_i^\dagger, \rho_{Q\bar{Q}}(t)\right\}\right]$$

$H_{Q\bar{Q}}$: $\{Q, \bar{Q}\}$ kinetics + screened potential V

L_i : Collapse operators (or dissipators), depend on the properties of the medium… linked with the imaginary potential between Q and Qbar.

3 important conservation properties :

$\rho_{Q\bar{Q}}^\dagger = \rho_{Q\bar{Q}}$	$\mathrm{Tr}[\rho_{Q\bar{Q}}] = 1$	$\langle\varphi\|\rho_{Q\bar{Q}}\|\varphi\rangle > 0, \forall\|\varphi\rangle$
(Hermiticity)	(Norm conservation)	(Positivity)

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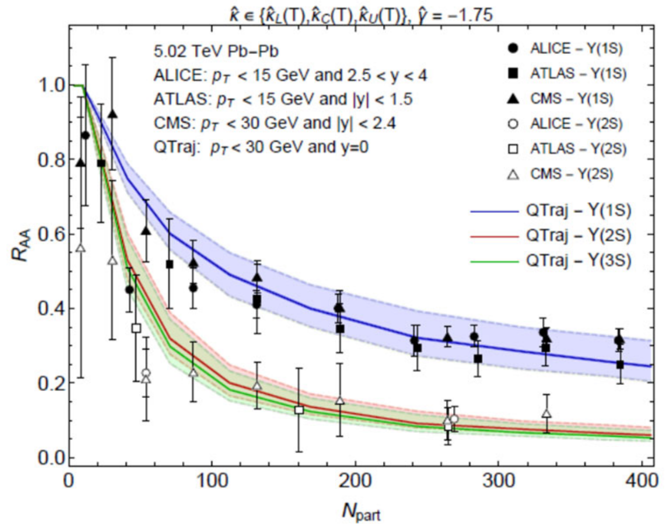
  - Encodes both dissociation AND recombination (from a unique initial pair)
  - Collapse operators obtained from NRQCD or from the Imaginary potential (evaluated through lQCD)

+ : Preserve quantumness
Deeply rooted to QCD properties like HQ diffusion coefficient
Naturally treats transitions btwn states

- : Heavy numerics
Linblad equation Appropriate for either Quantum Brownian Regime or Quantum optical regime
Rather strong dependence on the initial quantum state.



N. Brambilla, M.-A. Escobedo, M.S., A. Vairo, P. Vander Griend, and J.H. Weber, 2107.06222

τ_E: **environment correlation time**

$$\tau_E \sim \frac{1}{T}$$

τ_S: **system intrinsic time scale**

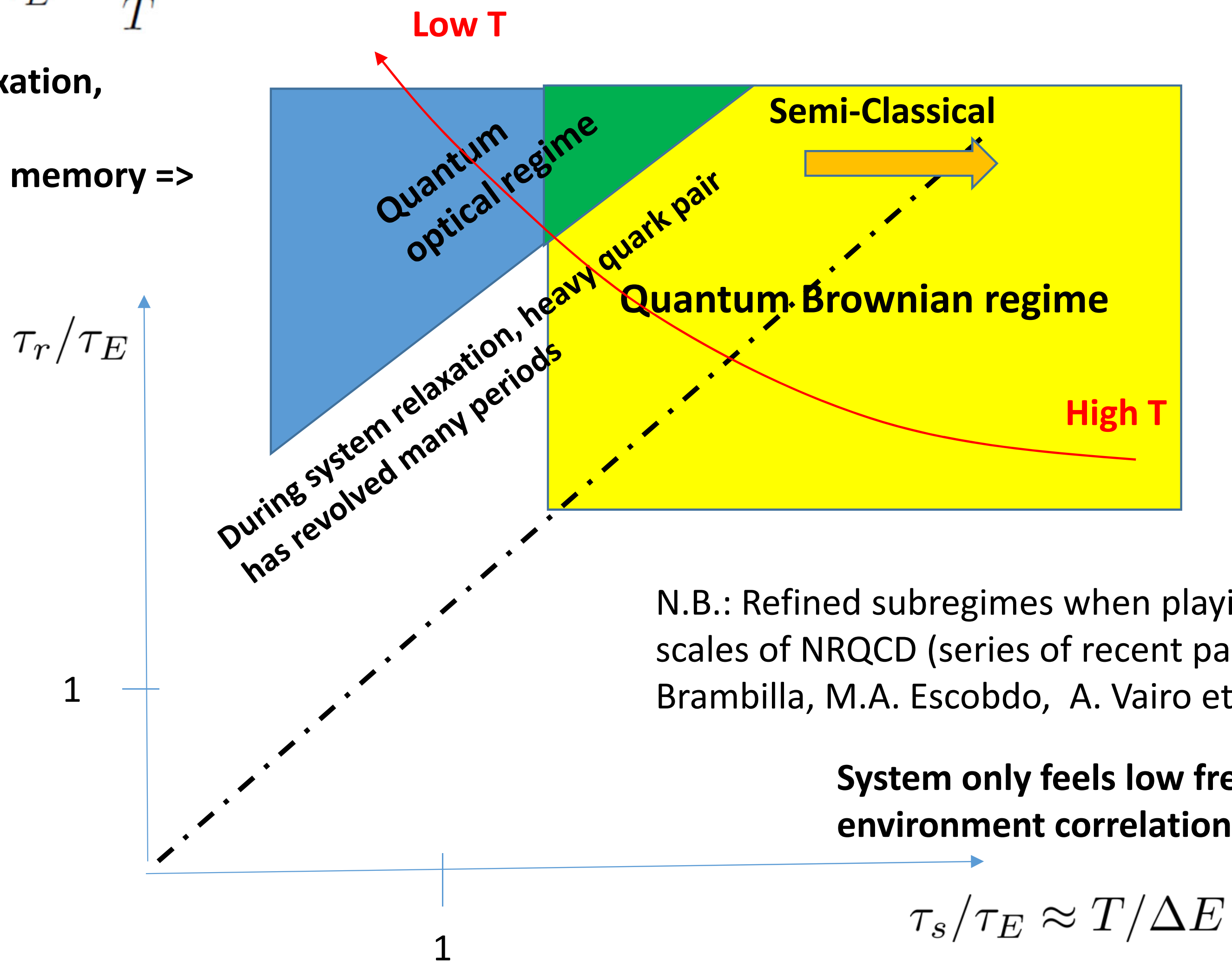
$$\tau_S \approx \frac{1}{Mv^2} \approx \frac{1}{\Delta E}$$

τ_R: **system relax time**

$$\tau_r \sim \frac{1}{\Gamma} \approx \frac{1}{\alpha T (m_D^2 \langle r^2 \rangle)}$$

$$\sim \frac{M^2}{T^3} \gg \tau_E$$

During system relaxation, environment correlation has lost memory => Markovian process



$$\frac{\tau_r}{\tau_E} \sim \frac{M^2}{T^2}$$

N.B.: Refined subregimes when playing with the scales of NRQCD (series of recent papers by N. Brambilla, M.A. Escobdo, A. Vairo et al)

System only feels low frequency part of environment correlation

Not clear all states goes from one regime to the other at the same T

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Prospect for 2030

- Matching between 2 regimes
- Initial state better constrained (CGC)
- Generalization of the OQS for intermediate and small systems
- Better contact with quarkonia formation in pp and pA (LDME)
- Contact with other approaches (transport, statistical hadronization)
- …

Prospect for charmonia ?

Usual Transport Equations (kinetic rates)

Statistical hadronization

: Working horses for most of the theory predictions

OQS ?

- Genuine OQS not applicable for many QQbar pairs ☹
- 2017 : Blaizot-Escobo : Derivation of semi-classical Langevin-like evolution equations for an ensemble of QQbar pairs (close to the statistical limit)
- 2009 : Seminal work from Shuryak and Young on Langevin dynamics for c-cbar pairs -> quarkonia
- 2018 (Delorme et al): Use of benchmark solutions to investigate the regime of validity for the Semi-Classical Approximation (ongoing)

Other ***microscopic*** approaches ?

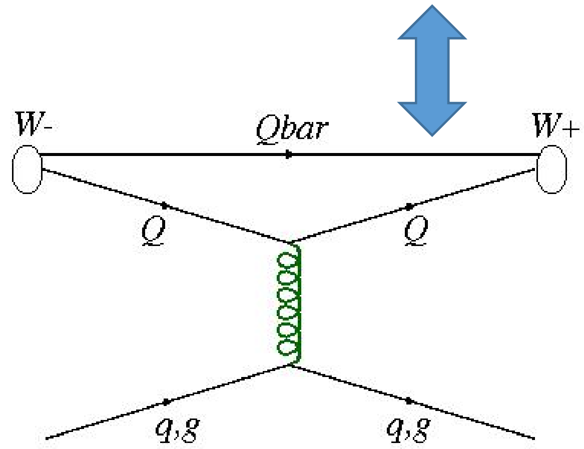
- 2018 -> Now : Arrebato, Aichelin & Gossiaux : Remler formalism based on the reduction of the Von Neuman equation + Wigner transforms: allows to treat interference between various off-diagonal contributions.

Remler formalism at work

Combining the expression of the Wigner's functions and substituting in the **effective rate equation** :

$$\Gamma^{\Psi}(t) = \sum_{i=1,2} \sum_{j\geq 3} \delta(t-t_{ij}) \int \frac{d^3p_i d^3x_i}{h^3} W^{\Psi}_{Q\bar{Q}}(p_1, x_1; p_2, x_2) \left[W_N(t+\epsilon) - W_N(t-\epsilon)\right]$$

- The quarkonia production in this model is a three body process, the HQ (anti-quark) interact only by collision !!!
- The "details" of H_{int} between HQ and bulk partons are incorporated into the evolution of W_N after each collision / time step (nice feature for the MC simulation)
- $W_N(t+\varepsilon)$ and $W_N(t-\varepsilon)$ are NOT the equivalent of gain and loss terms in usual rate equation
- Dissociation and recombination treated in the same scheme

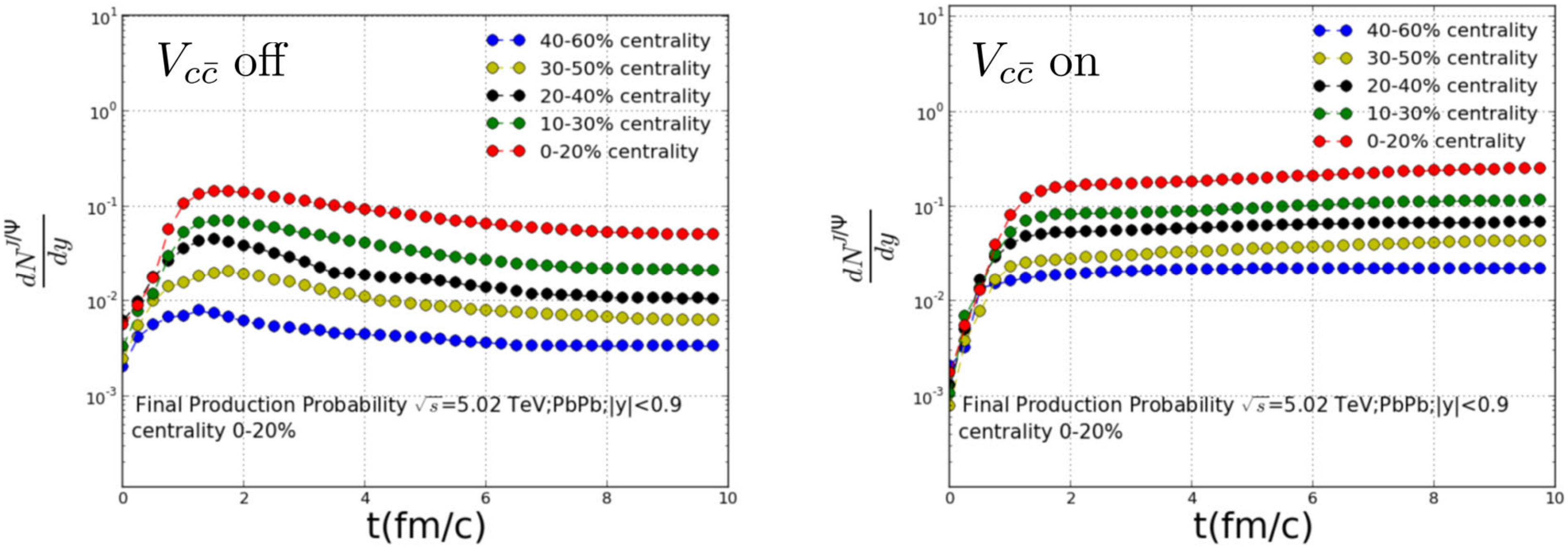


Interaction of HQ with the QGP are carried out by EPOSHQ (good results for D and B mesons production)

Then: $P^{\Psi}(t) = P^{\Psi}(t_0) + \int_{t_0}^{t} \Gamma(t')dt'$

NB: Also possible to generate similar relations for differential rates

Results : J/ψ production vs time



- Without interaction potential between c and cbar, the collisions with the medium manage to destroy the native J/ψ.
- With the interaction potential between c and cbar « on », one observes a steady rate of J/ψ creation (reduction of Γ^{col}, increase of Γ^{local} wrt potential « off »)
- No adiabaticity, but no instantaneous formation either.

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Prospect for 2030

- Microscopic transport codes coupling Heavy Quarks and Resonant Quarkonium states
- Approximations not solely based on dimensional analysis but supported by benchmarks solutions in ideal cases
- Matching with usual transport and statistical hadronization
- Potential for Q-Qbar pair at finite p_T
- Jet contribution for the « initial » production (through gluon splitting)

Various extra thoughts

- Consequences on phenomenology
  - Υ(1S) : formed early vs charmoni : formed late => possibility to probe various stages of the evolution
  - If sequential suppression, then sequential hadronization may lead to different slopes as well as different v_n

- Quarkonia production from pp -> pA -> AA.
  - How to marry the dominant space-time picture in AA with the momentum space picture in pp ?
  - Do the LDME also apply at the end of some hot / warm phase ? Other universal elements ?