SQM 2016 - TH Summary for EMMI RRTF-HQ

Vincenzo Greco University of Catania

EMMI Rapid Reaction Task Force
"Extraction of HQ transport coefficient in QCD matter"

July 18th, 2016, GSI- Germany

Overview

- ✧ TH Plenary Talks: 10
- ✧ TH Parallel Talks: 42 (4 parallel sessions)
- ✧ TH Theory Summary: 1

Time evolution

	Mon-27	Tue-28	Wed-29	Thur -30	Fri - 1
Plenary	3	1	4	2	
Parallel	0	24	0	18	

Outline

✧ No Intro/Overview of the field but only some:

- Open Heavy Flavor
- Quarkonia

slides from SQM2016

Open Heavy Flavor

One remark

Differences with bulk QGP dynamics:

- Initial state known (FONLL- pp, pA data)
- Non-equilibrium $\tau \geq \tau_{QGP}$ → Carry info on detailed dynamics

❖ After ≈ 12 years we still struggle with R_{AA} and V_2
Differently w.r.t. to light bulk - hydrodynamics
T dependence of interaction very relevant

Open Heavy Flavor

One remark

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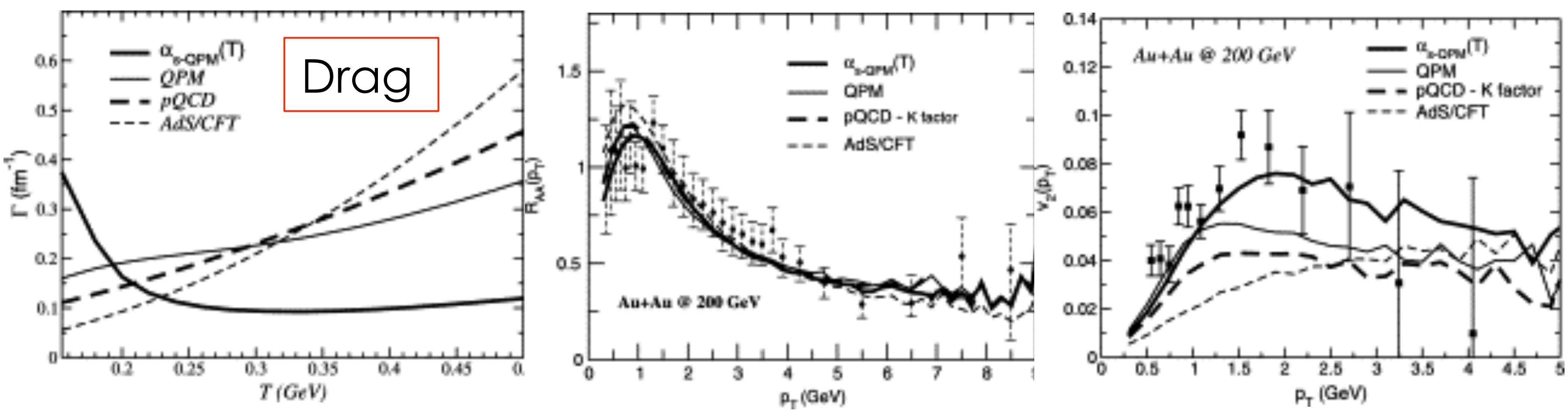
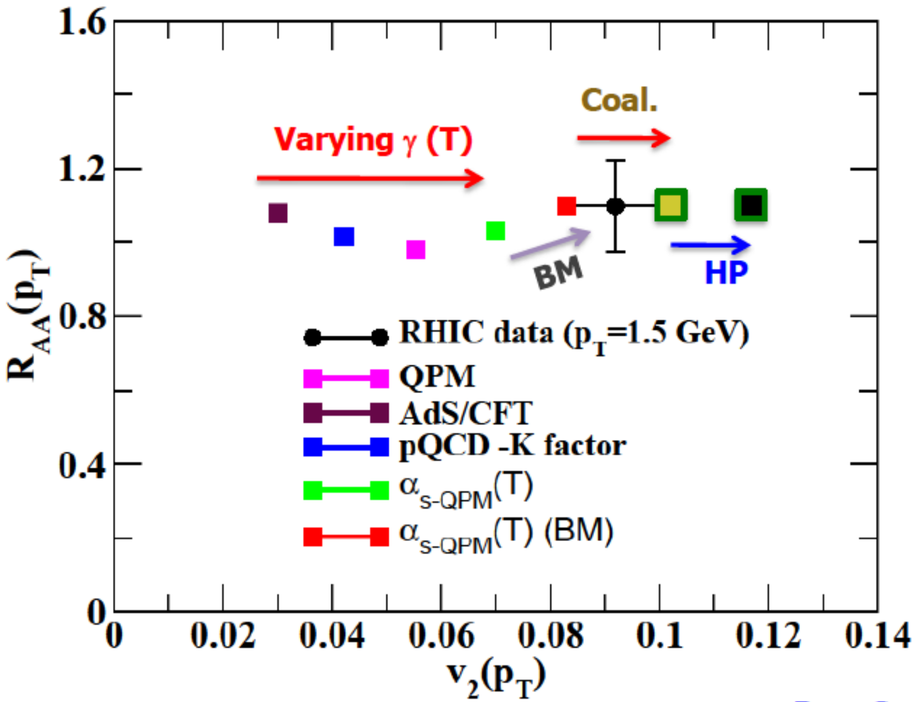


S. Cao, Mon 14:30

S. Das et al., PLB747 (2015) 260

$R_{AA} - V_2$

S. Das, Thu 16:30



Tuning all cases to similar R_{AA} drag $\Gamma(T)$ for HQ much more impact than $\eta/s(T)$ for bulk evolution:

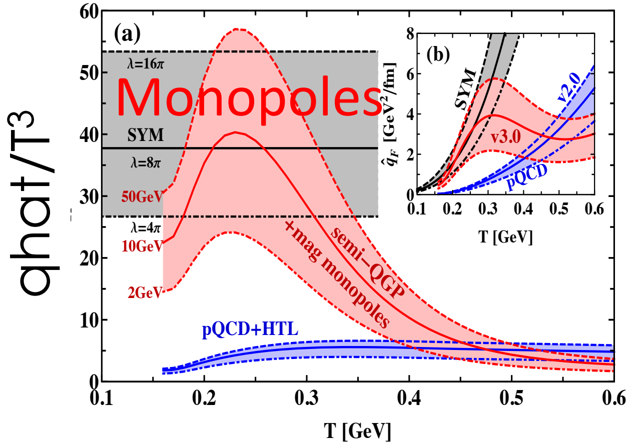
- factor 2.5-3 in v_2 of HQ **vs** 15-20% in v_2 light hadrons

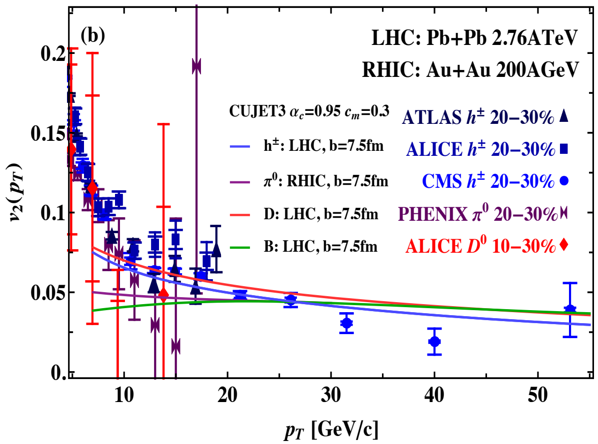
✧ Both pQCD (α_s=cost) & AdS/CFT $\Gamma \approx T^2$

✧ At RHIC solution for R_{AA}-v_2, not clear is sufficient at LHC (still large error bars)

Open HF – High p_T jets

J. Liao, Wed 12:00





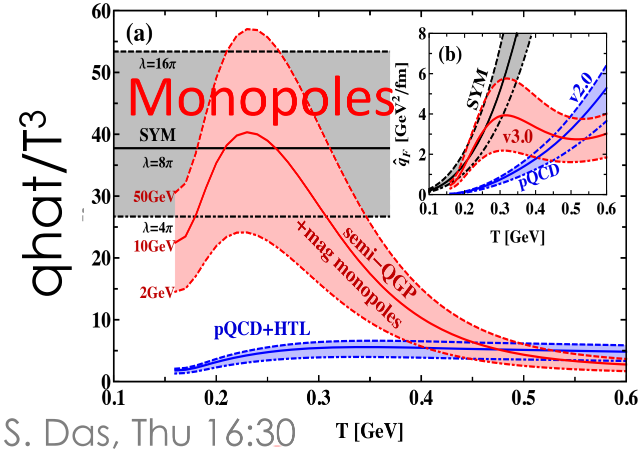
[J. Xu et al. arXiv: 1411.3673]
CUJET3.0 explains 7 sets of E_{loss} data at RHIC +LHC

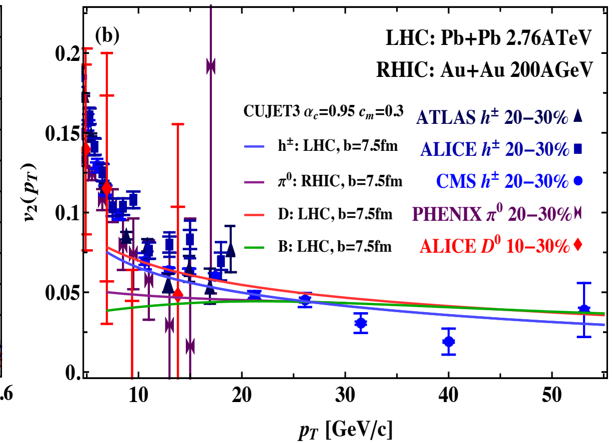
See also Caio Prado's Talk, Thu 11:20 – also prediction v_3

Both Non-eq. dynamics

Open HF – High pT jets

J. Liao, Wed 12:00





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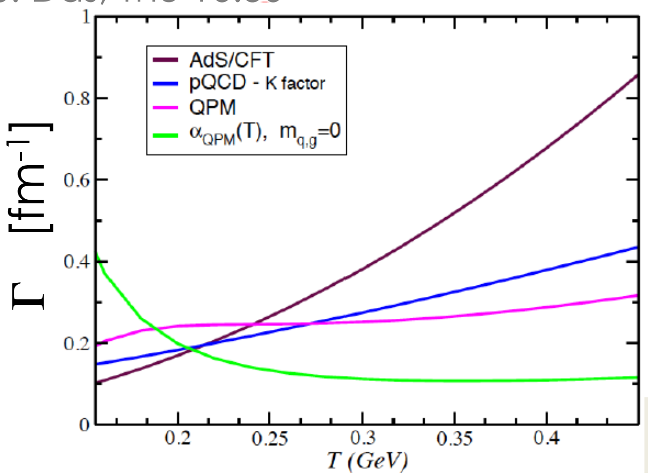
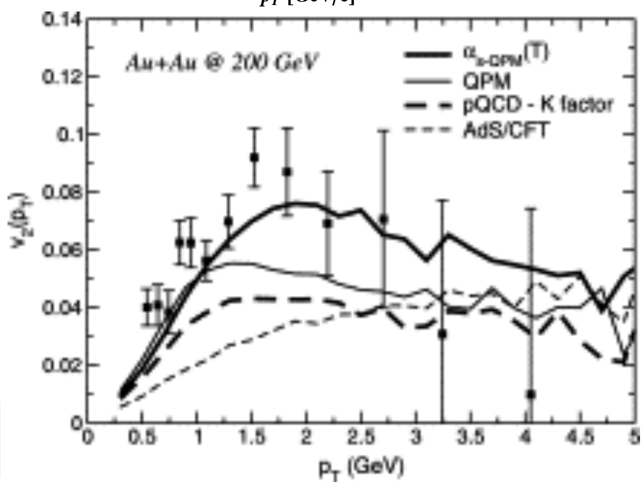
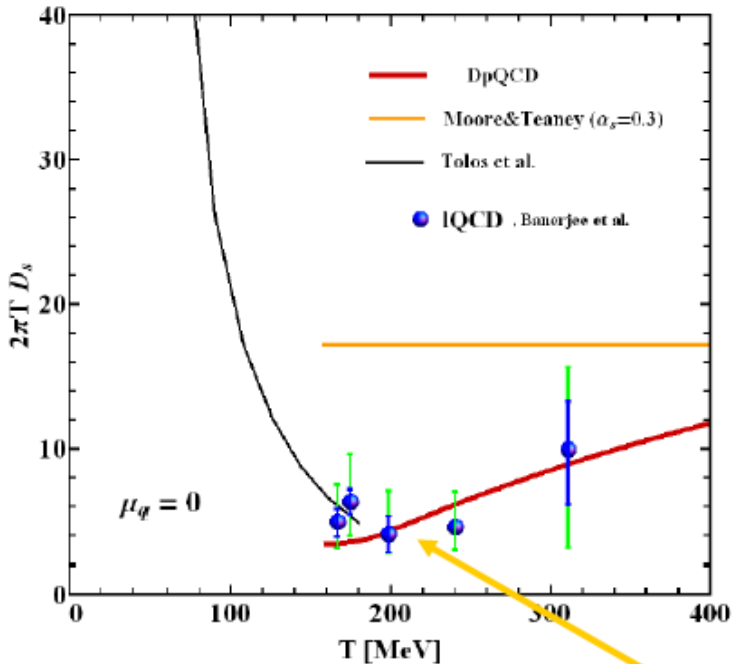




Drag (HQ transp.)	Diff. space (lQCD)	Jet transp. Coeff.
AdS/CFT, pQCD → $\Gamma \approx T^2$	$D_s(2\pi T) \approx$ cost	$q/T^3 \approx$ cost
QPM, PHSD, → T-matrix, CuJet3... $\Gamma \approx T^{0\text{-}1}$	$D_s(2\pi T) \approx T^{1\text{-}2}$	$q/T^3 \approx 1/T^{1\text{-}2}$

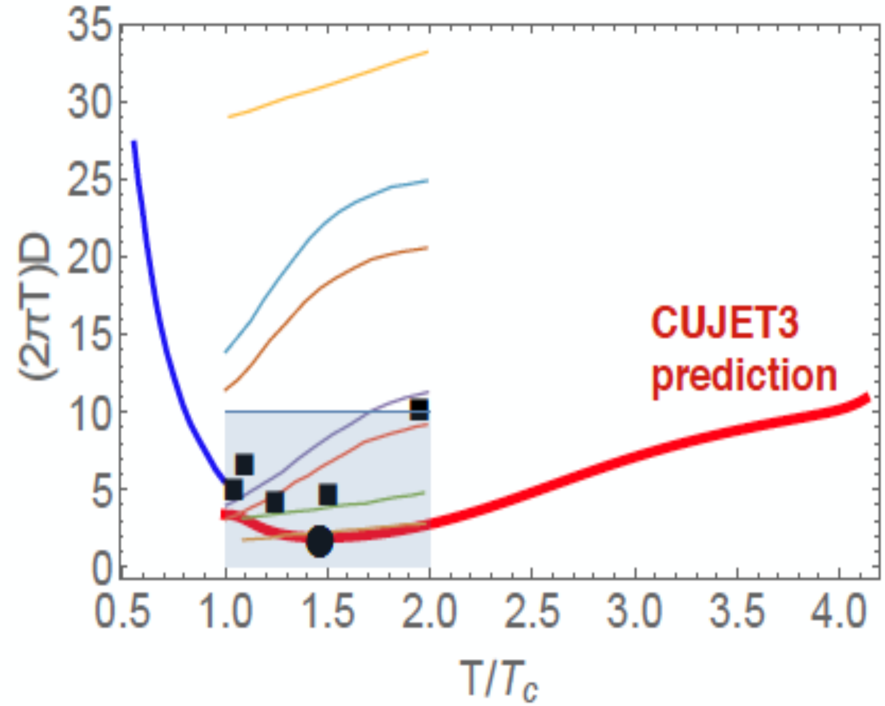
From HQ



❑ **T < T_c : hadronic D_s**

E. Bratkovaskaya's talk, Tue 16:20
Similar for TAMU, Nantes, Catania…

From Jets



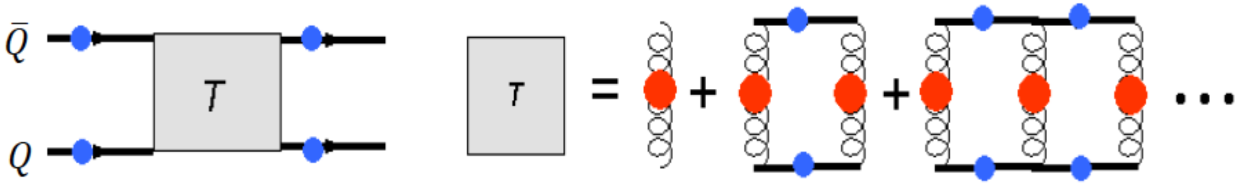
J. Liao's talk

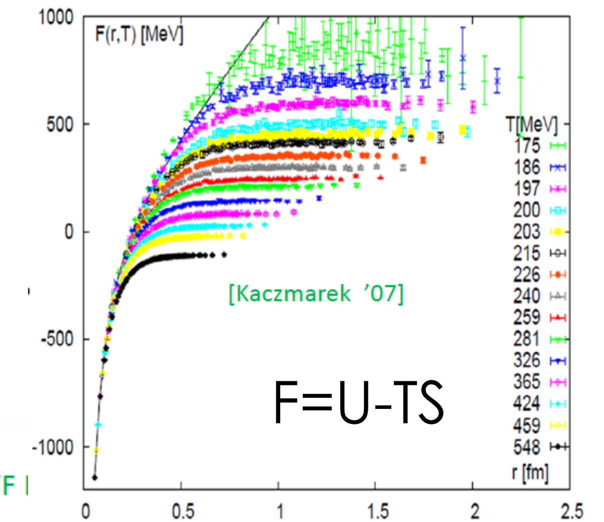
This is a result nearly independent on the microscopic dynamics

T-matrix developments

SYF Liu, Tue 16:00

❖Infinite-mass limit: T-matrix can calculate $\tilde{G}^{>}(-i\tau, r)$ as:

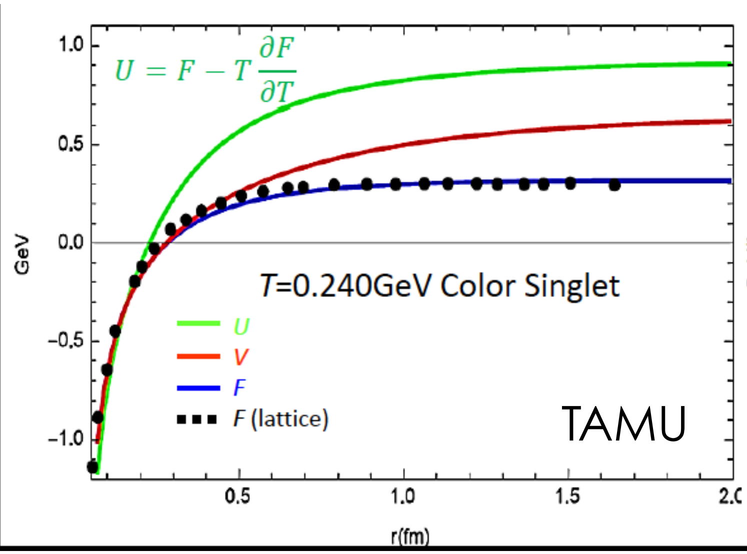




Fit screened Cornell V(r)+ Im. part. (pert.-like ansatz)

$$F_{Q\bar{Q}}(T,r) = -T\ln\left(\int_{-\infty}^{\infty} dE\, \frac{-1}{\pi} \frac{(V+\hat{\Sigma})_I(E)}{\left(E-(V+\hat{\Sigma})_R\right)^2 + (V+\hat{\Sigma})_I^2(E)} e^{-\beta E}\right)$$

➢ Compare T-matrix $F_{Q\bar{Q}}(T,r)$ with lattice $F_{Q\bar{Q}}(T,r)$ to extract in-medium $V(r)$ and $\hat{\Sigma}$



- ➢ A way to solve the issue of V from F=U-TS
- ➢ Potential keeps long range remnants of confinement
- ➢ Outlook: Σ self-consistent from T-matrix, quarkonium correlator, HQ susceptibilities, EoS, 3-body?

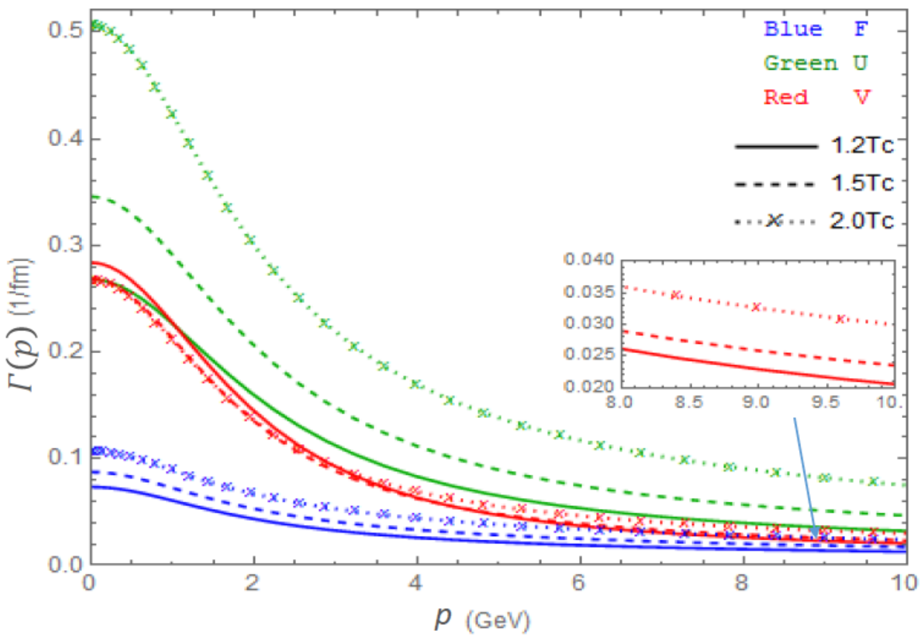
T-matrix developments:

SYF Liu, Tue 16:00

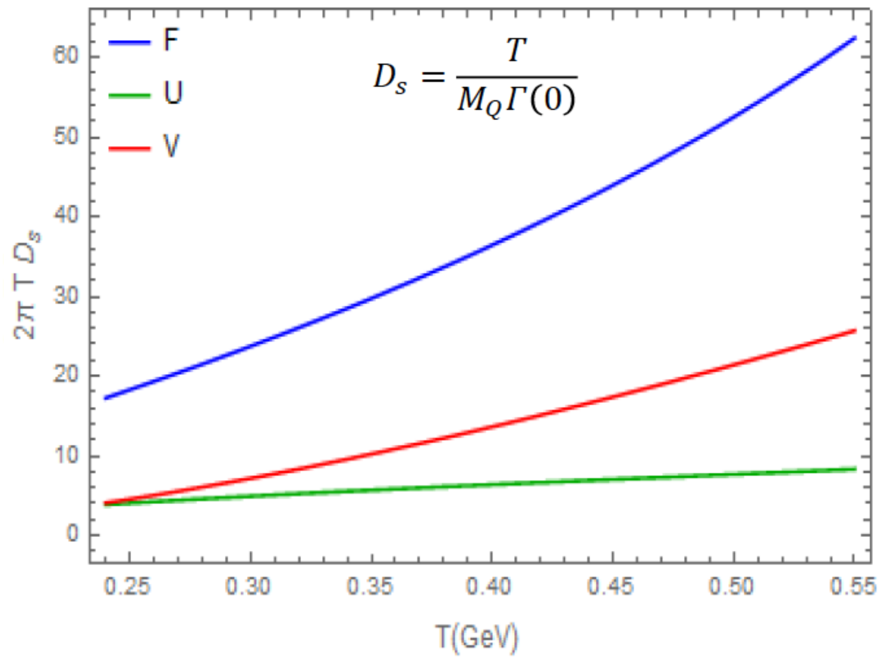
- Relaxation rate (drag coefficient)

$$\Gamma(p) = \frac{1}{2\omega_Q(p)} \sum \int d^3\tilde{q} d^3\tilde{q}' d^3\tilde{p}' n_i(\omega_q) \cdot \frac{(2\pi)^4}{d_c} C_f |T(E_{cm}|\mathbf{p}_{cm}, \mathbf{p}'_{cm})|^2 \delta^4(p+q-p'-q') \left(1 - \frac{p\,p'}{p^2}\right)$$

Relaxation rate for *F U V*



Spatial Diffusion Coefficient



- **For *V***
  - **Infrared enhancement due to long range force**
  - **Different (slightly reversed) *T* dependence at low *p***
  - **Recover usual *T* dependence at high *p***

Open Heavy Flavor

Medium Energy Loss

S. Cao, Thu 12:00

Linearized Boltzmann Transport : Rad. + Coll. E_{loss} (LBL-CCNU)

Inelastic Scatt. Probab. based on the average number of medium-induced gluon

Average gluon number in *Δt*:

$$\langle N_g\rangle(E,T,t,\Delta t) = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

Spectrum of medium-induced gluon (higher-twist formalism):

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)}{\pi k_\perp^4} \hat{q} \left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4 \sin^2\left(\frac{t-t_i}{2\tau_f}\right)$$

Number *n* of radiated gluons during *Δt* – Poisson distribution:

$$P(n) = \frac{\langle N_g\rangle^n}{n!} e^{-\langle N_g\rangle}$$

Probability of inelastic scattering during *Δt*: $P_{\text{inel}} = 1 - e^{-\langle N_g\rangle}$

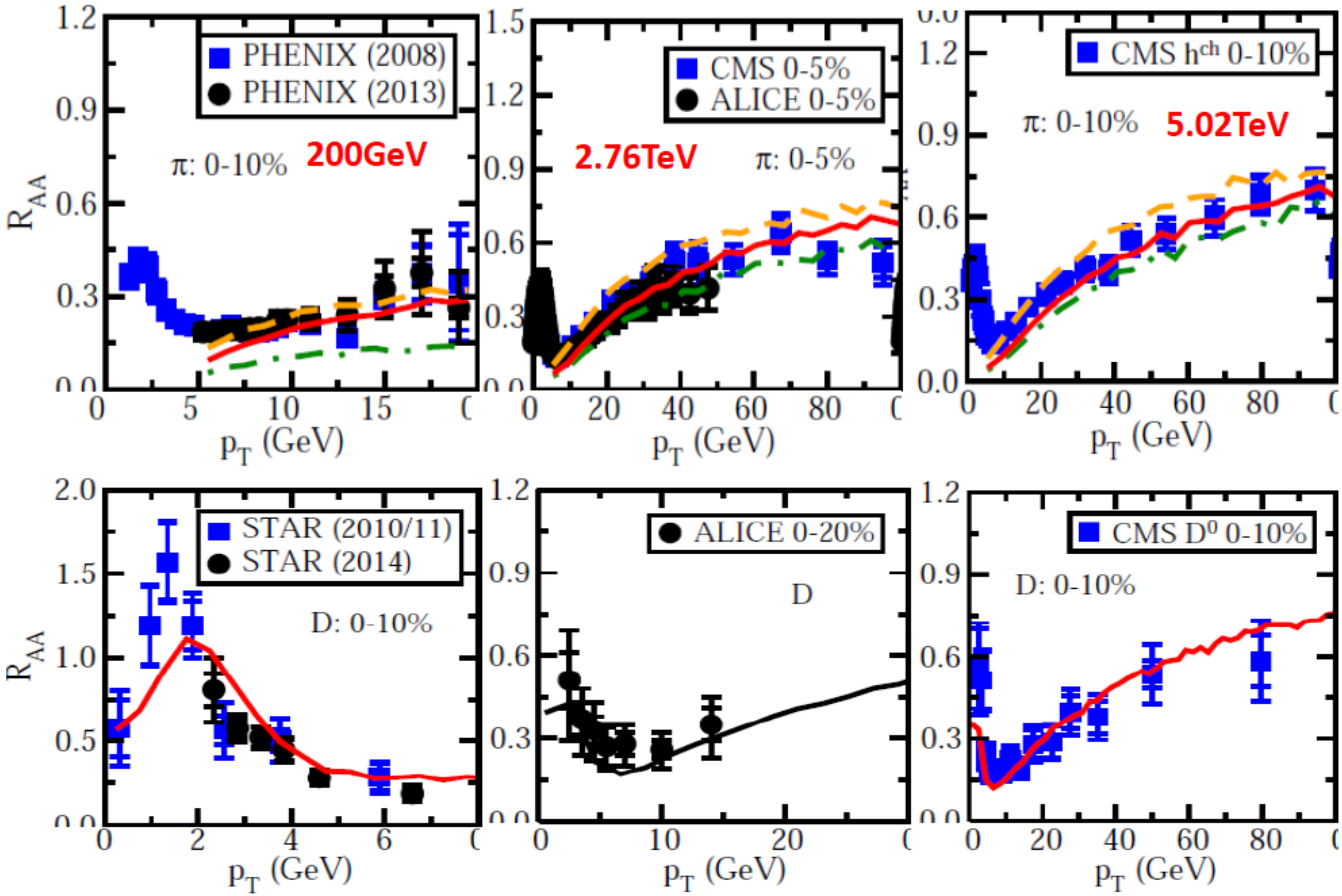
[Guo and Wang (2000), Majumder (2012); Zhang, Wang and Wang (2004)]

[S.Cao, Luo, Qin and Wang, arXiv: 1605.06447]

G.-Y. Qin, Tue 15:20 S. Cao, Thu 12:00

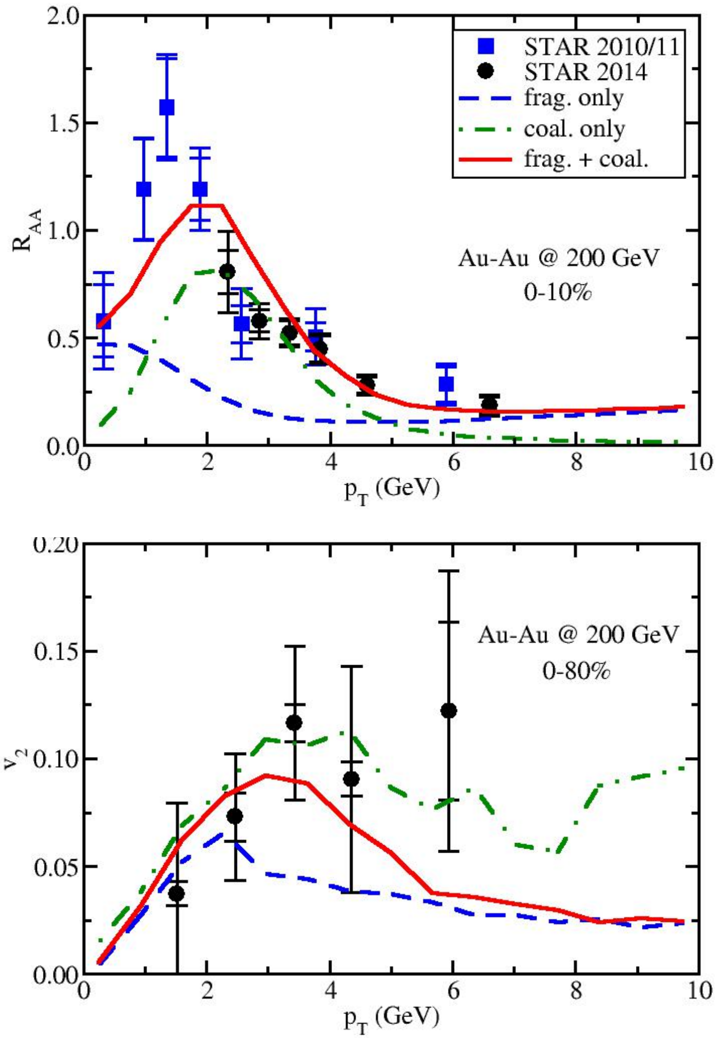
Open Heavy Flavor

R_{AA} from LBT (heavy & light flavor hadrons)



Medium Energy Loss

S. Cao, Thu 12:00



[S.Cao, Luo, Qin and Wang, arXiv: 1605.06447]

- Starting from pQCD T and p depedent K factor are needed:

$$\hat{q} = \hat{q}_{pQCD} \cdot K^2 \left[1 + A_p e^{-\frac{p^2}{2\sigma_p^2}} \right] \left[1 + A_T e^{-\frac{(T-Tc)^2}{2\sigma_T^2}} \right]^2$$

5 dimensional Parameter space: [K, A_p, σ_p, A_T, σ_T]

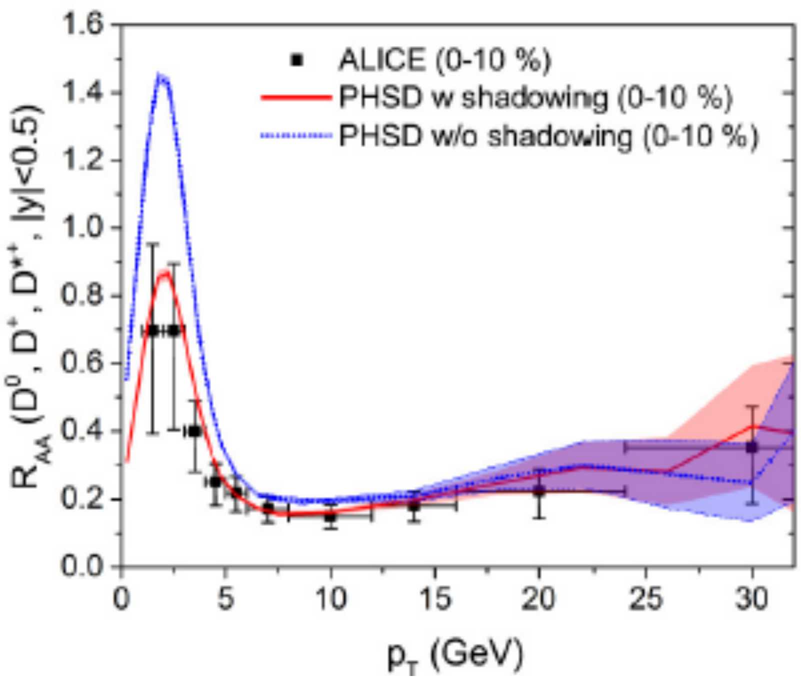
- Compare to data and extract best set of parameters: Gaussian emulator and Bayesan [now undergoing w DUKE Langevin]

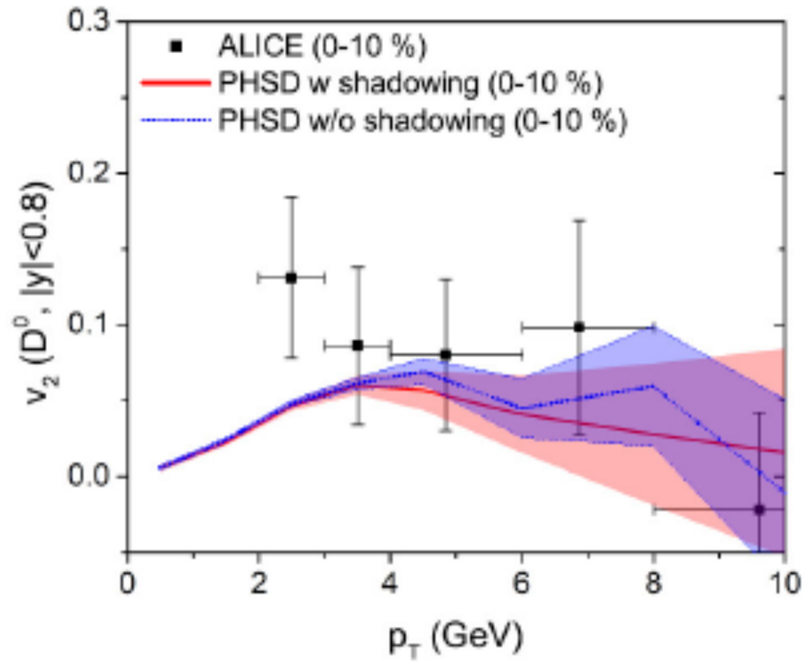
✧ Also PHSD – E. Bratkovaskaia talk, Tue 16:20

✧ Angular correlations between **heavy and light** mesons: inelastic vs elastic processes M. Rohrmoser's talk (Nantes), Thu 10:00

PHSD: extension to high p_T

E. Braktovakaia, Tue 16:20



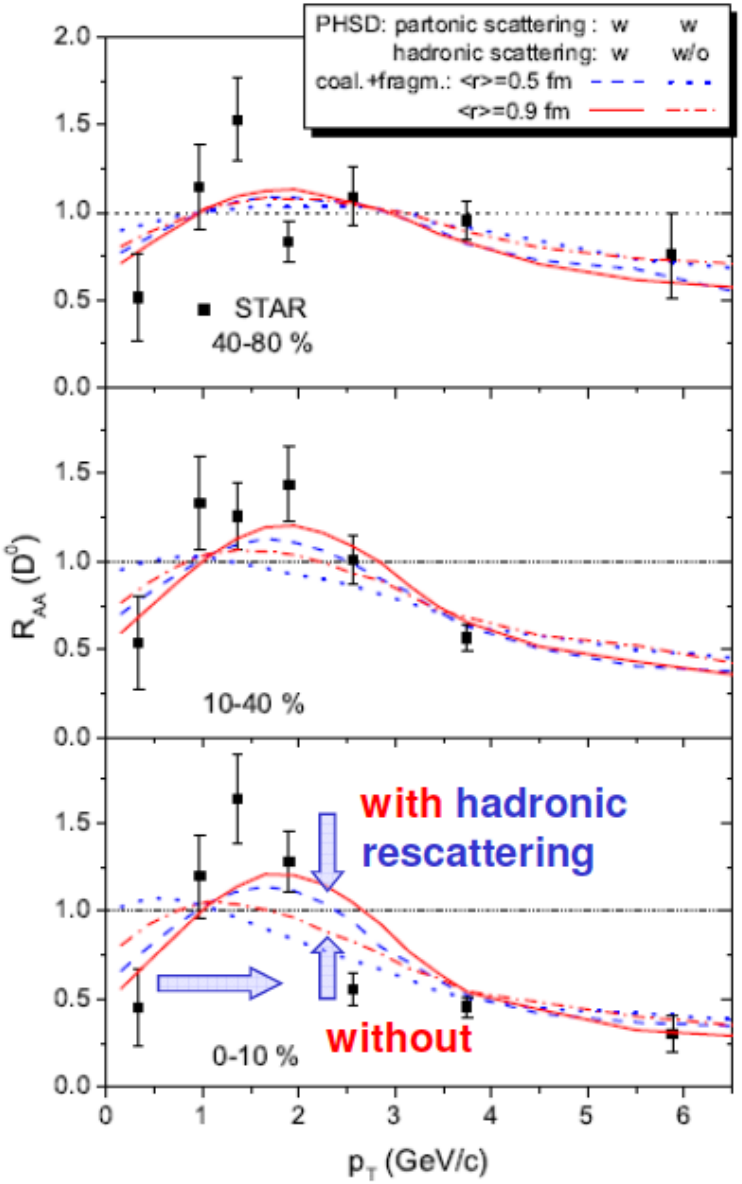


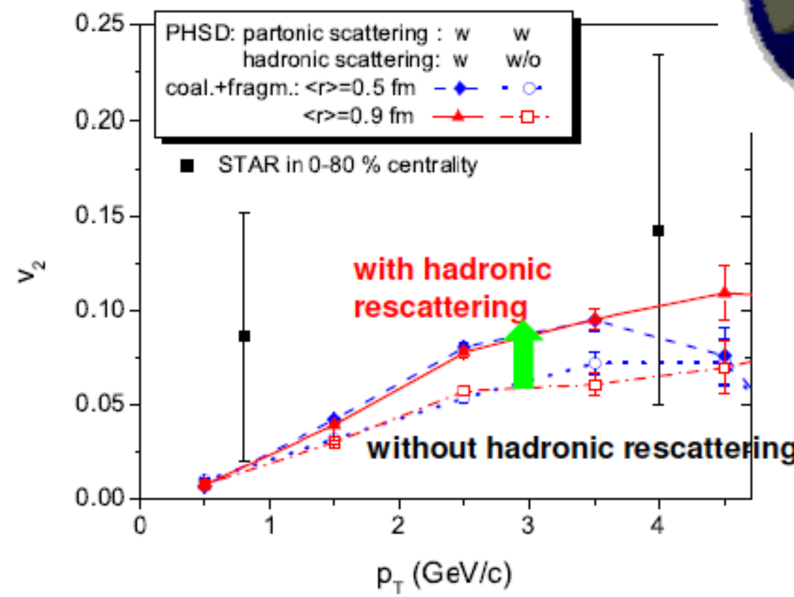
- ✧ Shadowing OK at low p_T
- ✧ No radiative E_{loss} (m_g large)
- ✧ Hadronic rescattering moves R_{AA} peak and increase v_2

T. Song et al., PRC 93 (2016) 034906, arXiv:1512.0089

Hadroni rescatt. & coalescence

E. Braktovakaia, Tue 16:00





- Hadronic rescattering moves R_{AA} peak to higher p_T !
- substantially increases v_2 at larger p_T

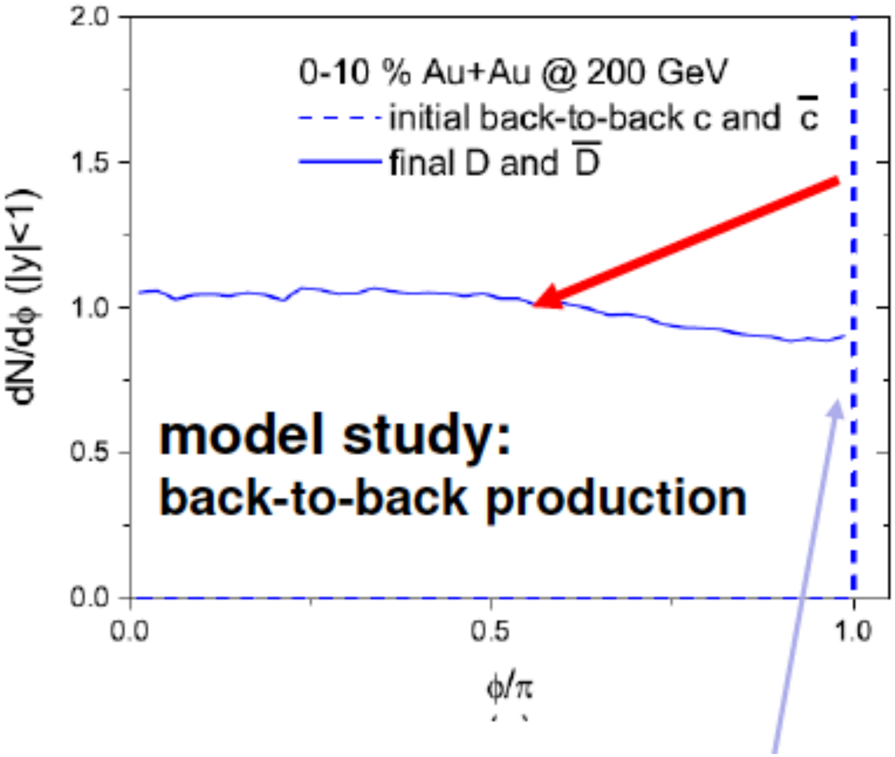
T. Song et al., PRC 92 (2015) 014910, arXiv:1503.03039

11

- Elastic scattering in QGP w QP at finite width
- Hadronization: coal.+ fragm.
- Hadronic Rescattering (incl. resonant)

PHSD: Azimuthal angular correlations

E. Braktovakaia, Tue 16:00



➔ Initial azimuthal angular correlation of QQbar pairs is completely washed out during the evolution of the heavy-ion collision, even in case they are assumed to be initially produced back-to-back (model study) mainly due to the transverse flow + interactions

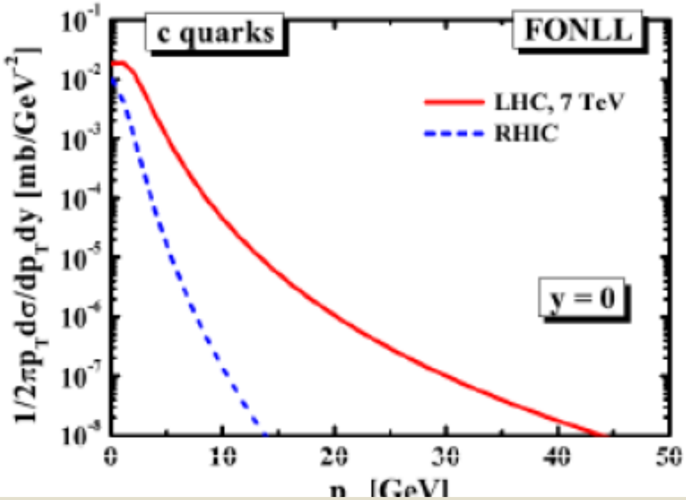
- Is it the same also in other approaches?
- What happens in peripheral AA and in pA?
- P_T-cut?

EPOS3+MC@sHQ

MC@sHQ+EPOS2 model

- **production** of heavy quarks at the original NN scattering points according to the **FONLL spectra**

  M.Cacciari et al., Phys. Rev. Lett. **95** (2005), JHEP **1210** (2012)



- **bulk evolution:** 3+1d ideal hydro stemming from **EPOS2** initial conditions; provides **temperature** and **velocity** fields

EPOS3: viscous hydro + Nonlinear parton evolution + modified core-corona

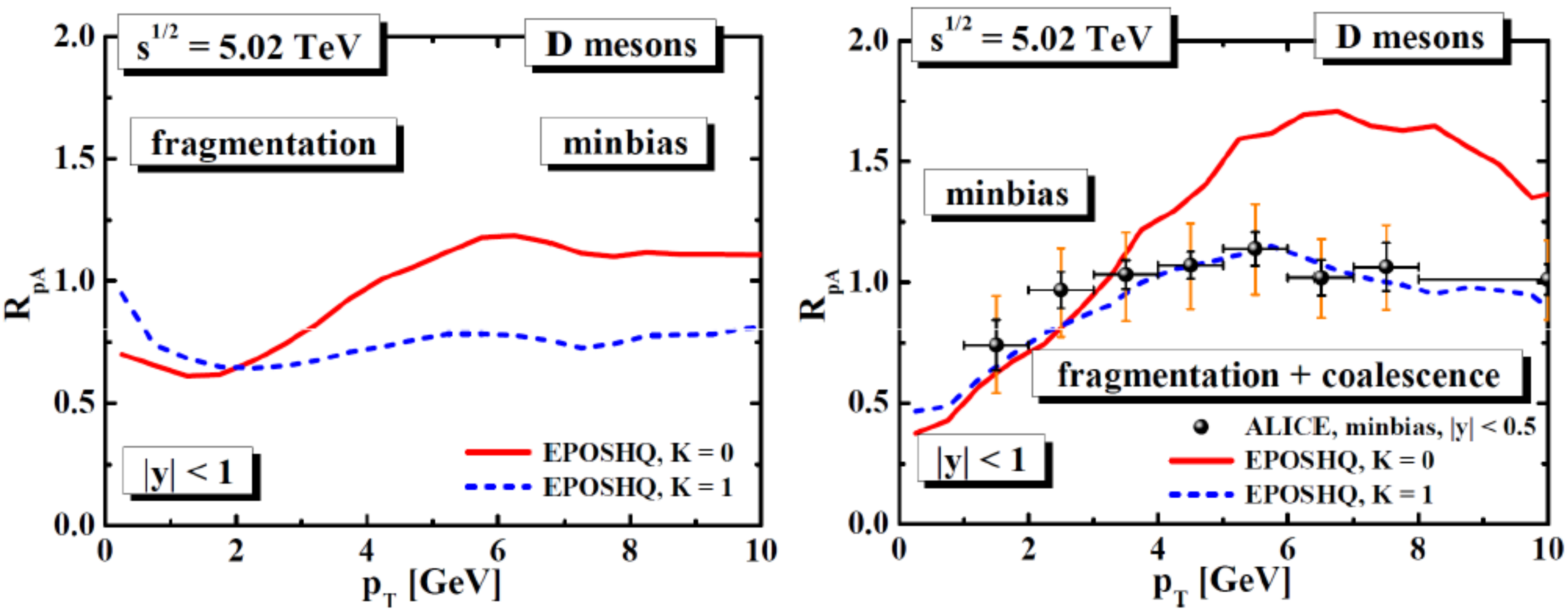
- **evolution of HQ** in the bulk: the **Boltzmann equation**
- **interaction of HQ** in the bulk: by either **elastic** or **radiative** collisions   Elastic from pQCD + HTL+ semi-hard propag. [Aichelin-Gossiaux]
- **hadronization of HQ: coalescence** (low p_T) and **fragmentation** (high p_T)

$$T_c = 155 \text{ MeV}$$

EPOS3+MC@sHQ

V. Ozvenchuk, Tue 17:20

RpA of D meson in pPb@5.02TeV



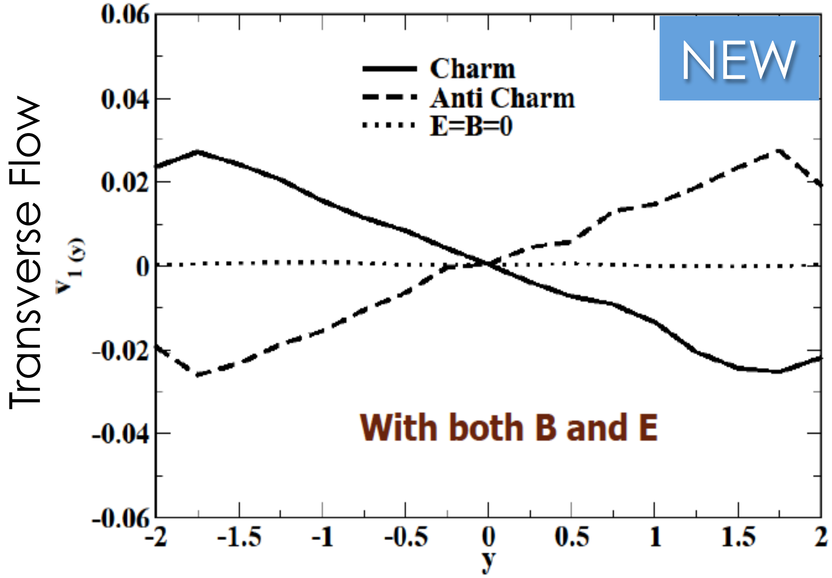
- **suppression of c-quark yield** at low pT for K=0 (no interactions) shows the presence of **shadowing** initially
- **good agreement** for RpA of D mesons for **whole range of pT**

✧ R_{AA} of D good only at low p_t, hadronc rescatt. to be added, v_2 to be calculated

✧ **STRENGTH: Connect pA and AA**

Magnetic Field

S. Das, Thu 16:30

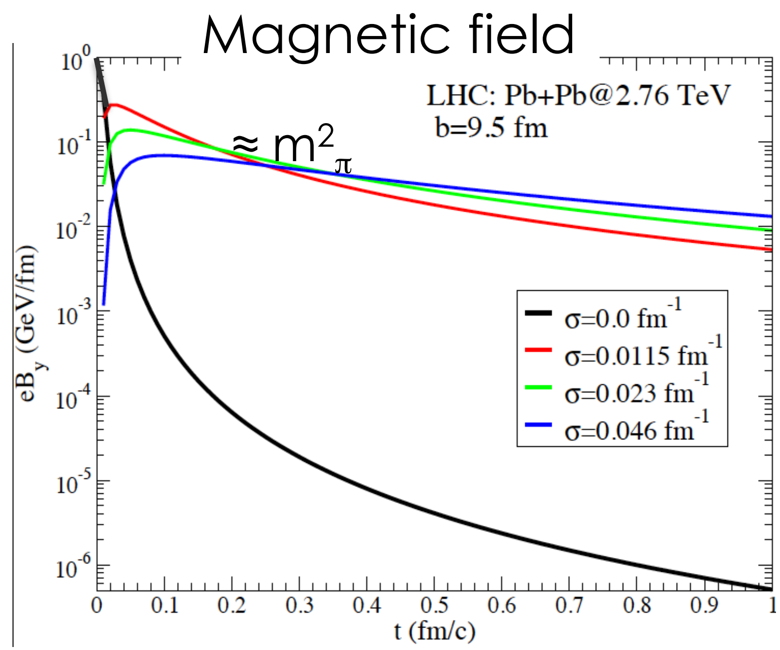


HQ best probe for v_1 from B:

- $\tau_{form} \approx 0.1$ fm/c vs q << g at this time
- do not mix with CME [c no chiral]
- do not mix CVE, c opposite $\bar{c}$
- Needed evolution at t >0.1-0.2 fm/c

E,B field like Gursoy, Kharzeev, Rajagopal, PRC 89(2014)

$$eB_{y,s} = -Z \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi' \int_{x_{\rm in}(\phi')}^{x_{\rm out}(\phi')} dx'_\perp x'_\perp \rho_-(x'_\perp) \qquad (2.9)$$
$$\times \left(eB_y^+(\tau,\eta,x_\perp,\pi-\phi) + eB_y^+(\tau,-\eta,x_\perp,\phi)\right) ,$$



Effect of strong magnetic field on heavy quark diffusion $K_T >> K_{||}$ qualitative effect on v_2

H.-U. Yee's talk, Thu 10:20

Charmonia

K. Zhou, Mon 16:00

History?

Static Screening / Potential

Color Screening, Survival of J/Ψ, $\Psi(2S)$, Υ,… up to 1.2 T_c, 1.4 T_c, … 2 T_c

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th}$$

Coalescence/Statistical

✧ gluon dissociation+ recombination

$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

or

$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi (N_\psi - N_\psi^{eq})$$

Dynamical /Transport Approach

Different Approaches

K. Zhou, Mon 16:00

History?

Static Screening / Potential

Color Screening, Survival of J/Ψ, Ψ(2S), Υ,… up to 1.2 T_c, 1.4 T_c, … 2 T_c

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Coalescence/Statistical

- ✧ Quantum treatment: Schroedinger- Langevin eq. beyond independent quarkonia decays (see P. Gossiaux's talk- Thu 12:00)

- ✧ Damping + gluon dissociation+ recombination

$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi (N_\psi - N_\psi^{eq})$$

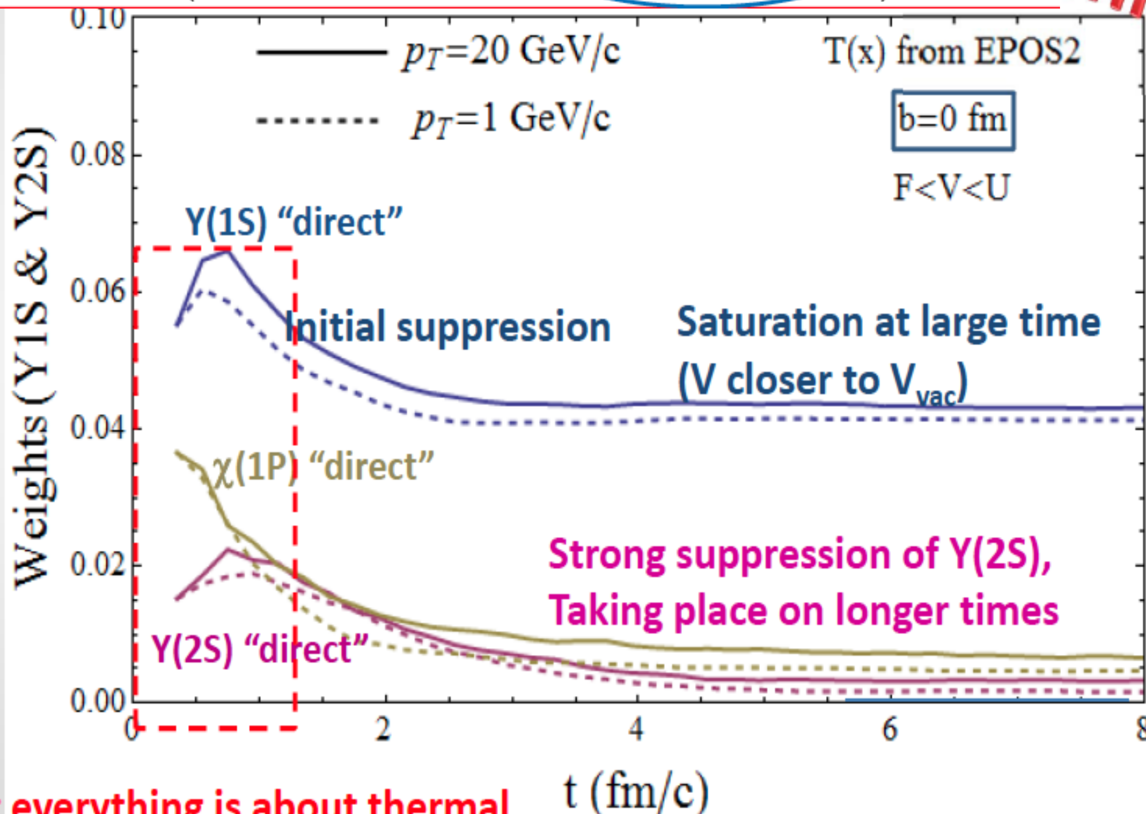
Dynamical /Transport Approach

Quantum Evolution: Schrodinger-Langevin

P. Gossiaux, Thu 12:00

Full EPOS2 evolutions

$$i\hbar\frac{\partial\Psi_{Q\bar{Q}}(\mathbf{r},t)}{\partial t} = \left(\widehat{H}_{\mathrm{MF}}(\mathbf{r}) - \mathbf{F_R}(t).\mathbf{r} + A\left(S(\mathbf{r},t) - \langle S(\mathbf{r},t)\rangle_{\mathbf{r}}\right)\right)\Psi_{Q\bar{Q}}(\mathbf{r},t)$$

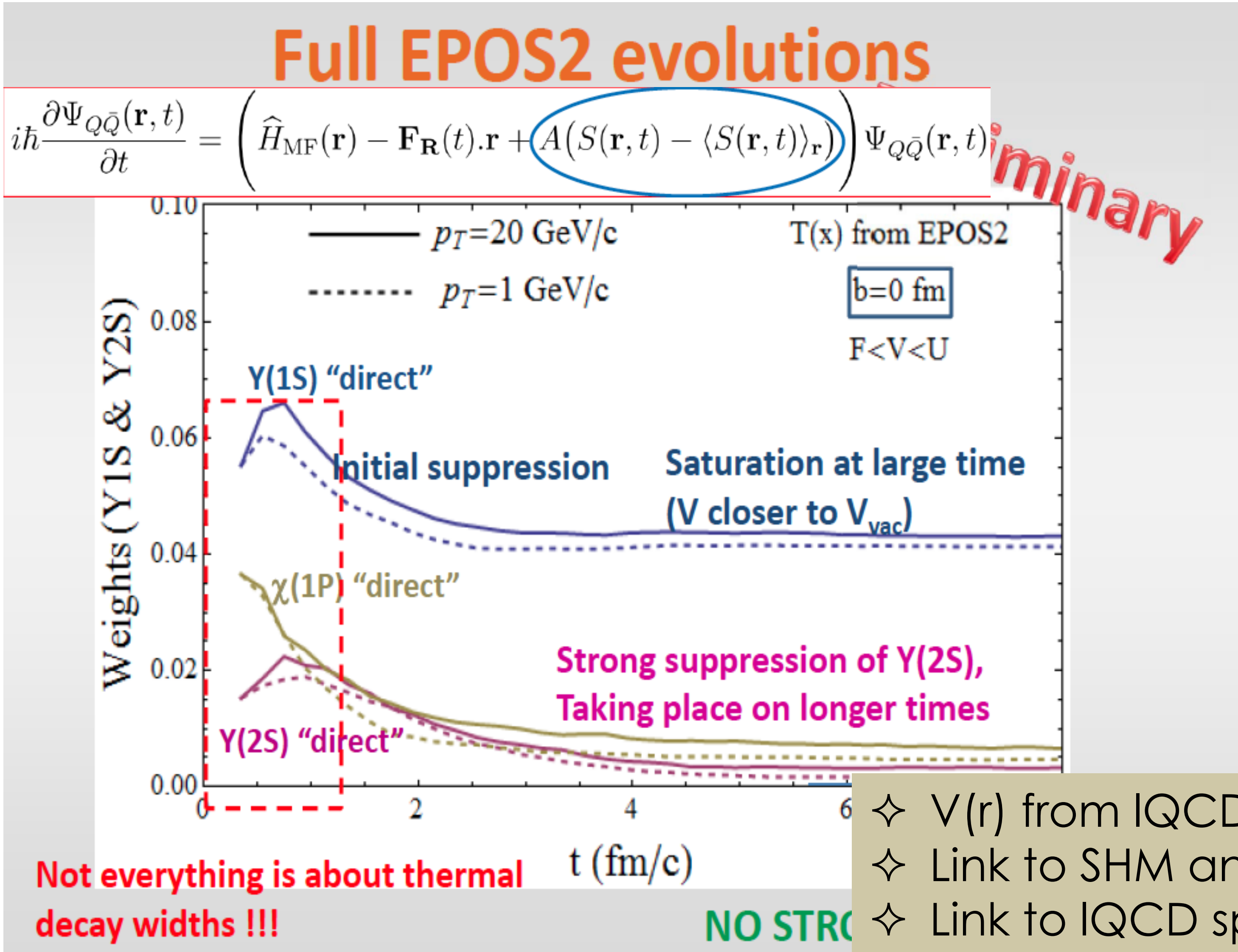


Not everything is about thermal decay widths !!!

NO STRONG p_T DEPENDENCE

Quantum Evolution: Schrodinger-Langevin

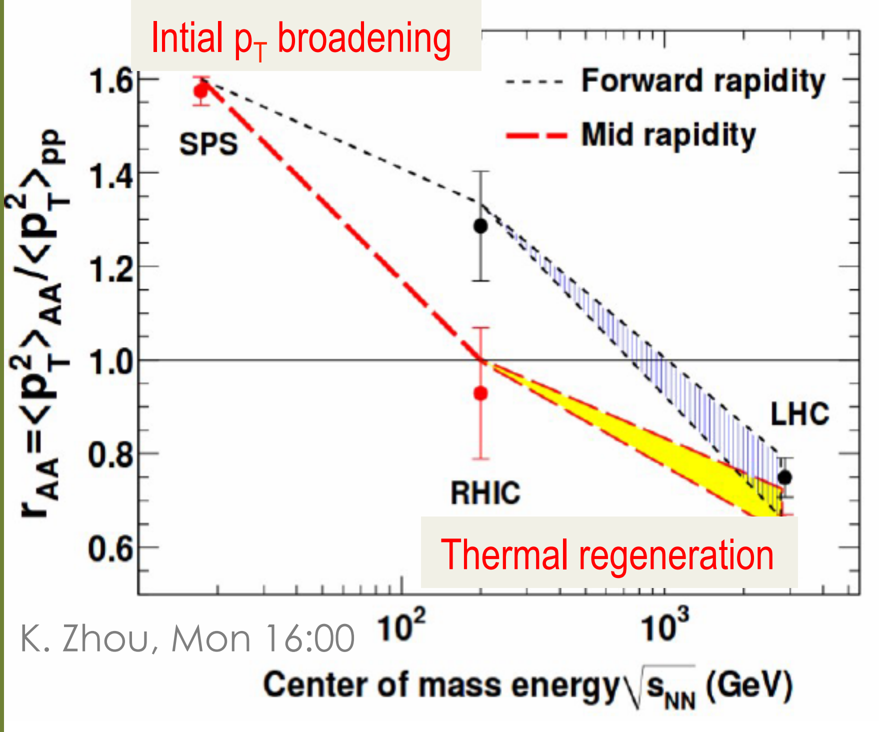
P. Gossiaux, Thu 12:00



- ✧ V(r) from lQCD
- ✧ Link to SHM and class. Transp.
- ✧ Link to lQCD spectral function
- ✧ Add recombination?

Success of Regeneration

Static Screening / Potential



K. Zhou, Mon 16:00

Coalescence/Statistical

- ✧ Damping + gluon dissociation+ recombination

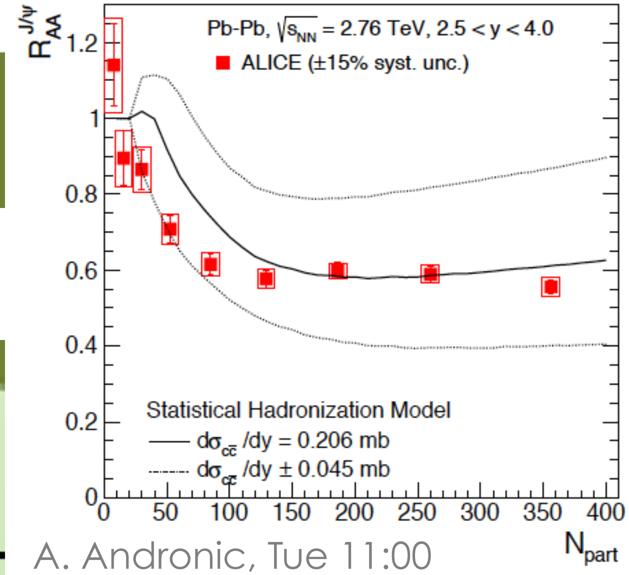
$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$

Dynamical /Transport Approach

SHM vs Dynamical

Static Screening / Potential

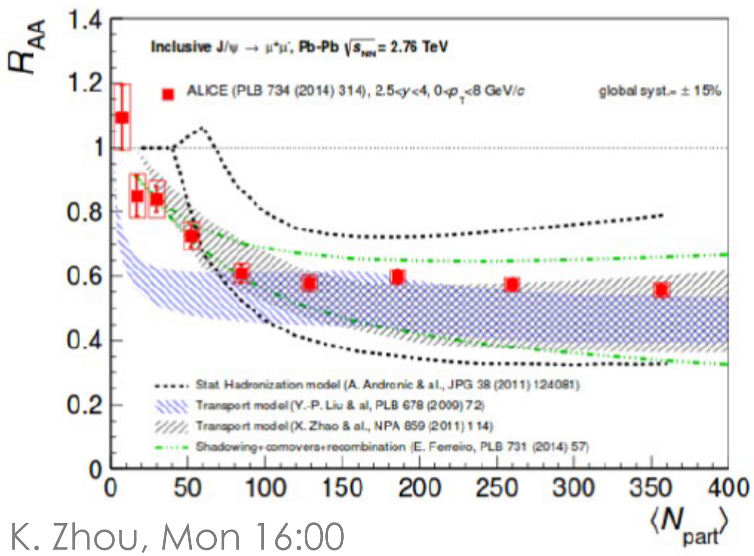
$$N_{J/\psi} = g_c^2 V n_{J/\psi}^{th}$$



A. Andronic, Tue 11:00

Coalescence/Statistical

$$\partial_t f + \vec{v}_T \cdot \nabla_T f + v_z \partial_z f = -\alpha f + \beta$$



K. Zhou, Mon 16:00

Cross section measurement crucial
- Hope improved precision
- Must employ current exp. constraint

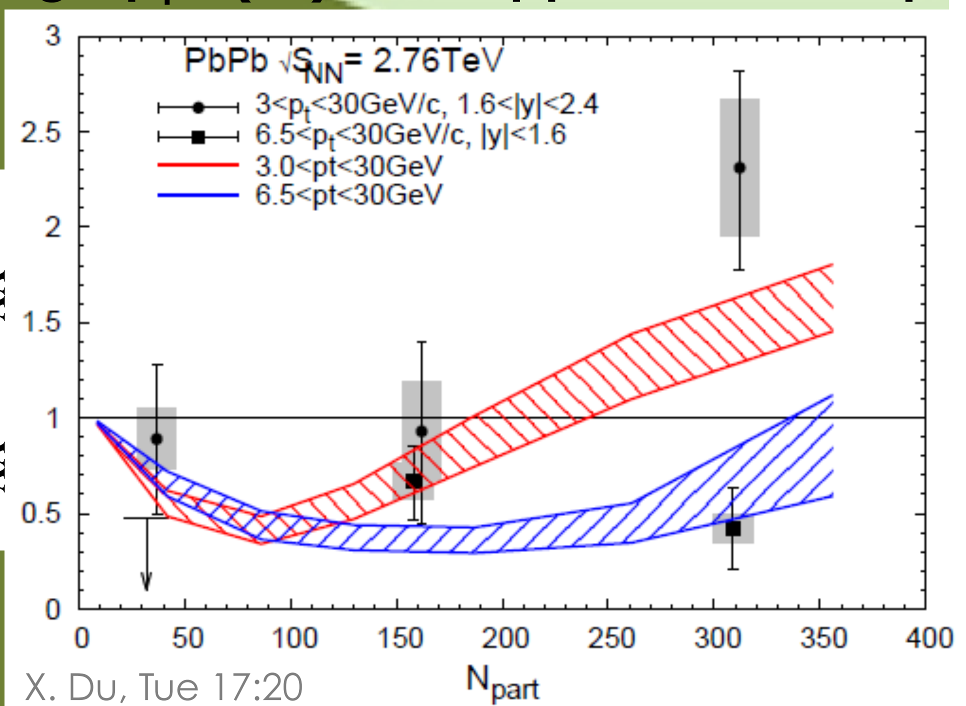
Dynamical /Transport Approach

Quarkonia at Phase boundary?

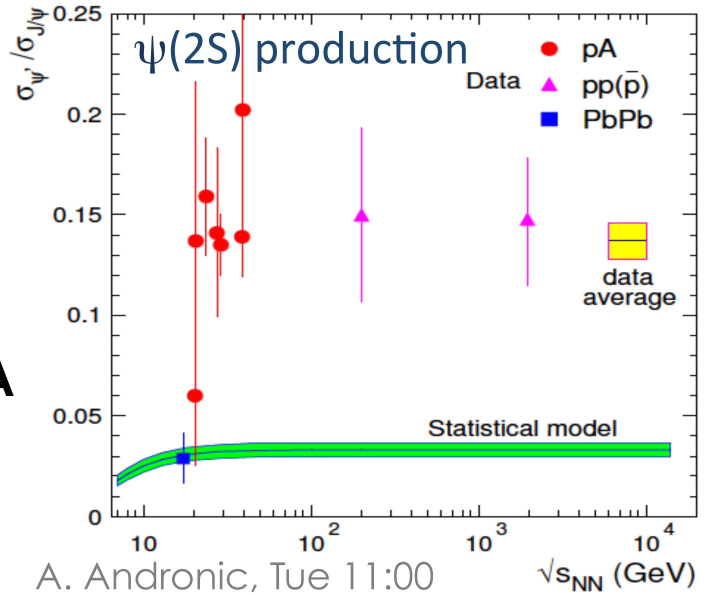
K. Zhou, Mon 16:00

Static Screening / Potential

High-p_T $\Psi(2S)$ less suppression than pA



X. Du, Tue 17:20



A. Andronic, Tue 11:00

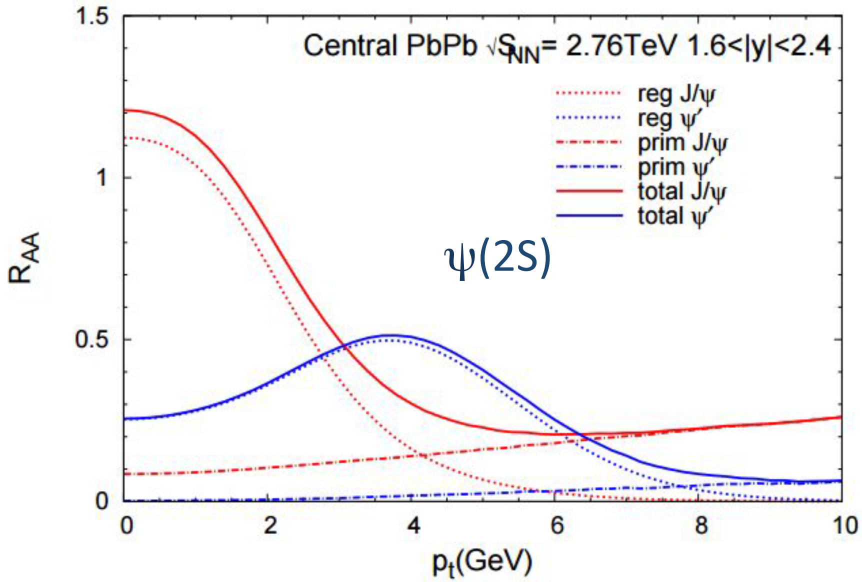
Coalescence/Statistical

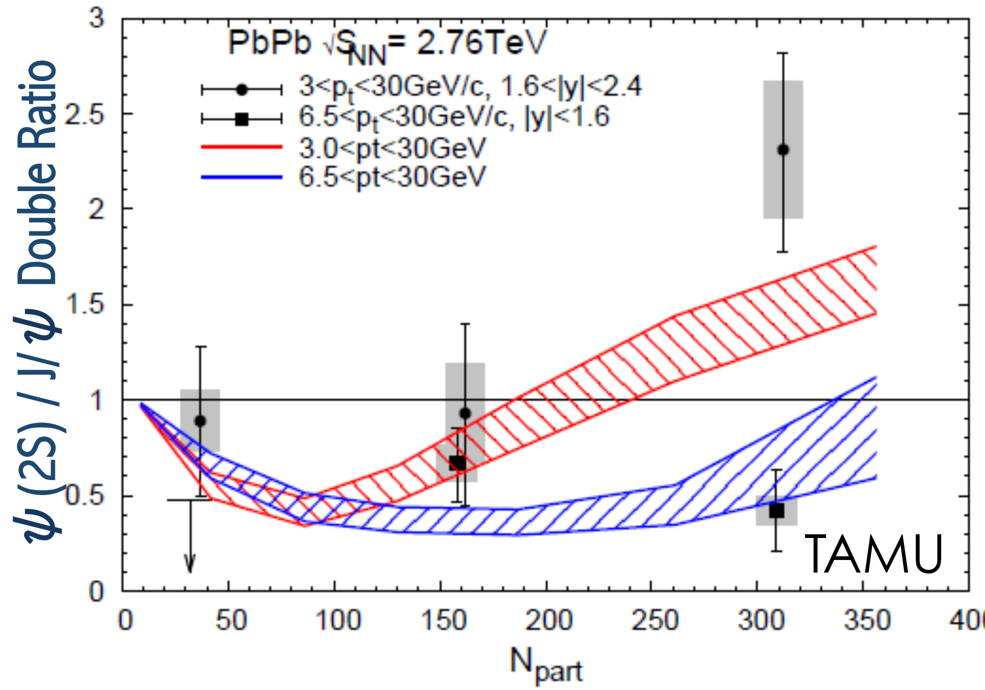
Dynamical /Transport Approach

Sequential Regeneration

X. Du, Tue 17:20

ψ(2S) Suppression in d/p-A

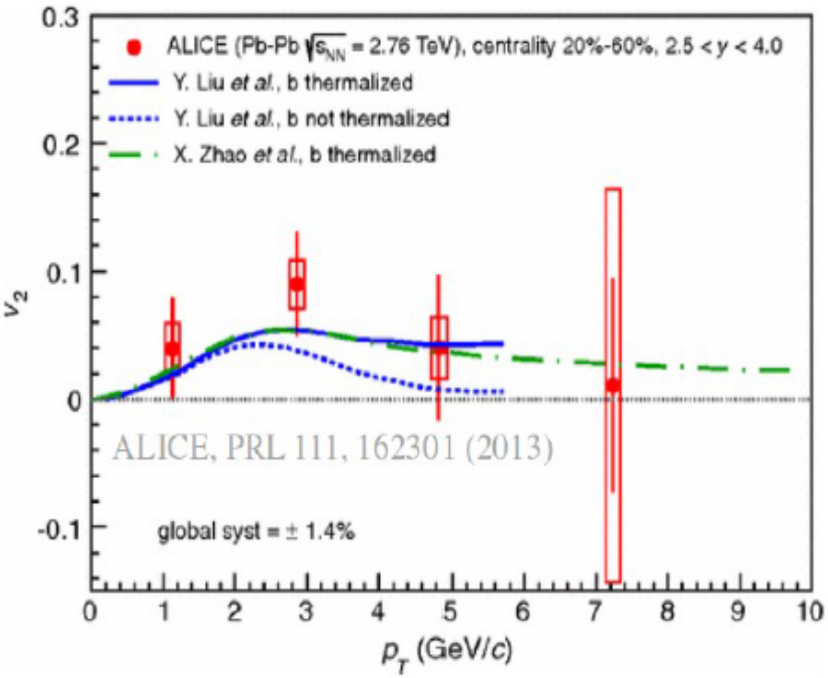




- Hadronic ψ(2S) suppression ⟹
- ψ(2S) regenerated in **Pb-Pb** later, with larger flow, than **J/ψ**

SHM/Dynamical regeneration

How to resolve Quarkonia at phase boundary?



Precise measurement of $v_2(J/\Psi)$ greatly helps, generation at T_c larger v_2

Open HF ←→ Charmonia

V.G., R. Rapp, C.M. Ko, PLB(2004)

✧ *Observable* $\sigma_{c\bar{c}}$ *indepedent*

Conclusions

Conclusions

- Just let’s start our Heavy Work Week ….

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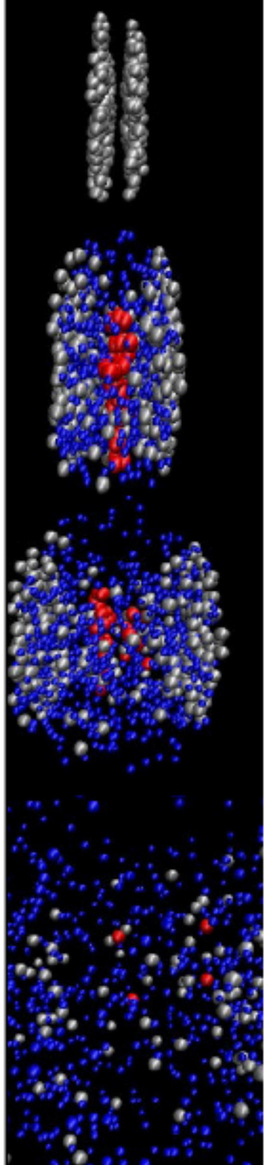
An underlying issue I have not discussed:

- LBL, CCNU, Nantes, Catania → (linearized **Boltzmann**)
- Frankfurt → 1st order Kadanoff-Baym ≈ **Boltzmann**
- Duke, TAMU, Torino, (Catania) → **Langevin**

Parton-Hadron-String-Dynamics (PHSD)



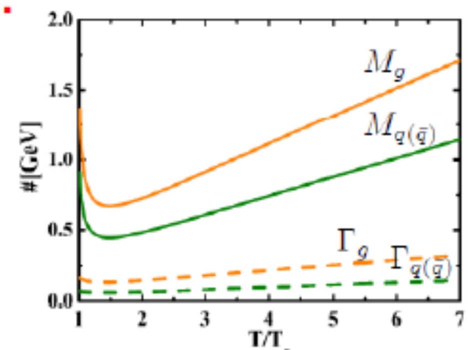
PHSD is a non-equilibrium transport approach with

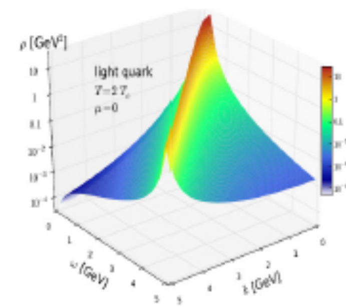
- explicit phase transition from hadronic to partonic degrees of freedom
- lQCD EoS for the partonic phase (‚crossover' at low μ_q)
- explicit parton-parton interactions - between quarks and gluons
- dynamical hadronization

❑ QGP phase is described by the Dynamical QuasiParticle Model (DQPM) matched to reproduce lattice QCD

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
W. Cassing, NPA 791 (2007) 365: NPA 793 (2007)

- strongly interacting quasi-particles: massive quarks and gluons (g, q, q_{bar}) with sizeable collisional widths in a self-generated mean-field potential





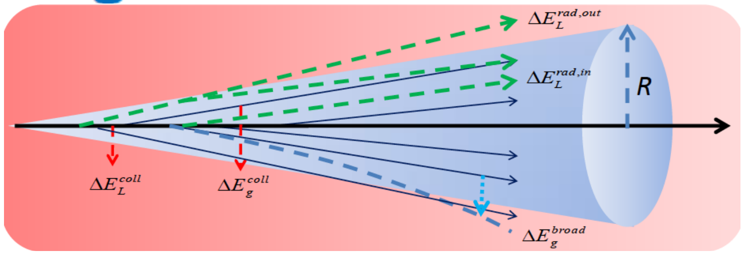
- Spectral functions:

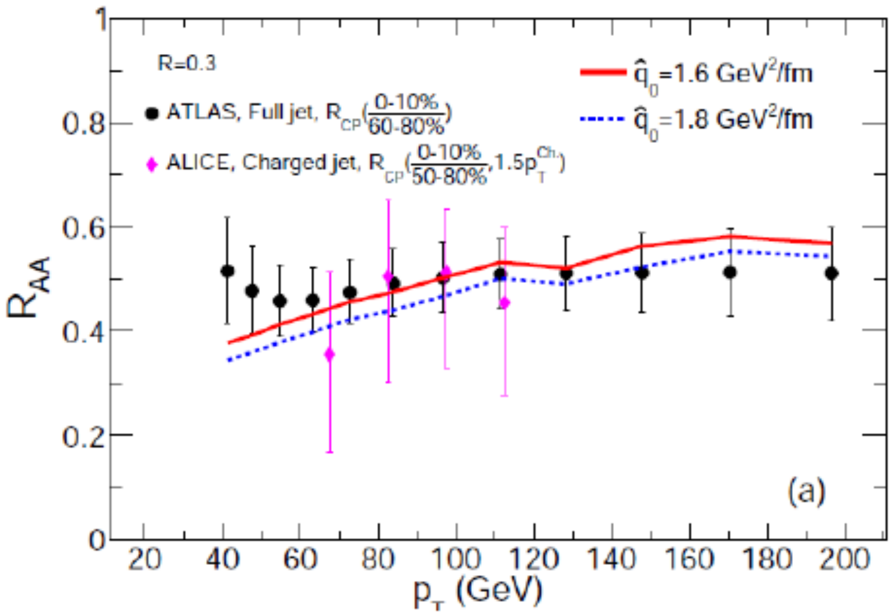
$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \quad (i = q, \bar{q}, g)$$

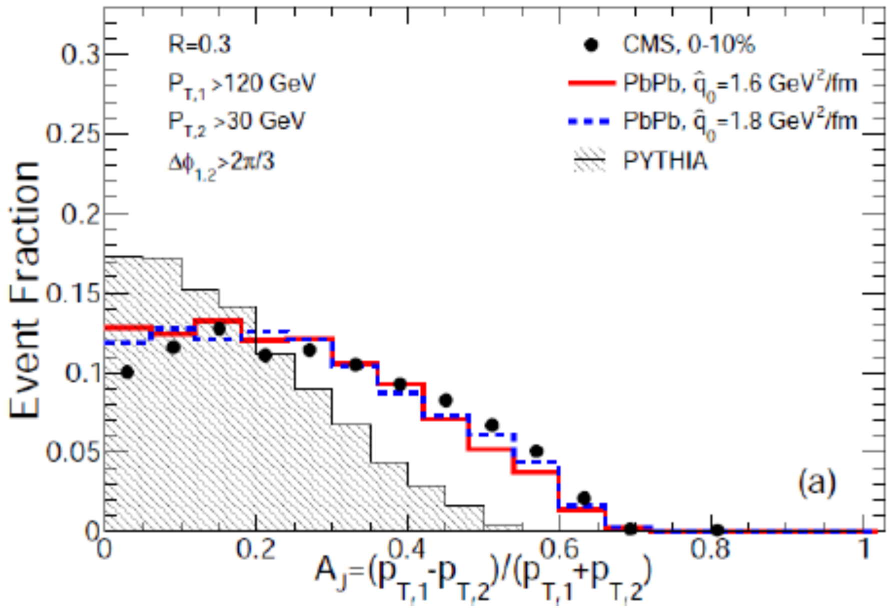
❑ Transport theory: generalized off-shell transport equations based on the 1st order gradient expansion of Kadanoff-Baym equations (applicable for strongly interacting systems!)

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; W. Cassing, EPJ ST 168 (2009) 3

- **Probe medium-induced *broadening* (q^{hat}) via jet-like angular correlations**



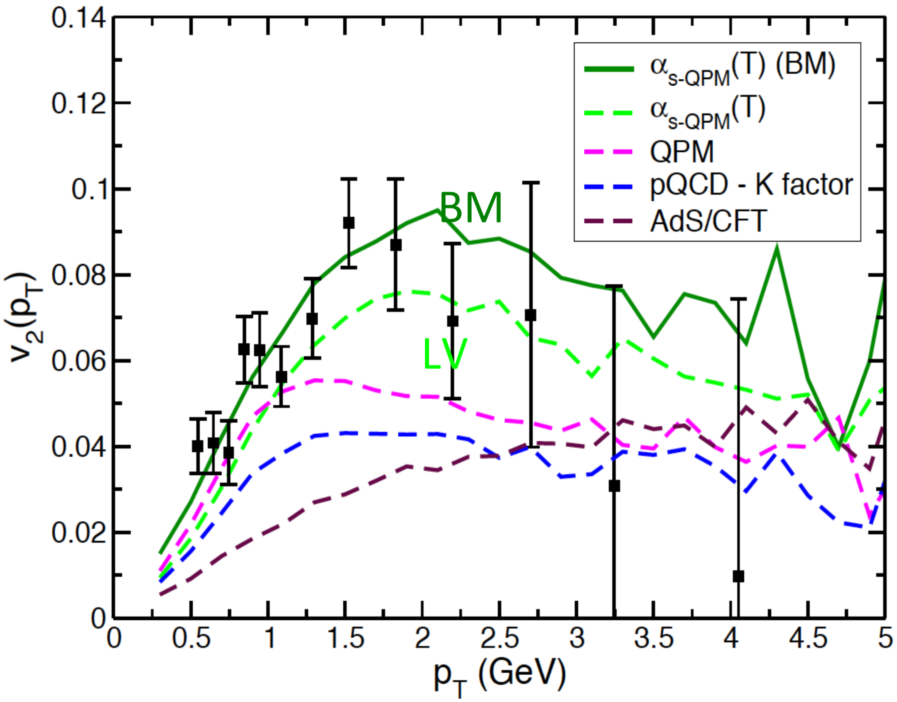




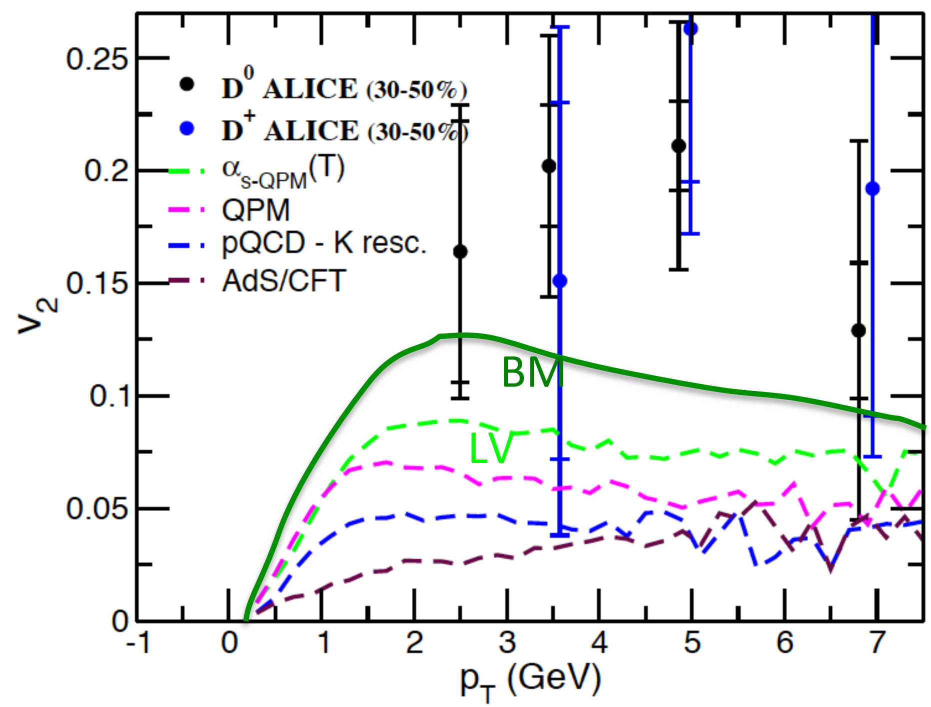
Ningbo Chang, GYQ, arXiv:1603.01920

v_2 Boltzmann vs Langevin

Au+Au@200AGeV, b=8 fm



LHC – Pb+Pb@2.76ATeV



No coalescence included, only fragmentation