Hard Probes 2018 (CERN + Aix Les Bains)

Heavy Flavors + Quarkonia Theory

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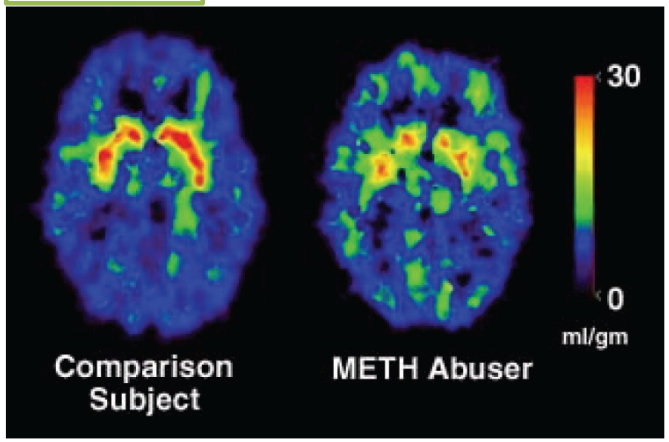
Disclaimer: This ultra short STUDENT lecture…

- … Are just meant to be an introduction to the topic for fresh students so that they can get something from the talks
- => NOT intended to enter in any technical aspect
- => NOT intended for the specialists in the field (they'd better visit Geneva)
- => NOT intended to resolve ambiguities or express my personal opinion
- => NOT intended to cover all the fascinating topics

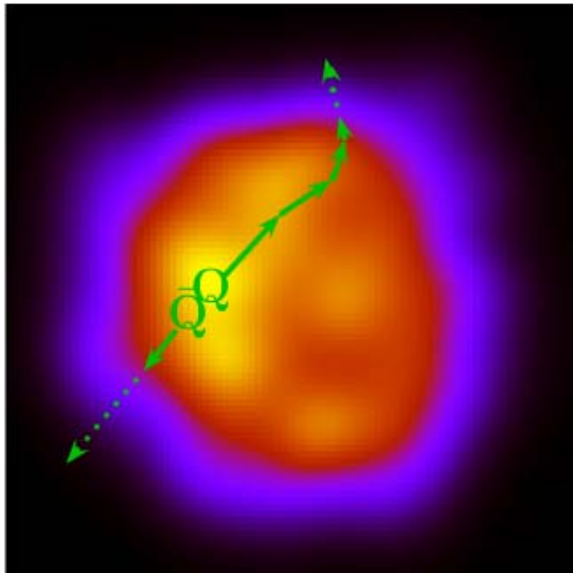
A13

Extracting density profiles with HF Tomography ?

Schematic diagram of a PET scanner



PET scan showing abnormal brain function of a METH user



QGP tomography with Q-Qbar pairs

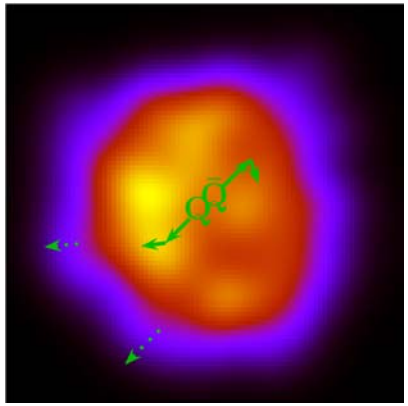
Seems pretty attractive concept…

← Well formulated inverse problem.

Hard probing QGP in URHIC with the help of HF ?

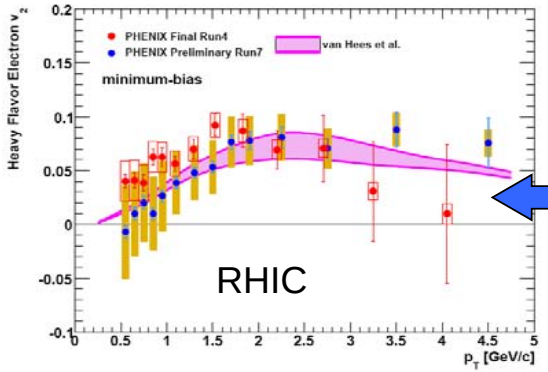
1. Φ: Heavy quarks are produced early, number conserved through time evolution (even at LHC) $\Rightarrow$ signature of early (hot) phase
2. Φ: Weakly affected by late time evolution (heavy, colour transparency)
3. Φ: *Strongly (even too strongly ?) affected by the QGP phase*
4. Theory: Allows *some* pQCD calculations for the initial production and annihilation,…
5. Exp: Quarkonia suppression: clear decay channel $\rightarrow$ leptons

Usually advocated as an ideal *probe* of dense matter



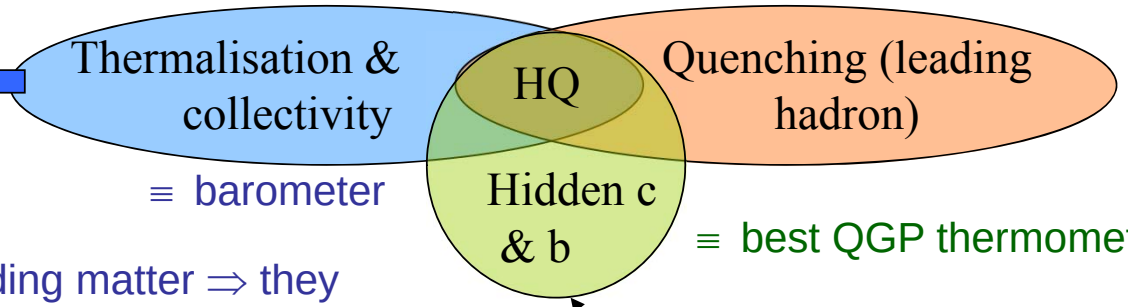
Why open heavy flavors in A-A ?

- Those are for sure sensitive to the early stages
- Much simpler then quarkonia and also sensitive to the medium properties (t_{equil} (α M_Q/T^2) $\Rightarrow$ clear hierarchy for s, c and b).
- Mandatory to understand Q-Qbar evolution in QGP & quarkonia production



HQ are imbedded in expanding matter $\Rightarrow$ they participate to collective motion and gain elliptic flow (v_2:azimutal asymmetry) at finite b… with additional inertia effect

The Trilogy:



≡ densimeter

≡ barometer

≡ best QGP thermometer ???

Quarkonia suppression and Dimuons product; heavy Q thermal production

Challenge:

Description of HQ E-loss / equilibration from fundamental theory. In fact we are at the same time probing the system but also using the results to better understand our probe (and the coupling to QGP) at the same time !

Some open heavy flavor history

74 : Discovery of heavy-flavor

78-80 (Shuryak): Thermal production of c-cbar in QGP. Nice idea; not observed up to now

82 (Rafelski): Thermal production of strangeness

85 (Cleymans & Ray): relativistic Fokker-Planck equation for q

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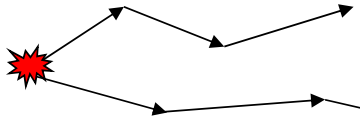
88 (Svetitsky): Fokker Planck equation for HQ (collisional), motivated by consequences for J/Psi: large stochastical localization but « extreme » parameters.



$R^2(t) \alpha t$

30 years of J/Psi enhancement !!!

Why Fokker – Planck (AKA Langevin forces) ?

Bona fide answer: because HQ are heavy => long relaxation times => accumulate many collisions before thermalization => the "details" are averaged (central limit theorem) .

μ-model

$$R(\mathbf{p},t) = \frac{1}{2E_{\mathbf{p}}}\int\frac{d^3\mathbf{q}}{(2\pi)^3 2E_{\mathbf{q}}}\int\frac{d^3\mathbf{q}'}{(2\pi)^3 2E_{\mathbf{q}'}}\int\frac{d^3\mathbf{p}'}{(2\pi)^3 2E_{\mathbf{p}'}} \times \frac{1}{\gamma_c}\sum|\mathcal{M}|^2(2\pi)^4\delta^4(p+q-p'-q') \times [f(\mathbf{p}')g(\mathbf{q}')\tilde{g}(\mathbf{q}) - f(\mathbf{p})g(\mathbf{q})\tilde{g}(\mathbf{q}')]\,,$$

$$A_i = \langle\langle (p-p')_i \rangle\rangle$$

$$\kappa_{i,j} = \langle\langle (p-p')_i (p-p')_j \rangle\rangle$$

Recovers the averages from the μ-model

mesoscopic model (FP equation)

$$\frac{\partial f}{\partial t} = \vec{\nabla}_p \cdot \left[\vec{A} f + \frac{1}{2}\vec{\nabla}_p(\hat{\kappa} f)\right]$$

distribution f in phase space… which fulfills

$$\frac{d}{dt}\langle\vec{p}\rangle_f = -\langle\vec{A}(T)\rangle_f$$

$$\frac{d}{dt}\langle\vec{p}_i\vec{p}_j\rangle_f = \langle\kappa_{ij}(T)\rangle_f$$

$$\Delta\vec{p} = -\vec{A}\Delta t + \vec{\xi}$$ for each Δt

Random force (fluctuations)

… also because it is much easier to solve than sampling the rate !

MC simulation then writes:

Why Fokker – Planck (AKA Langevin forces) ?

Other transport coefficients:

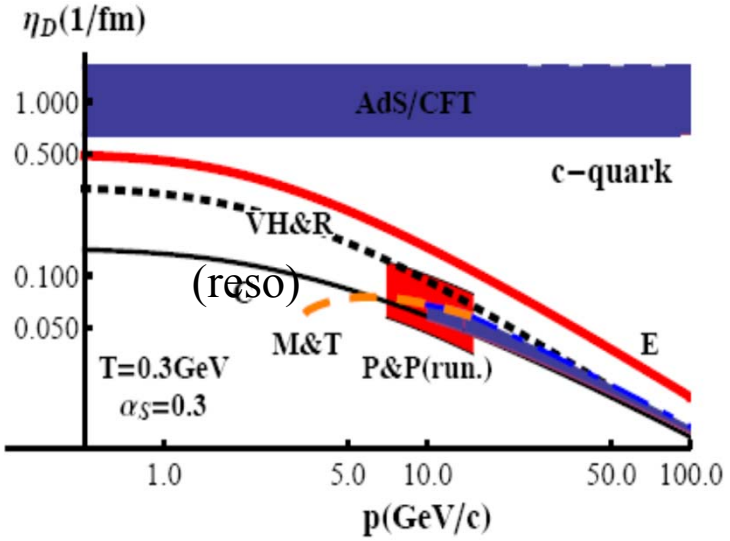
I) Isotropic medium => $\vec{A}(\vec{p},T) = \eta_D(\vec{p},T) \times \vec{p}$ $\quad \frac{d}{dt}\langle\vec{p}\rangle_f = -\langle\vec{A}(T)\rangle_f$

$$\langle\vec{p}\rangle_f \approx \langle\vec{p}\rangle_f(t=0) \times e^{-\eta_D t}$$

$\eta_D\,[\mathrm{fm}^{-1}]$: drag (friction) coefficient; relaxation rate

(typical inverse relaxation time)

… also because it allows to access physical quantities of interest more “directly” than in the microscopic model



Why Fokker – Planck (AKA Langevin forces) ?

II) Isotropic medium => $\hat{\kappa}(\vec{p}) = \kappa_L(p)\hat{\Pi}_L(\vec{p}) + \kappa_T(p)\hat{\Pi}_T(\vec{p})$

Long. diffusion coefficient

Transverse. diffusion coefficient

with $\left(\hat{\Pi}_L(\vec{p})\right)_{ij} := \frac{p_i p_j}{p^2}$

Projector along HQ instantaneous momentum

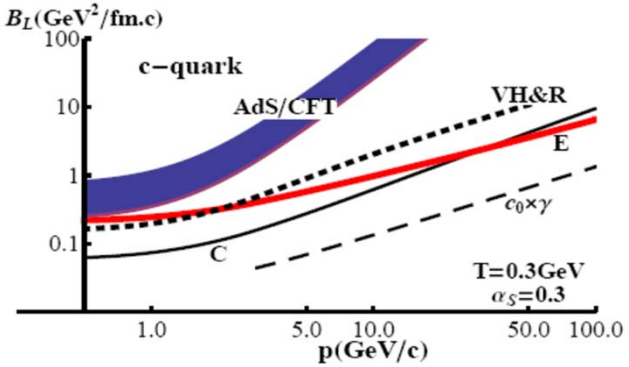
with $\left(\hat{\Pi}_T(\vec{p})\right)_{ij} := I_{i,j} - \frac{p_i p_j}{p^2}$

Projector ⊥ HQ instantaneous momentum

$\kappa_T[\mathrm{GeV}^2\mathrm{fm}^{-1}]$: Transverse diffusion coef. (p space)

Link with well known qhat coefficient

$$\hat{q} = \frac{1}{v}\frac{d\langle p_\perp^2\rangle_f}{dt} \approx 2\kappa_T$$



Some open heavy flavor history

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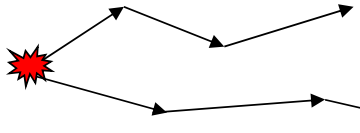


$R^2(t) \alpha t$

30 years of J/Psi enhancement !!!

94-96 (Vogt et al, Fein et al, Gavin et al): dominant «high-p_T lepton » source comes from heavy flavour decay $\Rightarrow$ HQ will obscure the thermal leptons (HQ = bad guys !)

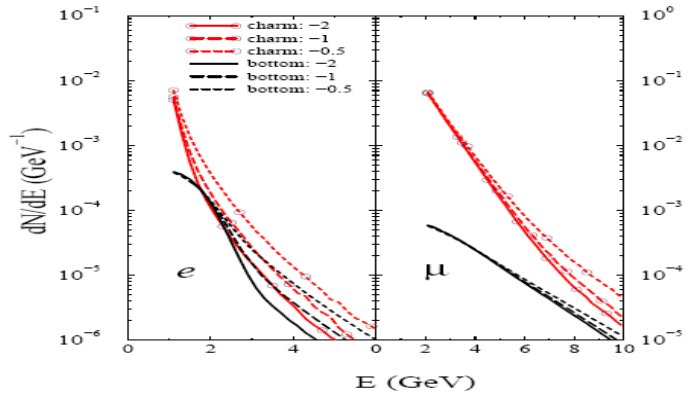
But: No Energy loss !

Some open heavy flavor history

97 (Shuryak): not the dominant (high-p_T) lepton source anymore if one includes a constant dE/dx of 2 GeV/fm (good for thermal leptons)

98 (Lin et al.): "Energy loss effects on charm and bottom production in high energy heavy-ion collisions": first paper on HQ tomography. Idea: access dE/dx via R_{AA}. Mostly «Realistic » ingredients for global scenario. 3 values of energy loss tested: 0.5,1 & 2 GeV/fm

Massless BDMPS (radiative Eloss)



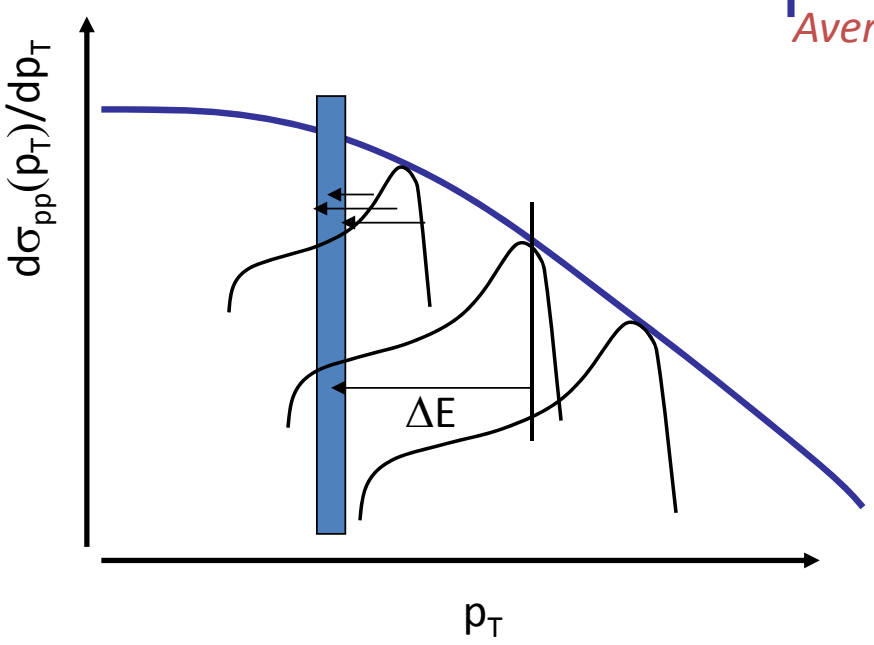
20 years of HQ tomography

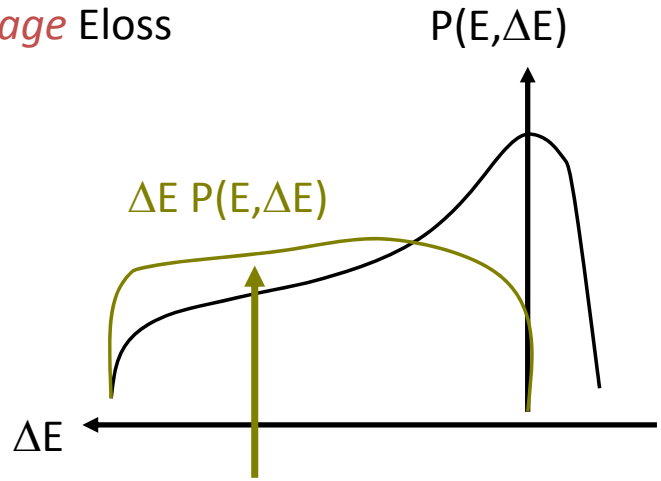
98 (Mustafa et al): solves Fokker-Planck equation (with no diffusion, i.e. no fluctuations) with coefficient depending on time dependent fugacity $\lambda(t)$; infinite medium $\Rightarrow$ $\Delta E/E$=10% (RHIC) and 40% (LHC) for charm (α_s=0.3).

Some open heavy flavor history

01 (BDMS): $R_{AA}(p_T)$ is *not* $d\sigma_{pp}(p_T+\Delta E)/dp_T$ / $d\sigma_{pp}(p_T)/dp_T$

Average Eloss





The weight ΔE biases the density P towards large values. Average value is not the typical value.

Eloss Fluctuations do matter ! (beware of FP)

Better: Shift parameter S: $R_{AA}(p_T) = d\sigma_{pp}(p_T+S(n,p_T,\ldots))/dp_T$ / $d\sigma_{pp}(p_T)/dp_T$

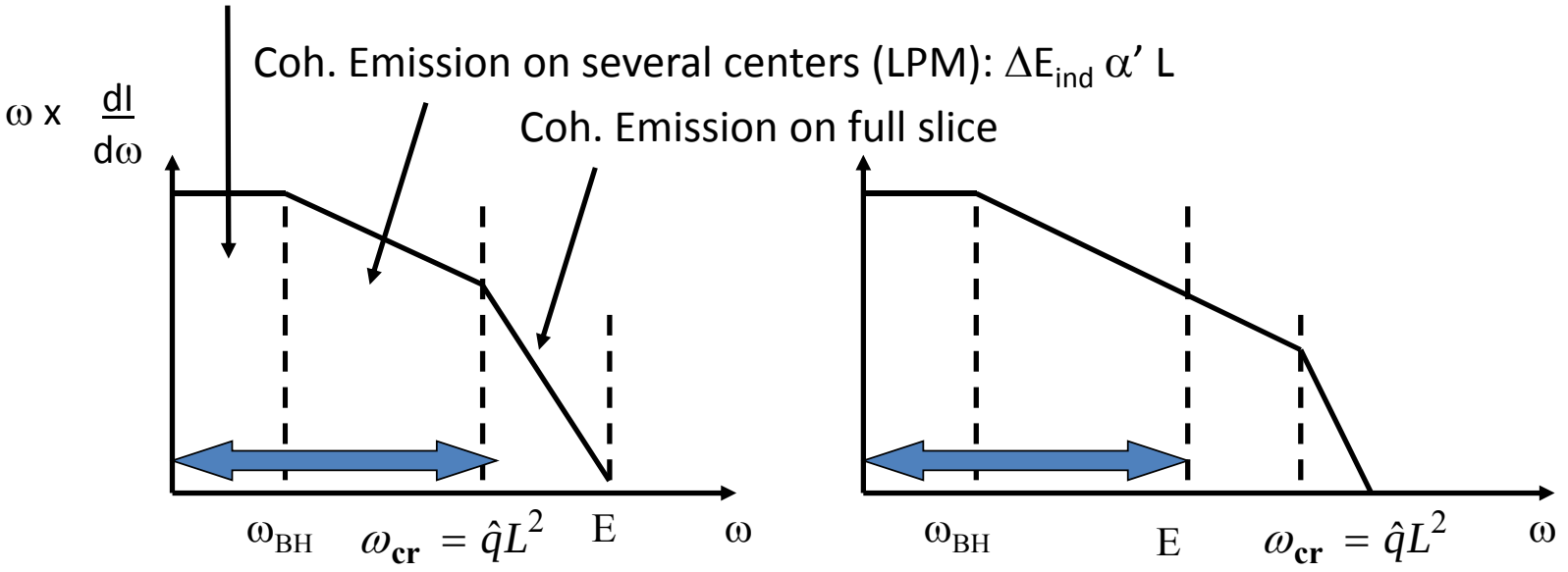
Effective radiation for the quenching: ω from $E \rightarrow E/n$

Some open heavy flavor history

01 (DK): contrarily to previous, HQ induced radiation is suppressed w.r.t. light quark: DEAD CONE EFFECT

gluon radiation from *massless* parton

Indep. Emission on individual centers (BH): ΔE_{ind} α L



$\Delta E_{\mathrm{ind}}(\mathrm{L}) \propto \hat{q}L^2$

$\Delta E_{\mathrm{ind}}(\mathrm{L}) \propto \sqrt{\hat{q}}L$

Some open heavy flavor history

Soft gluon emission in hard process

$$\frac{d\theta}{\theta} \rightarrow \frac{d\theta}{\theta} \times \frac{1}{\left(1+\left(\frac{M}{E\,\theta}\right)^2\right)^2}$$

gluon radiation from *massive* parton (initial Bremsstrahlung)

Suppression factor DC(θ)

taken at $\theta^2 = \langle \theta^2 \rangle_{\text{BDMPS}} = \sqrt{\frac{\hat{q}}{\omega^3}}$ for $t_f \sim \sqrt{\frac{\omega}{\hat{q}}}$

Suppression factor DC(ω)

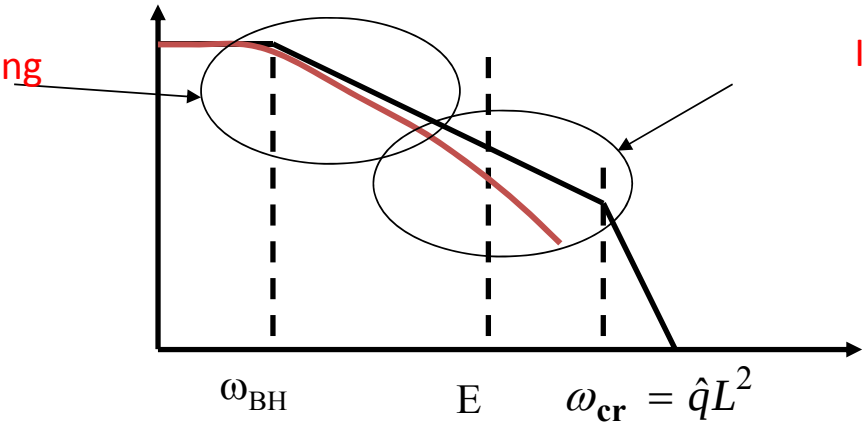
$$\frac{dI}{d\omega} \rightarrow \frac{dI}{d\omega} \times DC(\omega)$$

$$DC(\omega) = \frac{1}{\left(1+\left(\frac{\omega}{\omega_{DC}}\right)^{3/2}\right)^2}$$

New scale $\omega_{DC} = \left(\frac{E^4 \hat{q}}{M^4}\right)^{1/3}$

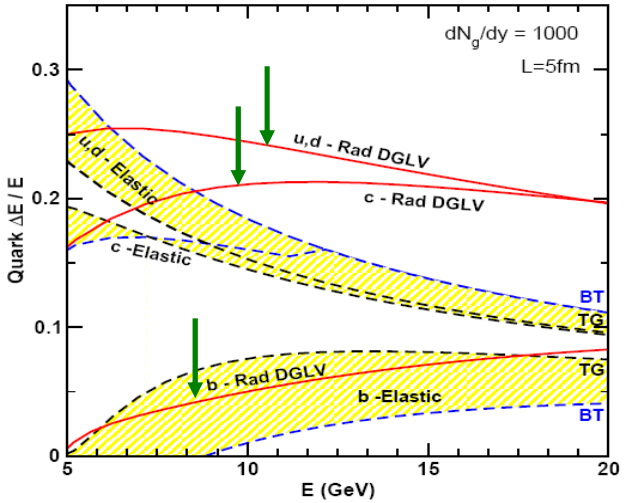
Moderate for quenching

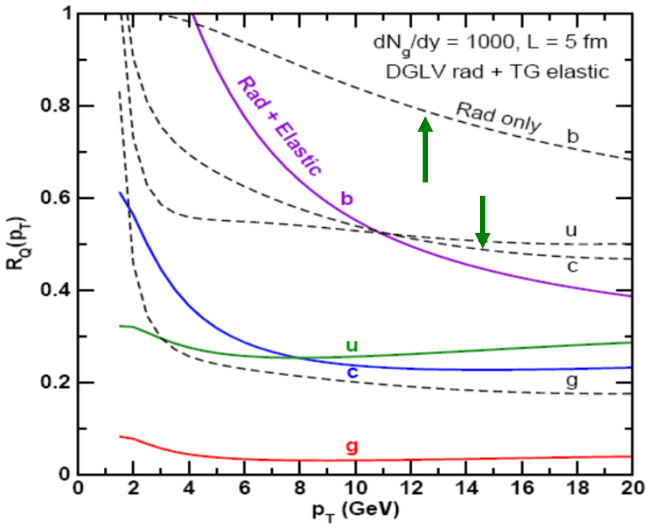
Important for ΔE



Some open heavy flavor history

WHDG 07

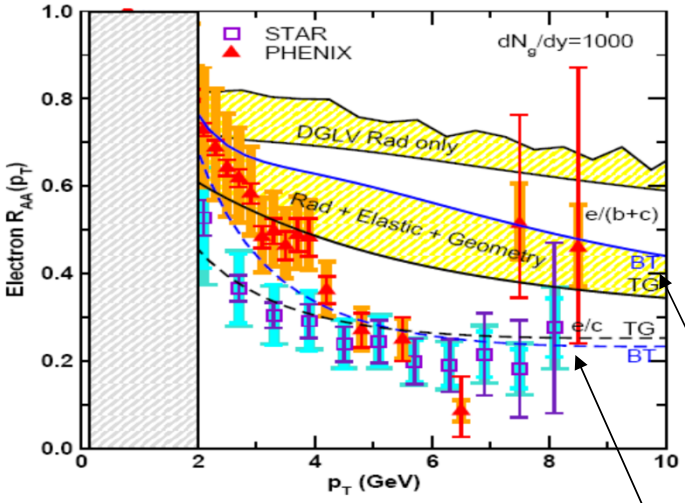


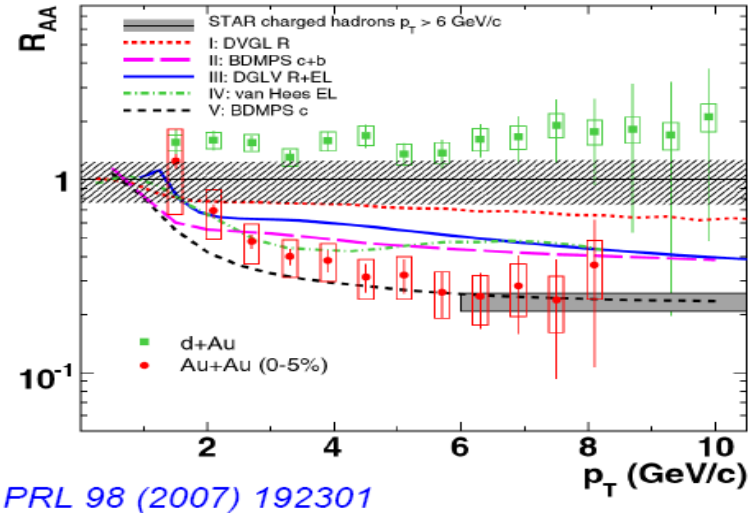


Mass hierarchy in radiative energy loss

… but it is also present in the « usual » elastic energy loss

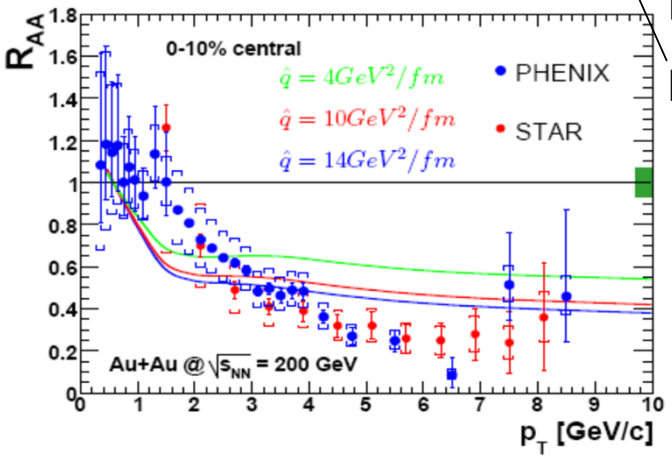
… more Eloss than expected from pQCD, even adding elastic part (often neglected up to then)



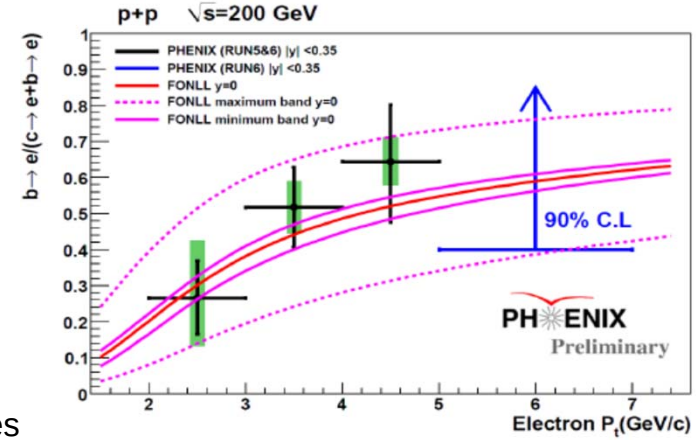


PRL 98 (2007) 192301

Elastic Eloss strikes back (Mustafa 05, Dutt Mazumber 05)



b quark is the puzzle and is definitively there:

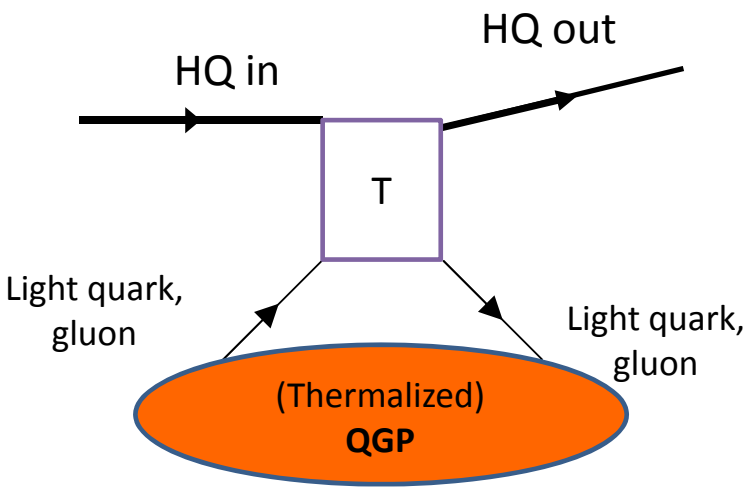


Meanwhile: dN/dy(y≈0) scales like N_{bin}

Collisional (elastic) vs Radiative

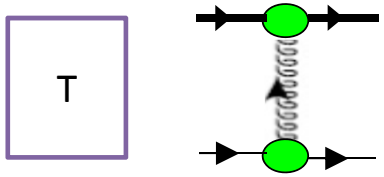
Strictly speaking: Both terms apply to pQCD processes (small and moderate coupling), or to pQCD-inspired processes for which quasi-particles still exists

Collisional (elastic): $2 \rightarrow 2$

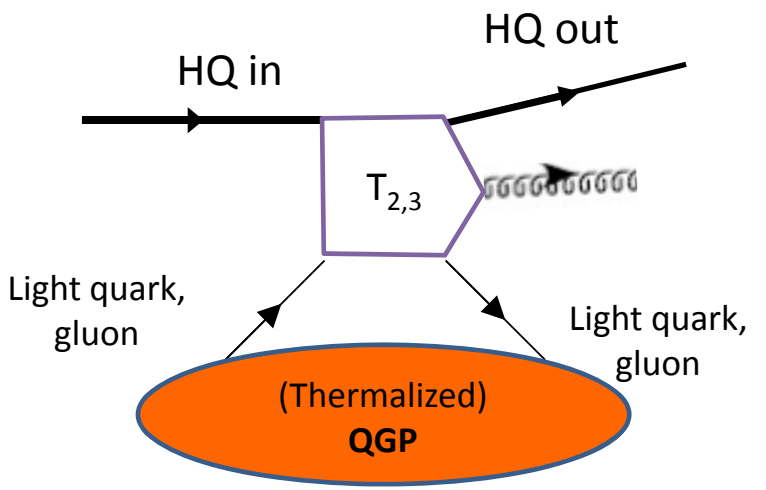


Energy flows from HQ $\leftrightarrow$ medium

e.g. :

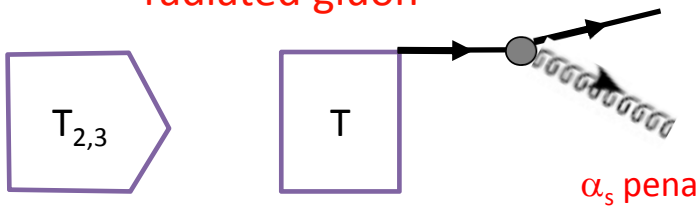


Radiative : $2 \rightarrow 3$



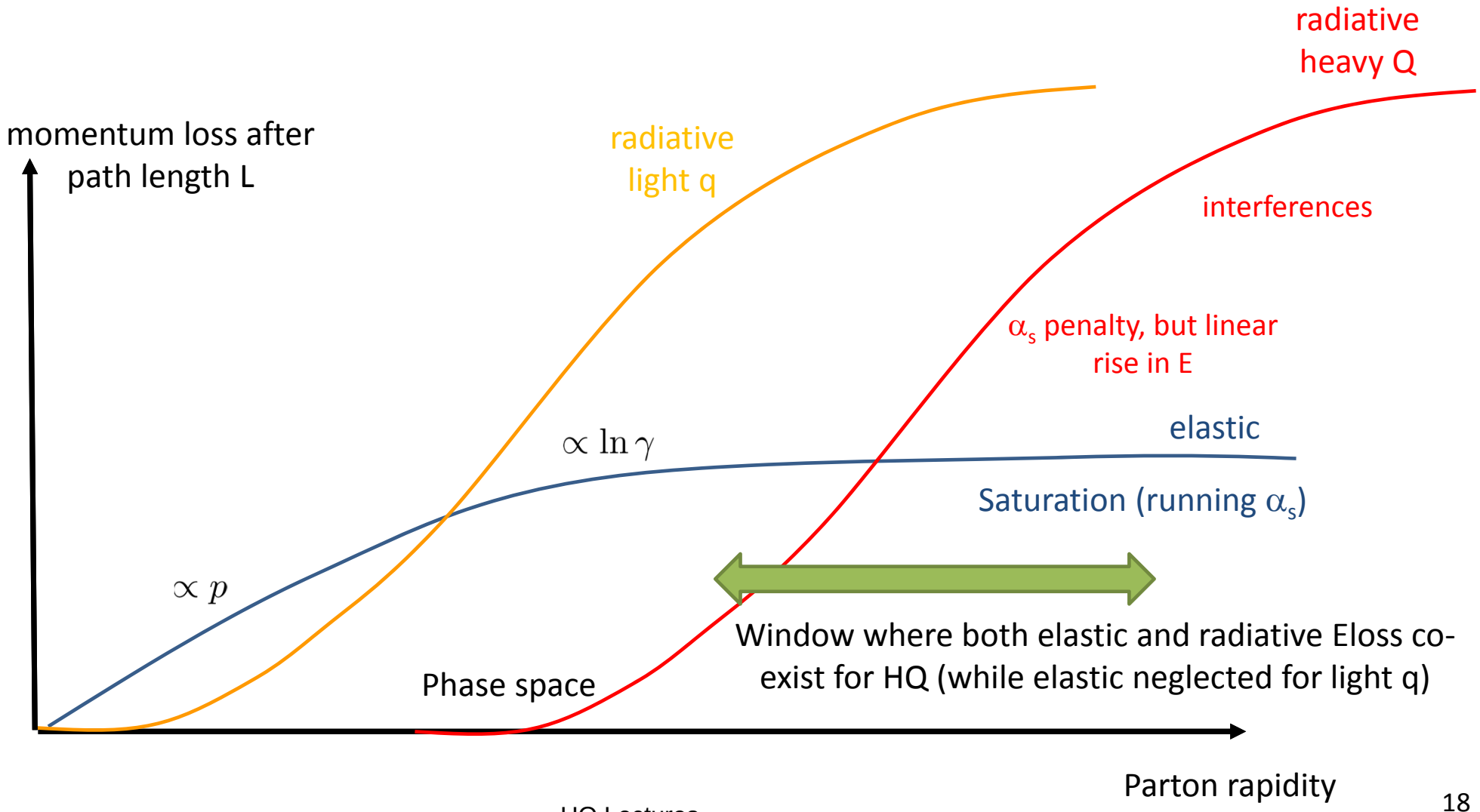
Most of energy flows from HE HQ $\rightarrow$ radiated gluon

e.g. :

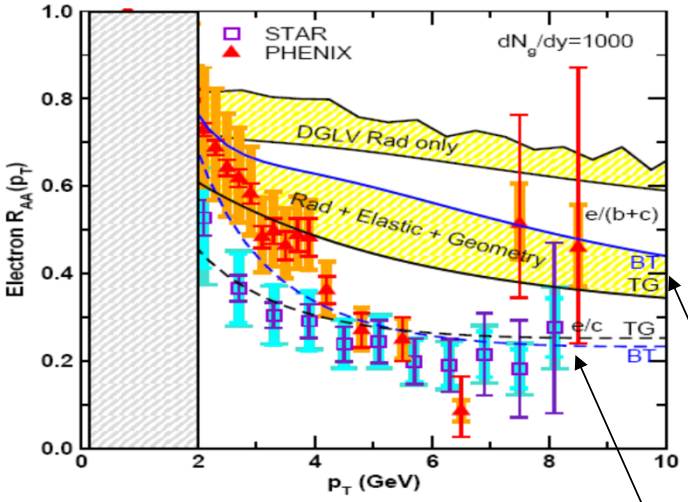


α_s penalty

Collisional (elastic) vs Radiative

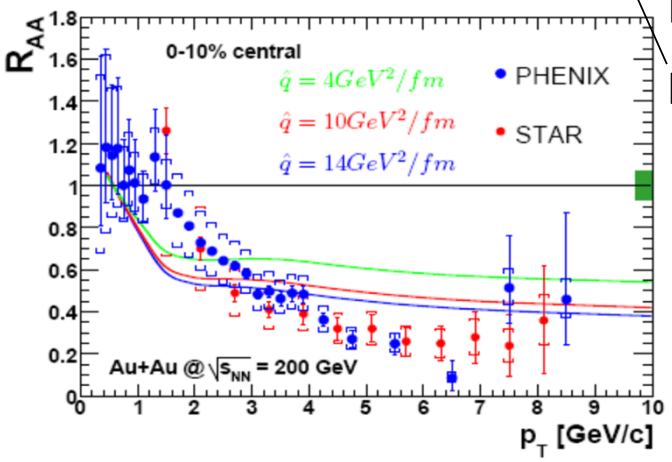


… more Eloss than expected from pQCD, even adding elastic part (often neglected up to then)



In the meanwhile, several improvements in the theoretical framework => the DGLV approach based on pQCD can reproduce the “high pT” data (see talk by M. Djordjevic)

Elastic Eloss strikes back (Mustafa 05, Dutt Mazumber 05)



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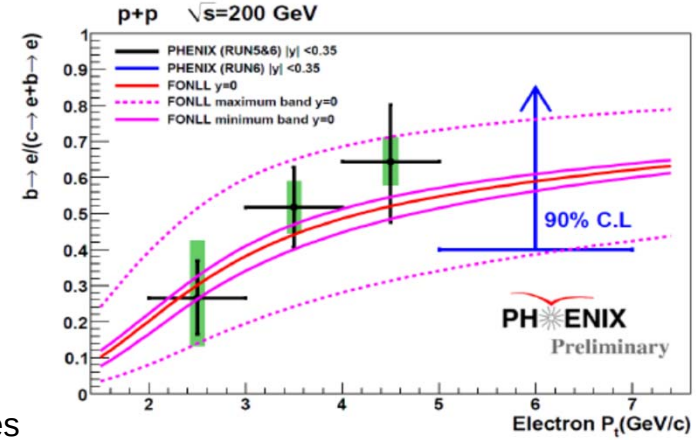


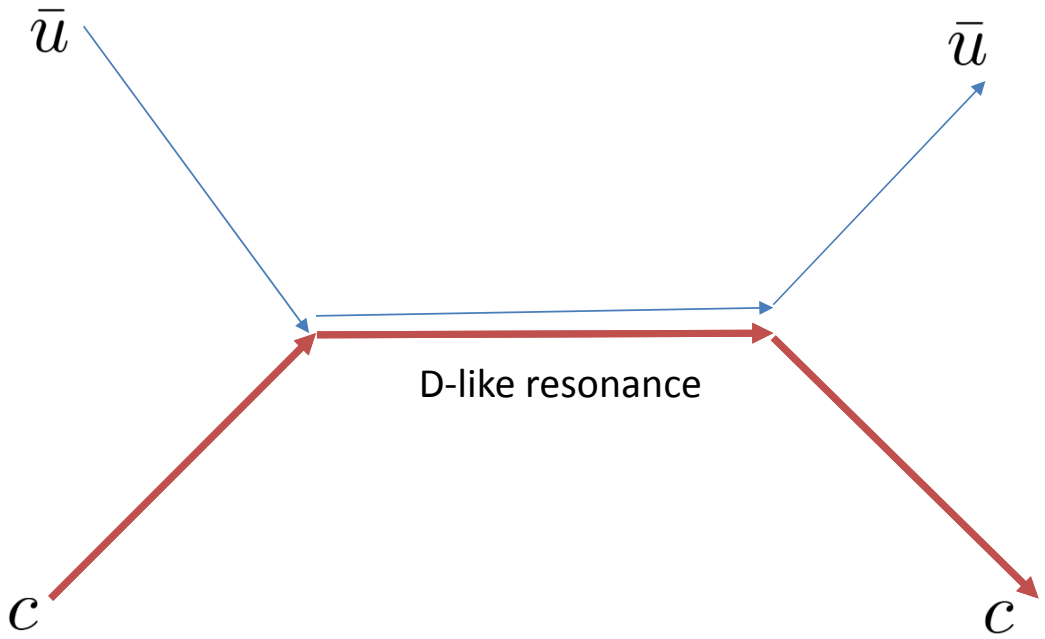
Meanwhile: dN/dy(y≈0) scales like N_{bin}

more *thermalisation* than expected from pQCD, some ways out

- Rapp and Van Hees (2004 ->): pQCD collisional + additional « strength » from quasi-bound D-like states, resorting to Langevin Dynamics

$$\Delta\vec{p} = -\vec{A}\Delta t + \vec{\xi}$$ for each Δt

Random force (fluctuations)



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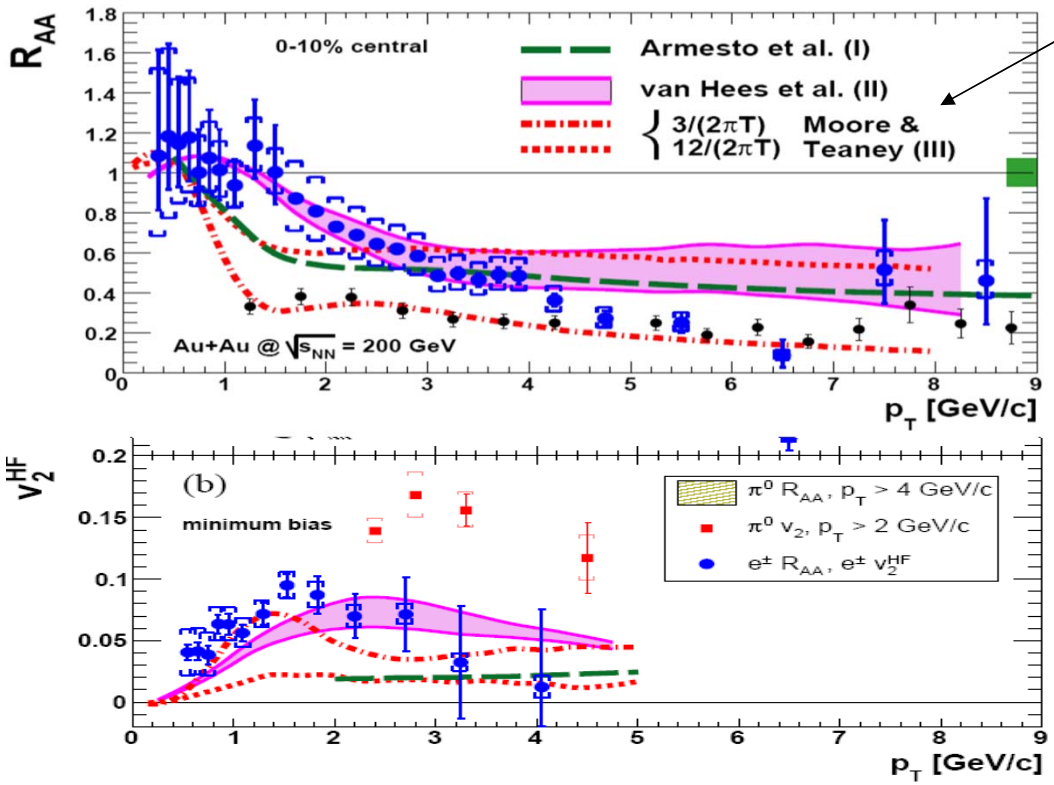
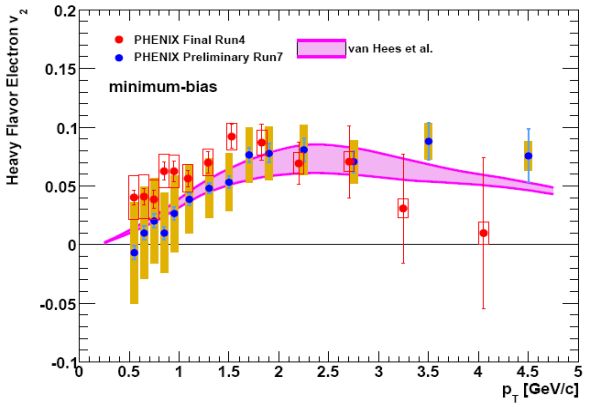


D: spatial diffus coeff (fm^2/fm/c)

pQCD: $D \approx \frac{6}{2\pi T}\left(\frac{0.5}{\alpha_s}\right)^2$

$\approx 24/(2\pi T)$

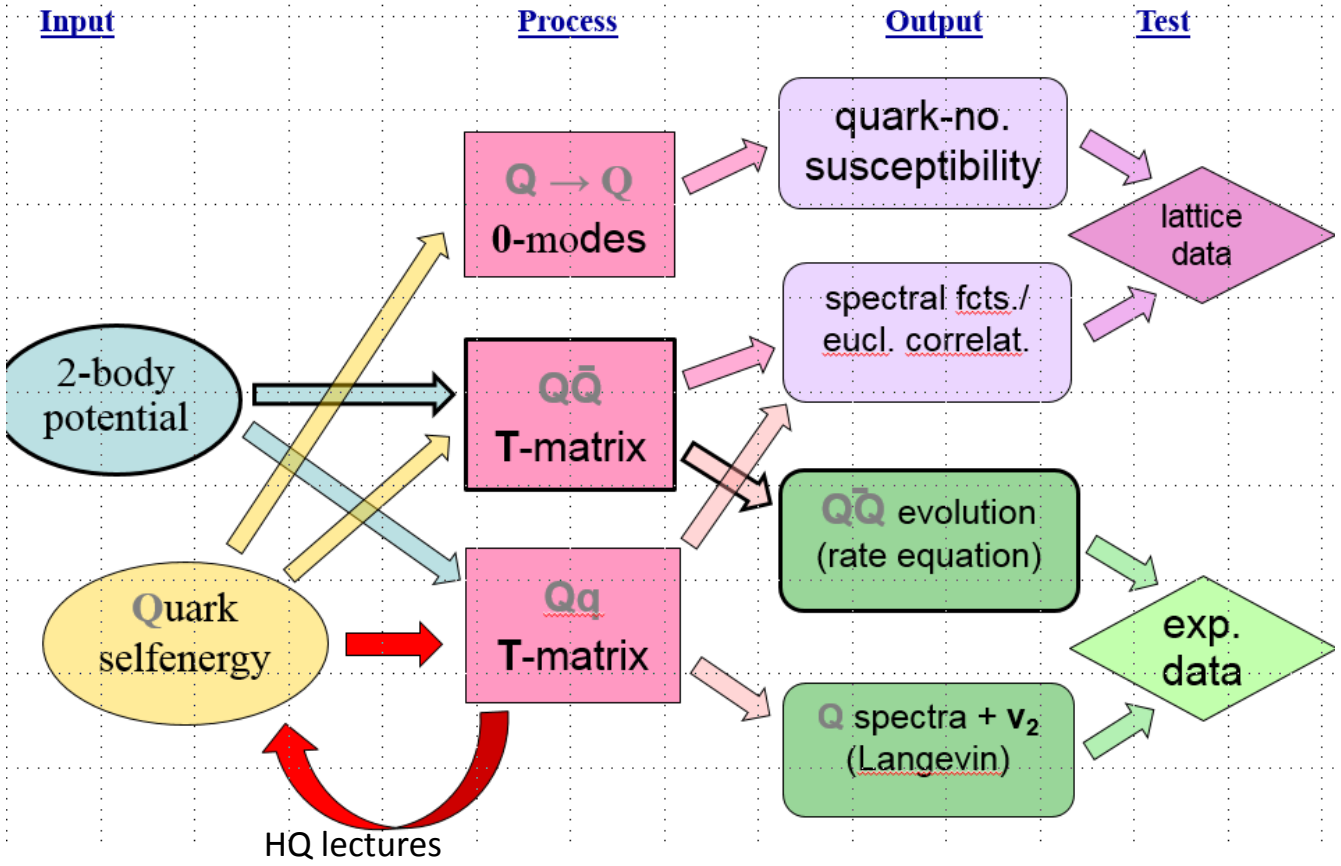
Charm flows !!!



Intermediate-p_T Q marginally lie in the pQCD regime, but this is the bulk of production. For the time, we deal with phenomenology: Strategy: *Reproduce* maximum of existing experimental data with models (transport theory) *inspired* from QCD containing at less ingredients as possible… and make predictions for others

more *thermalisation* than expected from pQCD, some ways out

- Rapp and Van Hees (2004 ->): pQCD collisional + additional « strength » from quasi-bound D-like states; then (2008) systematically developped using the T-matrix resummation of a bona-fide 2 body potential



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)

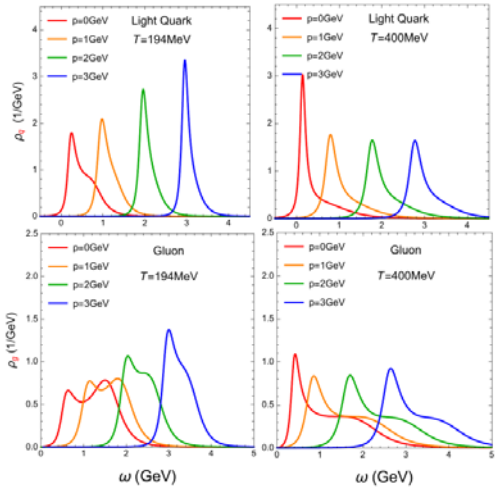
- Comprehensive sQGP approach for the EoS, light quark & gluon spectral functions, quarkonium correlators and HQ diffusion.

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!

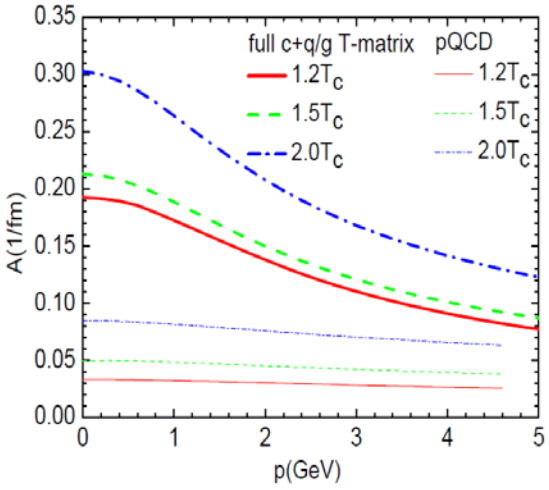
M. He, R. Fries, R. Rapp PRC 82 (2010), PRC 86 (2012)

- Implementation through Langevin dynamics in hydro evolution or in URQMD also corresponds to the disappearance of well defined quasi particles (for which Boltzmann breaks down while Langevin still holds)



No good quasiparticle at low p

$\eta(c/fm)$



Large coupling at small p_Q

Open question, some ways out

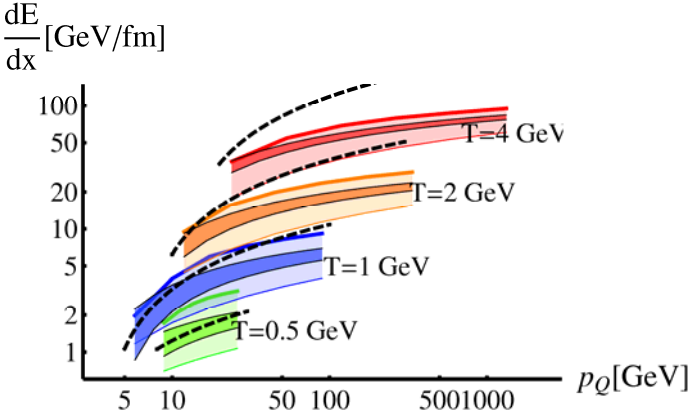
- Rapp and Van Hees (2004 ->): pQCD collisional + additional « strength » from quasi-bound D-like states; then (2008) systematically developped using the T-matrix resummation of a bona-fide 2 body potential
- *Running* of α_s could have dramatic consequences (Peshier 06) => effective model and numerical *Boltzmann* implementation by Peshier (2008), Gossiaux & Aichelin (2008), then Uphoff & Greiner)

pQCD inspired models (f.i. Nantes)

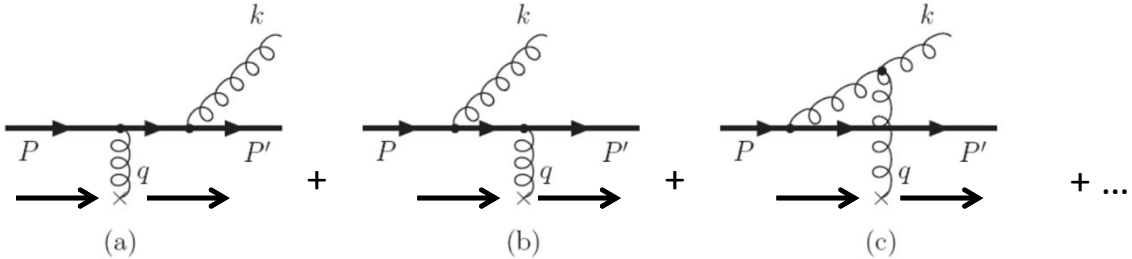
Colisional component

- One-gluon exchange model: reduced IR regulator $\lambda\, m^2_D$ in the hard propagator, fixed on HTL Energy loss
- 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 (ΔE_{rad} α 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

HQ lectures

But also BAMPS, LBL-CCNU, Duke,…

Open question, some ways out

- Rapp and Van Hees (2004 ->): pQCD collisional + additional « strength » from quasi-bound D-like states; then (2008) systematically developped using the T-matrix resummation of a bona-fide 2 body potential
- *Running* of α_s (Peshier 06, then Gossiaux & Aichelin 08, then Uphoff & Greiner)
- sQGP: “supersymetric + AdS/CFT” (application to R_{AA} by Horowitz and Gyulassy, later implementation by Akamatsu)

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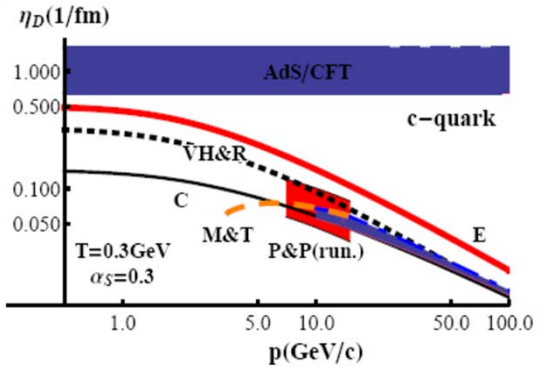
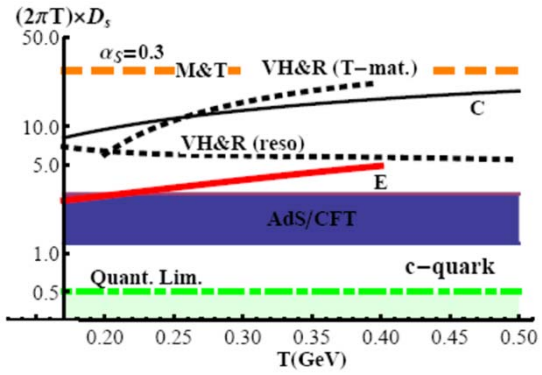
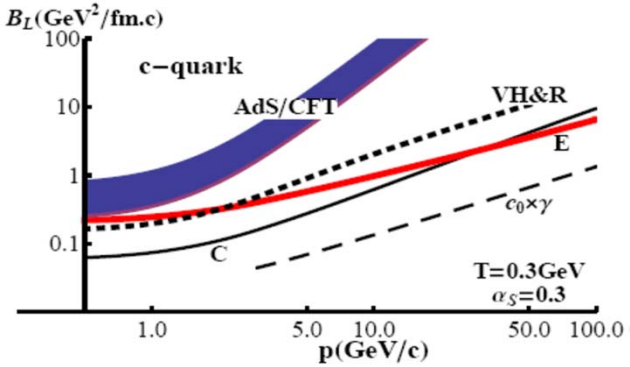
- sQGP: “supersymetric + AdS/CFT” (application to R_{AA} by Horowitz and Gyulassy, later implementation by Akamatsu)
- Leptonic decay through Λ_c (Martinez et Crochet)
-



Drag coefficient



Spatial Diff. coefficient



Long. fluctuations

Already 3 classes of models: collisional, radiative, ADS/CFT + genuine theory (lQCD)

The weak to strong axis for HQ

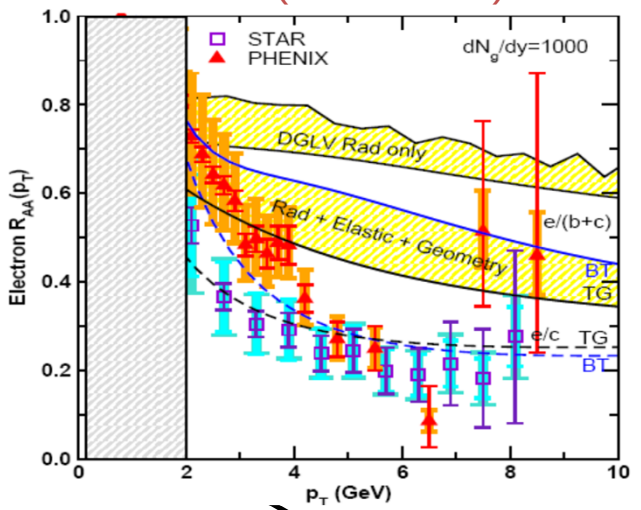
"Naive" pQCD
(WHDG, ASW,…)

$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

"Optimized" pQCD
(ok with pions)

So-called "Failure of pQCD approach" aka "the non photonic single electron puzzle"

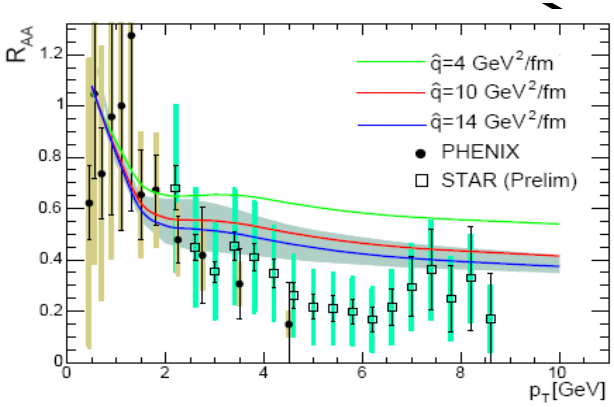
coll Eloss (BT and TG) + radiative Eloss



WHDG

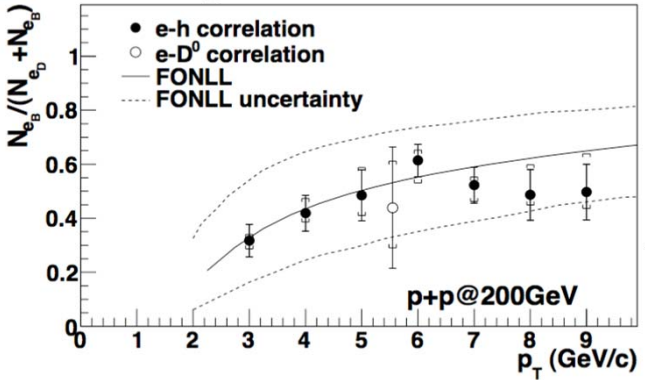
Beauty is the problem… but beauty is found to contribute

ASW (pure rad. energy loss; extended BDMPS)



Armesto et al Dainese, Phys. Rev D (hep-ph/0501225) & Phys.Lett. B637 (2006) 362-366 hep-ph/0511257

Conclude to rough agreement, subjected to b/c ratio in p-p



M Aggarwal et al, STAR, PRL 105 202301

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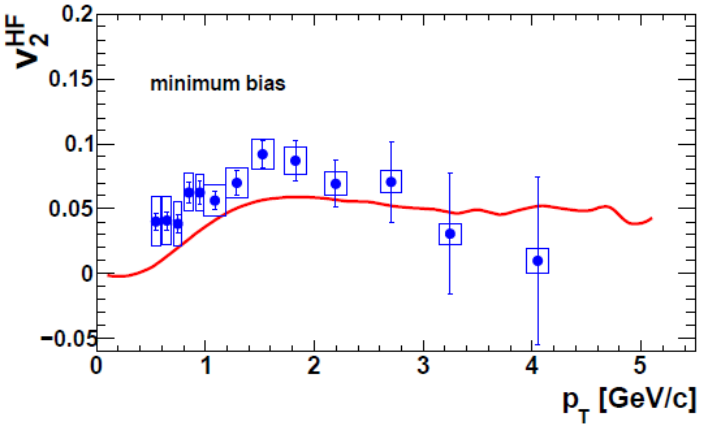
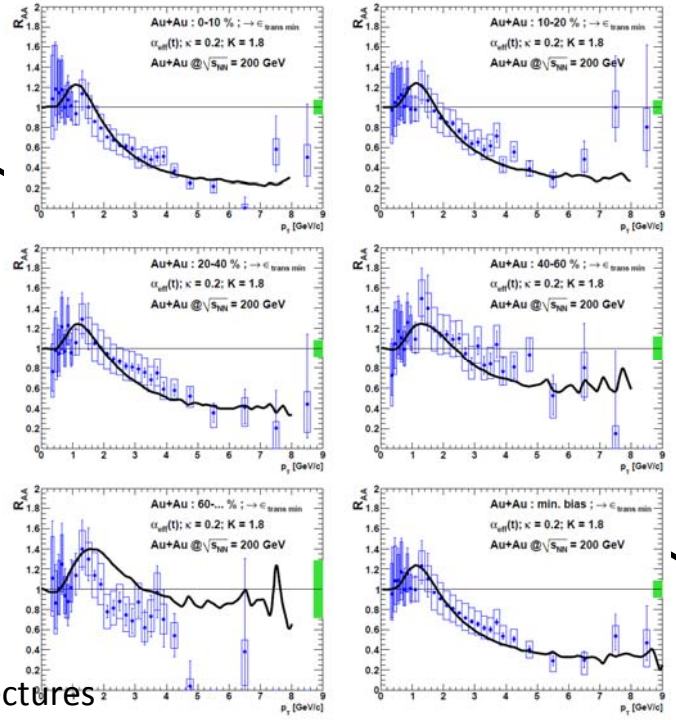
"Optimized" pQCD
(ok with pions)

Collisional model with running α_s and optimized gluon propagator (Peshier, Gossiaux and Aichelin, BAMPS)





The weak to strong axis for HQ

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"Optimized" pQCD

Running α_s (Peshier, Gossiaux & Aichelin, Uphoff & Greiner)

Distorsion of heavy meson fragmentation functions due to the existence of bound mesons in QGP, R. Sharma, I. Vitev & B-W Zhang 0904.0032v1 [hep-ph]

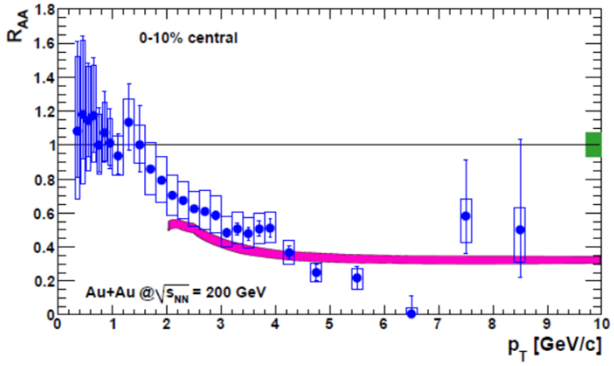

FIG. 41: (Color online) R_{AuAu} in 0–10% centrality class compared with a collisional dissociation model [78] (band) in Au+Au collisions.

The weak to strong axis for HQ

"Naive" pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

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"Optimized" pQCD

Running α_s (Peshier, Gossiaux & Aichelin, Uphoff & Greiner)

Distorsion (
fragmentat
existence (
R. Sharma
0904.0032

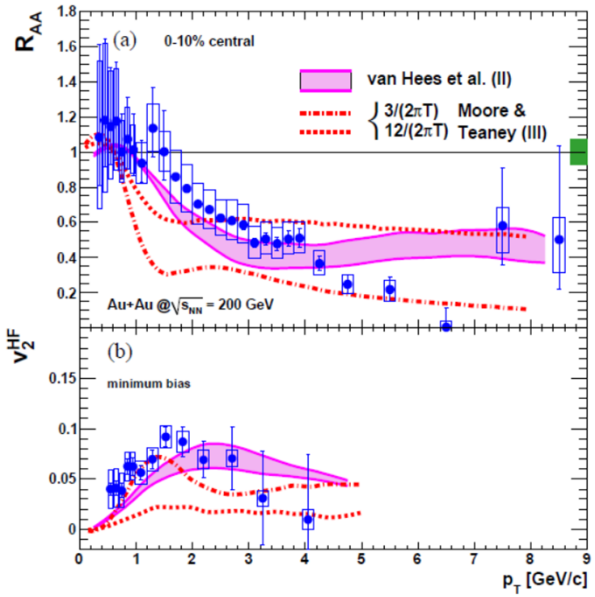
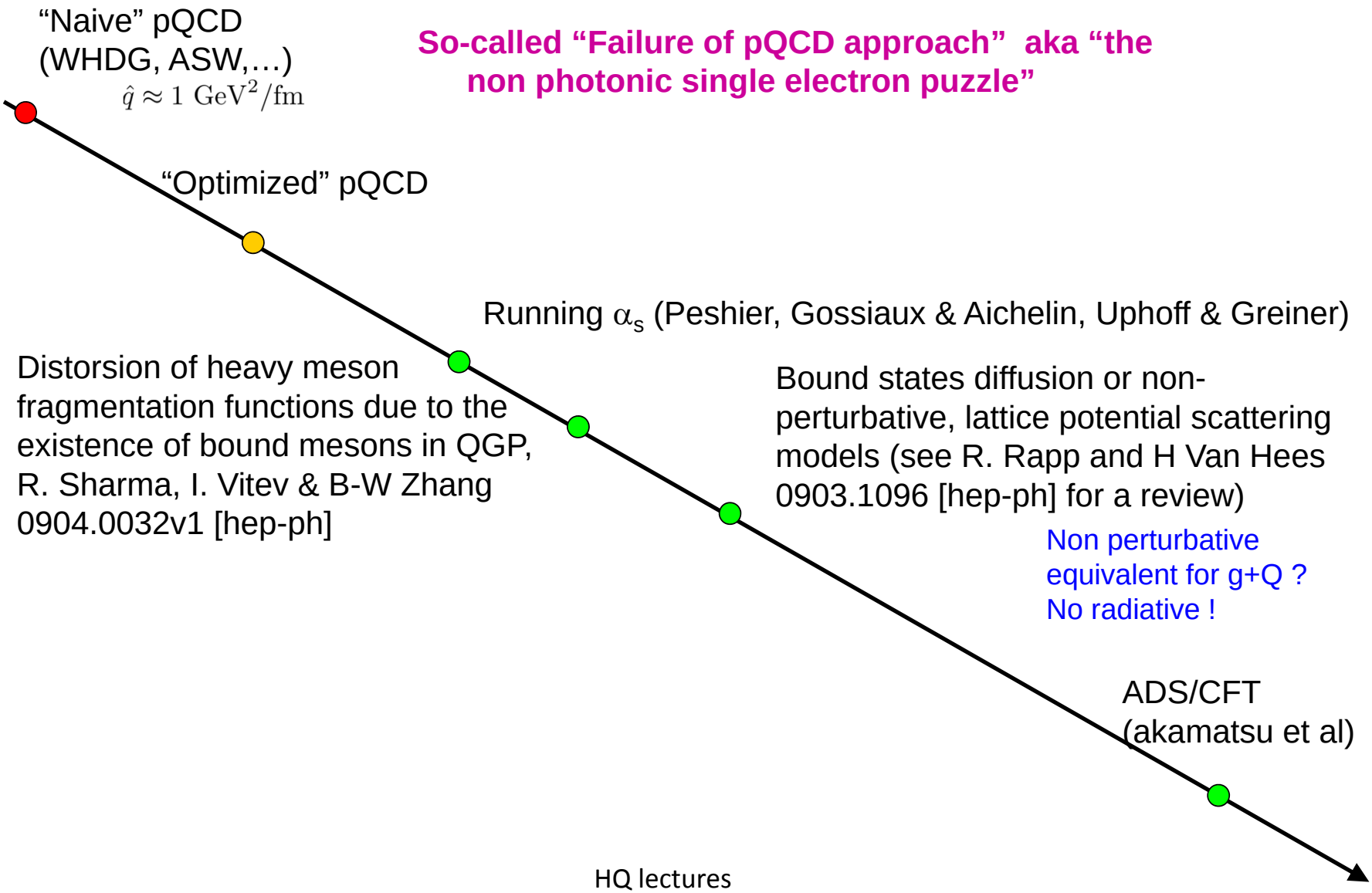


FIG. 40: (Color online) Comparison of Langevin-based models from [74–76] to the heavy flavor electron R_{AuAu} for 0-10% centrality and v_2 for minimum-bias collisions.

Bound states diffusion or non-perturbative, lattice potential scattering models (see R. Rapp and H Van Hees 0903.1096 [hep-ph] for a review)

Non perturbative equivalent for g+Q ?
No radiative !

The weak to strong axis for HQ



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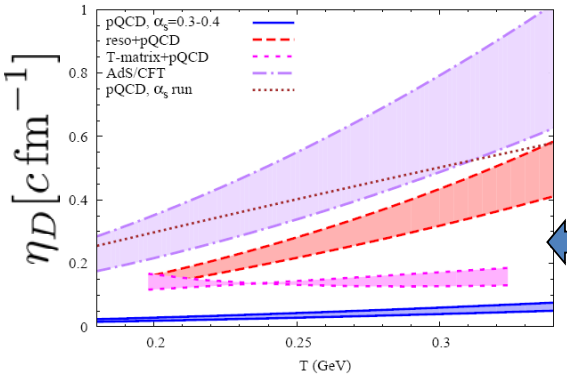

from Rapp & Van Hees 0903.1096

Lesson n°1 (pre LHC):

Several models containing either non perturbative features or tunable parameters are able to reproduce the HQ data, but many questions remain… and how to reconcile them all stays a challenge

ADS/CFT (akamatsu et al)

The LHC Era: 2010 -> Now

- Huge data from LHC constraining the models (at high pT as well as in the b sector)
- Constrains from the fundamental theory : lQCD estimates
- A last class of model: Quasi Particle Model
- Alternate observables (correlations)
- The way towards more collective work in the theory community
- HQ-jets
- HQ in small systems
- ….

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Quasi particle models (f.i DQPM)

- Nonperturbative 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)

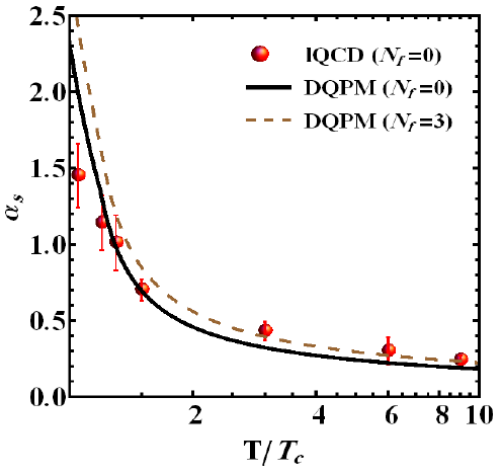
- Coupling between the effective DOF is then taken as α_s(T)=> Relaxation rates larger then in pQCD for all T relevant for QGP, slightly smaller than the ones from TAMU

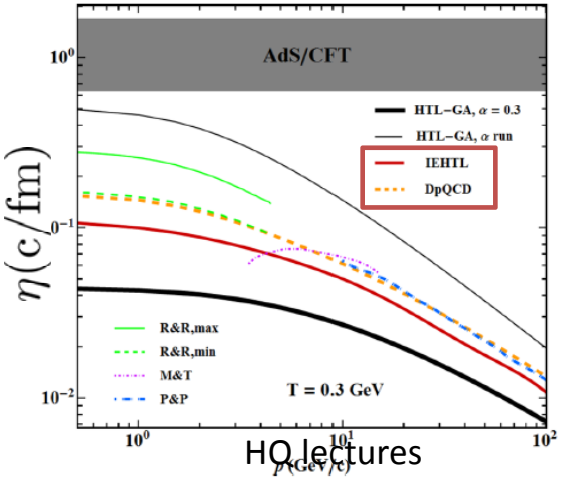
H. Berrehrah et al, PHYSICAL REVIEW C 90, 064906 (2014)

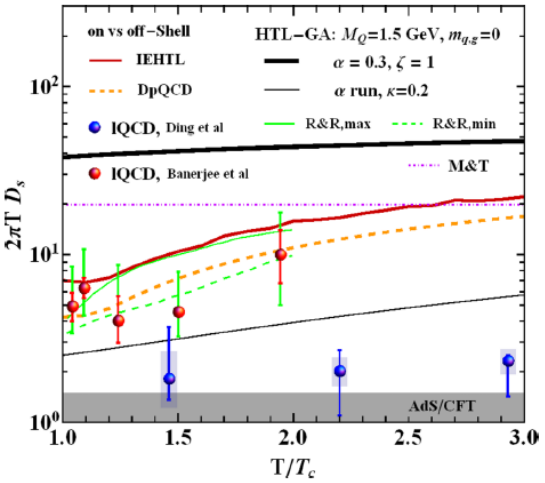
- Implemented for HF dynamics in e.g. PHSD (full off-shell, off-equilirium transport).

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

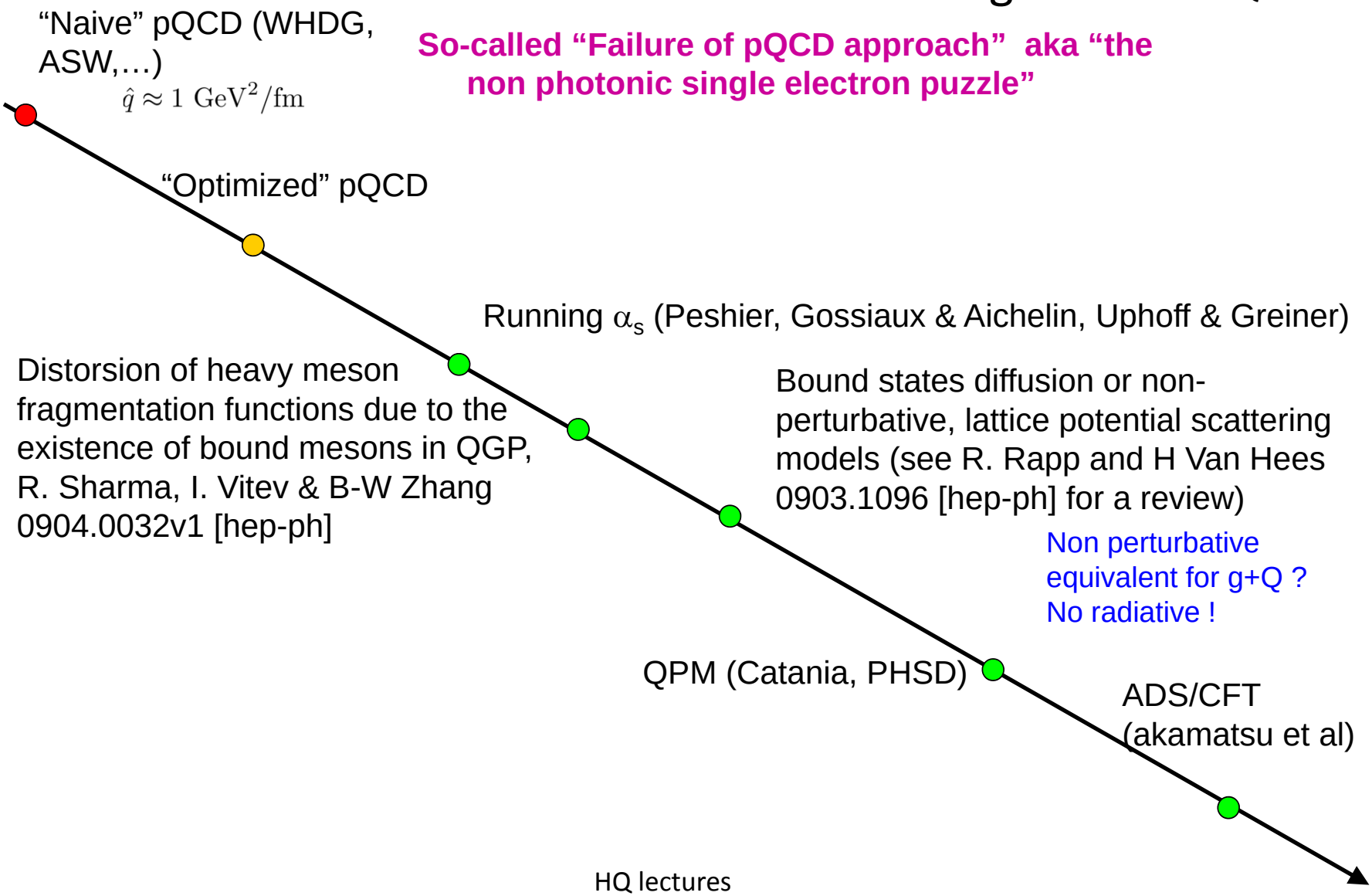
But also CATANIA







The weak to strong axis for HQ



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- HQ-jets
- HQ in small systems
- ….

Transport coefficients at low momentum $p \approx m_Q$

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

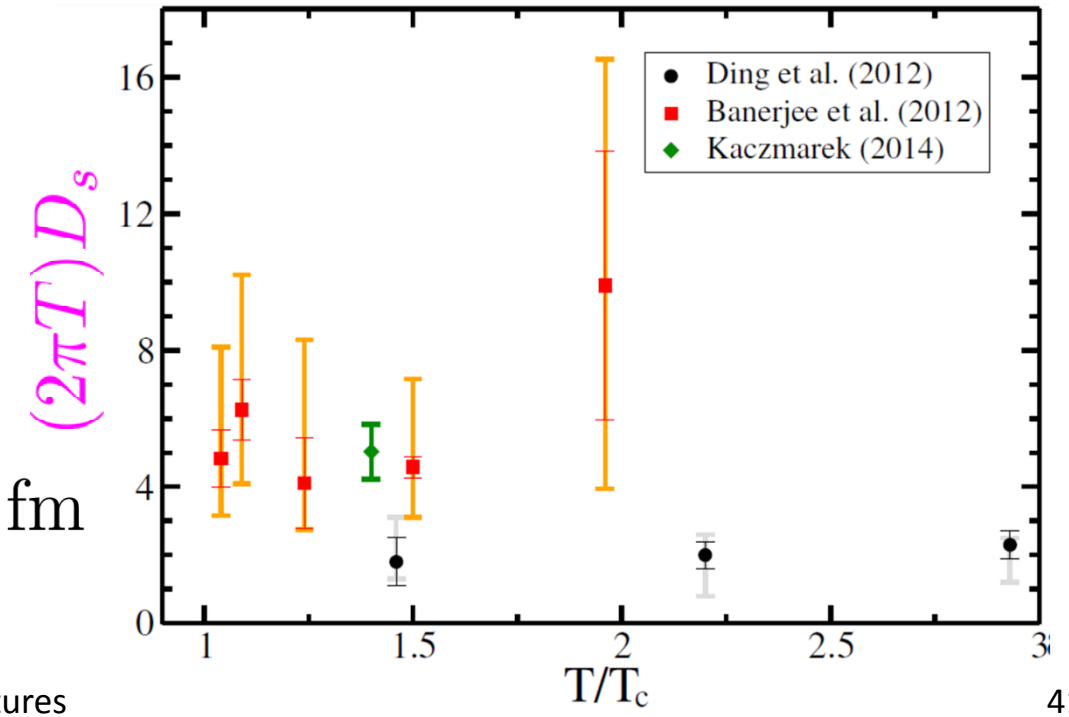
$$\langle r^2(t)\rangle = 2dD_s t$$

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

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

lQCD results

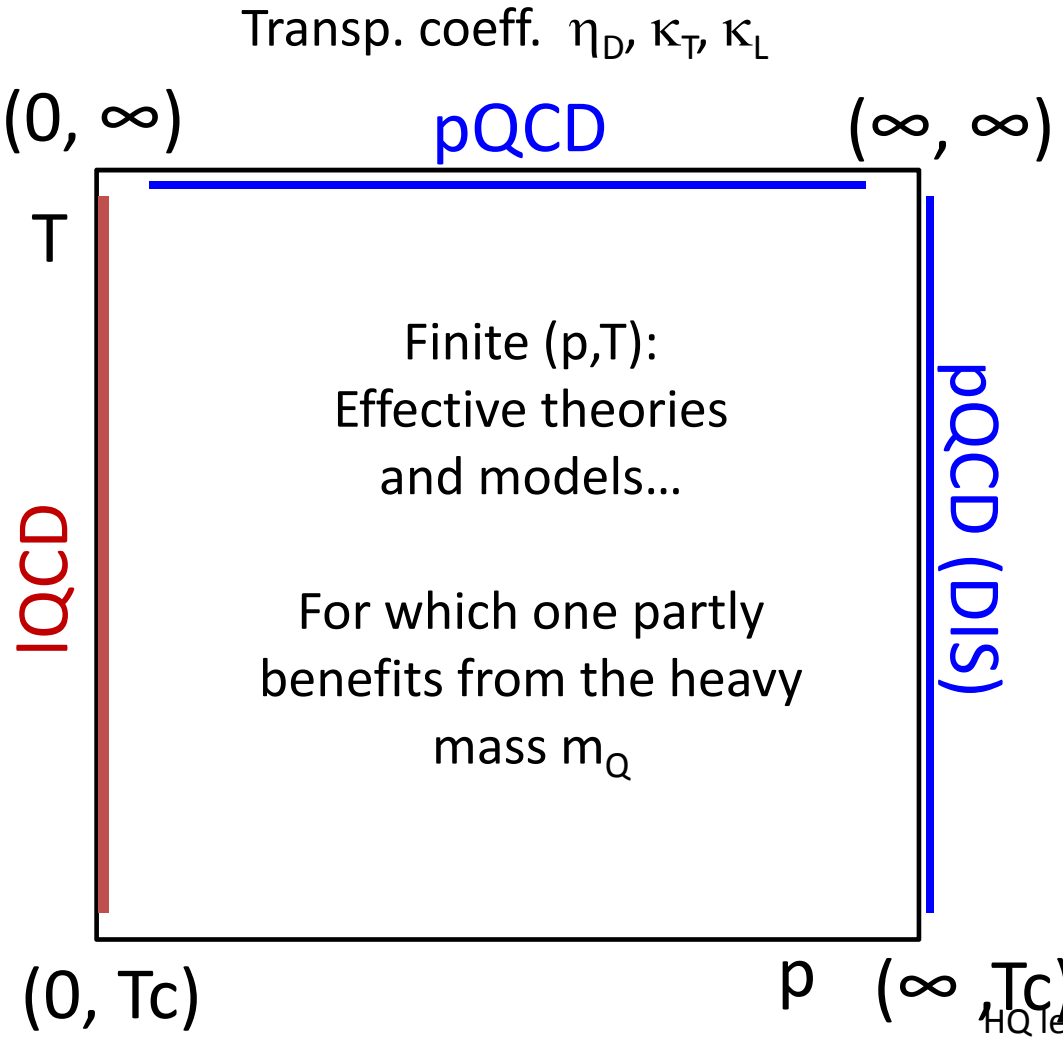
The sole direct rigorous calculation of the transport coeff to my knowledge

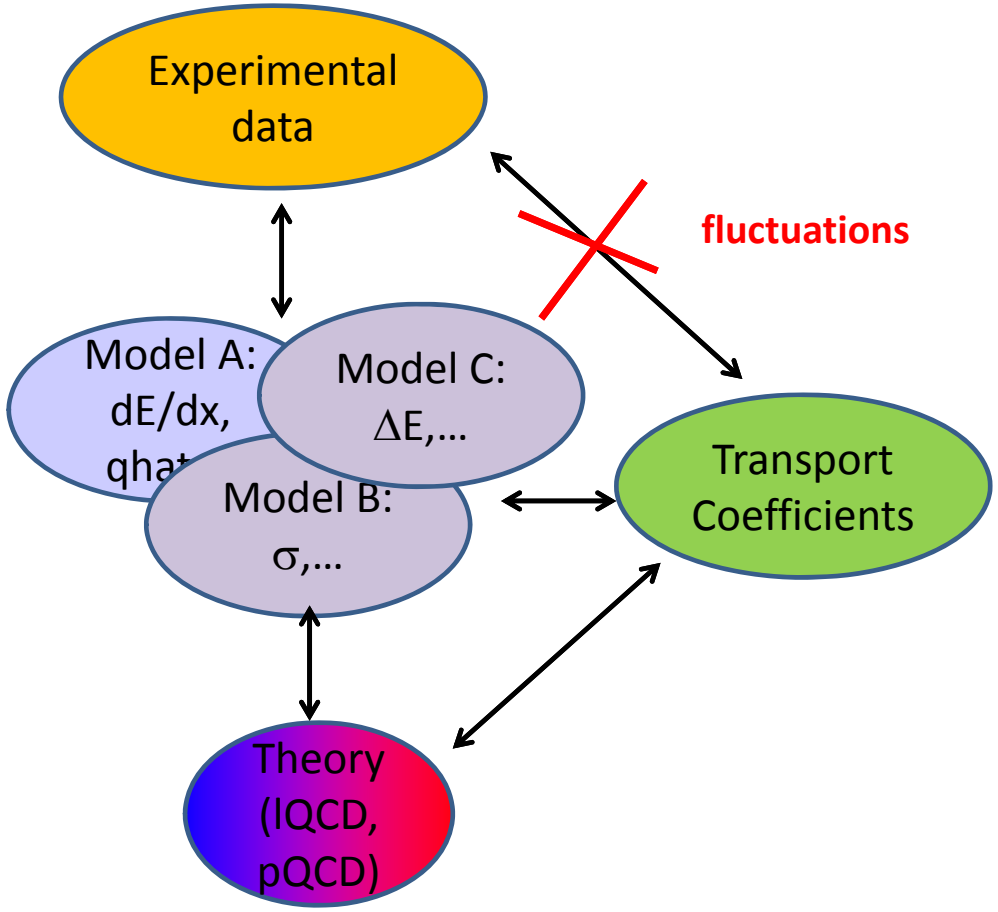


$$\tau_{\rm relax}(T_c) \approx m_Q[\text{GeV}] \times (3 \pm 1.5)\ \text{fm}$$

For b: Indeed a hard probe !

Lanscape of HF theory and modeling in URHIC

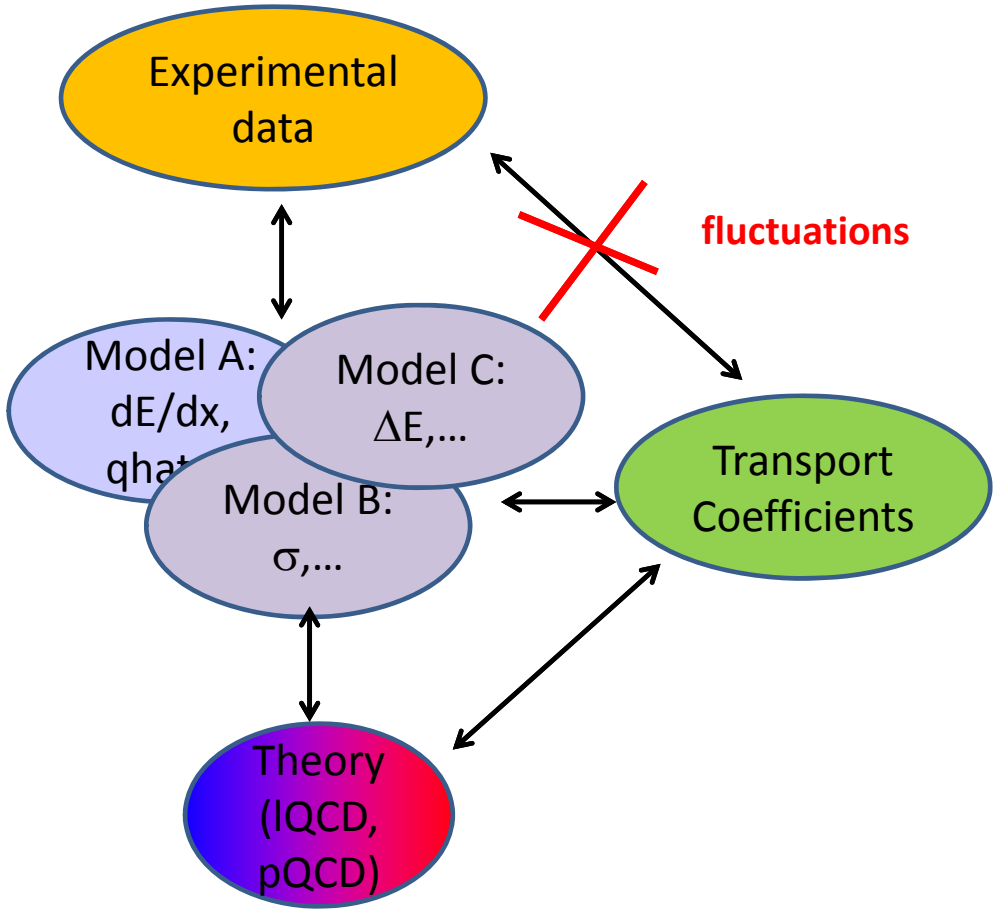




Today Stakes and Motivation

- Very subttle interplay between fundamental theory and experimental data to build and calibrate / constrain the models in order to better understand HF – QGP interaction (including QGP constituents)
- Then maybe one day: probing the bulk !
- On a more phenomenological and data driven level: Are we able to constrain / extract the in – medium transp. coefficients with a « reasonnable » precision ?
  - => What is the impact of various « extra » ingredients ?
  - Do we agree on what « reasonnable » means (x 2 ? 50% ?, 10% ?)
- Need to intercompare the approaches.

Big motivations for this talk



Major goal for the future:
from indication to real quantification!

Transport coefficients: theory vs models

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

$$\langle r^2(t)\rangle = 2dD_s t$$

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

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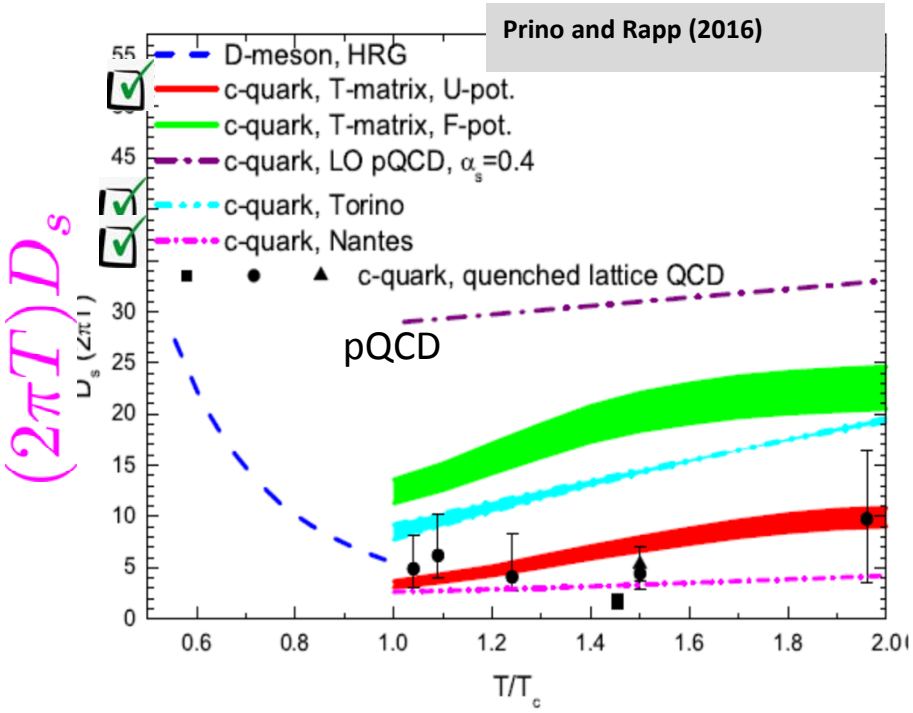
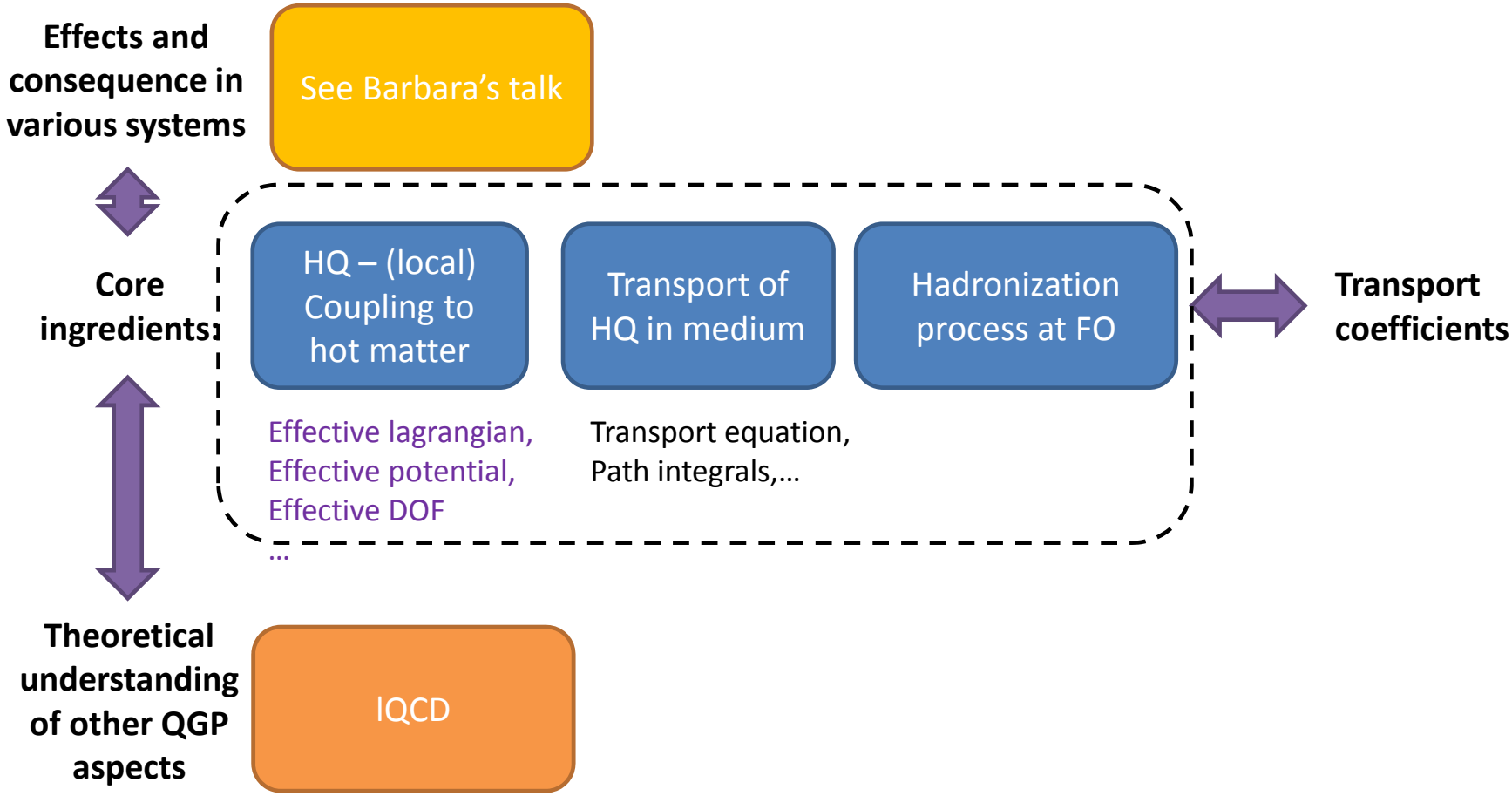
Most of the models which reproduce exp. observables (☑) are compatible with lQCD constrains

Prino and Rapp (2016)



A bit of structure

- HQ propagation in QM & URHIC…



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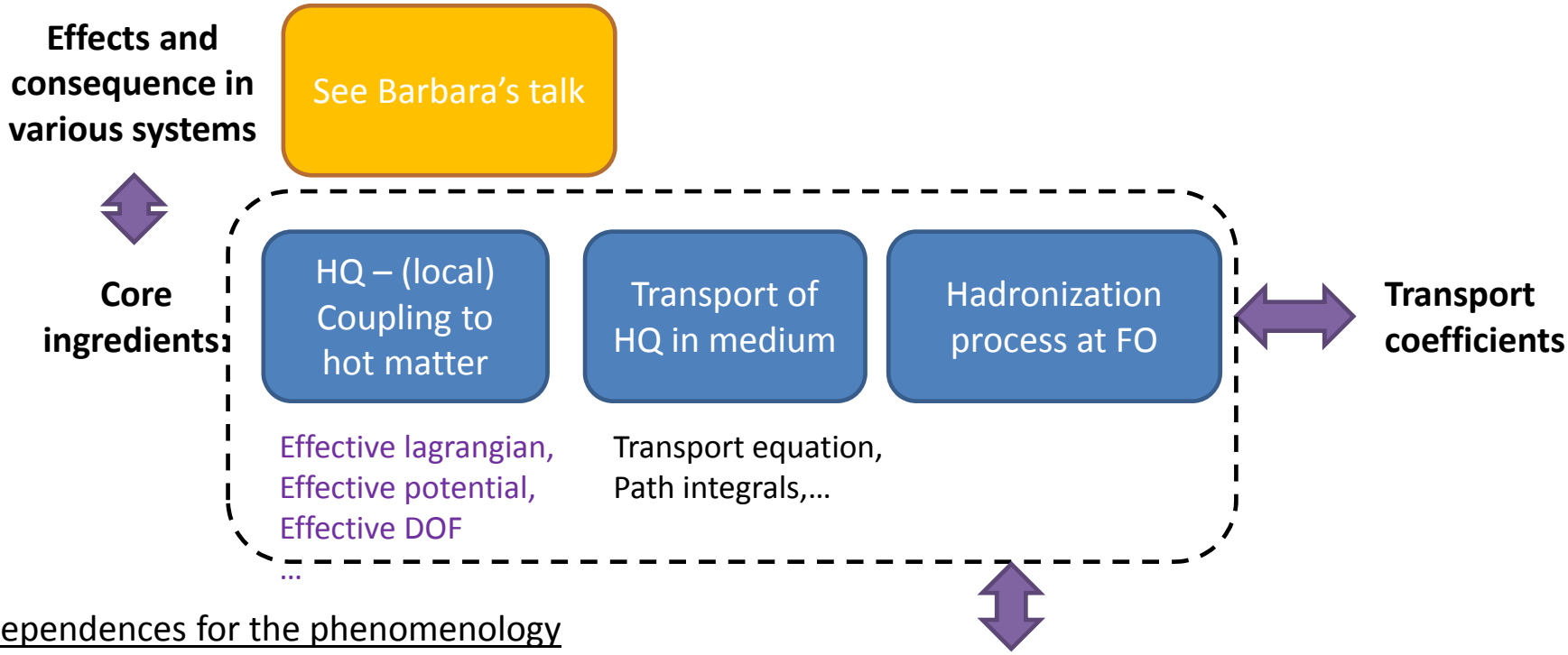
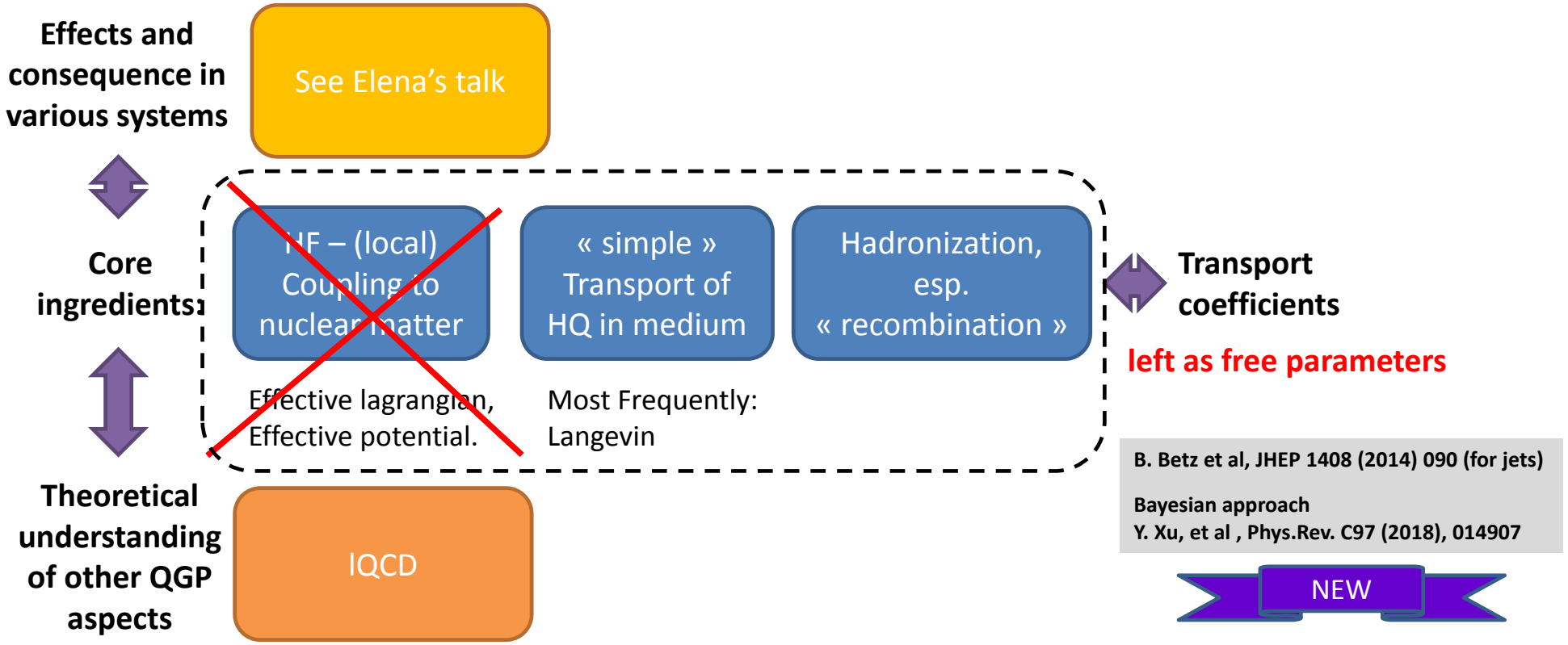


4 important dependences for the phenomenology

- Energy dependence : the saturation at large E explain the restoration -> 1 at large p_T
- Mass dependence => less thermalization for b quarks
- T dependence weigths differently the initial stage and the late evolution (for which flows have developped)
- Path length dependence => makes it more transparent to the radiative in small systems ($\Delta E_{rad} \propto L^2$)

A bit of structure

- No Model approach



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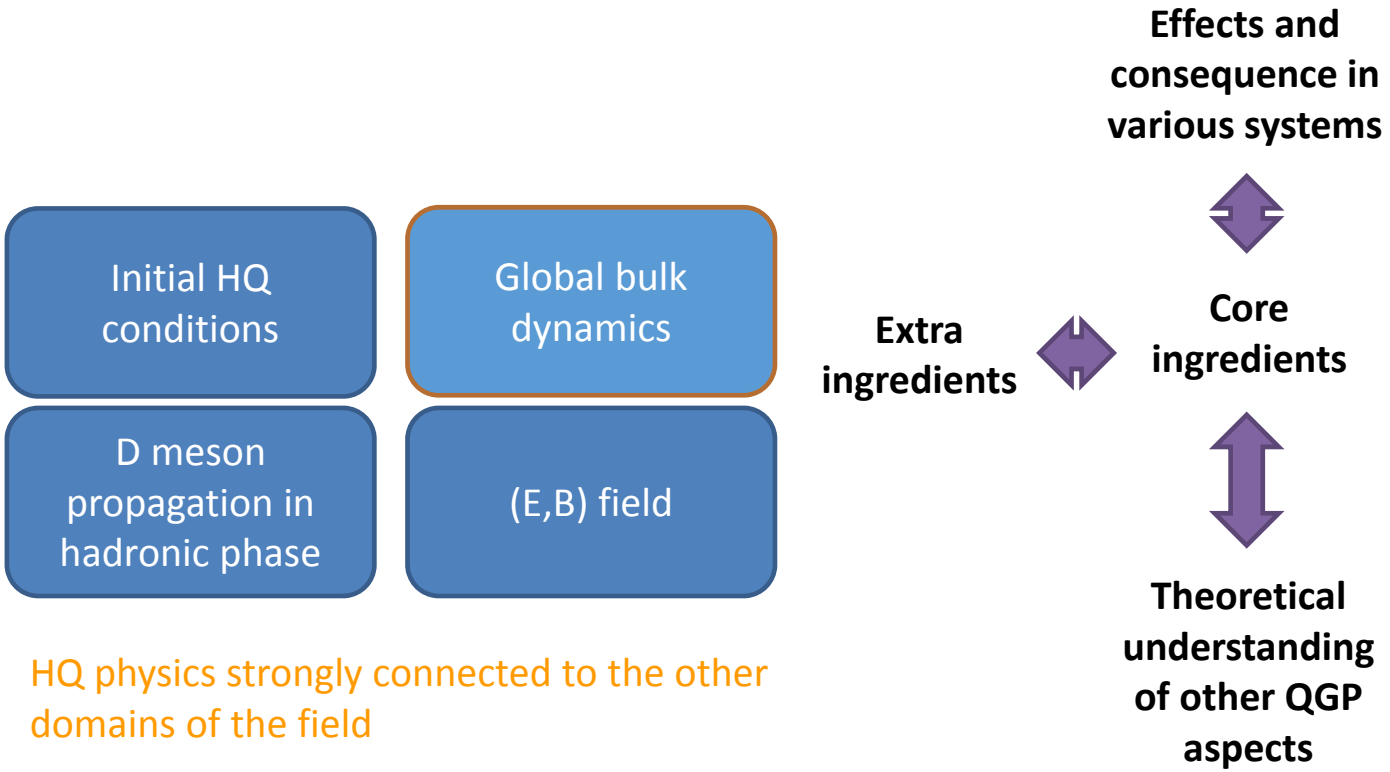


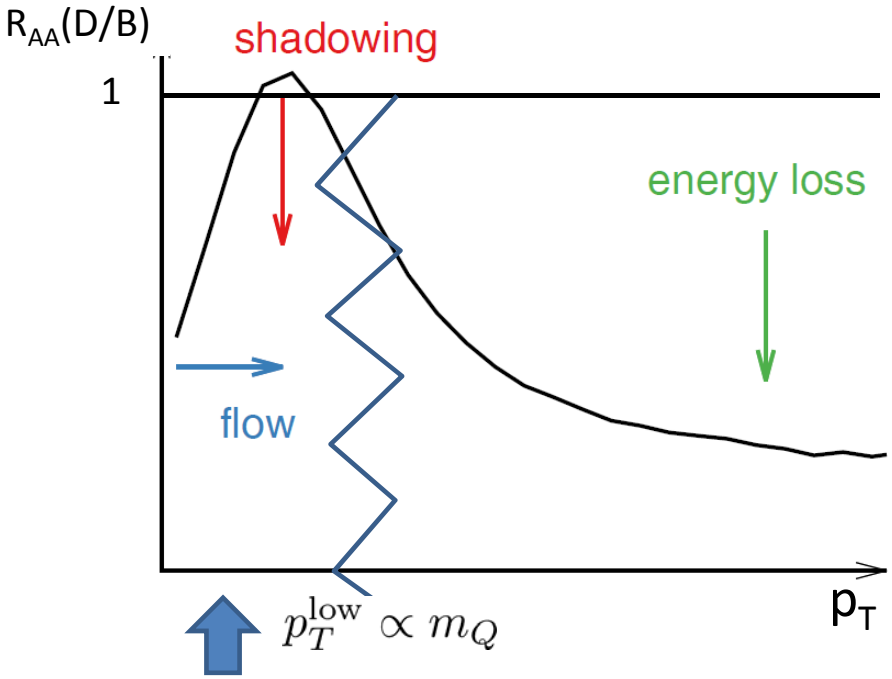
Models & Effective Theories

	elastic	Elastic + radiative	radiative	Other
Transport coefficient based (LV,…)	TAMU POWLANG HTL Catania LV	Duke	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	Djordjevic et al MC@sHQ el + rad BAMPS CUJET3 HYDJET++ Abir and Mustafa LBL-CCNU VNI/BMS *LIDO (see talk W. Ke)*	$SCET_{G,M}$	

Red: Transport models

Basic Consequences of HQ interaction with 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*

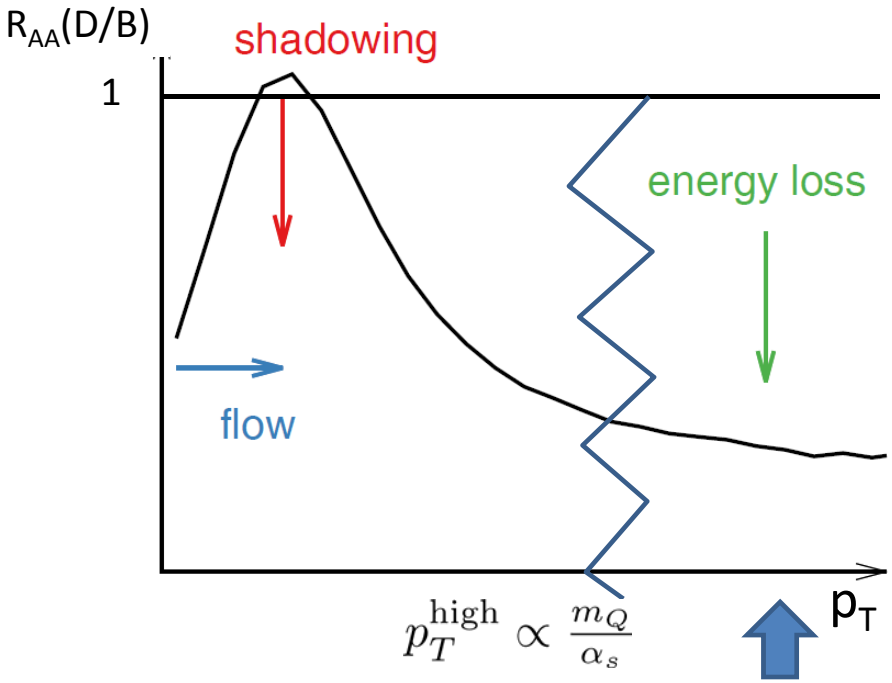
shadowing: due to *initial state nuclear effects*

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



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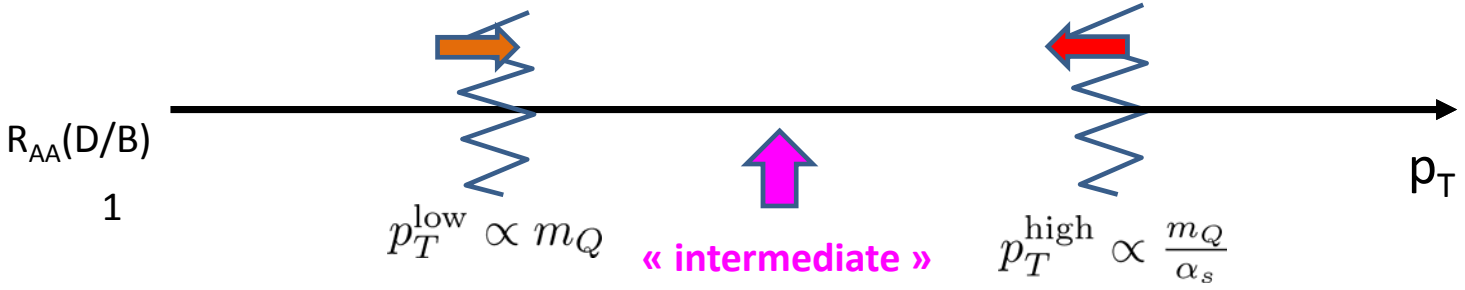
shadowing: due to *initial state nuclear effects*

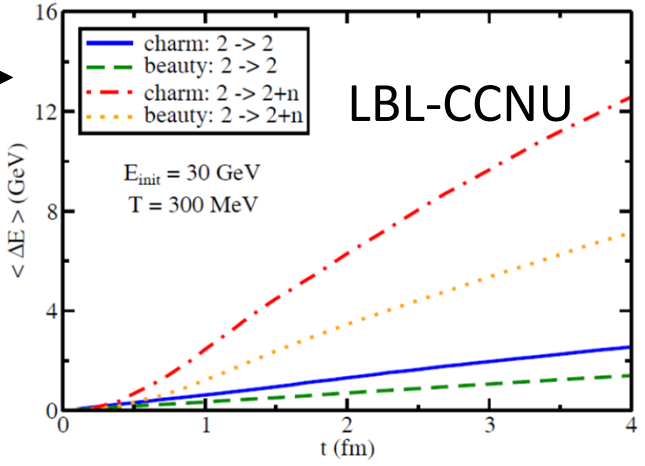
Quenching & energy loss: due to
- elastic and *inelastic* scatterings
- *opacity of the medium*

- 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 ($m_Q << p_T$)

Basic Consequences of HQ interaction with 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 $\hat{e}_2$



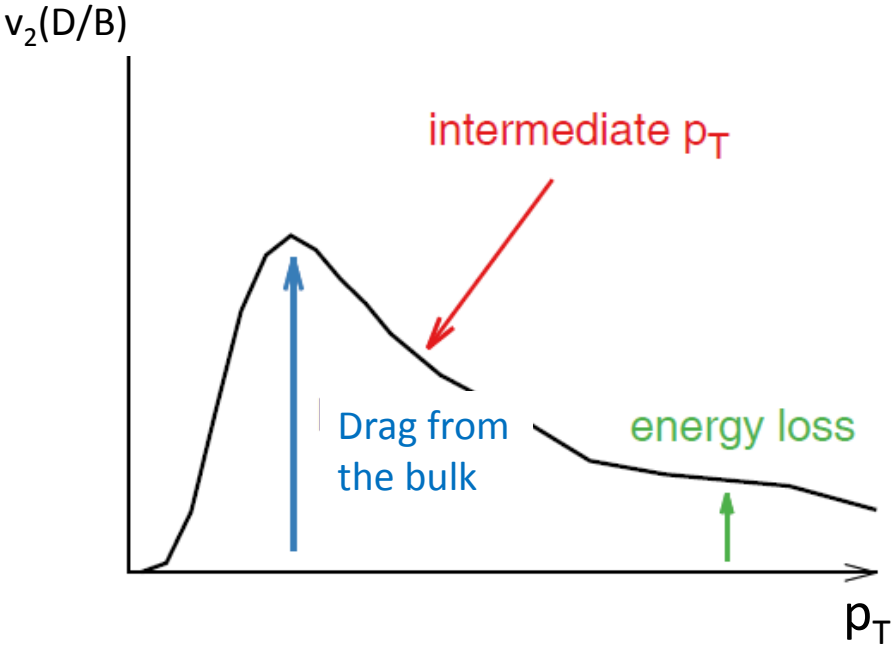
S. Cao et al, Phys. Rev. C 94, 014909 (2016)

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

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

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

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.

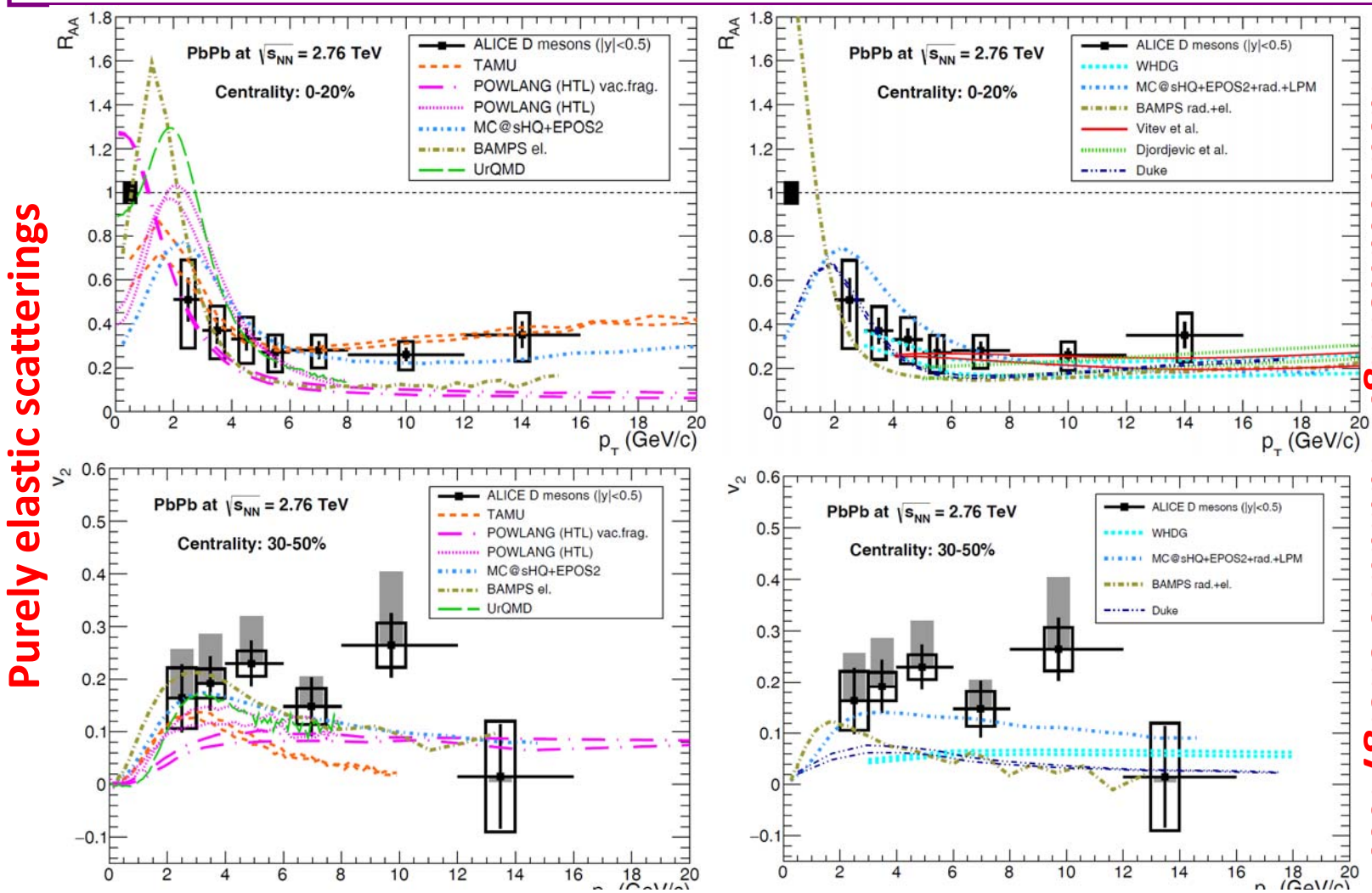
!!! Alternative pointed out recently within transport model (AMPT & MPC) study: so-called « escape mechanim » characterized by a large v_2 component stemming from $N_{coll} \approx 1$

L. He et al, Physics Letters B753 (2016) 506

2 Important remarks:

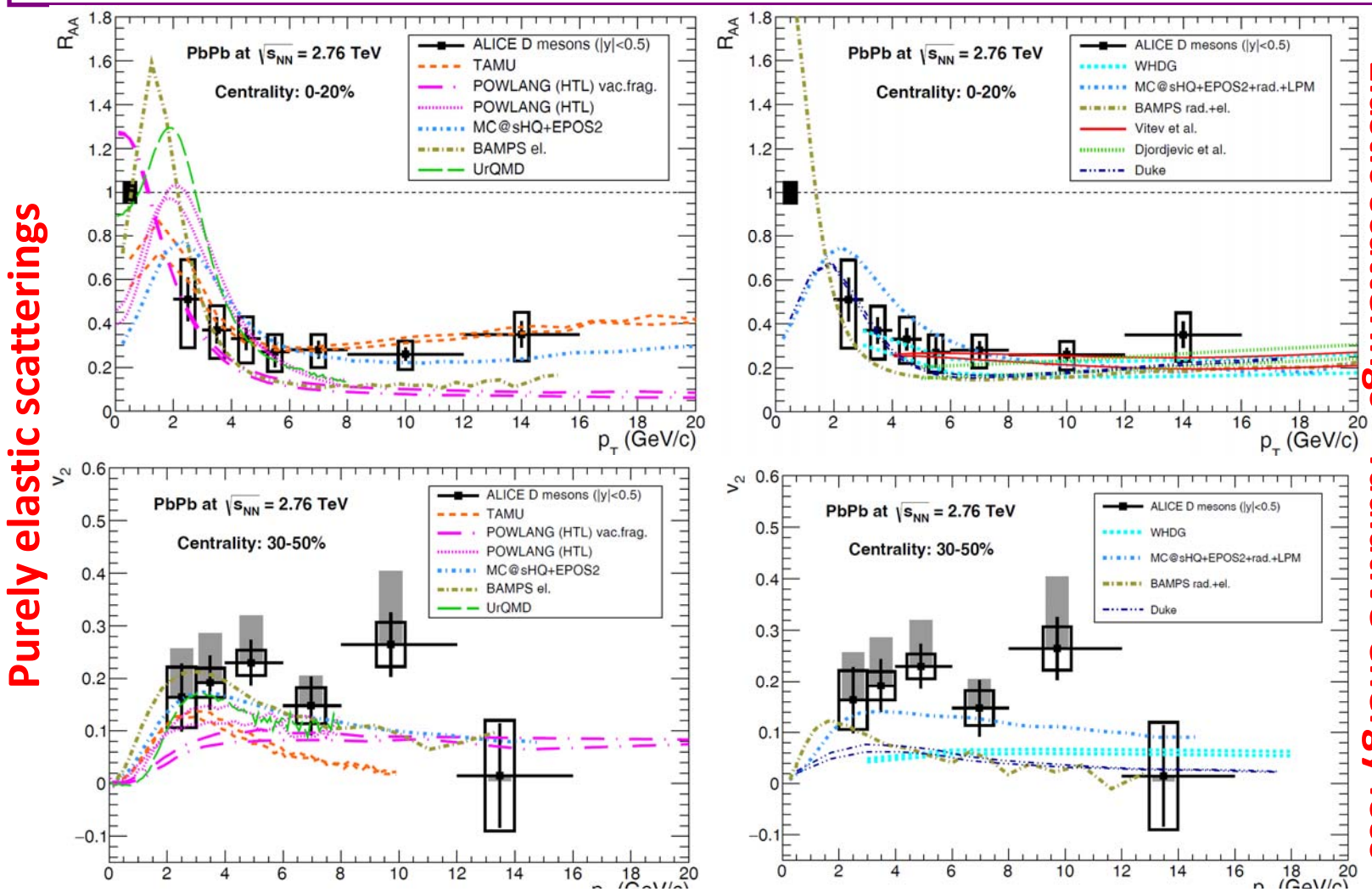
- Any energy loss model, even the roughest one, will generate these typical structures in the R_{AA} and the v_2. Getting a correct **quantitative** agreement is much more involved.
- Quantitative predictions also depends on those « extra ingredients »

Models vs DATA at LHC (Sapore Gravis Report compilation)



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

Models vs DATA at LHC (Sapore Gravis Report compilation)

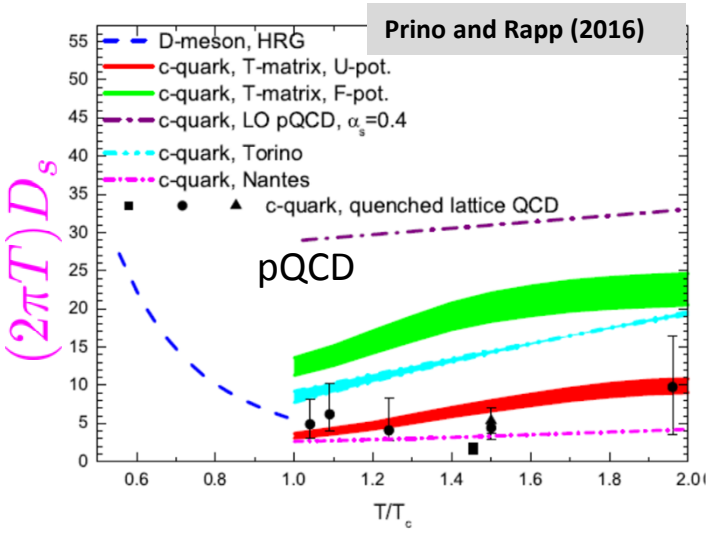


Purely elastic scatterings

Elastic scatterings + radiative energy loss

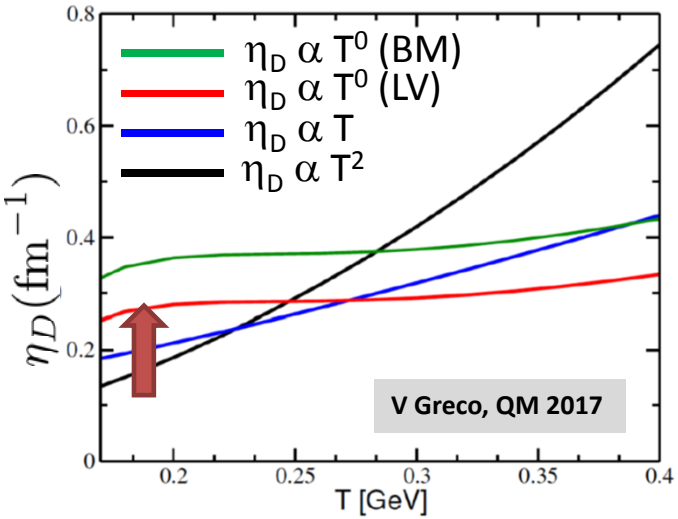
Some advocated tension between R_{AA} and v_2

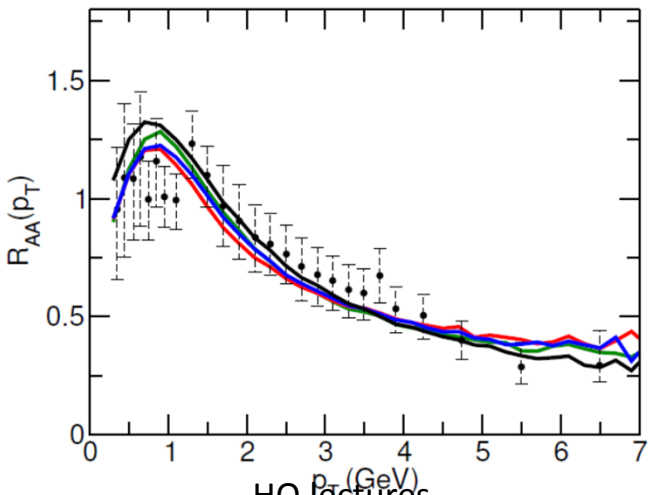
Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail



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

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



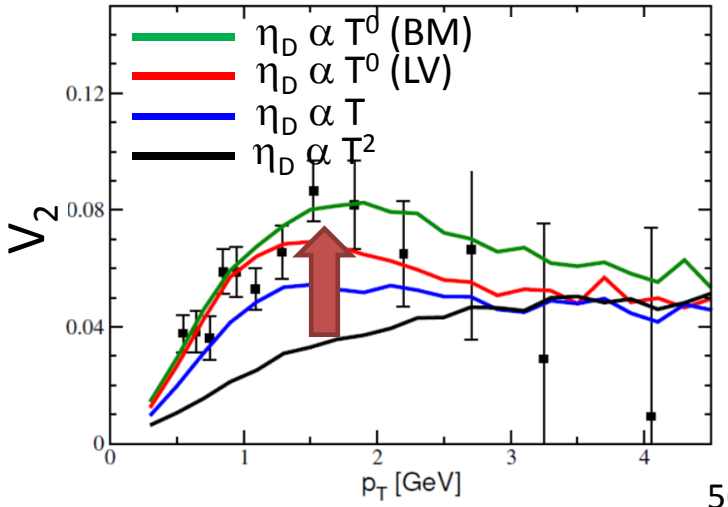


η_D α T^2: pQCD (fixed α_s), AdS/CFT

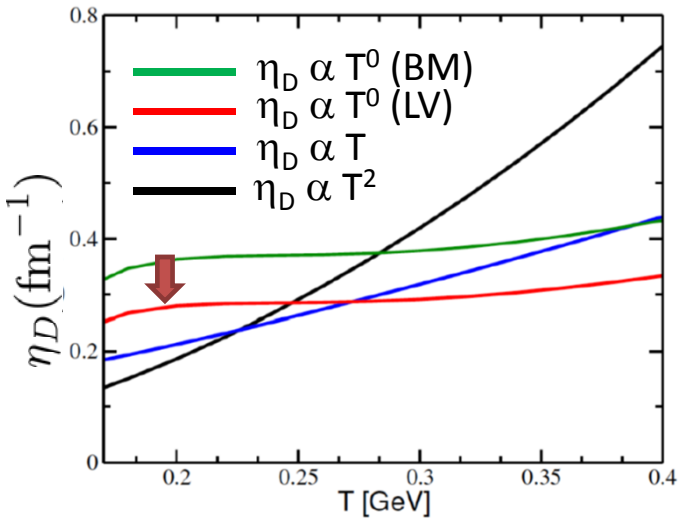
η_D α T: pQCD (running α_s)

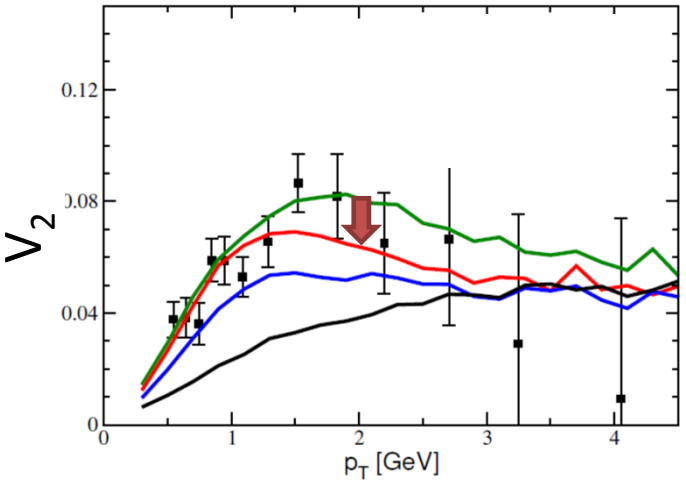
η_D α T^0: QPM, DQPM, U potential (TAMU)

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



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





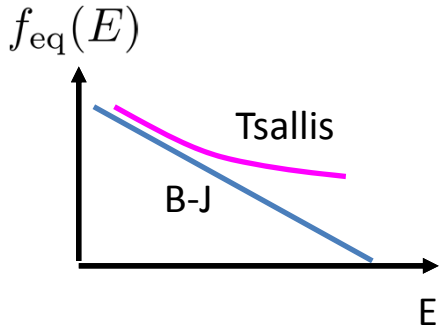
Extra increase from LV => Boltzmann dynamics

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

In models considering γ α T^0 like QPM, DQPM, TAMU: microscopic dσ/dθ 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).

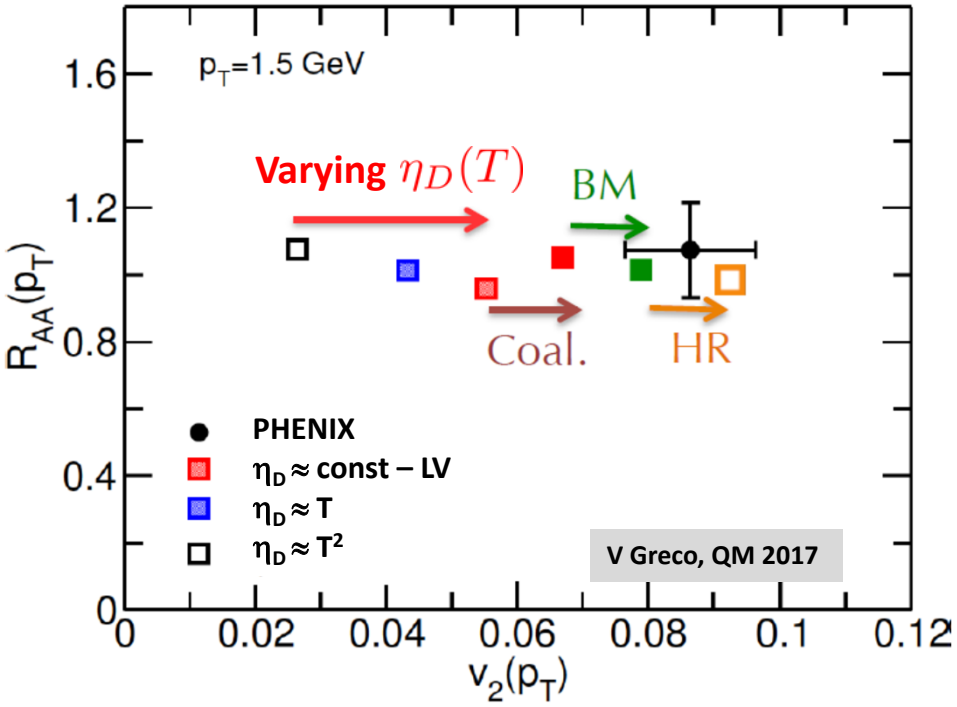
=> For dynamical evolution, one needs to cranck down the interaction and the FP coefficients in order to reproduced a « given » R_{AA}



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

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

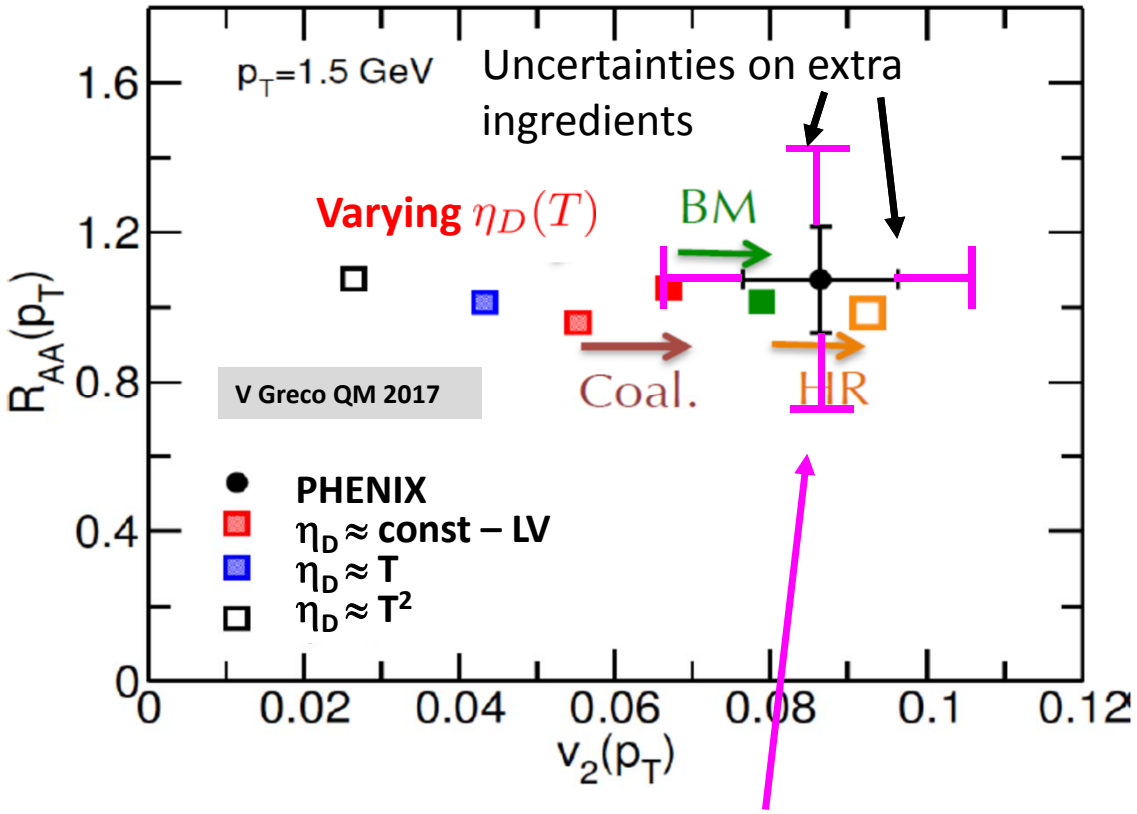
Tension between R_{AA} and v_2 (at low p_T): the Catania Cocktail

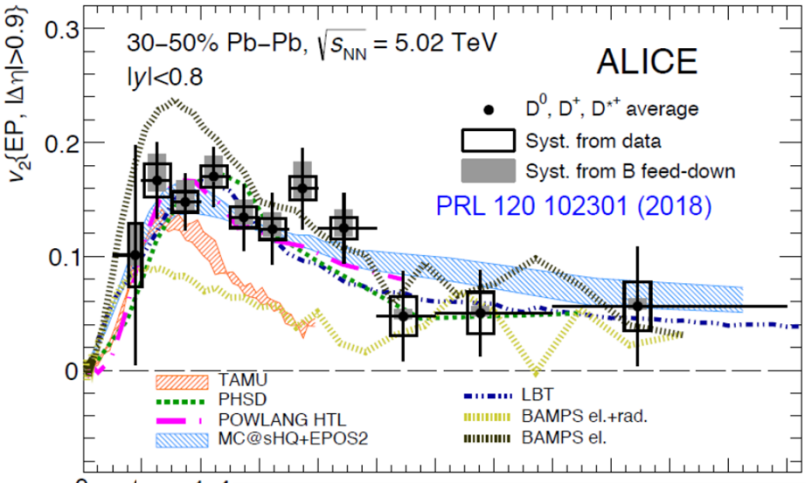


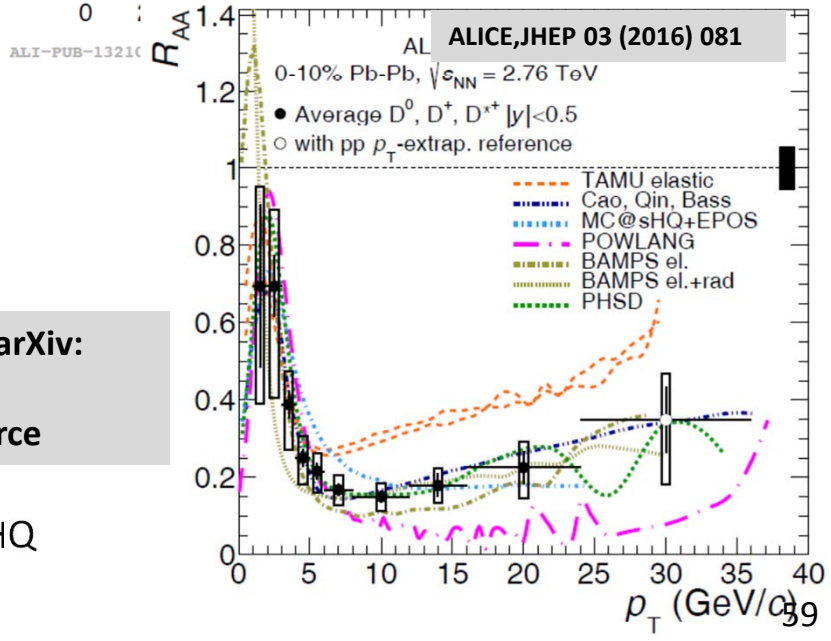
Nice guideline but need:

- 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.

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







- Extra uncertainties stemming from extra ingredients, analysis in

R. Rapp et al, arXiv: 1803.03824
EMMI Task Force

- Probably one of the reasons why some models – like EPOS2+MC@sHQ – with NOT (const. η_D) can cope both with R_{AA} and v_2.

Data driven extraction of transport coefficients

NEW

Y. Xu et al
arXiv:1710.00807v1

« Minimal model approach » : Bayesian analysis by the Duke group

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g \leftarrow \frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s P(x)\hat{q}_g}{\pi k_\perp^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2M^2}\right)^4$$

Higher twist

Usual Langevin $\langle \xi_i(t)\xi_j(t')\rangle = \kappa\delta_{ij}\delta(t-t')$ with $\kappa = \frac{2T^2}{D_s}$

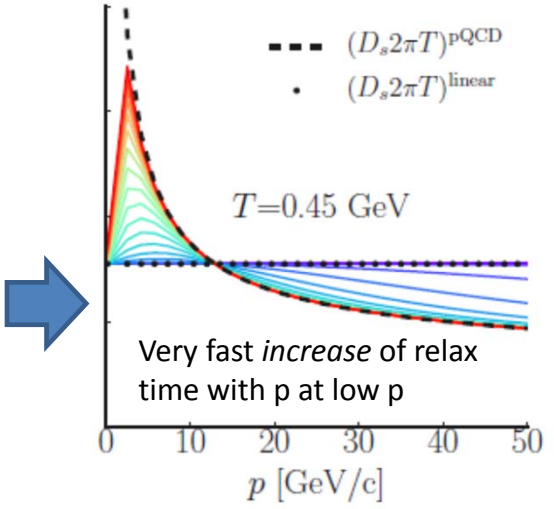
+ coal / frag hadronization and hadronic rescattering

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

$$(D_s 2\pi T)^{\rm pQCD} = 8\pi/(\hat{q}/T^3)$$

$$(D_s 2\pi T)^{\rm linear} = \alpha\cdot(1+\beta(T/T_c - 1))$$

Encodes possible Non Perturbative Effects around T_c through parameters α (magnitude), β (slope) and γ (inverse momentum range of NP effects)



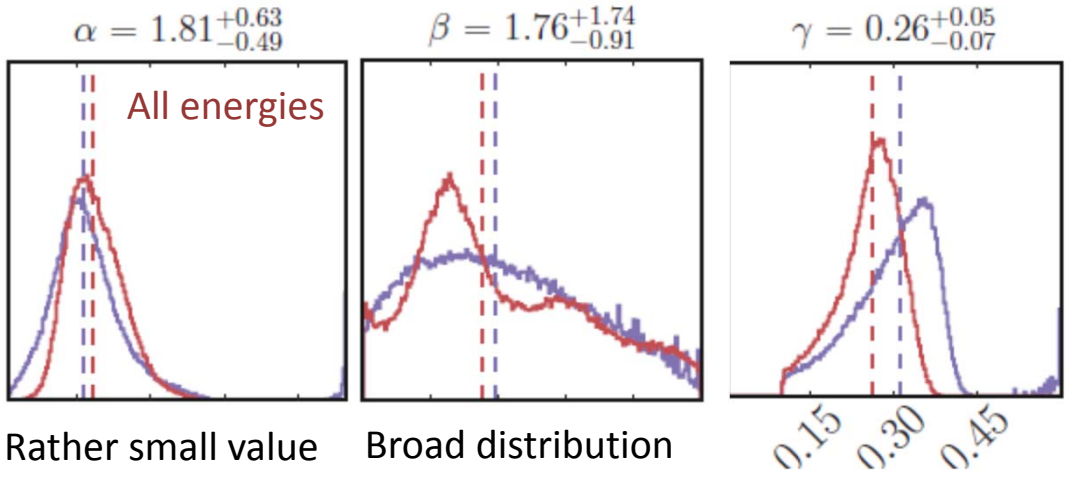
Duke “Bayesian approach”

- Choice of 60 « prior » for which the physical observabes are calculated
- Gaussian emulator to build a fast surrogate of physics
- Random walk throughout parameter space, with acceptance and rejection according to likelihood (with all uncertainties assumed to be uncorrelated).

Let the data speak

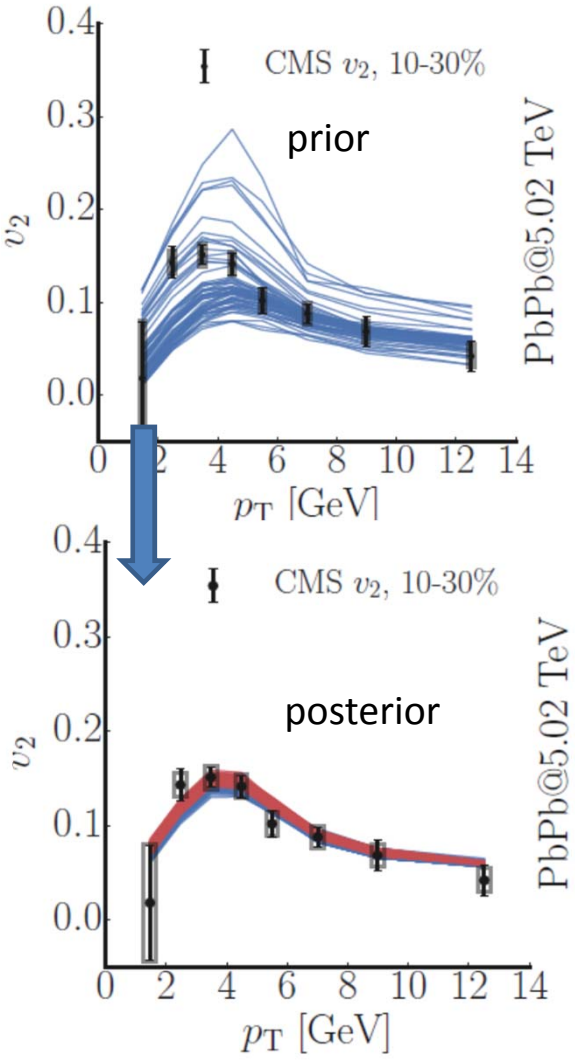
$$(D_s 2\pi T)^{\text{linear}} = \alpha \cdot (1 + \beta(T/T_c - 1))$$

RESULTS

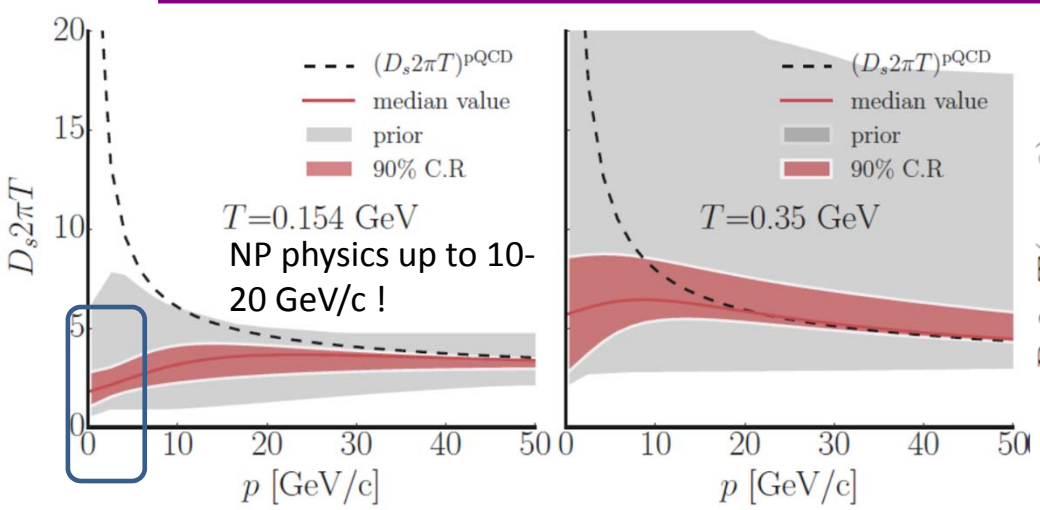


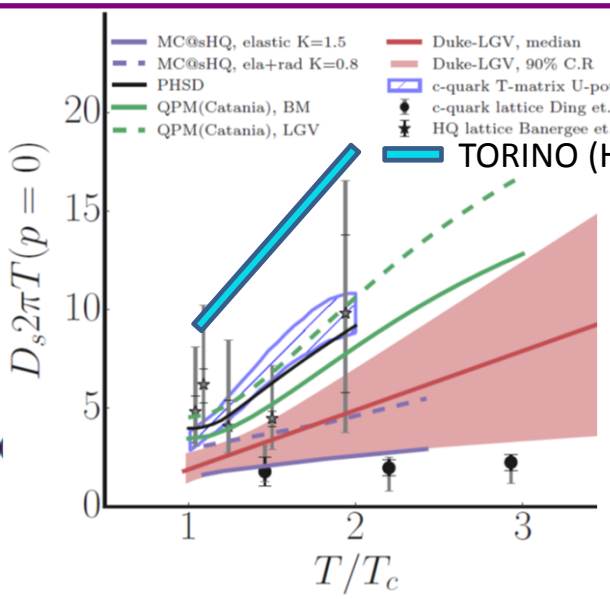
Rather small value => strong coupling !

Broad distribution



Duke "Bayesian approach" vs models





Mild lin. increase of $2\pi D_s T$… ⇔ physics beyond pQCD.

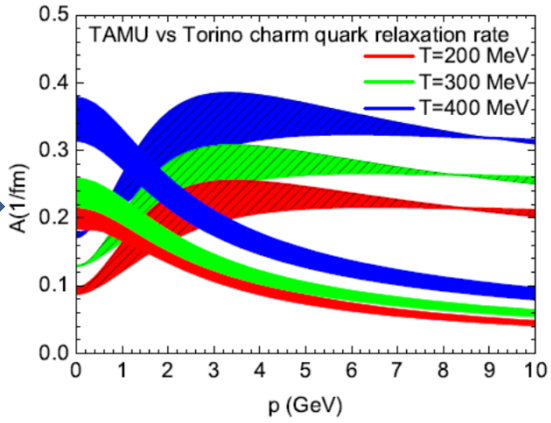
See as well analysis in the LBL-CCNU model with similar conclusions

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

All together (lQCD, Bayesian analysis and most recent models) make a strong case for NP physics « around T_c » and at «low» p_T … needs to be precised in the future

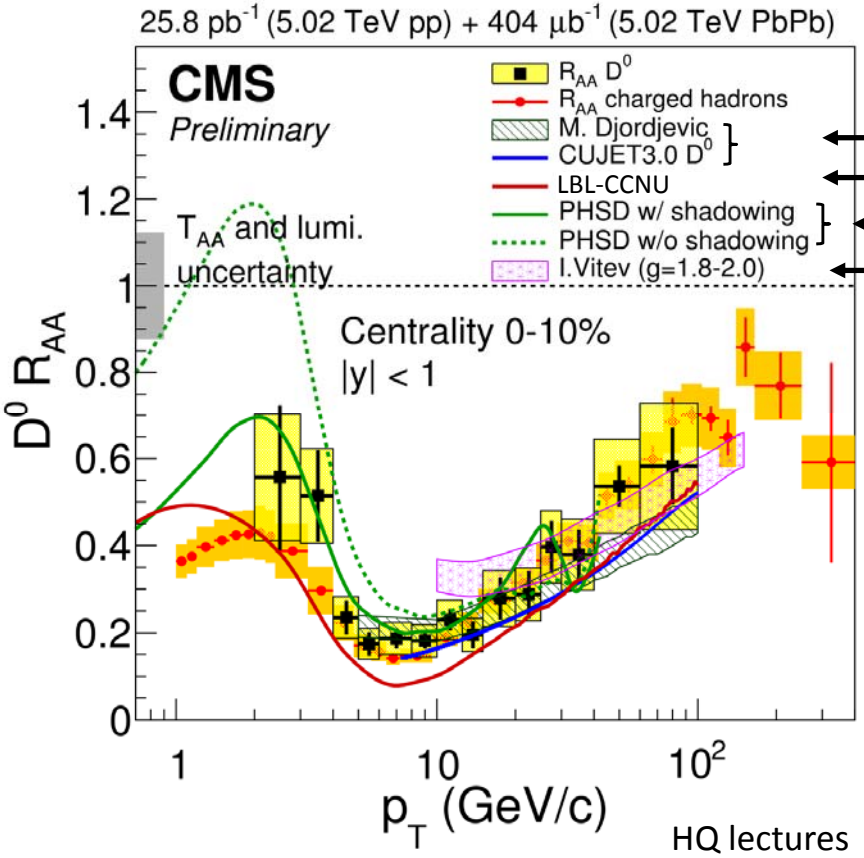
- Does not mean that all models inhold the same physics…
- D_s (p=0) does not represent the full physics (different momentum dependences)
- D_s (finite p) in Duke's el + rad approach should not be compared to the same quantity in purely elastic models (additional contribution to energy loss due to the rad. part)

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



Status of high p_T HQ

Over the past years, steady development of several sophisticated pQCD-based radiative Energy loss schemes in order to cope with the radiation of energetic partons: BDMPSZ, AMY, higher twist, DGLV, SCET… some of them leading to successful comparison with the data in their numerical implementation…



DGLV (el.+ radiative)

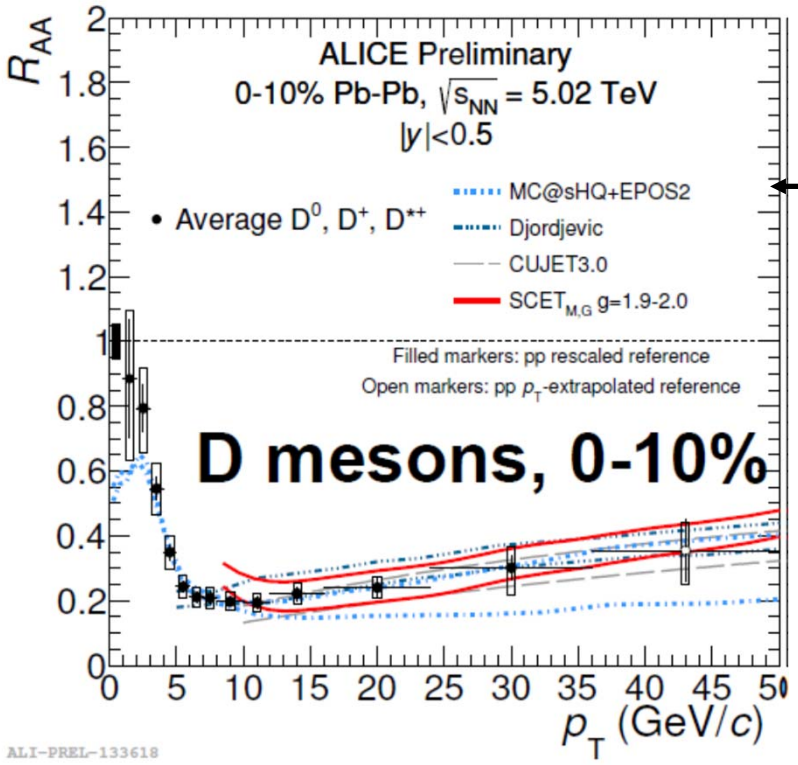
Higher Twist (el.+ radiative)

Pure elastic !

SCET$_G$ (Pure radiative)

Status of high p_T HQ

Over the past years, steady development of several sophisticated pQCD-based radiative Energy loss schemes in order to cope with the radiation of energetic partons: BDMPSZ, AMY, higher twist, DGLV, SCET… some of them leading to successful comparison with the data in their numerical implementation…



← BDMPS (« infinite » path length regime)

Although some « extra ingredients » differ…

pQCD e-loss MODELS	Collisional energy loss	Radiative energy loss	Coalescence	Hydro	nPDF
CUJET3.0 JHEP 02 (2016) 169	✔	✔	✘	✘	✘
Djordjevic PRC 92 (2015) 024918	✔	✔	✘	✘	✔
MC@sHQ+EPOS PRC 89 (2014) 014905	✔	✔	✔	✔	✔
SCET JHEP 03 (2017) 146	✔	✔	✘	✘	✔

… Overall success of pQCD for describing the gluon radiation from a hot medium.

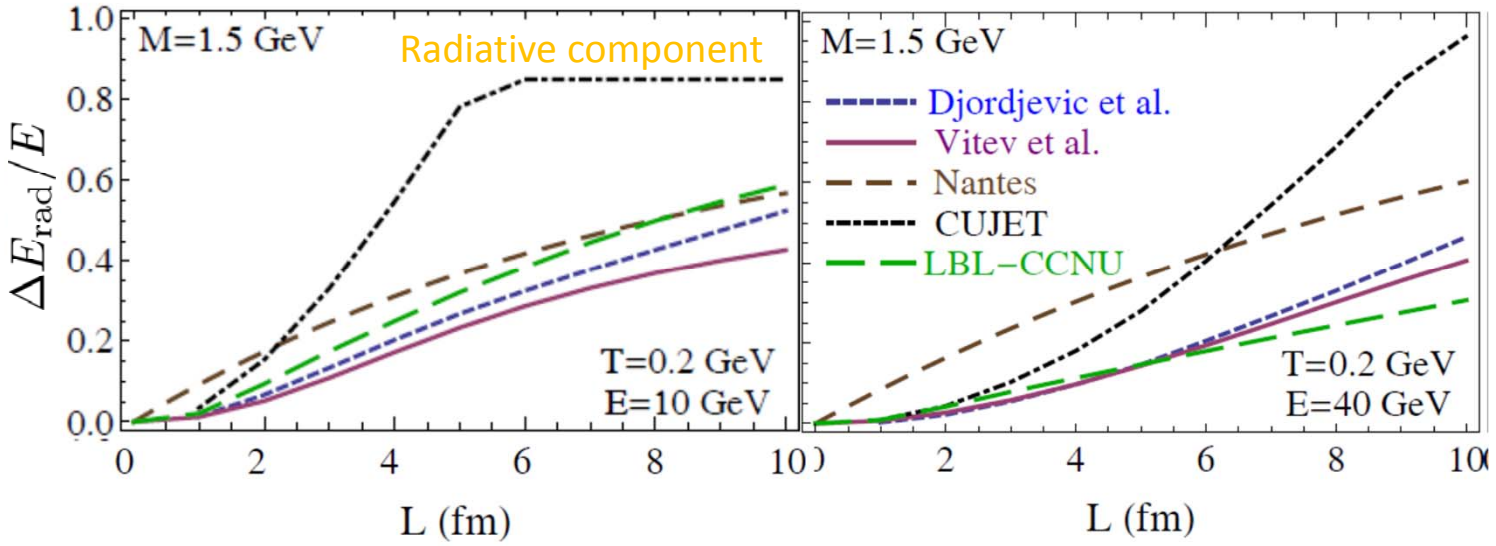
Beware : $\hat{q}$ is « just » an indirect result in some of those formalisms

Status of high p_T HQ: prospects

… Overall success of pQCD for describing the gluon radiation from a hot medium…. However, in a regime where m/p_T is small => The genuine mass ordering has still to be quantified and scrutinized more precisely between various approaches

Clear case for b-quark physics

Comparing some callibration curve for main approaches:



R. Rapp et al, arXiv: 1803.03824
EMMI Task Force

- Rather good agreement between Djordjevic ans $SCET_G$ (same α_s=), and also with LBL-CCNU (although smaller value of α_s.
- Trend reproduced by Nantes implementation of BDMPS for intermediate pT (for which it should apply)
- Much increased value for the CUJET3 stemming from the assumption of magnetic monopoles « around » Tc => If all other ingredients are under control, offers a unique opportunity to probe the QGP dof with high p_T partons

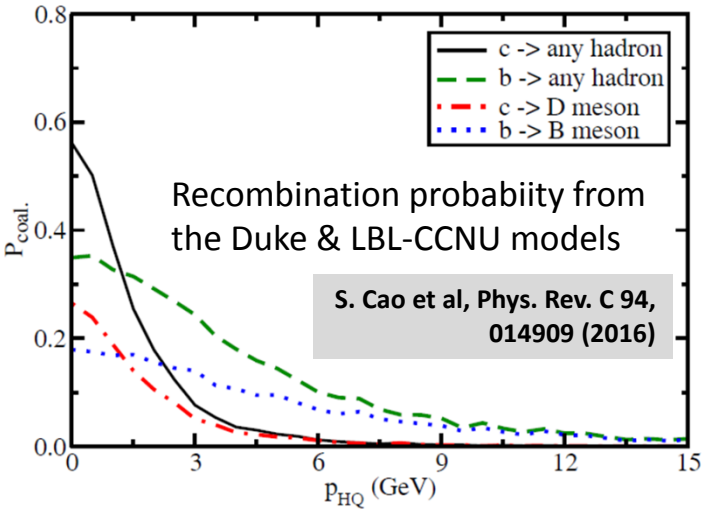
HQ-Hadronization (would deserve a full talk)

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,…)

Uncertain (and not disputed enough):

- Genuine physical recombination process !

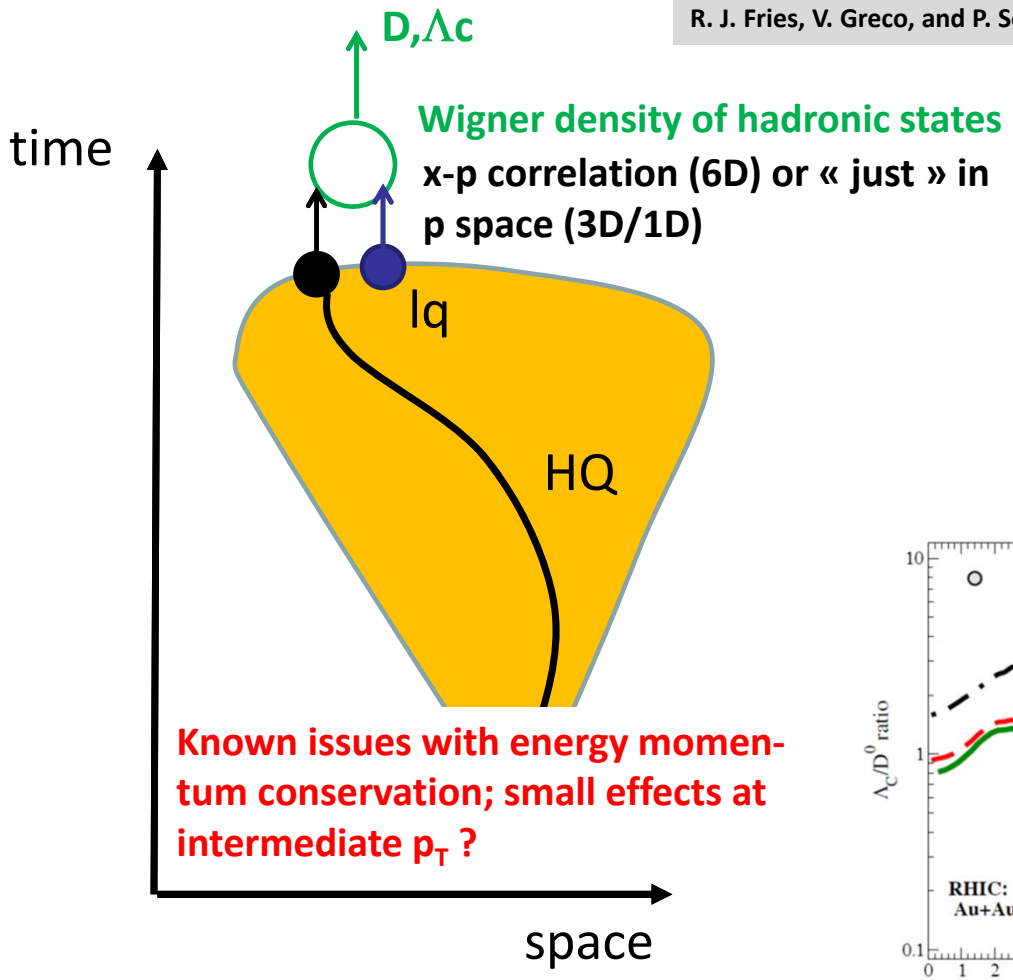
HQ - Recombination

Instantaneous coalescence:

Greco, Ko & Levai. Phys. Rev. C 68 (2003) 034904
V. Greco, C. Ko, and R. Rapp, Phys. Lett. B 595 (2004) 202
Y. Oh et al, Phys. Rev. C79 (2009) 044905
R. J. Fries, V. Greco, and P. Sorensen, Ann. Rev. Nucl. Part. Sci. 58 (2008) 177

NEW

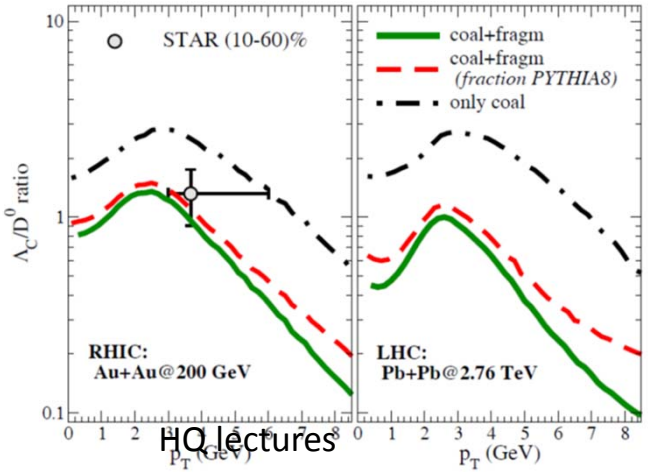
S Plumari et al. arXiv:1712.00730

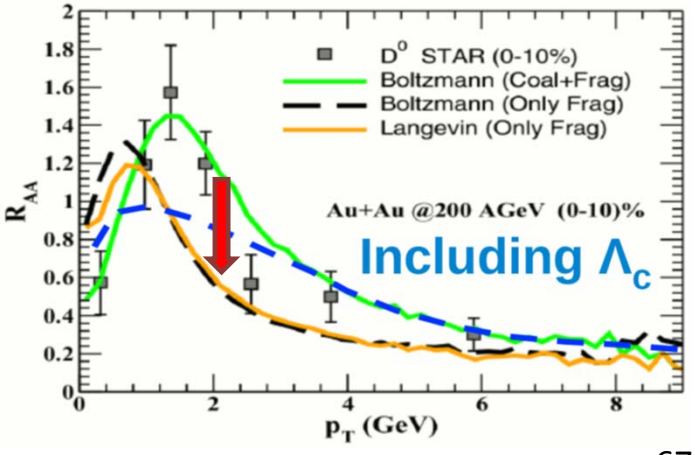


Known issues with energy momentum conservation; small effects at intermediate p_T ?

Latest Catania's coalesence model:

- Full 6D coalescence
- New normalization to impose P_{coal} -> 1 for p_T->0
- Resonance decay
- Mini jet contribution
- Inclusion of Λ_c baryonic states
  - => reduction of R_{AA}(D) at small p_T
  - => increase of Λ_c/D^0 wrt pp and pPb.



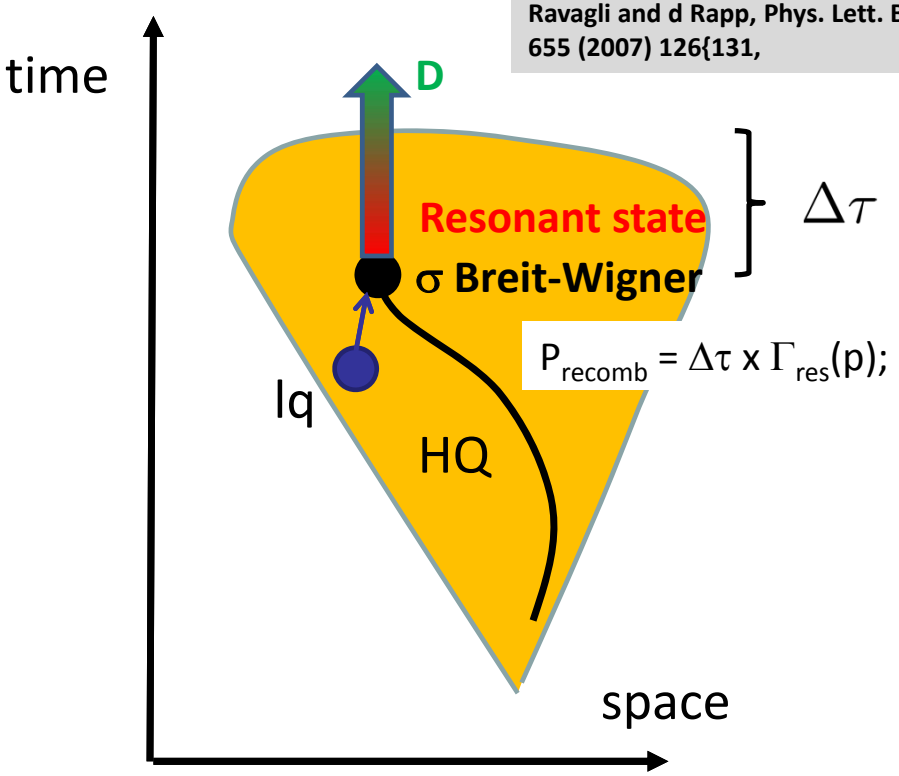


HQ - Recombination

Resonance Recombination Model:

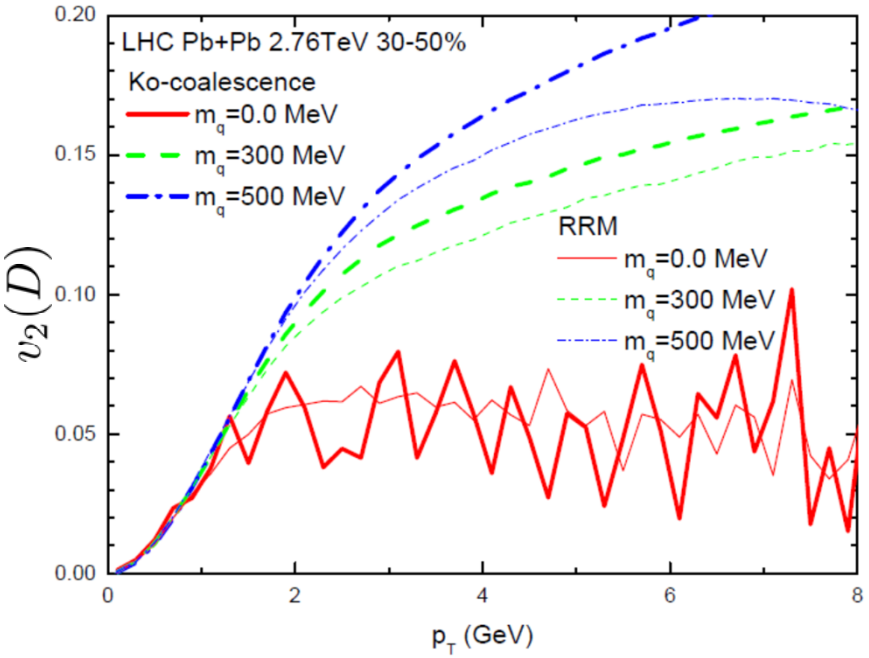
$$\left(\frac{\partial}{\partial t}+\vec{v}\cdot\vec{\nabla}\right)F_M(t,\vec{x},\vec{p})=-\frac{\Gamma}{\gamma_p}F_M(t,\vec{x},\vec{p})+\beta(\vec{x},\vec{p})$$

Ravagli and d Rapp, Phys. Lett. B 655 (2007) 126{131,



- Dynamical 2->1 process, implemented in the asymptotic limit of the kinetic equation
- A possible way to solve energy-momentum conservation
- Process governed by the interaction of HQ with QGP around T_c => natural link with the energy loss model.

In EMMI RRTF, comparison between Instant. Coal. & RRM



starting from the same bulk and from the same c spectrum

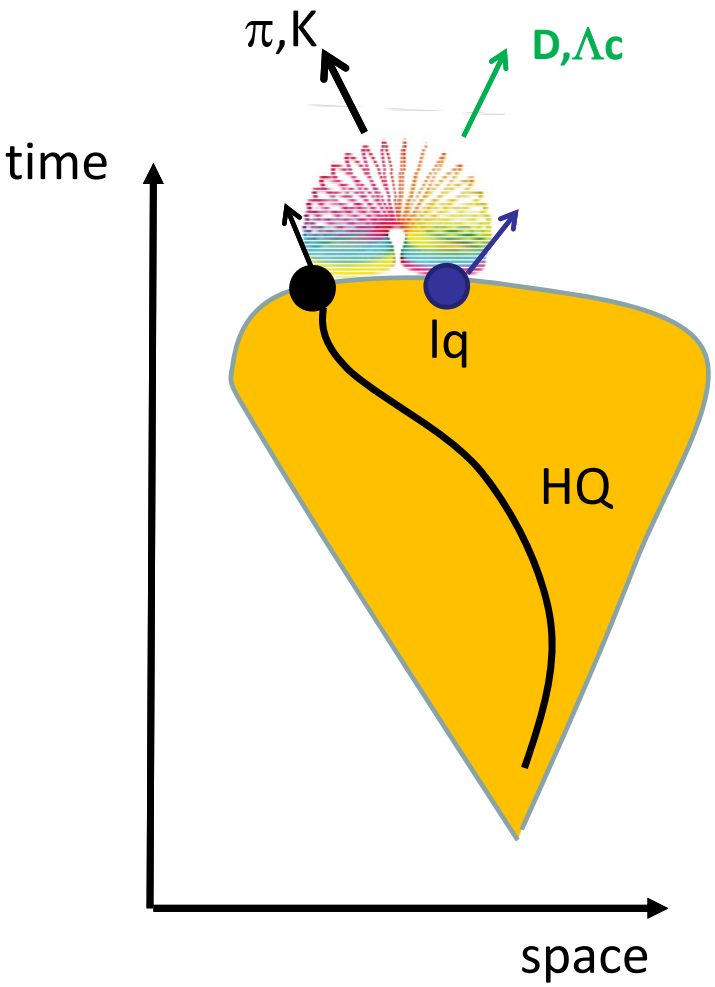
Significant differences found both for D meson p_T spectrum and v_2.

R. Rapp et al, arXiv: 1803.03824

HQ - Recombination

A Beraudo et al., Eur. Phys. J. C75 no. 3, (2015) 121

In-Medium recombination:



- String formed at Tc from HQ and light quark sampled out of thermal bath
- Novel mechanism which allows a natural transition from the low p_T to the high p_T
- Also leads to large flow bumps and extra v_2 contribution

HQ - Recombination

Acknowledged:

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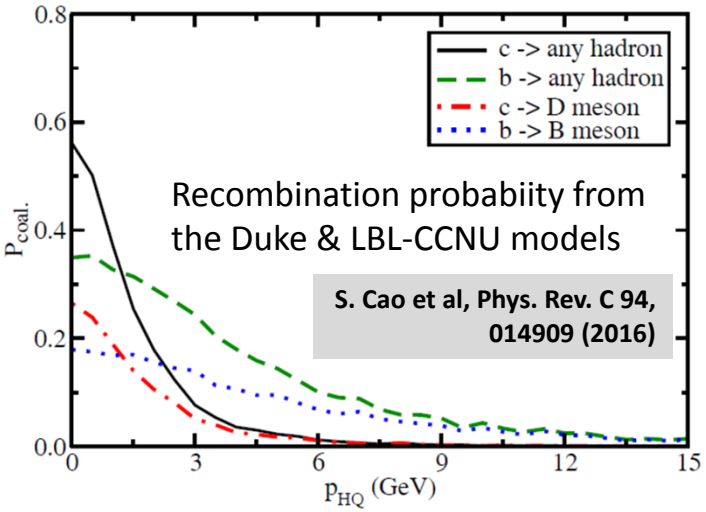
- The footprint of reconfinment (?!)
- Crucial to explain the flow bump in $R_{AA}(D)$ and sizable $v_2(D)$ => large impact.



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

The LHC Era: 2010 -> Now

- Huge data from LHC constraining the models (at high pT as well as in the b sector)
- Constrains from the fundamental theory : lQCD estimates
- A last class of model: Quasi Particle Model
- Alternate observables (correlations)
- The way towards more collective work in the theory community
- HQ-jets
- HQ in small systems
- ….

Recent Collective actions beyond Sapore Gravis

- **EMMI Rapid Reaction Task Force** (organizers: R. Rapp, PB Gossiaux, A. Andronic, R. Averbeck,, S. Maschiocchi):
  - Global strategy to extract the diffusion coefficient from the intercomparison between models and data
  - Collect and analyse all ingredients from various models
  - Identify constrains from lQCD
  - Initiate discussions to assess the limitations of some existing models.

R. Rapp*[1], P.B. Gossiaux*[2], A. Andronic*[3,4], R. Averbeck*[3], S. Masciocchi*[3], A. Beraudo[5], E. Bratkovskaya[3,6], P. Braun-Munzinger[3,7], S. Cao[8], A. Dainese[9], S.K. Das[10,11], M. Djordjevic[12], V. Greco[11,13], M. He[14], H. van Hees[6], G. Inghirami[3,6,15,16], O. Kaczmarek[17,18] Y.-J. Lee[19], J. Liao[20], S.Y.F. Liu[1], G. Moore[21], M. Nahrgang[2], J. Pawlowski[22], P. Petreczky[23] S. Plumari[11], F. Prino[5], S. Shi[20], T. Song[24], J. Stachel[7], I. Vitev[25], and X.-N. Wang[26,18]

Goal to attack the problem with a broad view right from the beginning…

R. Rapp et al, arXiv: 1803.03824
Published in NPA (sept)

(20 monthes since first meeting)

EMMI RRTF : Consequences from various **Hadronization Mechanisms**

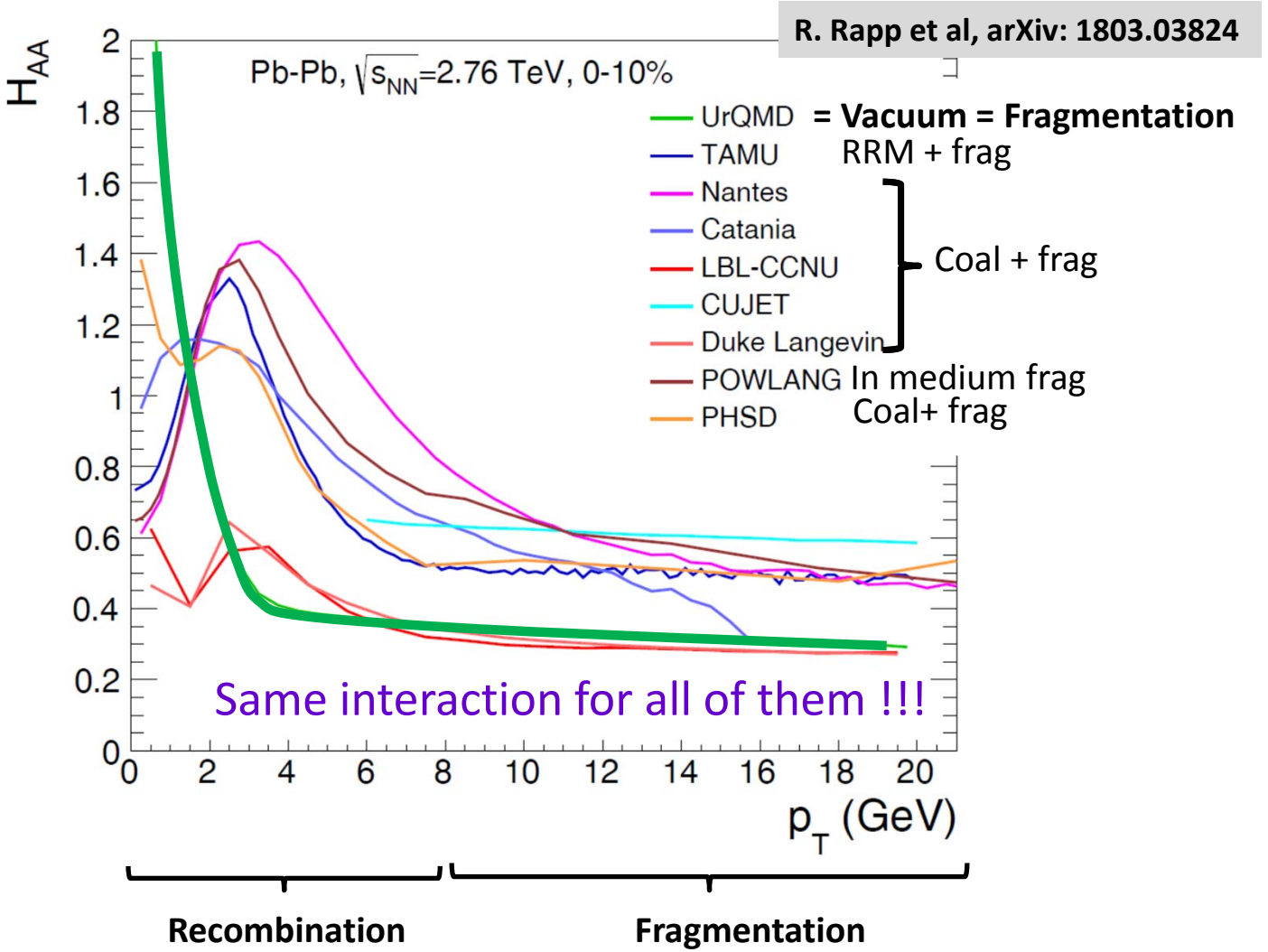
We define and display the H_{AA} quantity

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

…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



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- ….

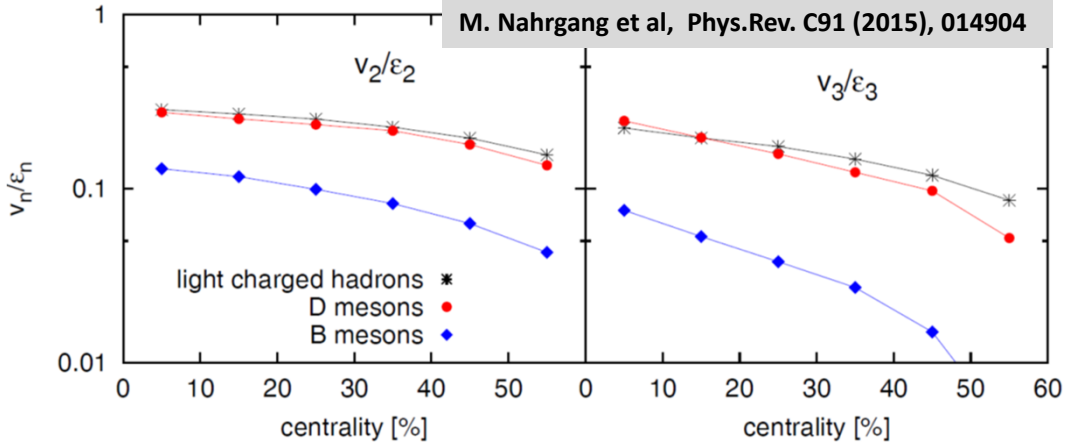
More on v_2 and higher flow harmonics

Goal: better understand the coupling btwn HQ and QGP by:

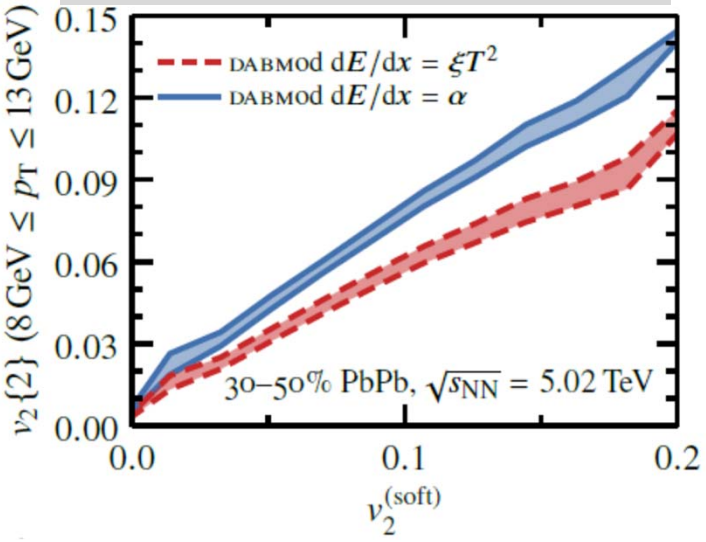
- departing from the nearly equilibrated regime
- exploring the consequences of inertia due to large m_Q
- Our observation: **reduction of v_n/ε_n for a) larger n, b) larger mass and c) larger centrality…**

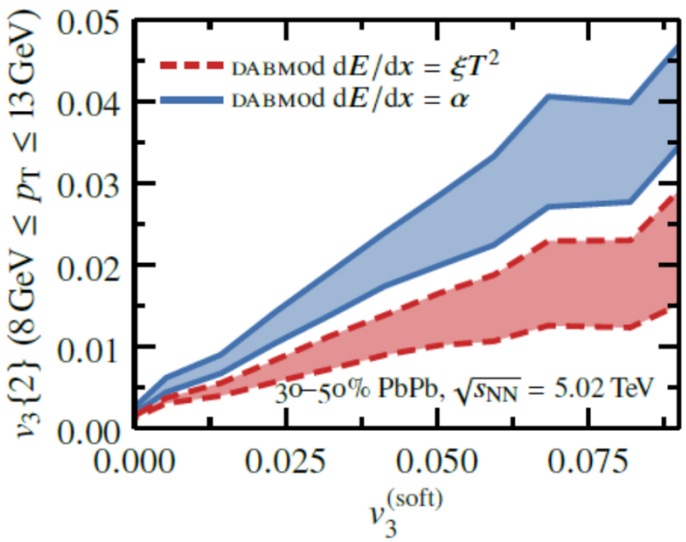
Does the HQ flow follows the light sector ? => EbE analysis

M. Nahrgang et al, Phys.Rev. C91 (2015), 014904

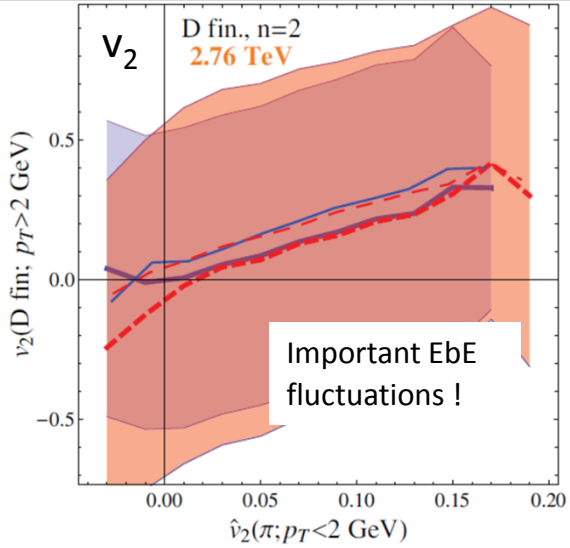


C.A. Prado et al, Phys. Rev. C 96, 064903 (2017)





Gossiaux et al EPJ Web Conf. 171 (2018) 18004



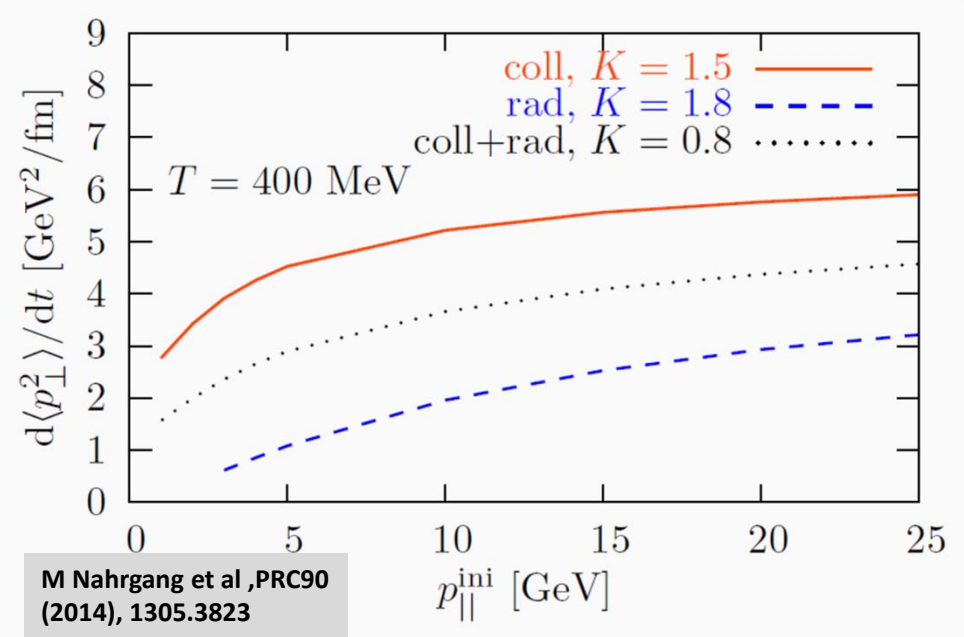
No saturation ./. Linearity BUT larger flow from $\frac{dE}{dx} \propto T^0$ and larger reduction for v_3

Alternate observables

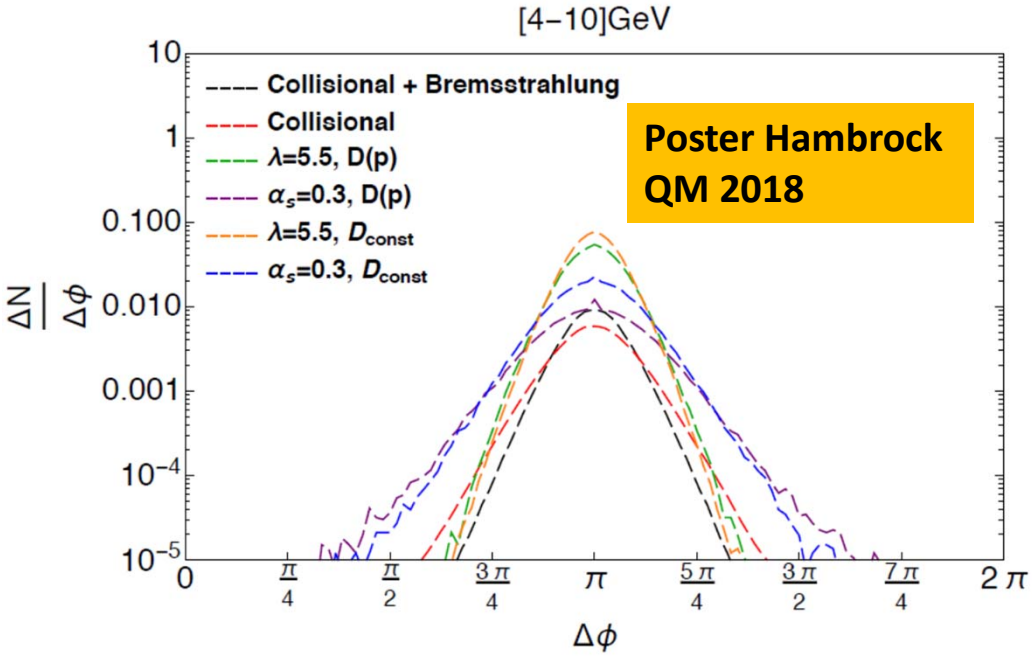
The nature of the interaction (Elastic vs Elastic + Radiative vs AdS/CFT) in the intermediate p_T range

One should exploit both

- Analysis of the path length dependence
- The larger "collinearity" found in radiative collisions, which could be seen in azimuthal correlations…



M Nahrgang et al ,PRC90 (2014), 1305.3823



… But not "short term" !!! WE NEED VERY GOOD MEASUREMENTS ON THIS

New Observables are coming

Short term, mid-term, long term,…

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 bitt too much for this poor observable ?

The LHC Era: 2010 -> Now

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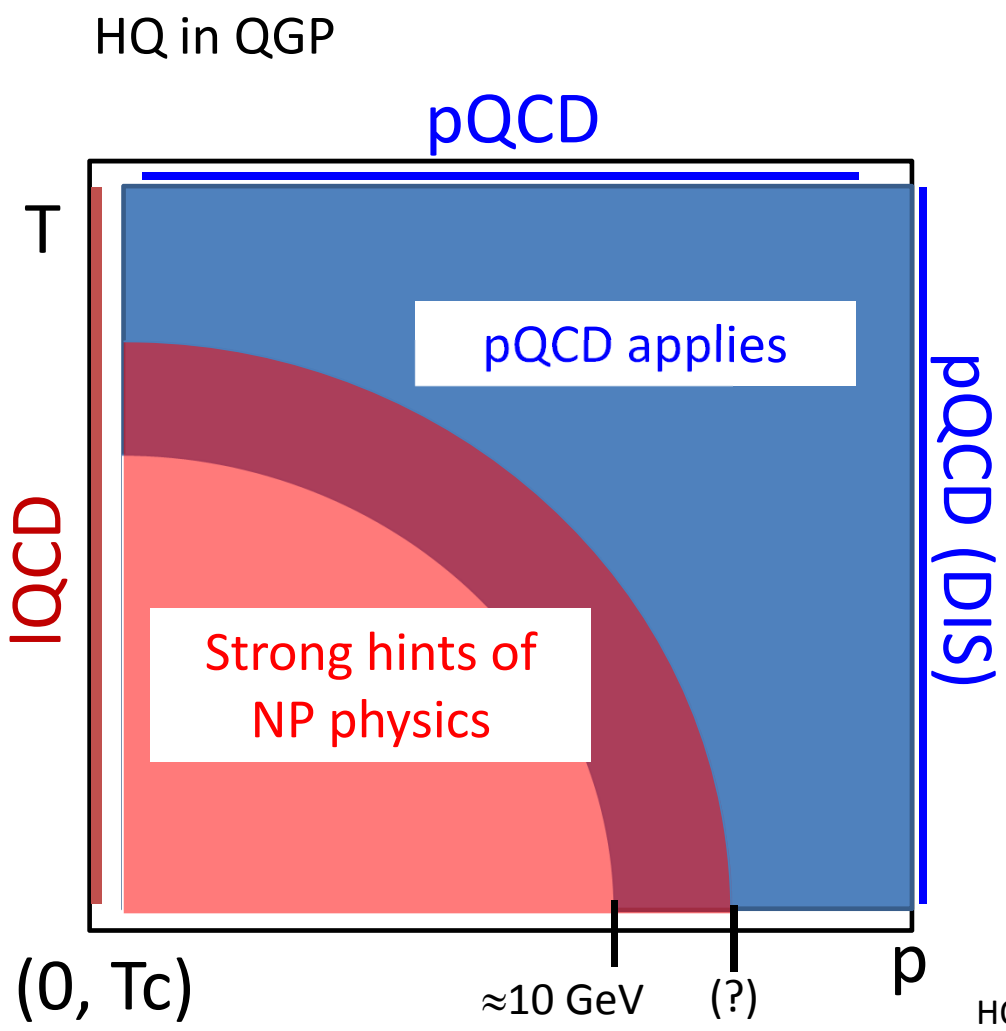
No time to cover. Please ask question if you wish

- ….

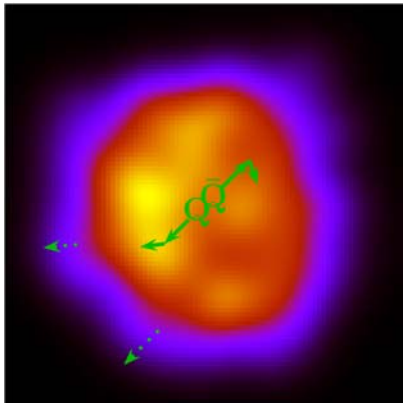
Conclusions for Open Heavy Flavors



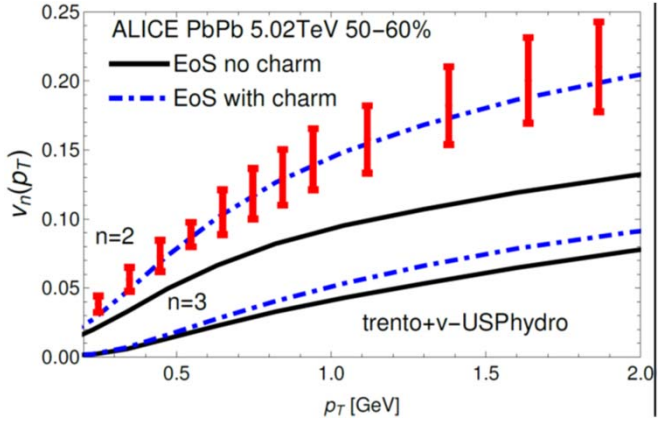
- Existing models offer the possibility to describe most of the OHF experimental AA data while being compatible with existing theory constrains…
- … however with unequal precision and no consensus on the physical NP content
- Improvements and quantitative understanding is on their way, but it will still take some time and a lot of efforts => need for ressources, bright 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.

Hard or soft probe ?

- Natural thought: m_Q and p_T>> local T => Hard probe
- But for p ≈ 0: τ_{relax} ≈ QGP lifetime = > Soft probe* ?!



- Allows contact with many other fields in Quark Matter and URHIC:
  - Quarkonia
  - Thermalisation of matter
  - Hadronisation
  - Jet physics
  - Small systems
  - CNM
  - MPI
  - Early magnetic field
  - …



J. Noronha-Hostler & Cl. Ratti, arxiv 1804.10661

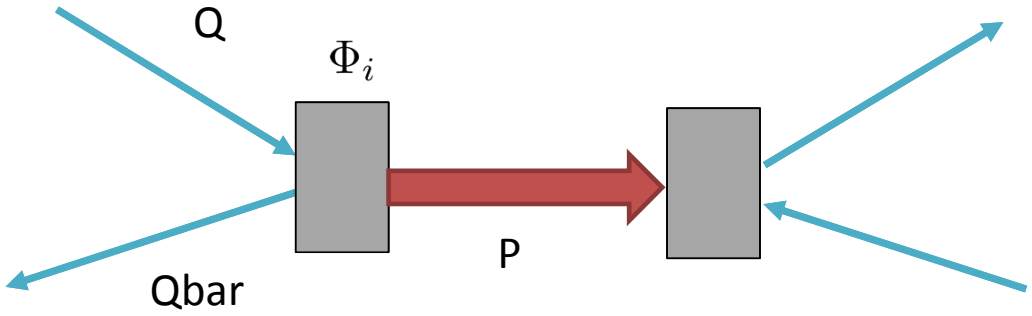
- This leads to richer physics, but also more complex to scrutinize

What is a quarkonia

What is a quarkonium ? Bound state of Q and Qbar quarks

Bound states in QFT ? $\hat{H}|\Psi\rangle = E\Psi\rangle$?

More convenient : analyse the Q-Qbar scattering amplitude S_2 for a given total 4-momentum P



And decompose it as

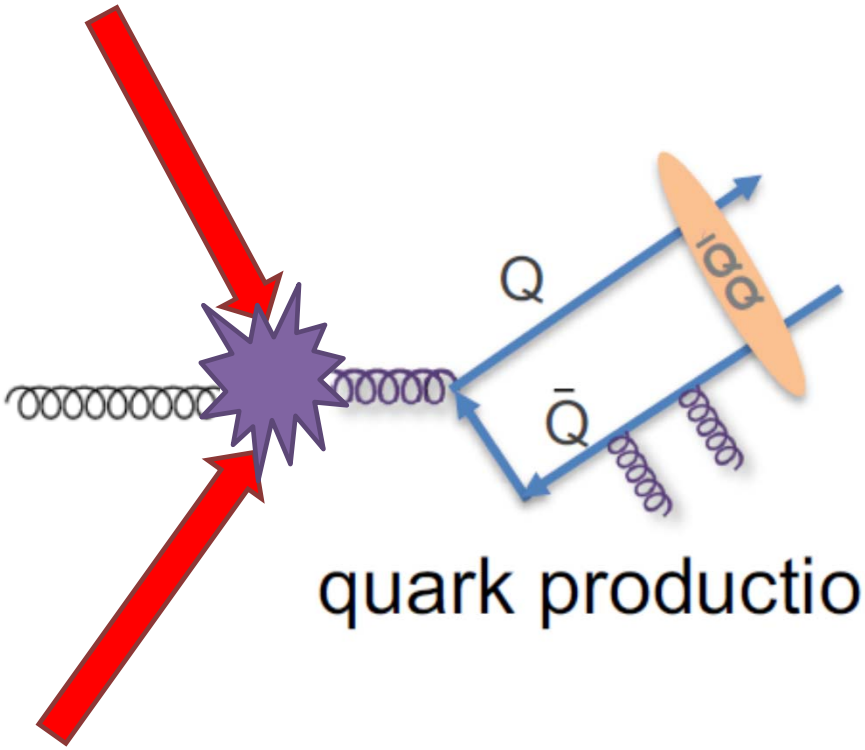
$$S_2 = \sum_i |\Phi_i\rangle \frac{1}{P^2 - M_i^2} \langle\Phi_i| + \cdots$$

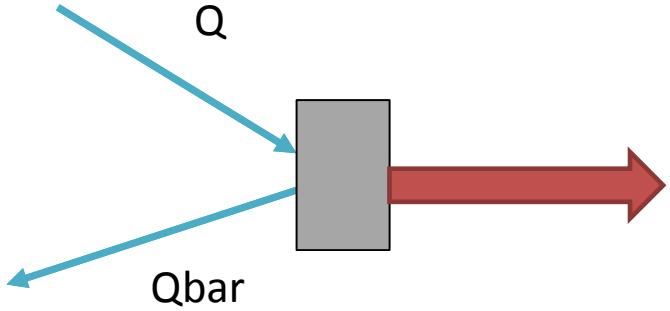
continuum

Then :
- M_i : bound state mass
- Φ_i (Bethe – Salpether) amplitude for Q-Qbar -> bound state transition

What is a quarkonia

This amplitude can thus be used to evaluate S – matrix and cross section for bound state formation in collisions





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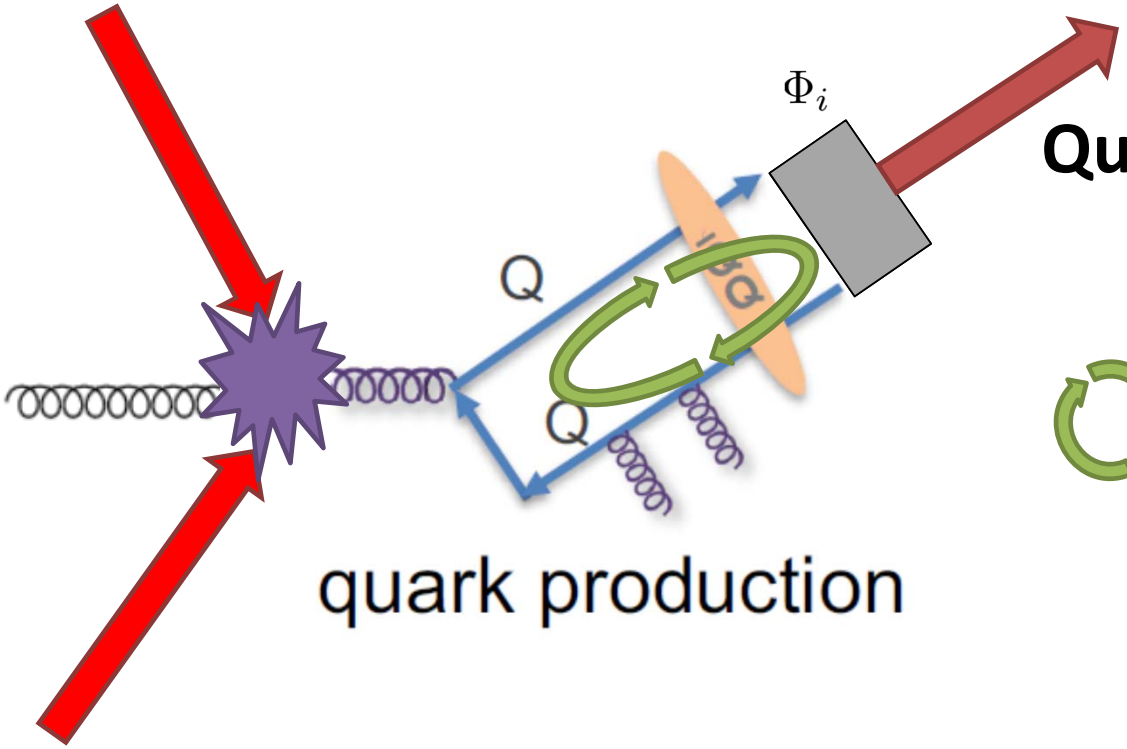


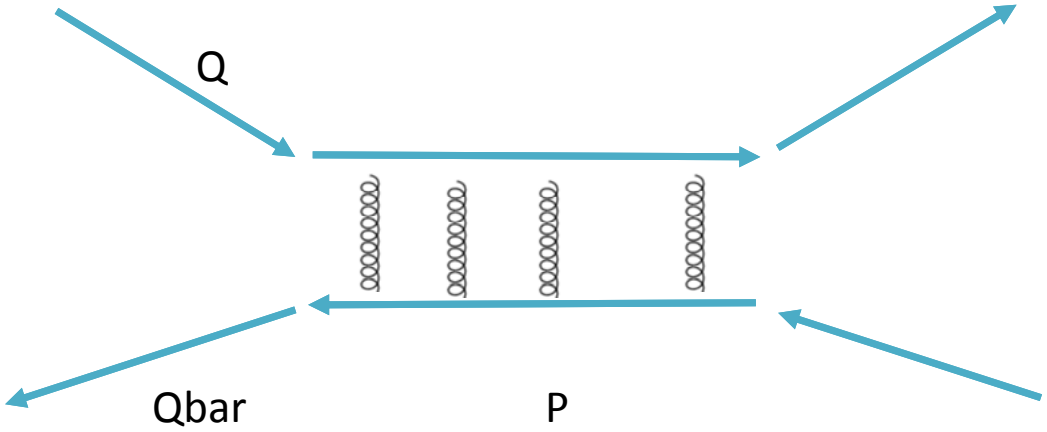
Quarkonium production

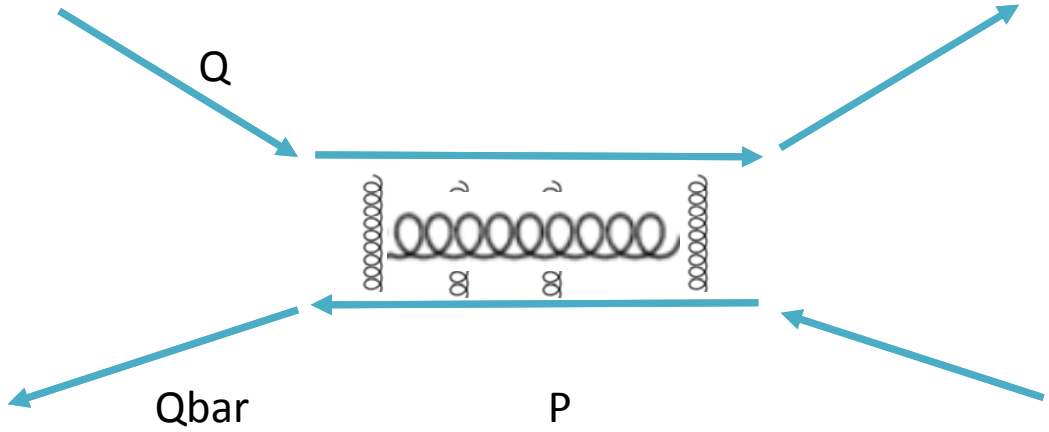
Loop integral on the 4-relative momentum

$$\approx \langle \Phi_i | Q\bar{Q} \rangle$$

What is a quarkonia

Evaluating the scattering amplitude from first principles:





« Easy »; protential like

« complicated »

One has to pay the price for QFT: the number of quanta at given « time » is not fixed:

$$|\Psi\rangle = |Q\bar{Q}\rangle + |Q\bar{Q}g\rangle + |Q\bar{Q}q\bar{q}\rangle \cdots$$

Possible strategies :

- ressumation
- effective theories
- models

What is a quarkonia

$|\Psi\rangle = |Q\bar{Q}\rangle + |Q\bar{Q}g\rangle + |Q\bar{Q}q\bar{q}\rangle \cdots$ ➡ Possible strategies :

- ressumation
- **effective theories** — NRQCD
- models

Benefit from $m_Q >> \Lambda_{QCD}$: small velocities

$$m_Q \gg \Lambda_{QCD} \;\&\; m_Q \gg m_Q v \sim |\mathbf{p}_{rel}| \gg m_Q v^2 \sim E_{bind}$$

1. Integrate out the momentum scales above mQ => Non relativistic description => no more g -> Q+Qbar vertex in diagrams (but contact terms) => NRQCD

2. Intgegrate scales ≈ m_Q v => eliminates on shell gluon propagation => potential like

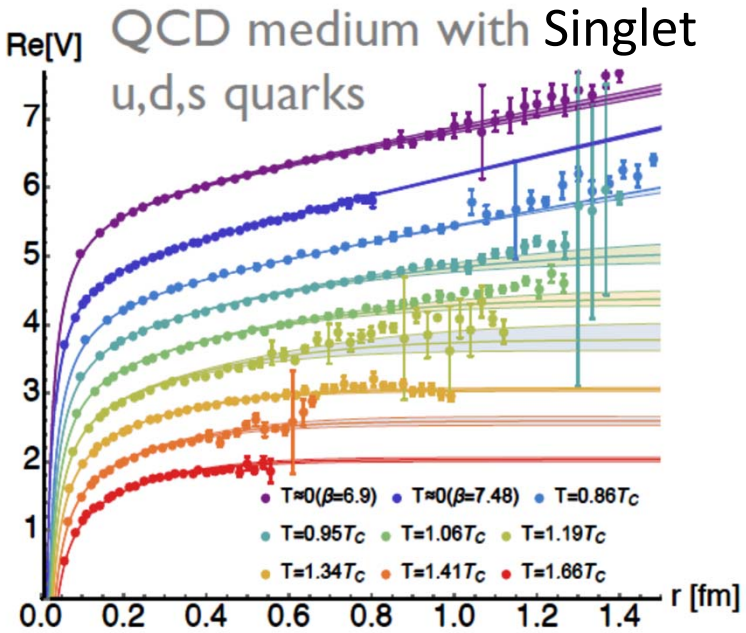
pNRQCD $\quad L_{\rm pNRQCD} = L^{\rm US}_{\rm NRQCD} + L_{\rm pot}$

Projection on the Q-Qbar sector => singlet and octet states

$$L_{\rm pot} = -\int d^3\mathbf{x}_1 d^3\mathbf{x}_2\; \psi^\dagger(t,\mathbf{x}_1)\chi(t,\mathbf{x}_2)\; V(\mathbf{r},\mathbf{p}_1,\mathbf{p}_2,\mathbf{S}_1,\mathbf{S}_2)\; \chi^\dagger(t,\mathbf{x}_2)\psi(t,\mathbf{x}_1)$$

What is a quarkonia

Protential (recent lQCD calculations)



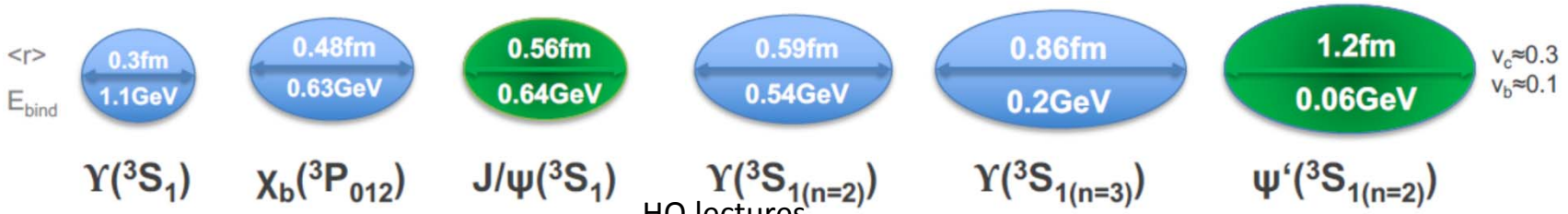
At T=0, well described by the Cornell shape:

$$V(r) = -\frac{\alpha}{r} + Kr$$

Quarkonia scales

- m_Q
- In vacuum: Binding energy / separation energy btwn levels: $\Delta E \; \alpha \; m_Q \; g^4$ (Coulomb part) => $v \; \alpha \; g^2$
- Radius : $(m_Q \; g^2)^{-1}$
- For a linear potental $\hbar\omega_0 = \left(\frac{\hbar^2 K_l^2}{m_b/2}\right)^{\frac{1}{3}} \approx 0.504 \text{ GeV}$

$$v \propto \left(\frac{K_l}{m_b^2}\right)^{\frac{1}{3}}$$



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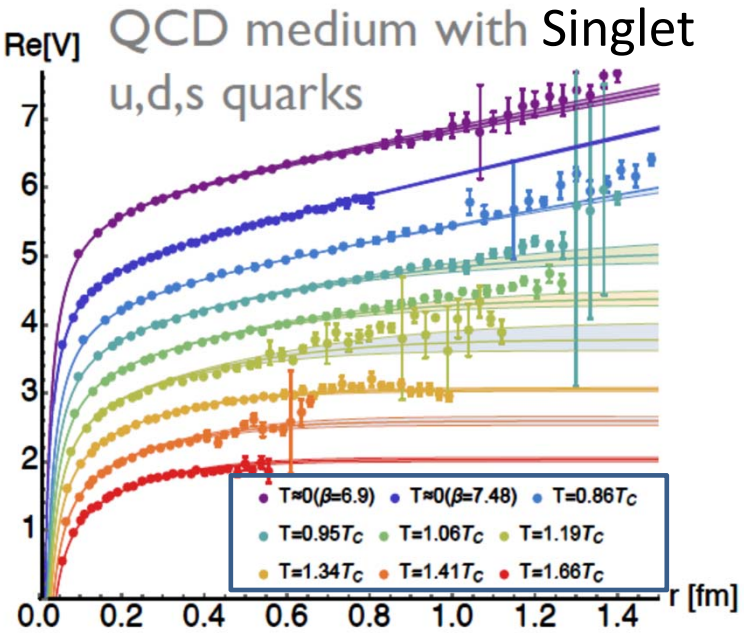

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$$\hookrightarrow \quad v \propto \left(\frac{K_l}{m_b^2}\right)^{\frac{1}{3}}$$

Compact and tightly bound states (at least for the lowest ones) => could survive QGP at low/mid T as well as to interactions with hadronic matter.

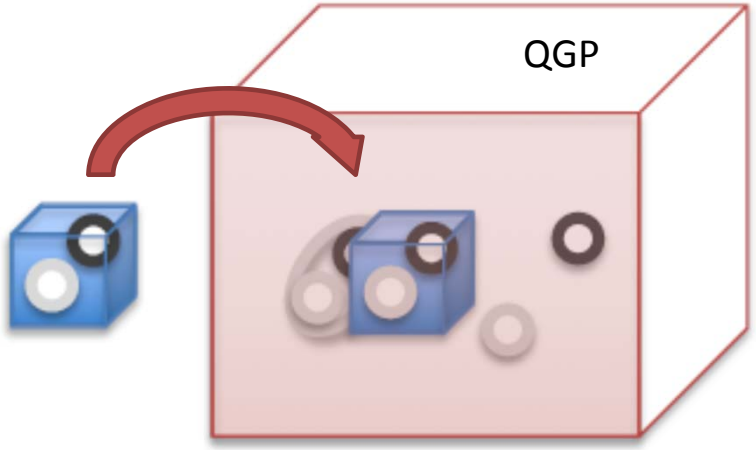
Quarkonia as a hard probe… of what ?

Once upon a time: quarkonia ⇔ small size => sensitive to correlations at small distance in nucleus (« filtering » in pA)

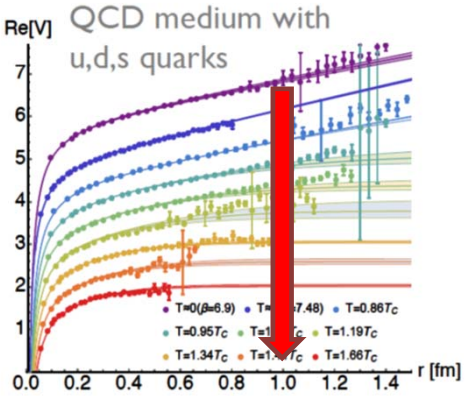
Most prominently : probing new state of matter in AA collision: Original idea by Matsui and Satz (86);

In both cases, additional scales as compared to OHF, due to the richness of the 2 body problem => More complex

Quarkonia in QGP



Strong modification of the potential



At small distance, can be assimilated to *Debye screening* with Debye mass $m_D \alpha$ gT

Principle: a state n is protected from melting provided

$r_D \alpha 1/m_D > r_n : 1/(gT) > c_n/(m_Q g^2)$

⇔ $T < T_{melt,n} = m_Q g / c_n$

growing c_n : $c_1 < c_2 < c_3$

Beyond this value: bound state disappears from the spectrum (« melting »)

HQ lectures

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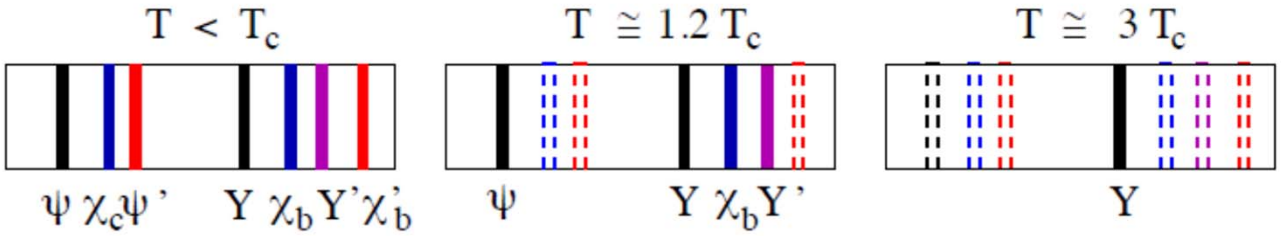

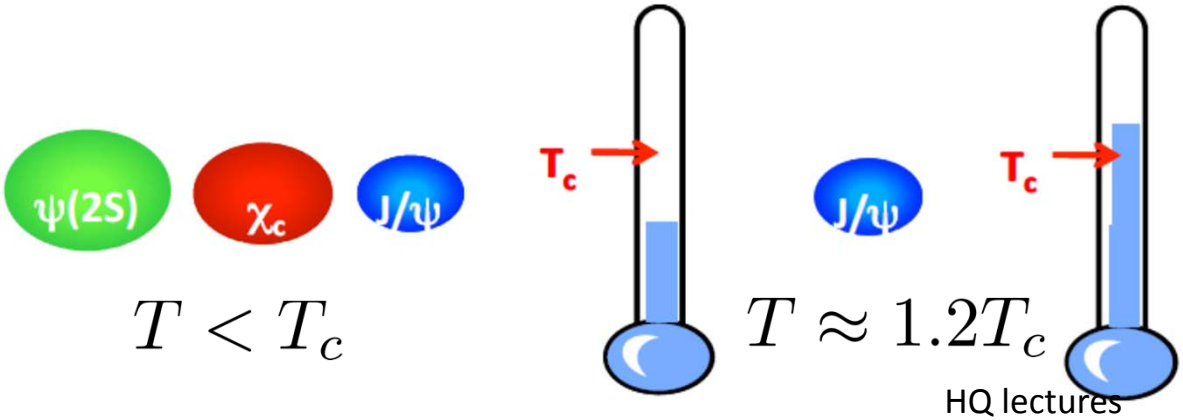

Ok for « physics in the oven » … What about realistic AA collisions ?

The concept of sequential suppression

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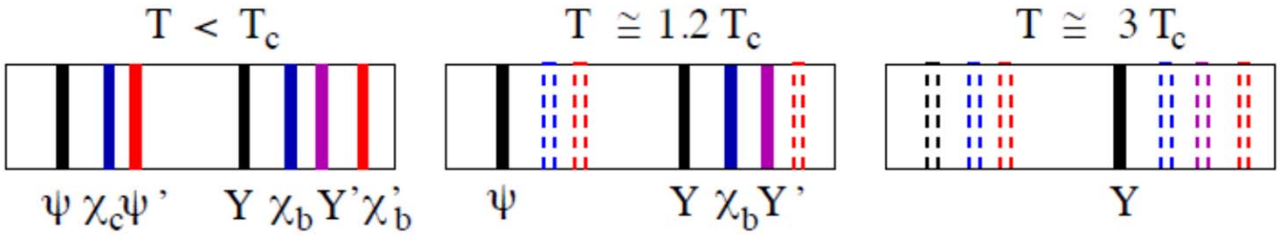
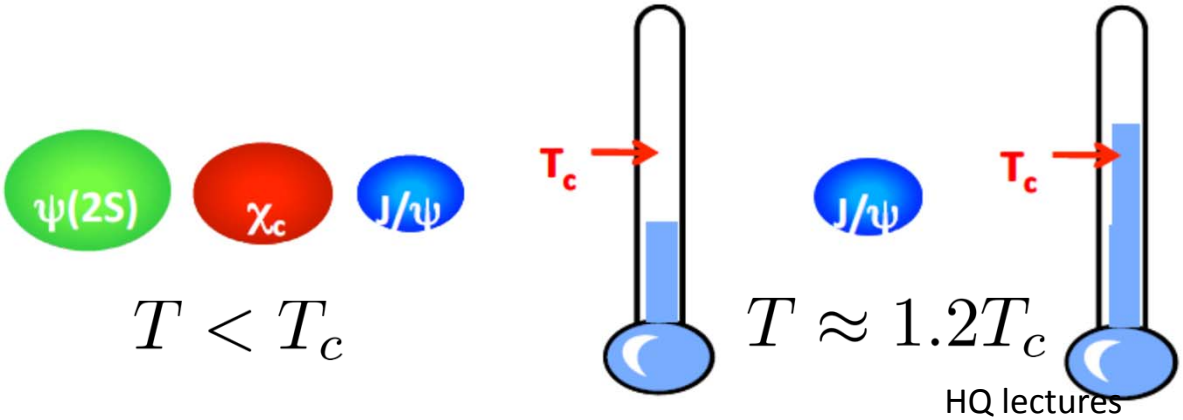
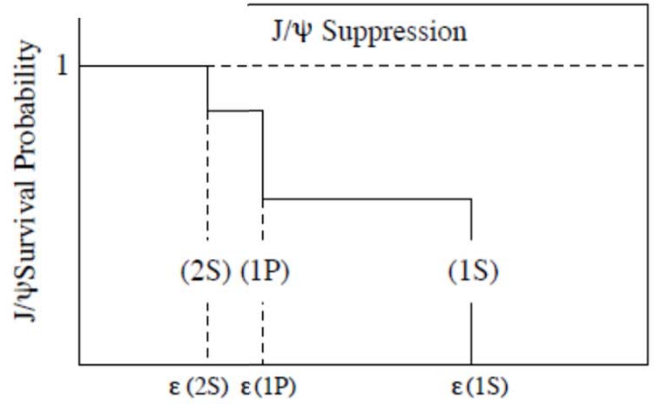


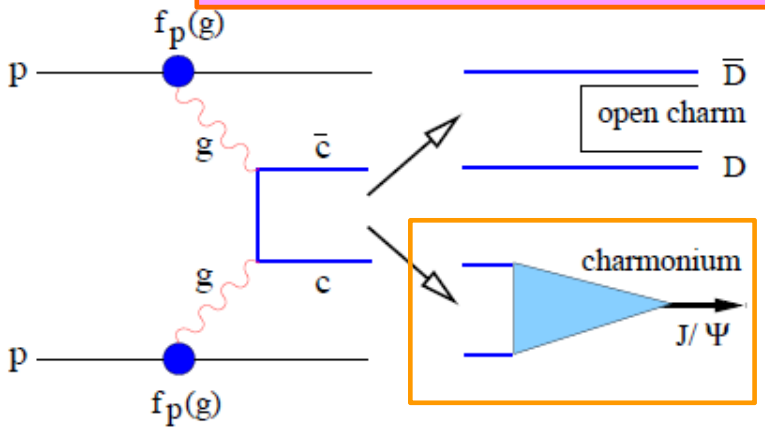




HQ lectures

energy density reached in the collision

Sequential "suppression"…

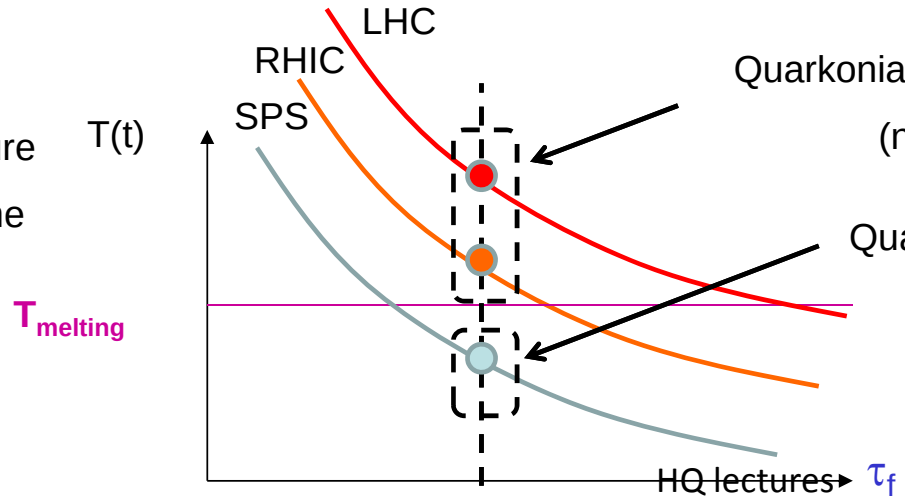


Formed after some "formation time" τ_f (typically the Heisenberg time), usually assumed to be independent of the surrounding medium

Standard folklore of sequential suppression: The quarkonia which should be formed at (τ_f, x_0) is not if $T(\tau_f, x_0) > T_{diss}$ => Q-Qbar pair is "lost" for quarkonia formation

Pictorially

Local temperature at formation time



Quarkonia state "suppressed" (not formed)

Quarkonia state formed as in the vacuum

… many issues !!!

- We know that AA do not lead to uniform profile for T => the steps can be vastly smoothened.
- Notion of formation time is not so well defined. Using this criteria blindly => abrupt jumps in the probability of formation that does not correspond with a genuine quantum calcultion (Gossiaux and Cugnon, early 90's)
- What do we do for bottomonium at early stages, i.e. formed before thermalization ? (does not mean we know how to treat it properly in alternate approach though).
- …

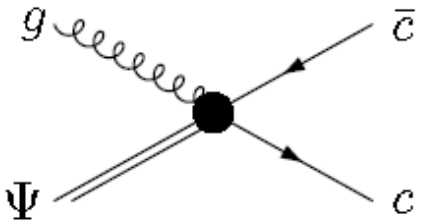
… many issues !!!

- Besides arguments based on the Debye mass / screening, it was pointed out already in the 90's that interactions with partons in the QGP could lead to dissociation of bound states (whose spectral function thus acquire some width Γ corresponding to the dissociation rate)

- Microscopic evaluation of the decay rate

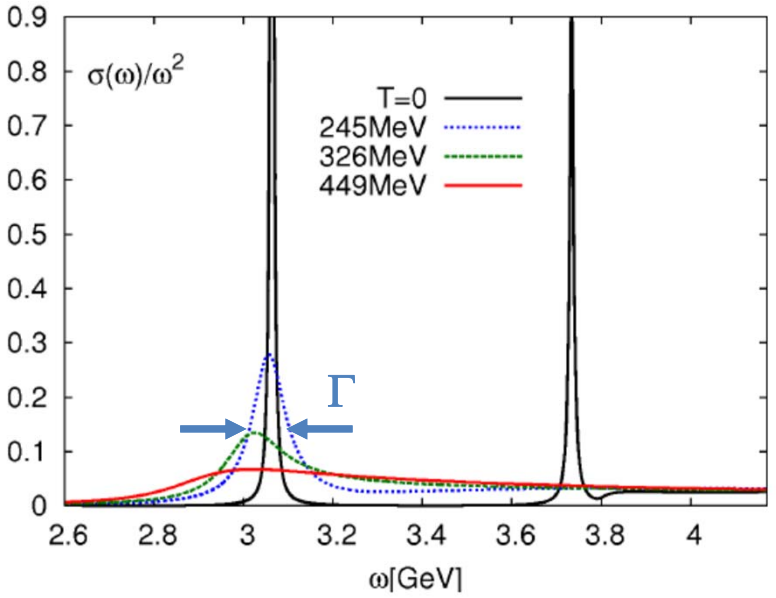
$$\Gamma_\Psi(\vec{x},\ \vec{p},\ \tau) = \sum_i \int \frac{d^3k}{(2\pi)^3}\ f^i(\omega_k; T(\tau))\ \sigma_{\Psi i}^{diss}\ v_{rel}$$

Typical dissociation process:



$$\sigma_{J/\psi}(\omega) = A_0 \frac{(\omega/\epsilon_{J/\psi} - 1)^{3/2}}{(\omega/\epsilon_{J/\psi})^5}$$

ω: gluon energy in the J/Psi rest frame

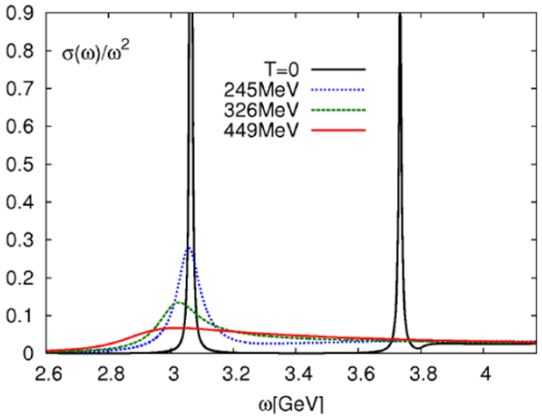


One has to abandon the idea of using quarkonia as some « static thermometer » towards concepts and methods more compatible with the dynamical nature of the QGP evolution including both « melting » and dissociation.

Modern era

Modern era…

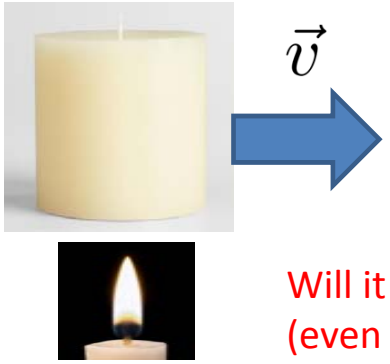
- Yet, these pictures might still be compatible with the notion of sequential « suppression »…
- However, this notion has to be made more precise : (LQCD) spectral function lQCD



$$\rho(\omega,p,T)=\frac{1}{2\pi}\mathrm{Im}\int_{-\infty}^{\infty}dte^{i\omega t}\int d^3xe^{ipx}\langle[J(x,t),J(0,0)]\rangle_T$$

At T=245 MeV, ψ' has disappeared but J/ψ still surviving for $\approx 1/\Gamma \approx$ a couple of fm/c … which needs to be compared with the local QGP cooling time τ_{cool} : $\Gamma \times \tau_{cool} > 1 \Leftrightarrow$ suppressed

- N.B.: The opposite phenomenom might also be relevant: some state above the « melting » temperature can survive (for a short while $< 1/\Gamma$) before getting lost definitively.

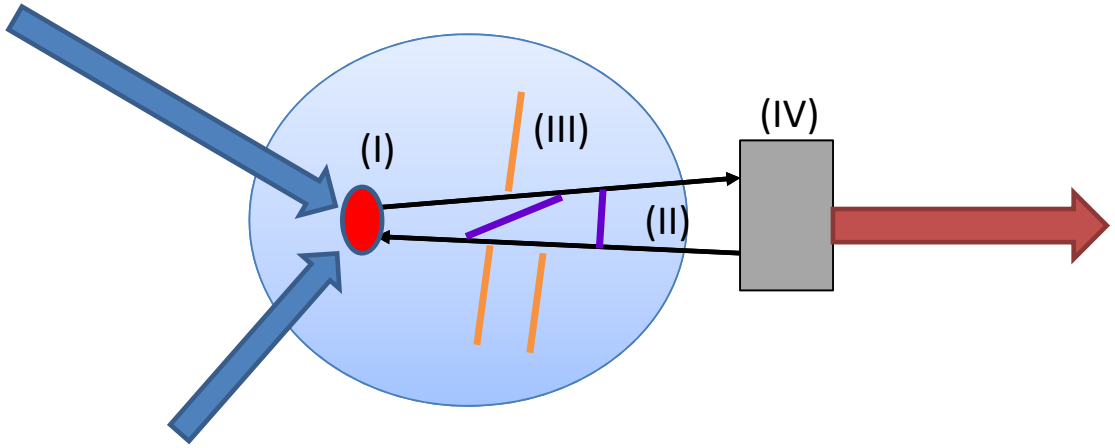


Will it melt (even party) ?

- Modern vision : do the quarkonia states (chemically) equilibrate with the QGP ?

Modern era…

A general « QFT fundamental » propagation of quarkonium (sketchy)



Need several « ingredients » that will probably be debated at length during this conference;

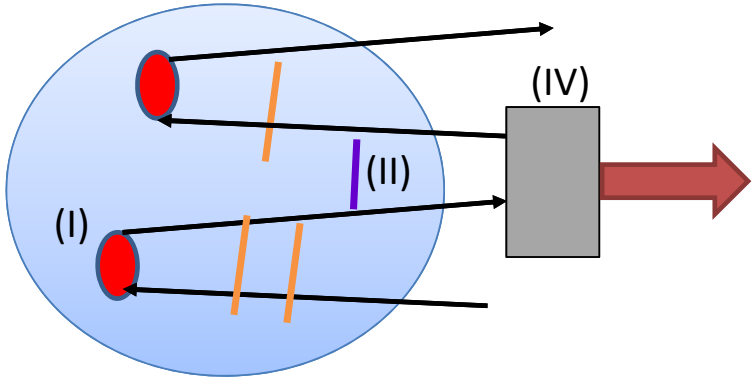
- (I) and (IV) should be ideally extracted from (or at least compatible with) pp
- (II) and (III) ⇔ time dependent evolution of Q-Qbar state

Complicated QFT problem (also due to the evolving nature of the QGP that mixes several scales)… only started to be addressed at face value recently

N.B.: Sequential suppression -> Equilibration with the medium

Modern era : The second face of quarkonia God

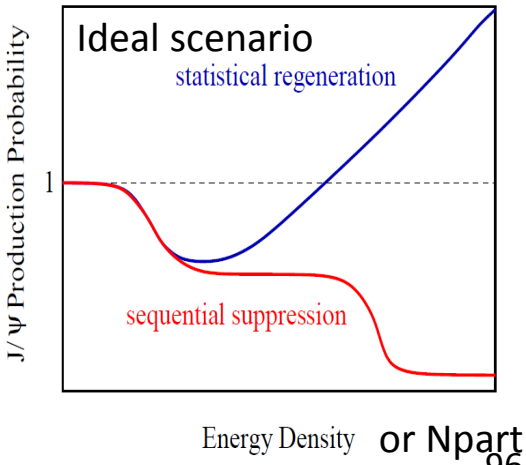
In fact, even more complicated when several Q-Qbar pairs are created



(Re)generation (PBM & Thews) : huge increase found in early years => people a bit disappointed now with R_{AA} still < 1 … however, the « excess » is found mostly at low p_T => compatible with (re)generation

Even if Q-Qbar are in principle not discernable : Onium = Onium_supp + Onimum (re)combination

- Completes the modern picture : quest for the (chemical) equilibration of quarkonia with both gain and loss terms.
- A central question with genuine consequence for observables: when does the recombination happens ? Strongly connected to our knowledge on the spectral function.



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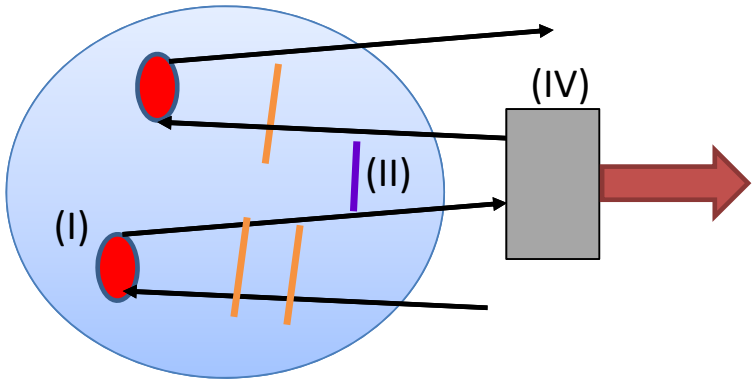

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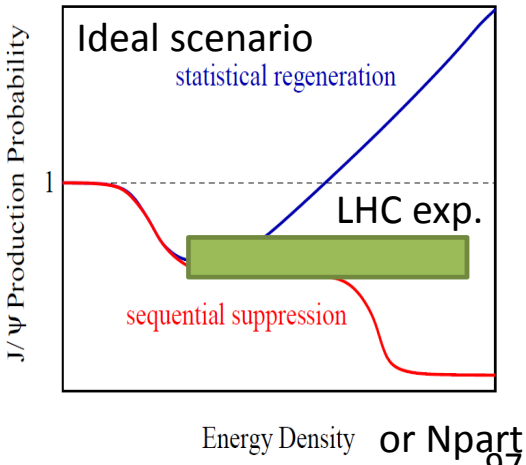
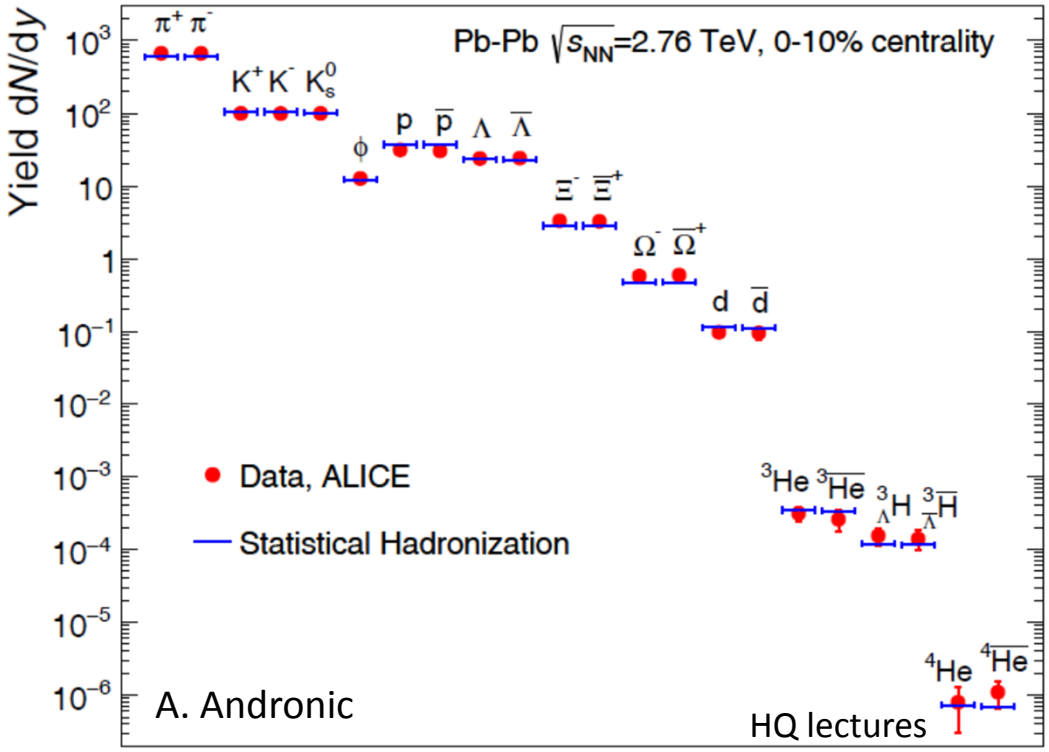


Effective theories, models and phenomenology

Then, some simplification made (often depending on the background) hoping to grasp the most significant aspects of physics:

I. *Statistical* regeneration. Based on simple assumptions:

- A statistical equilibrium is reached (locally) at the end of the QGP phase



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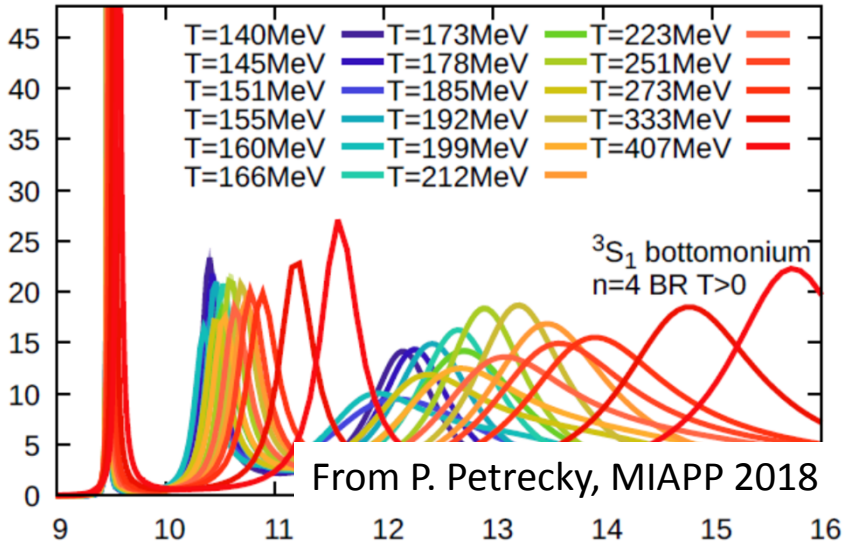
- All all quarkonia bound states are dissociated / melted during evolution (still hard probes ?)



From P. Petrecky, MIAPP 2018

Might be ok for charmonium, but at least Y(1S) seems to survive for $T >> T_c$.

Effective theories, models and phenomenology

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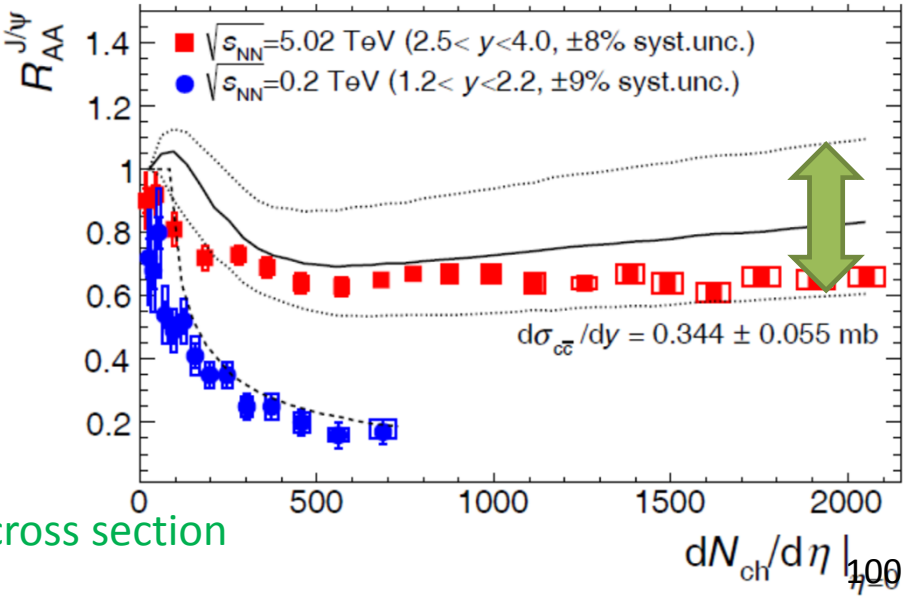
- All Q and Qbar recombine « instantaneously » around T_c.

⇒ Predictions for:

- dN_Φ/dy (large uncertainties stemming from $\sigma_{c\text{-}cbar}$)
- dN_Φ/dpT at low p_T.
- Higher states
- $v_{2\Phi}$



In this approach, uncertainties mainly stem from the total Q-Qbar cross section

Effective theories, models and phenomenology

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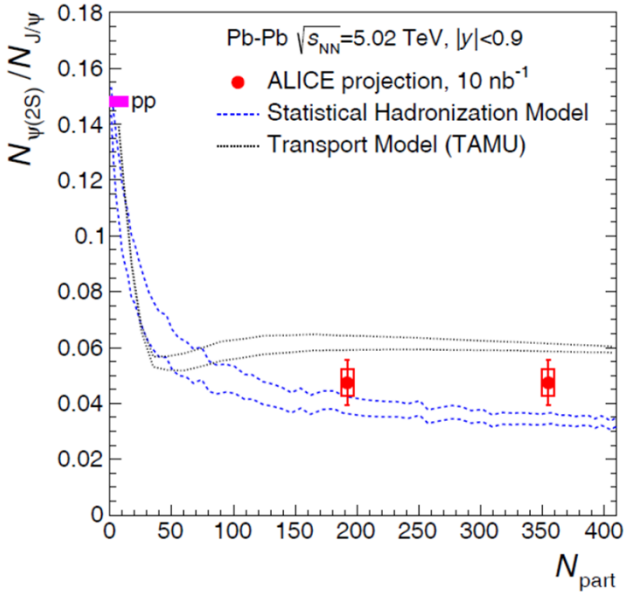

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- dN_Φ/dpT at low p_T.
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- $v_{2\Phi}$

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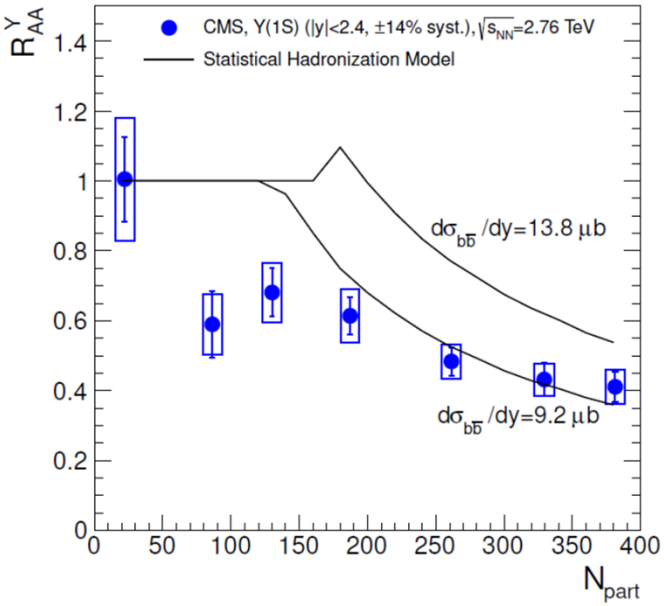

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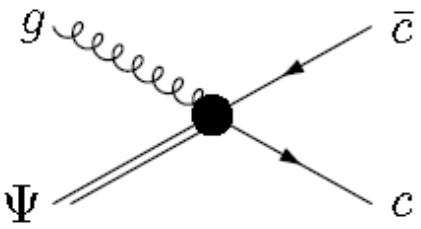
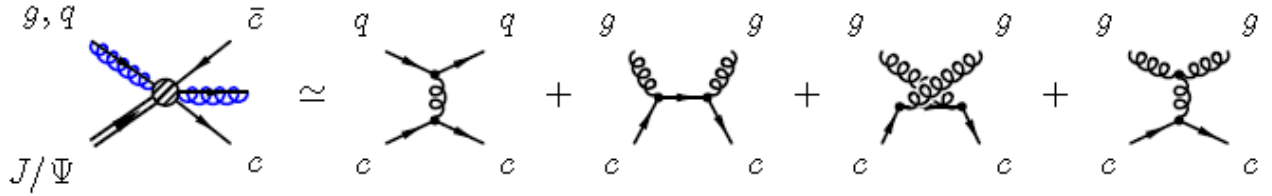
➡ Always a nice benchmark and a limit to be checked in other models in the large dissociation case !

Effective theories, models and phenomenology

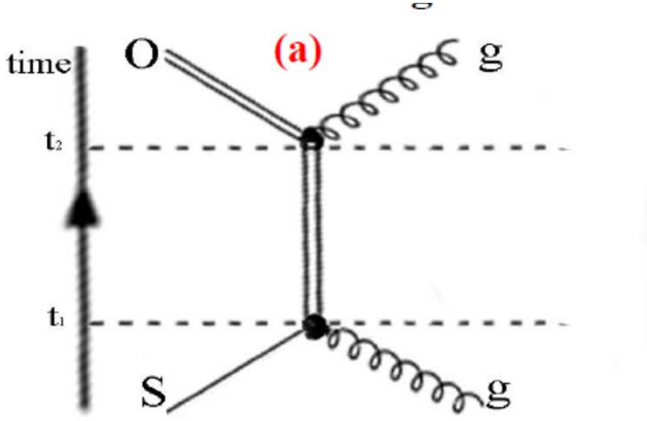
II. Transport models : more sophisticated approach based on some cross section to describe the interaction of quarkonium with QGP:

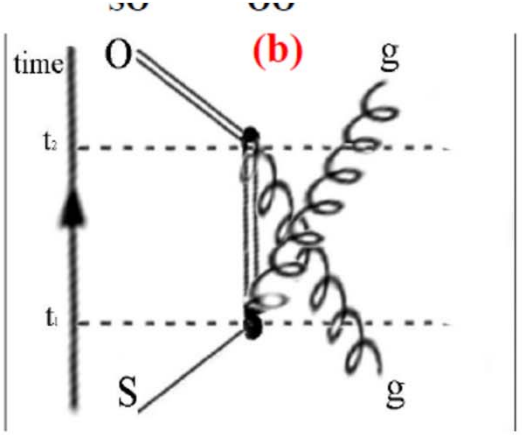


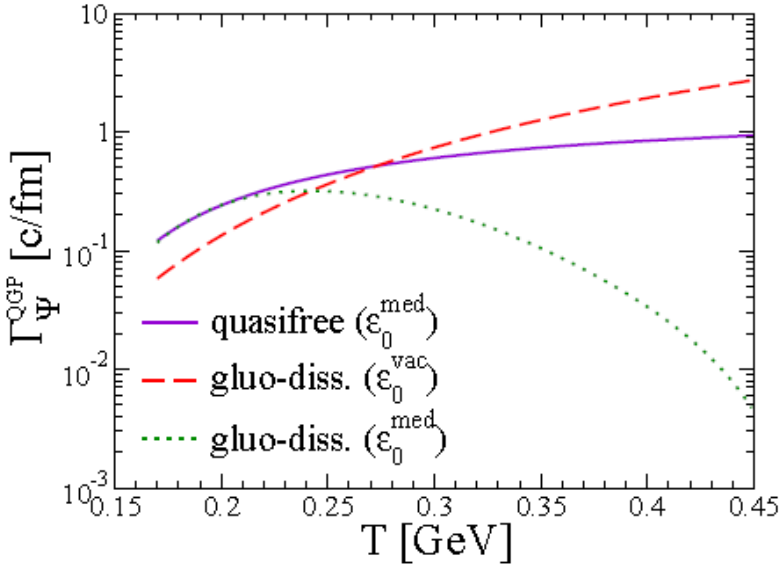
gluo dissociation (common in all approaches)



quasi free dissociation;
dominant at large temperature





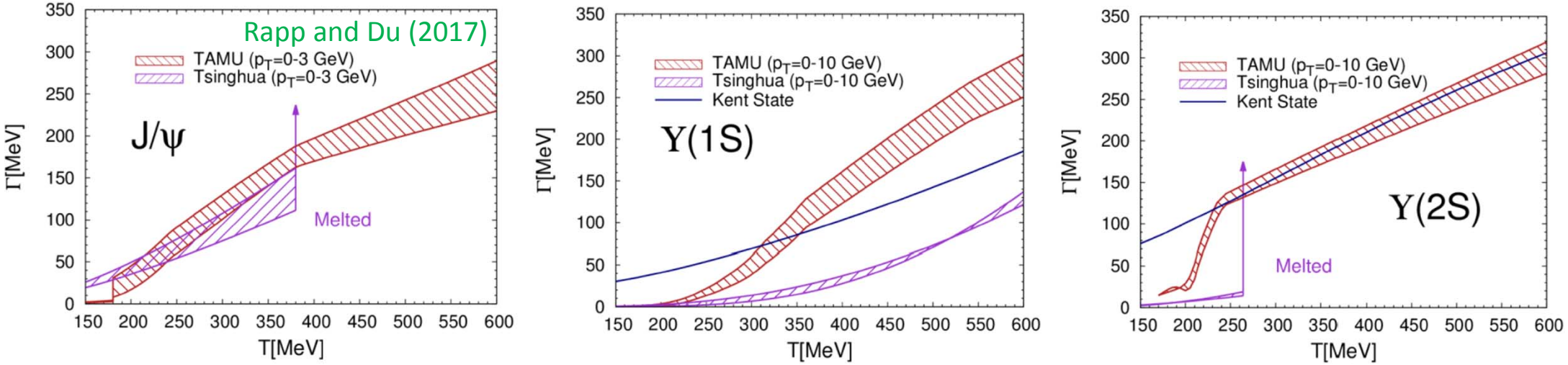


Recent systematic NLO calculation by M. He based on some effective Low Energy Hamiltonian

Effective theories, models and phenomenology

II. Transport models : … with significant subtle variations in each model:

- Underlying binding force between Q & Qbar
- Whether, on the top of dissociation, some « melting » is allowed
- ….



With significant consequences on the dissociation rate !

Yet, the working horse of most concrete predictions for quarkonium predictions in AA

Effective theories, models and phenomenology

II. Transport models : … with significant subtle variations in each model:

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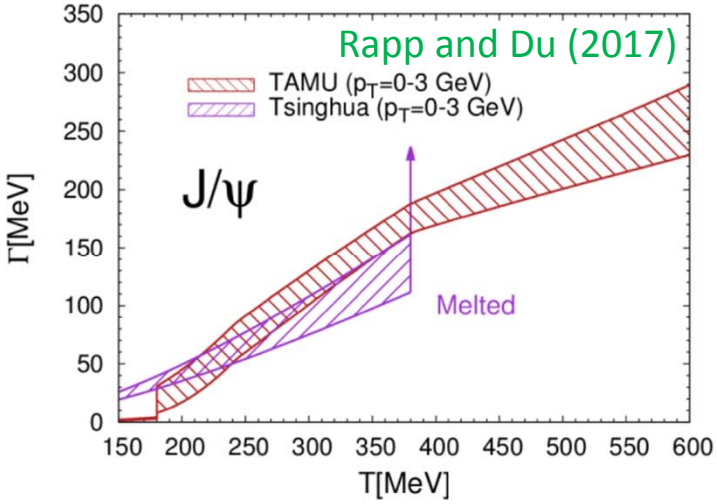
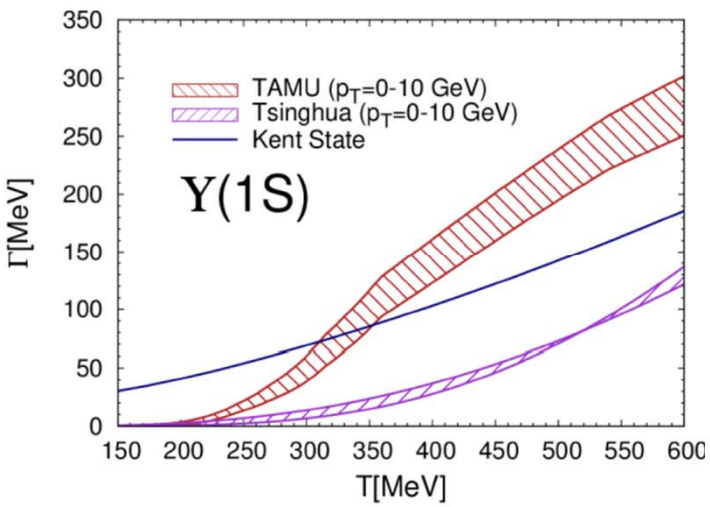
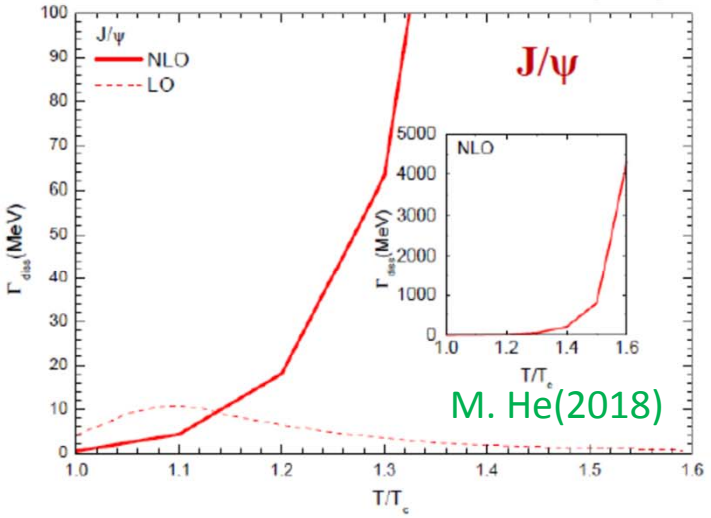
- Whether, on the top of dissociation, some « melting » is allowed
- ….







With significant consequences on the dissociation rate !

In some schemes (not most of them): connection with the force acting on single HQ (=> possible calibration; nice !)

Effective theories, models and phenomenology

II. Transport models (and rate equations) : different levels of « implementation »

$$\frac{dN_\Phi}{dt} = -\Gamma(T(t))\,(N_\Phi - N_{\Phi,\mathrm{eq}}(T(t)))$$

Global kinetic equation

Automatically takes care of the recombination at time t assuming HQ are in thermal equilibrium

Physics in Γ(T) can be more or less sophisticated (weakly coupled, strongly coupled,…)

$$\frac{dn_\Phi(\vec{x})}{dt} = -\Gamma(T(t,\vec{x}))\,(n_\Phi(\vec{x}) - n_\Phi(\vec{x},\mathrm{eq})(T(t,\vec{x})))$$

Local kinetic equation; well suited for implementation in fluid dynamics

Local transport equation in phase space (physical space + momentum)

Well suited to include off-equilibrium effects in HQ distribution, quarkonia production at finite p_T,… but there is a trade off: one thus needs more microscopic knowledge about the medium – onium interaction (typically: cross section)

Effective theories, models and phenomenology

III. Rate equations

In pNRQCD, Schroedinger – like equation for the correlation : $\langle \psi_s(t) | \psi_s(0) \rangle$

$$i\partial_t \langle \psi_s(t)\psi_s(0)\rangle = \left(V^{QCD}(R) + \mathcal{O}(m_Q^{-1}) + \Theta(R,t)\right)\langle \psi_s(t)\psi_s(0)\rangle$$

Laine et al. (JHEP 0703 (2007) 054) : real time formalism to deduce the potential V:

- Real part: « usual » screening at short distance
- Imaginary part: corresponding to gluo-dissociation and dissociation by scattering with external parton (appears as « Landau Damping » in the formalism

➡ Eigenstate for $\langle \psi_s(t) | \psi_s(0) \rangle$: $E = E_R + i\,E_i$ = $E = E_R + i\,\Gamma/2$

Interpreted as the dissociation ->
octet Q-Qbar states above threshold

➡ Dissociation rate

Effective theories, models and phenomenology

III. Rate equations

- At small distance (r<1/T): rare process in the QGP => can be interpreted in terms of usual cross sections

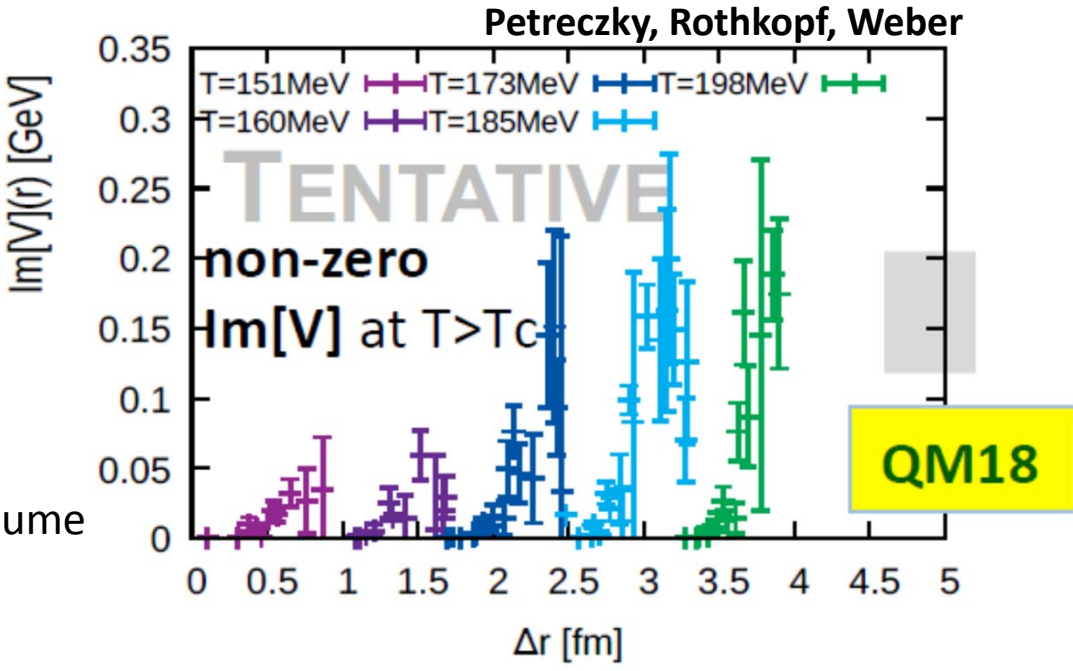
- Interesting feature: can also be evaluated at larger distances (where the interpretation in terms of individual collisions is less obvious) by implementing NRQCD on the lattice :

- => Bottomonium probability to survive:

$$S = \int_0^{+\infty} e^{-\Gamma(T(t))} dt$$

Averaged on the QGP volume

- Approach initiated by Kent State University (see slide « n-4 » for comparison with transport)

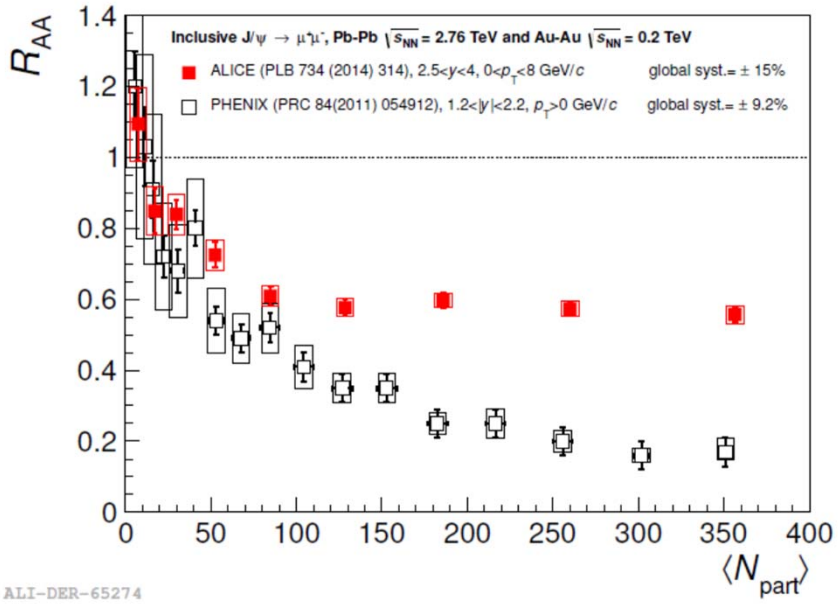


N.B.: lQCD still cannot solve the full problem but provides more and more valuable information

Consequences on R_{AA} and v_2

Charm sector: good overall consistency of the following facts:

- Increase of J/Psi production from RHIC -> LHC
- Mostly at low p_T where regeneration is expected



Not paying too much attention at CNM effects:

Consequences on R_{AA} and v_2

Charm sector: good overall consistency of the following facts:

- Increase of J/ψ production from RHIC -> LHC
- Mostly at low p_T where regeneration is expected
- Finite v2(J/ψ) observed for the first time with 5σ confidence
- Washing out of the spectral function (only J/ψ survive for T < 0.25 GeV)
- Statistical ratio achieved for ψ' / J/ψ at LHC for central and semi-central

Not paying too much attention at CNM effects:

With the interpretation that a large fraction of direct quarkonia are produced through recombination (also see in transport models)

N.B.: if state not dissociated / tightly bound, then little recomb. as well (small Γ) => cannot benefit from the v_2(c), except it some significant elastic scattering (no sign for this)

$$\frac{dN_\Phi}{dt} = -\Gamma(T(t))\,(N_\Phi - N_{\Phi,\mathrm{eq}}(T(t)))$$

Remaining challenges:

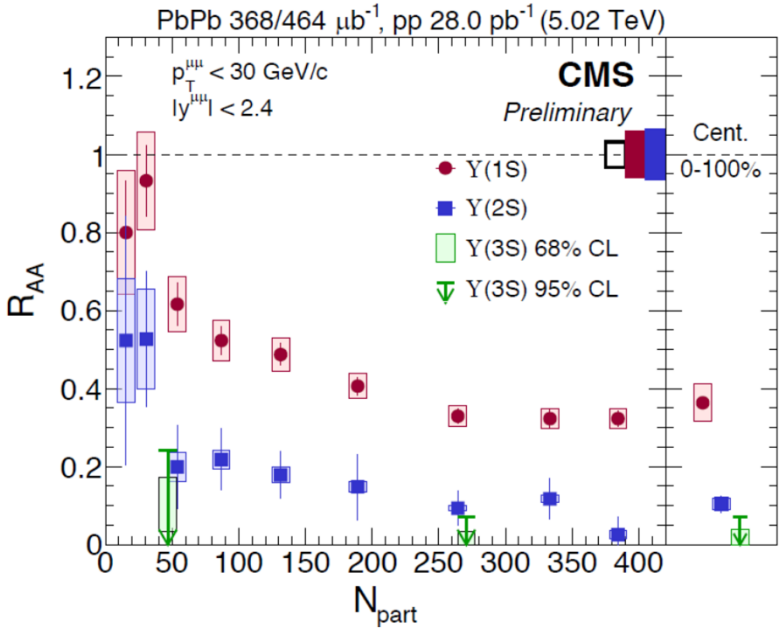
- v_2 at finite (5-10 GeV) p_T (A lot of effects can destroy the Onium, but how to give it v_2 ?)
- role of the magnetic field (not discussed)

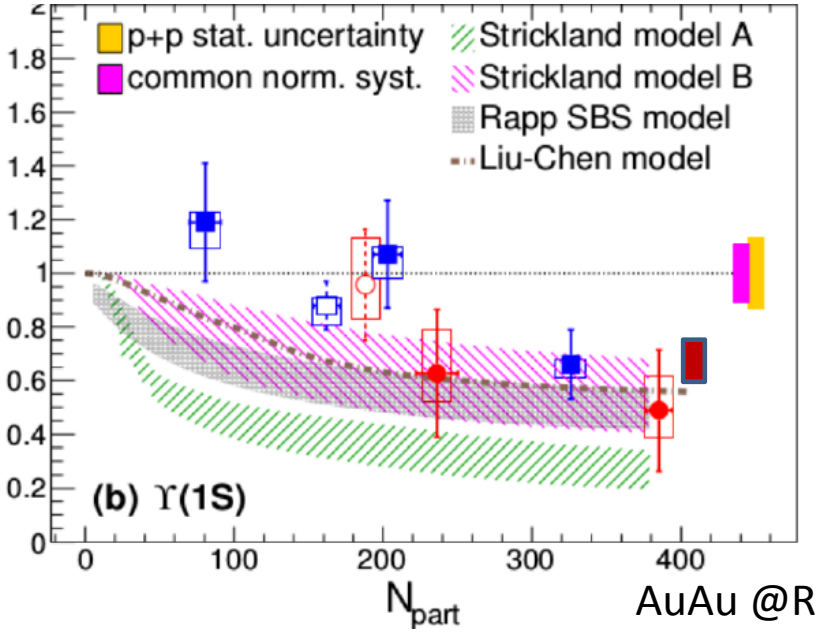
Consequences on R_{AA} and v_2

Beauty sector: good overall consistency of the following facts:

- Similar production of Y(1S) production from RHIC -> LHC
- Higher states strongly suppressed

Not paying too much attention at CNM effects:





AuAu @RHIC

Consequences on R_{AA} and v_2

Beauty sector: good overall consistency of the following facts:

- Similar production of Y(1S) production from RHIC -> LHC
- Higher states strongly suppressed
- Washing out of the spectral function (but the Y(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 Y(1S)) are suppressed both at RHIC and LHC in the QGP, while the gound state Y(1S) survive and is thus a genuine hard QGP probe; higher states could be produced (partly) through recombination

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

Consequences on R_{AA} and v_2

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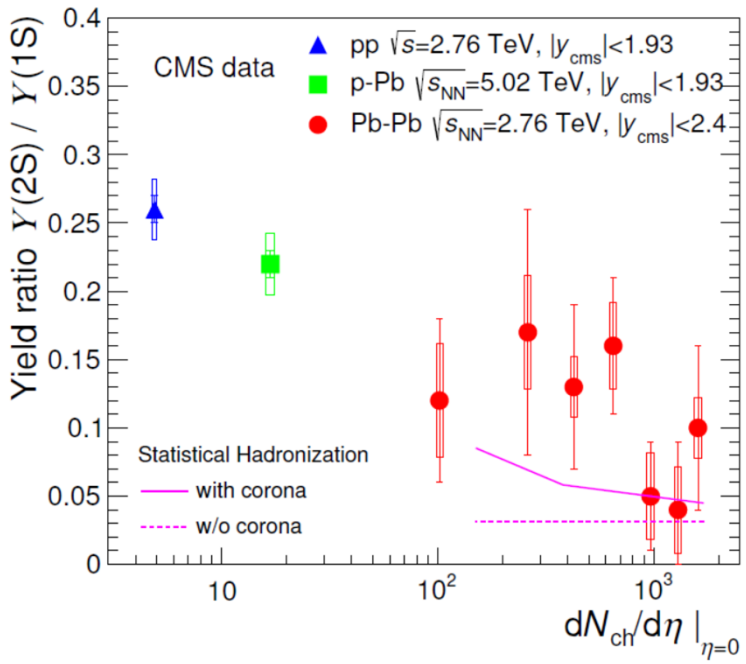
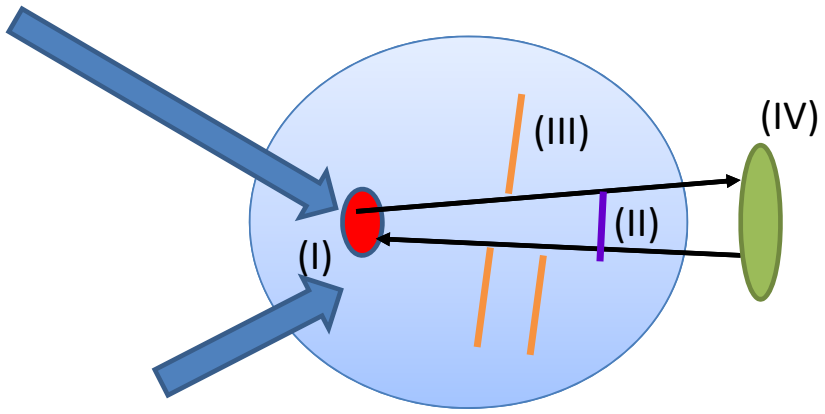
N.B.: Statistical ratio for Y(2S)/Y(1S) overshot at LHC for central and semi-central

Does not obviously fit into the global scheme (let us discuss this if you wish)



Post Modern Era: Open Quantum Systems

More sophisticated : transport (or transport inspired schemes). Different level of descriptions…



… but:

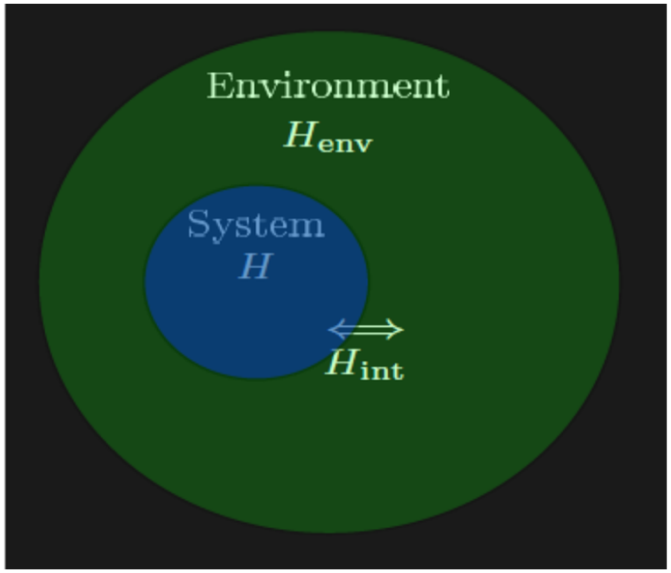
a) they all neglect (for good or bad reasons) quantum interference between states
b) If Γ relies on the notion of cross section: too large rates not compatible with independence between 2 reactions

One thus has to deal with the problem of the evolution of some quantum system coupled to an external heat bath: *iv) Open Quantum Systems*

$\Rightarrow$ Need to trace out the dof of the HB to concentrate on the Q-Qbar state. Such operation is not defined on the full quantum state $|\Psi\rangle$

$\Rightarrow$ Consider the density operator $\hat{\rho} = |\Psi\rangle\langle\Psi|$

$\Rightarrow$ $\hat{\rho}_{Q\bar{Q}} = \mathrm{tr}_{\mathrm{med}}\hat{\rho}$ whose time evolution can be treated



Post Modern Era: Open Quantum Systems

If you are interested:

- E. Ferreiro QM plenary talk
- A. Rothkopf QM student lecture

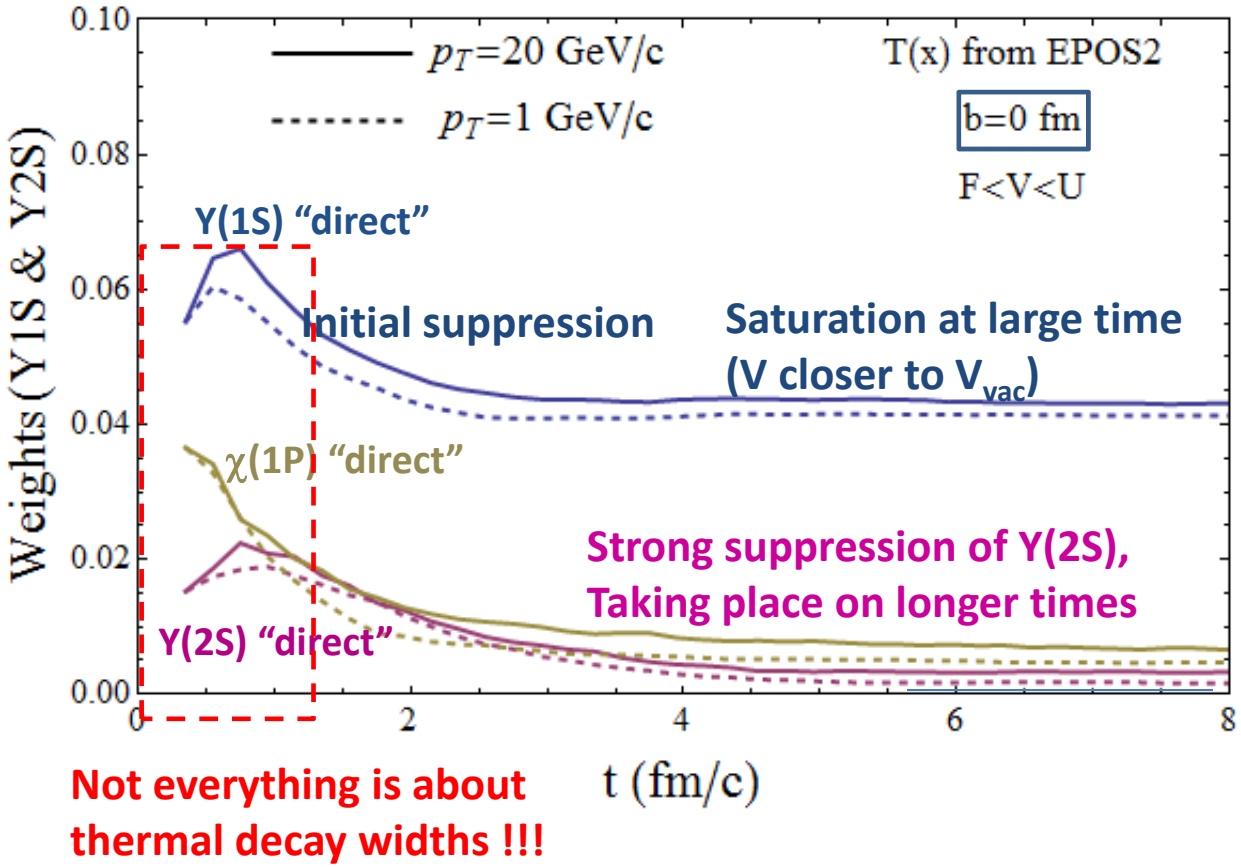
Non trivial effects founds (non monotoneous time evolution)

Nice feature: S <-> O continuous transitions

New vision Quarkonium suppression -> Quarkonium equilibration -> quantum decoherence (of the initial state)

BUT: need to know the initial quantum state ! Non trivial (see following discussion on pp)

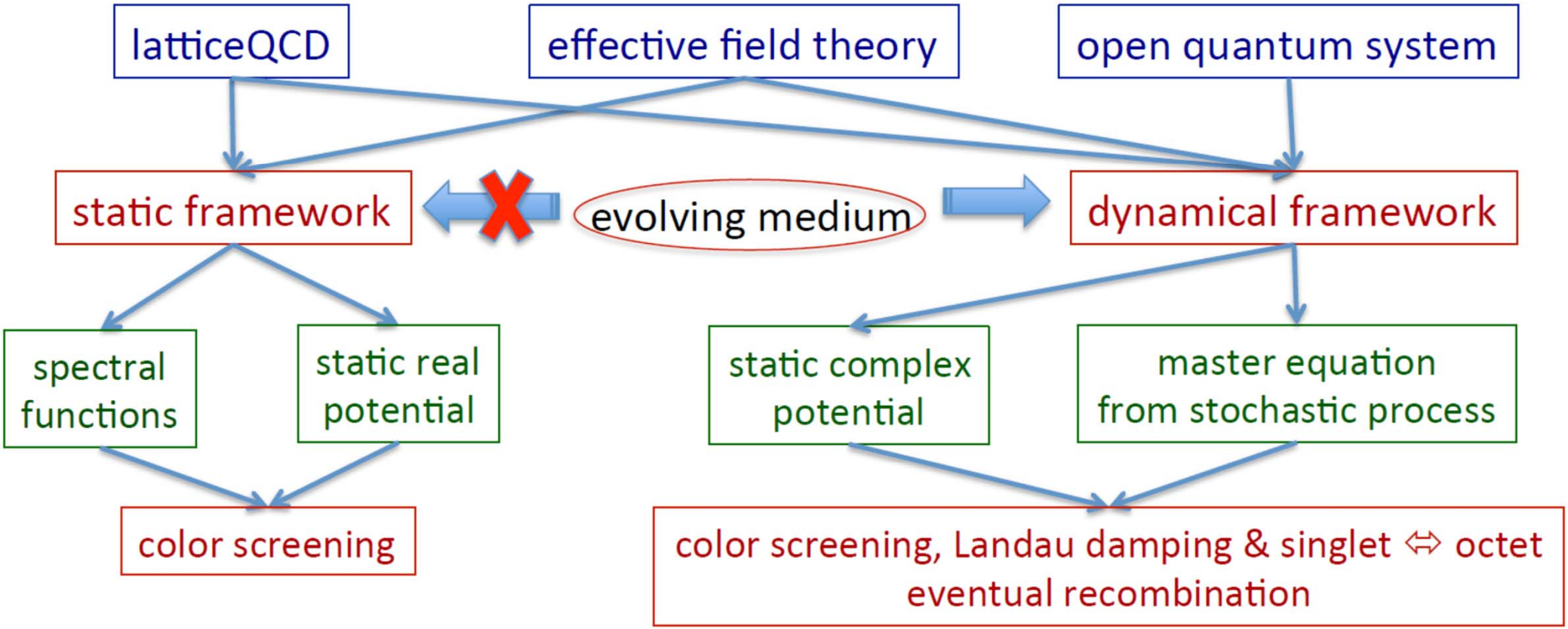
PB Gossiaux, SQM 2017



Not everything is about thermal decay widths !!!

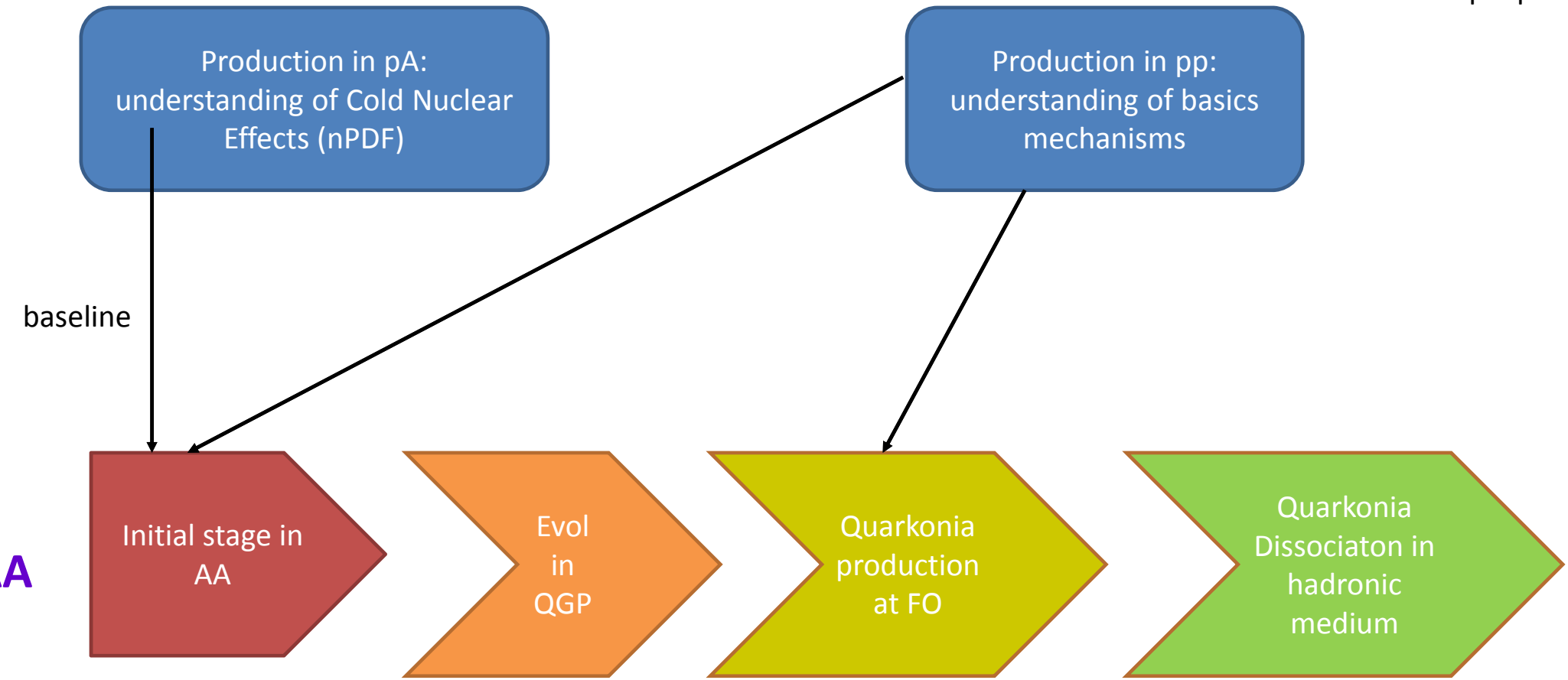
Summary (E. Ferreiro; QM 2018)

Caveat I: we need firm theoretical understanding of quarkonium production in pp collisions



pp & pA: baselines

Simple picture

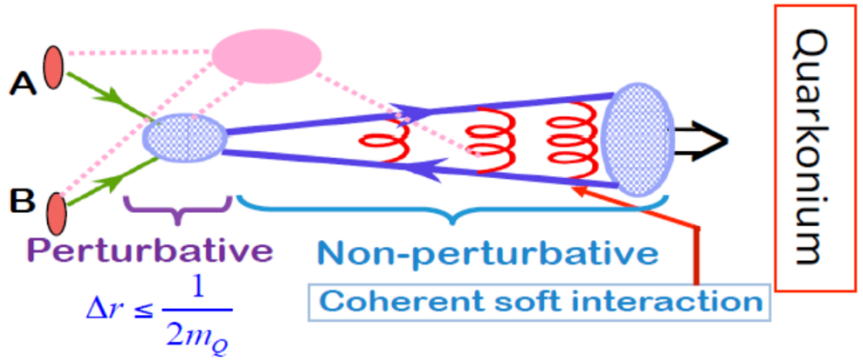


Quarkonia production in pp

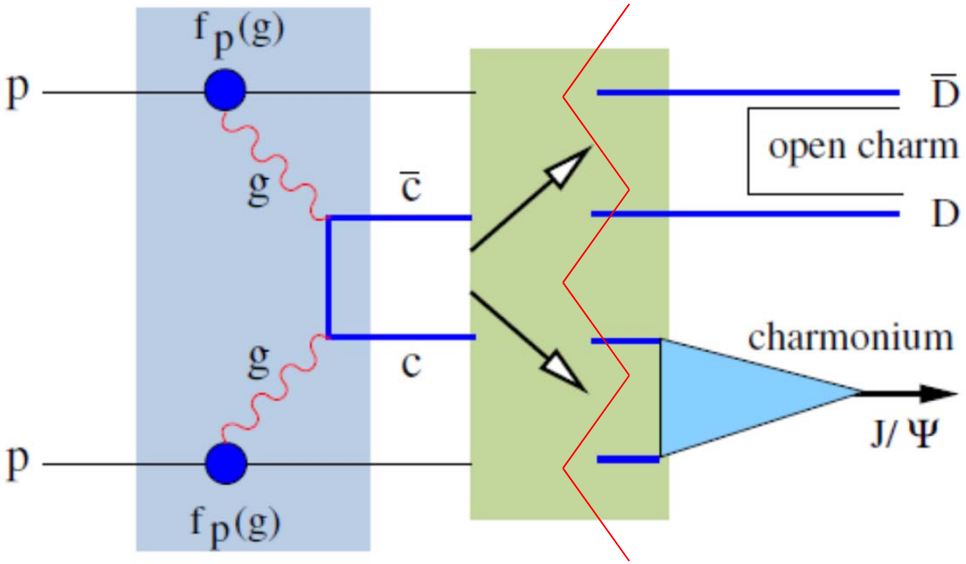
Oversimplistic picture

Quarkonium production involves perturbative and non perturbative QCD

- Production of the heavy-quark pair, $Q\bar{Q}$: perturbative
- Evolution of the $Q\bar{Q}$ pair into the physical quarkonium state: non-perturbative



Quarkonia production in pp



- For Q-Qbar production, usual colinear factorisation:

$$d\sigma^{pp\to Q\bar{Q}+X} = \sum_{i,j} f_i^p(x_1,Q^2) f_j^p(x_2,Q^2) d\sigma^{i,j\to Q\bar{Q}+X}$$

- Then 3 approaches for Q-Qbar -> Onium

- « Standard » rigorous scheme: NRQCD

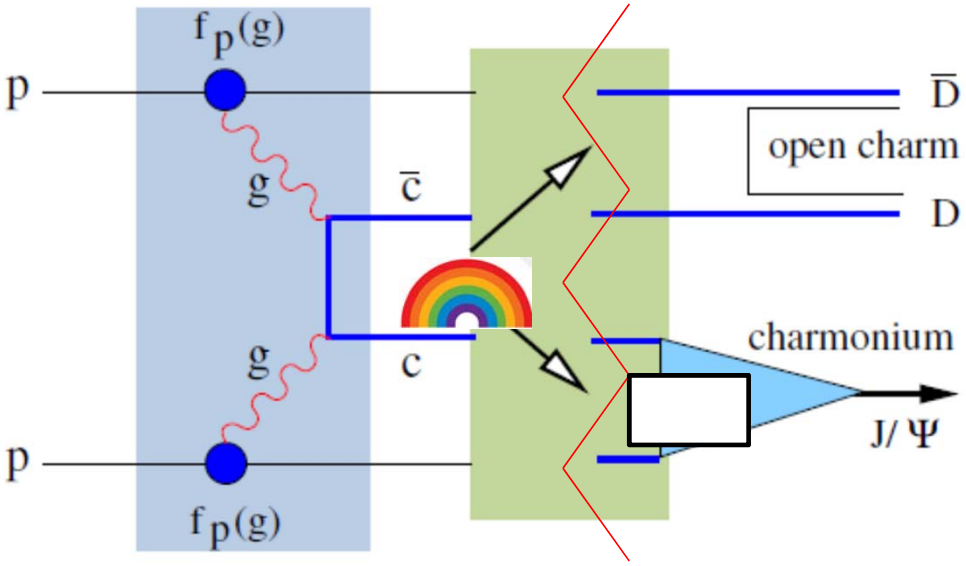
Caswell, Lapage (1986) Bodwin, Braaten, Lepage (1995), …

$$d\sigma^{pp\to J/\psi+X} \approx d\sigma^{pp\to c\bar{c}+X} \otimes \left(\kappa_1 \langle 0|\mathcal{O}_8(^1S_0)|0\rangle + \kappa_2 \langle 0|\mathcal{O}_8(^1P_0)|0\rangle + \dots\right)$$

- Series organized in powers of v and αs; contains octet -> Onium transitions (color neutrality is thought to be preserved by exchanges with the surrounding fields)

Transition matrix element between Q-Qbar state and quarkonia (wave function at origin); free parameterS of the effective theory

Quarkonia production in pp



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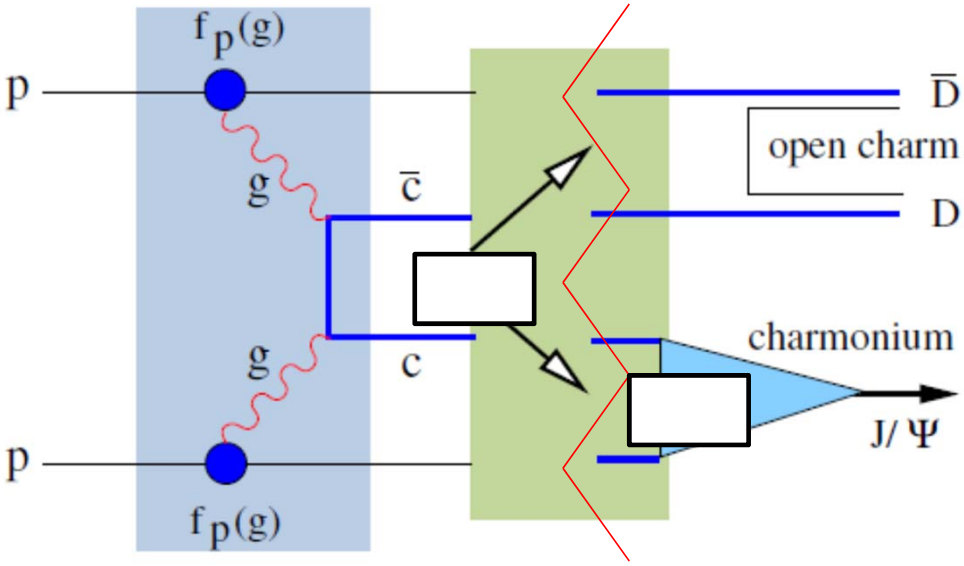
Fritsch (1977), Halzen (1977), …

- Color evaporation model: all Q-Qbar production from $2m_Q$ -> D-Dbar / B-Bar threshold is converted into bound states with statistical weights => Does not distinguish states with respect to their color and spin

- Assumes some « bleaching » of the color -> white objects (similar to NRQCD)

Quarkonia production in pp



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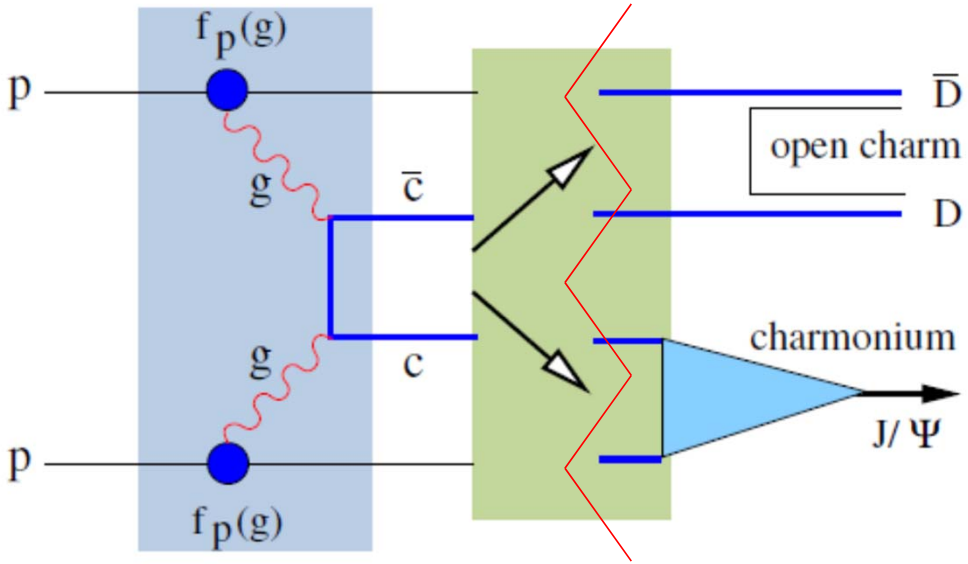
- Then 3 approaches for Q-Qbar -> Onium

Einhorn, Ellis (1975), Chang (1980), Berger & Jone (1981), …

- Color singlet model: Only the Q-Qbar with the right quantum numbers (color and spin) are hadronized -> Onium

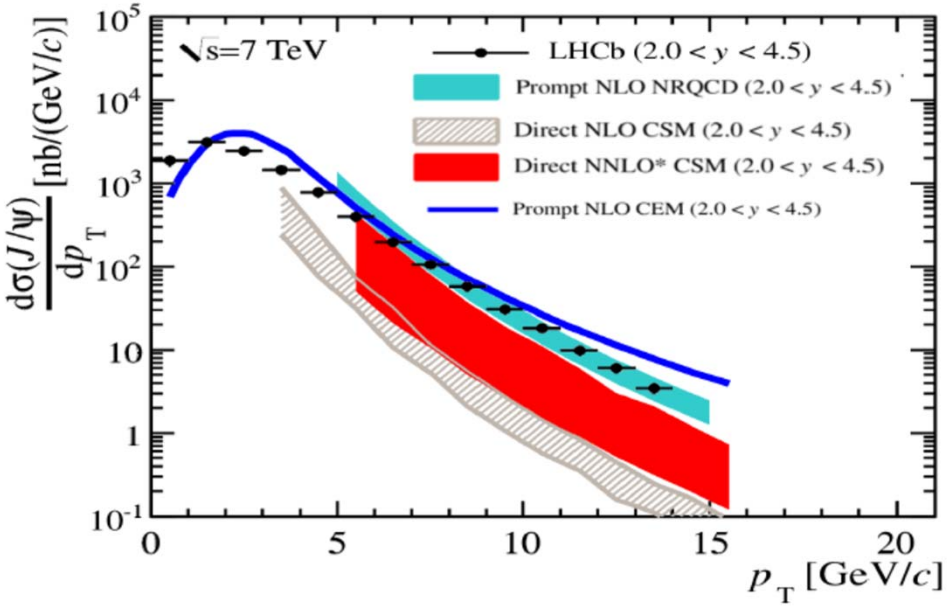
- Detractors of this model would say that CSM is just a fraction of the NRQCD sum.

Quarkonia production in pp



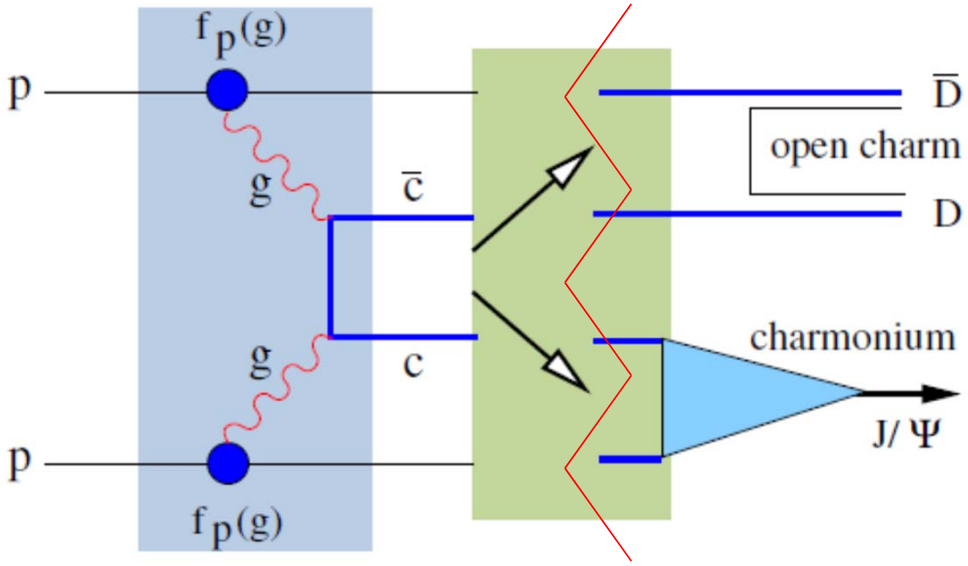
- No consensus on which approach should be retained

- …Then 3 approaches for Q-Qbar -> Onium



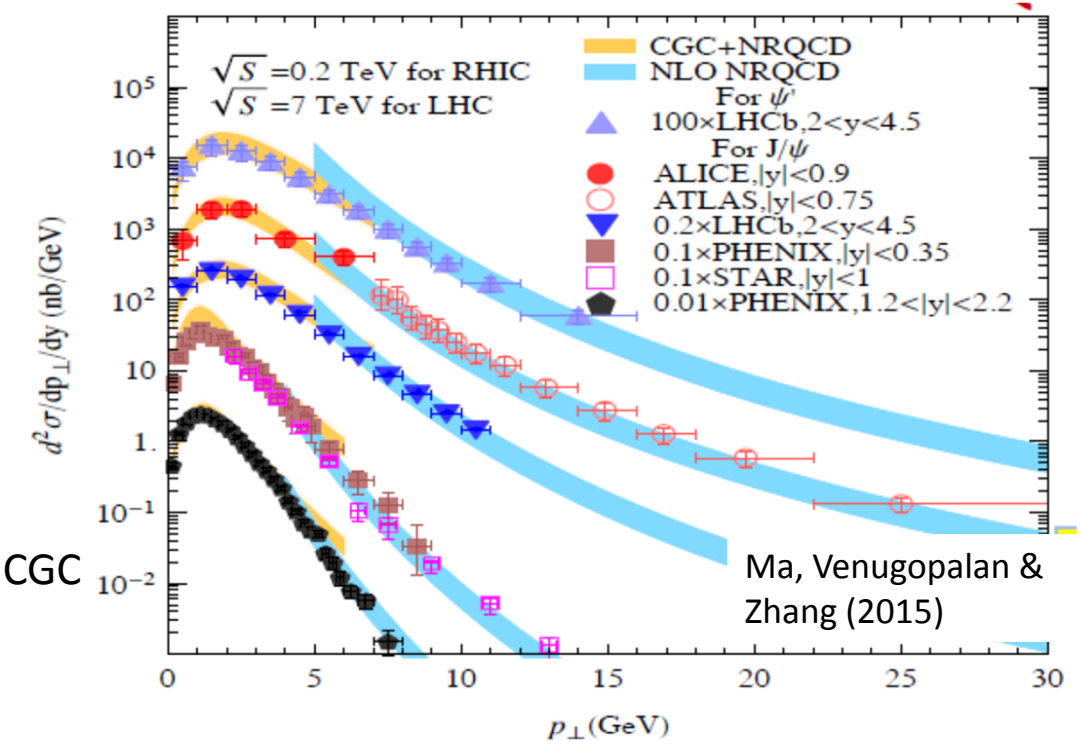
Sapore Gravis Review arXiv:1506.03981

Quarkonia production in pp



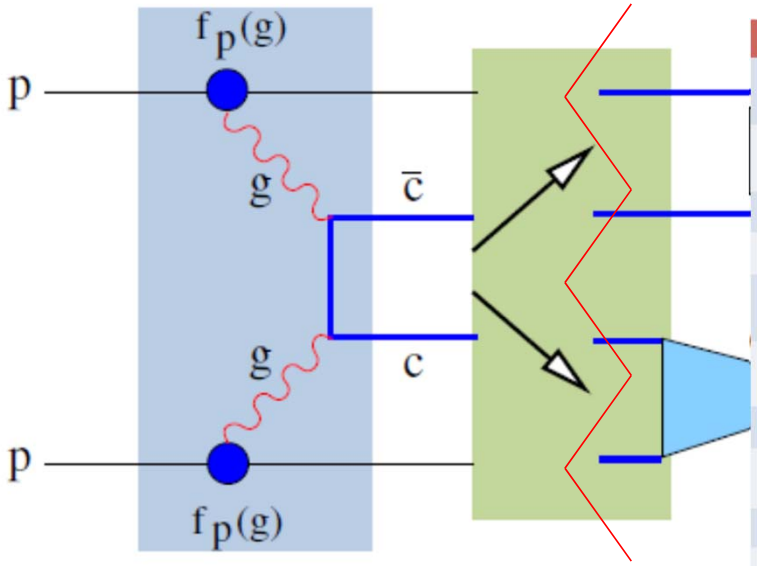
- No consensus on which approach should be retained
- Recent interesting work making the contact between CGC and NRQCD in order to cover the full p_T range.

- …Then 3 approaches for Q-Qbar -> Onium



Ma, Venugopalan & Zhang (2015)

Quarkonia production in pp

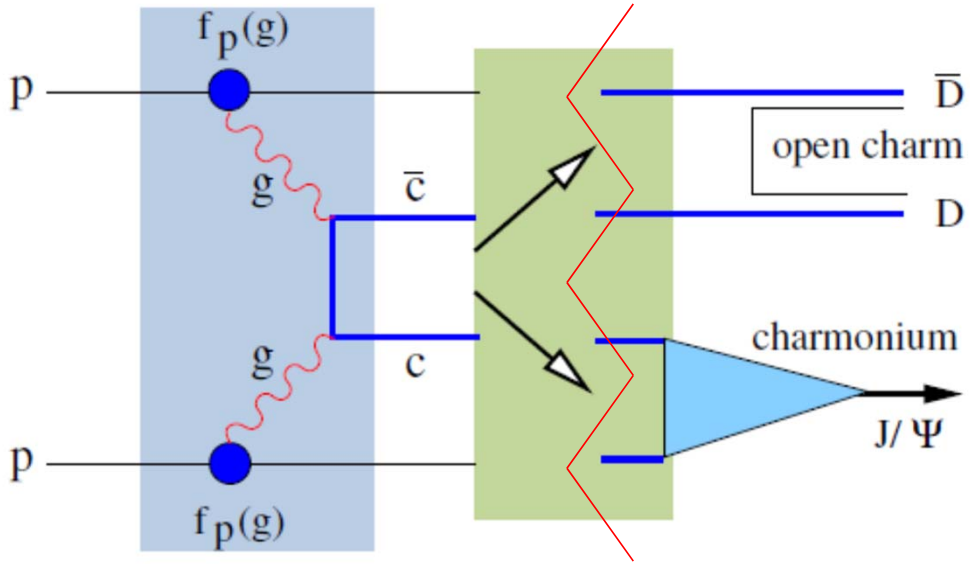


Observables	Experiments	CSM	CEM	NRQCD	Interest
J/ψ+J/ψ	LHCb, CMS, ATLAS, D0 (+NA3)	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CS dominant) + DPS + gluon TMD
J/ψ+D	LHCb	LO	LO ?	LO	Prod. Mechanism (c to J/psi fragmentation) + DPS
J/ψ+Υ	D0	(N)LO	LO ?	LO	Prod. Mechanism (CO dominant) + DPS
J/ψ+hadron	STAR	LO	--	LO	B feed-down; Singlet vs Octet radiation
J/ψ+Z	ATLAS	NLO	NLO	Partial NLO	Prod. Mechanism + DPS
J/ψ+W	ATLAS	LO	LO ?	Partial NLO	Prod. Mechanism (CO dominant) + DPS
J/ψ vs mult.	ALICE,CMS (+UA1)	--	--	--	Density effects (Saturation/Hydro)
J/ψ+b	-- (LHCb, D0, CMS ?)	--	--	LO	Prod. Mechanism (CO dominant) + DPS
Υ+D	LHCb	LO	LO ?	LO	DPS
Υ+γ	--	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CO LDME mix) + gluon TMD/PDF
Υ vs mult.	CMS	--	--	--	Density effects (Saturation/Hydro)
Υ+Z	--	NLO	LO ?	LO	Prod. Mechanism + DPS
Υ+Υ	CMS	NLO?	LO?	LO?	Prod. Mechanism +

Lansberg (2018)

- No consensus on which approach shou
- Recent interesting work making the cc
  order to cover the full p_T range.
- New observables could help to better understand quarkonia production mechanism

Quarkonia production in pp



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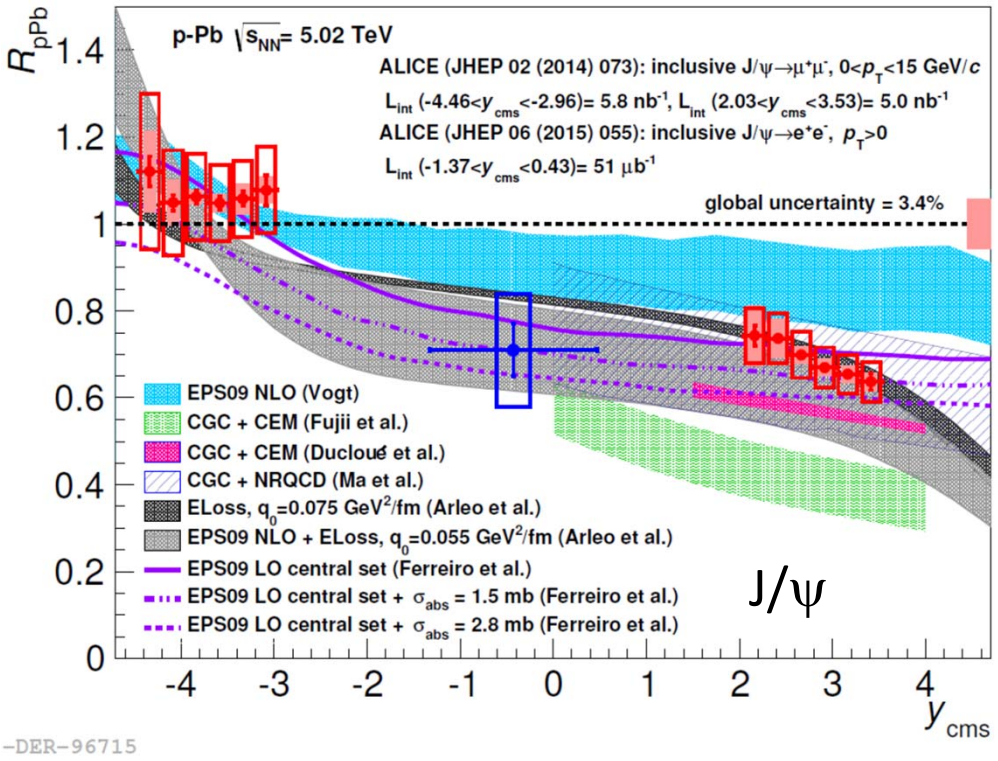
- Then 3 approaches for Q-Qbar -> Onium

Key issues from the view point of production in AA (and even in pA):

- How does the « color bleaching » associated to some models in pp translates -> AA ? Should one take the same matrix elements (after Q-Qbar evolution in QGP) irrespective of the fact that the surrounding field might differ ? N.B.: in this respect, CSM is the simplest.
- What are the time scales associated to the « non perturbative » component in pp ? Does it correspond to some well identified stage in AA ?
- What is the magnitude of the quantitative modifications that could stem from one prescription more then the other ?

More enjoyable considerations in pA



Most conservative : nPDF (initial state effects)

$$d\sigma^{pp\to Q\bar{Q}+X} = \sum_{i,j} f_i^p(x_1,Q^2) f_j^A(x_2,Q^2) d\sigma^{i,j\to Q\bar{Q}+X}$$

… but large uncertainties

CGC: natural scheme for saturation at small x2

Alternate explanations, as for instance coherent energy loss (does not scale with x_2); interference initial – final => no obvious scaling to AA.

Most of the approaches seen in AA do not translate easily to pA (no equilibration); however, some transport-like suppression (comovers; finite state effects) can have a significant role… (whatever they are !)

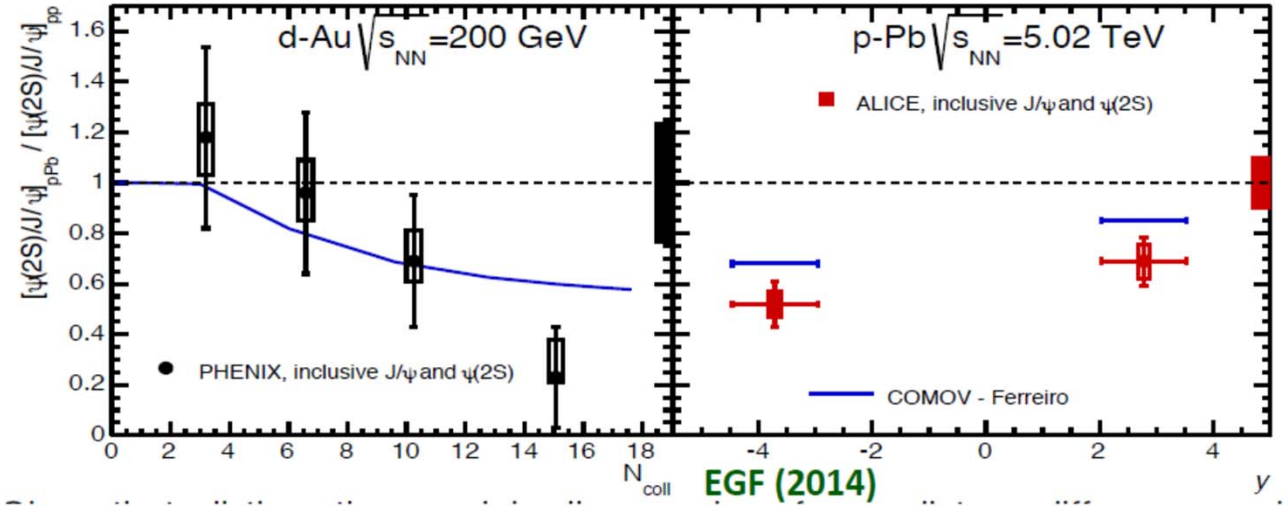
Still no common conceptual baseline for the absolute production in pA

Lessons from excited states in pA

Can they teach us something ? The standard argument is the following:

- Pure nPDF (effects α $p(x_2)$: same for resonance close in mass => cannot be the main effect
- Effects based on coherent Eloss at large y : formation outside the nucleus => the quantum state is the same => the final state should not matter (not quite obvious, but no concrete calculation)

$\Rightarrow$ Final state effects !... (aka Comovers)



$$\tau \frac{d\rho^{\psi}}{d\tau}(b,s,y) = -\sigma^{co-\psi}\,\rho^{co}(b,s,y)\,\rho^{\psi}(b,s,y)$$

$$\sigma^{co-\mathcal{Q}_{b\bar{b}}} = \sigma_{geom}\left(1 - \frac{E_{Binding}}{\langle E_{co}\rangle}\right)^{n}$$

Seems simple, but simple is sometimes the best

(of course, there still can be some common suppression f.i. by nPDF)

charm sector

Lessons from excited states in pA

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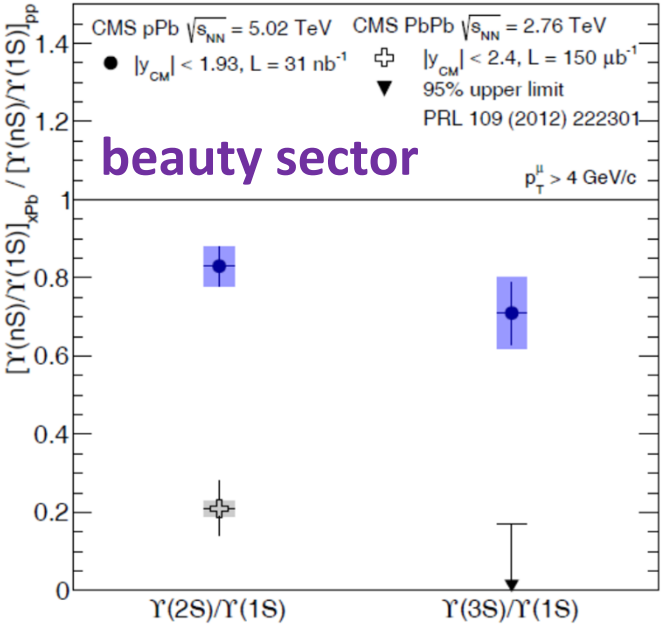
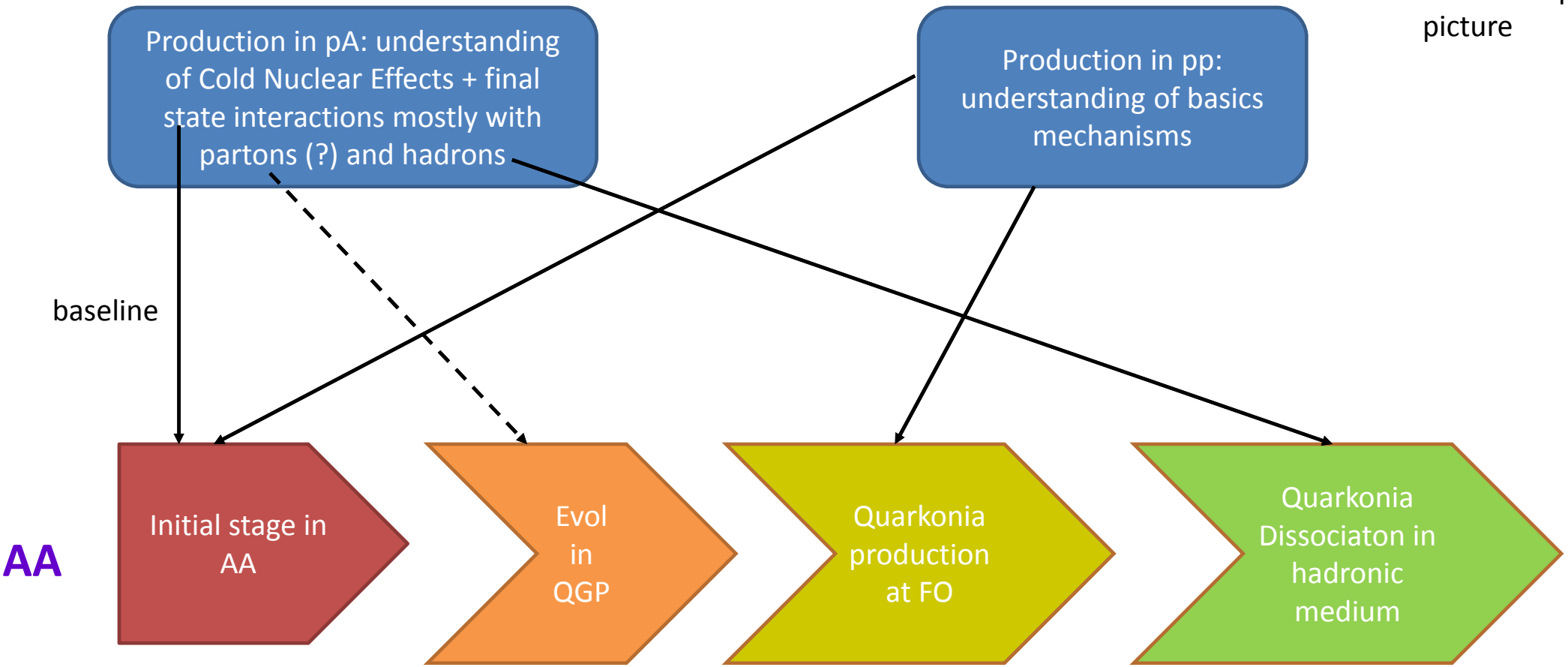


- Some difficulties in the community to accept it (because not defined from first principles ?)
- … but in any case, most of models aiming at describing quarkonium production in pA now include such component…

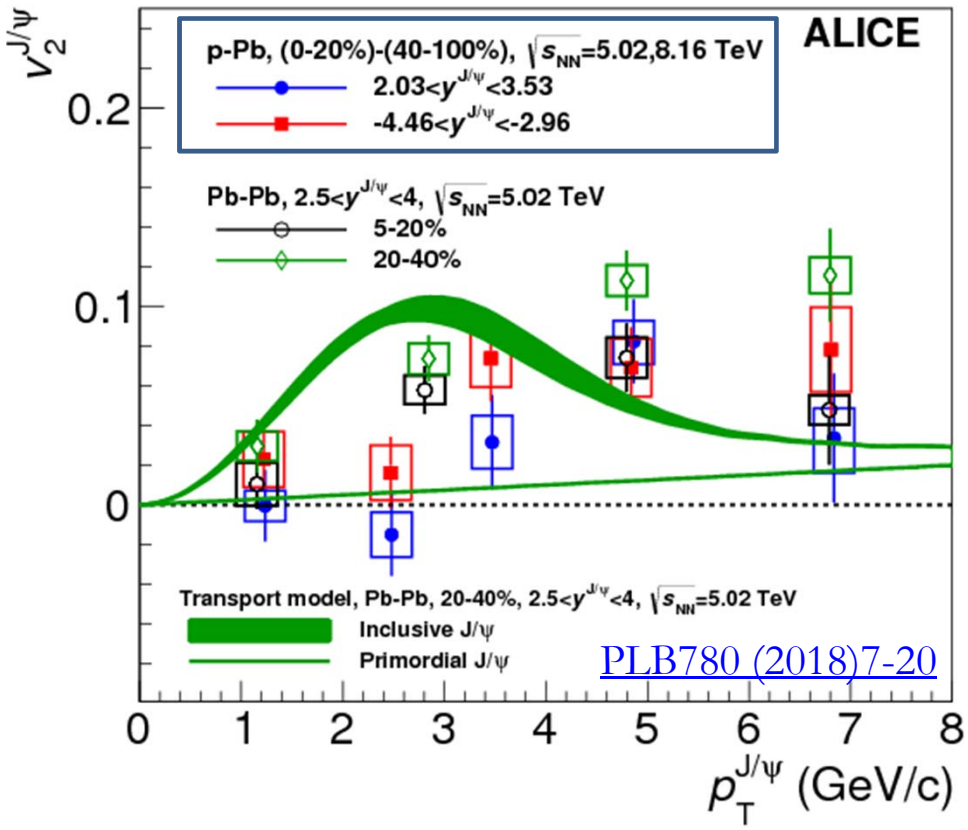
pp & pA: baselines and complications

Not so simple picture



Shocking facts from pA

- **J/ψ flows in pPb as well !!! => No need for recombination?**
- Undermine our « global » understanding of quarkonia production in AA. Of course one may argue that v_2(J/ψ) in pPb is mostly >0 at intermediate p_T where it is not well understood in AA either.



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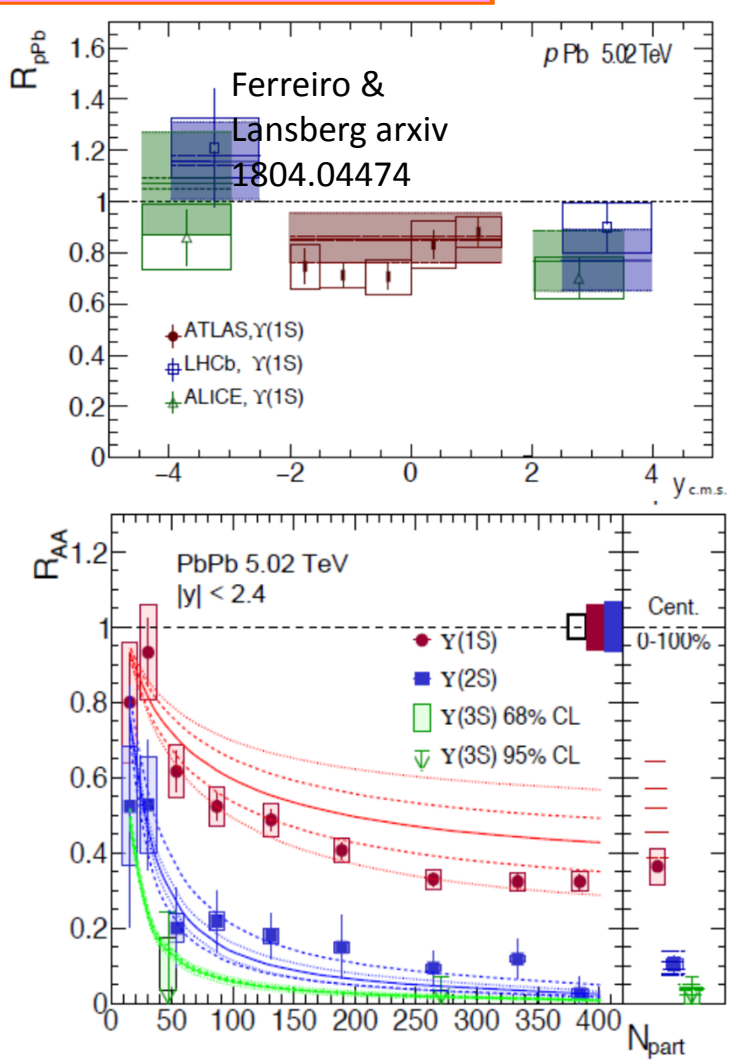
- **Ferreiro and Lansberg: reproduce all known suppression in pA and AA within a generalized comover scenario (+ nPDF), with the same physical content**…
- …No additional QGP physics from pA -> AA ?
- Need better understanding of the comover !
- Once upon a time: also applied for charmonium suppression at SPS

Effects recently discovered in pA are extremely interesting !

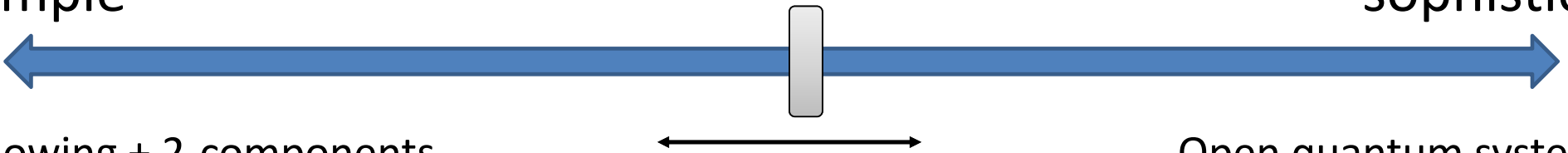
- **Quarkonia formation in pA should not be considered as a mere baseline for AA but as a subject of interest of its own**
- **Yet, seen as a « baseline », effects observed in pA have the potentiality to alter drastically the « global understanding » in AA**



Global picture for quarkonia: the 2 faces of “theory”

simple

sophisticated



Shadowing + 2-components model (comovers + statistical generation at FO)

Open quantum system with $H_{interaction}$ tuned on lQCD constrains

Where should we position the « cursor » in order to claim hard probing QGP with quarkonia ?

I invite you to make you own judgment, with the help of this great conference !