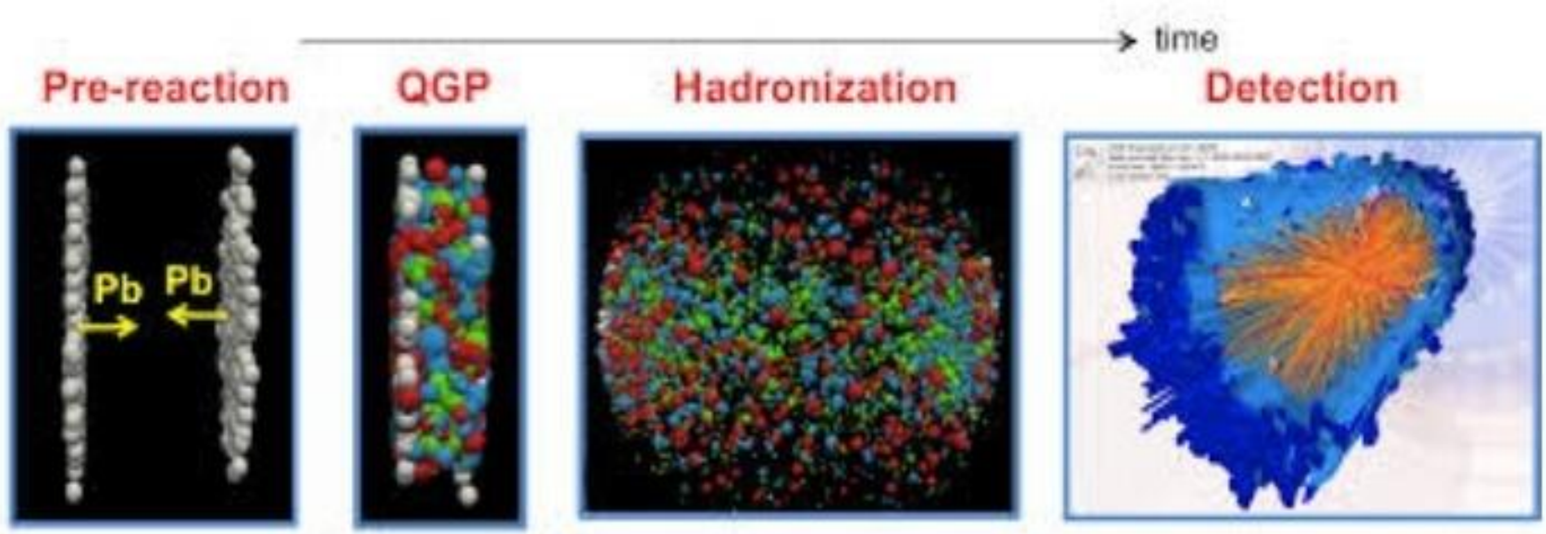
Heavy quark dynamics in QCD matter



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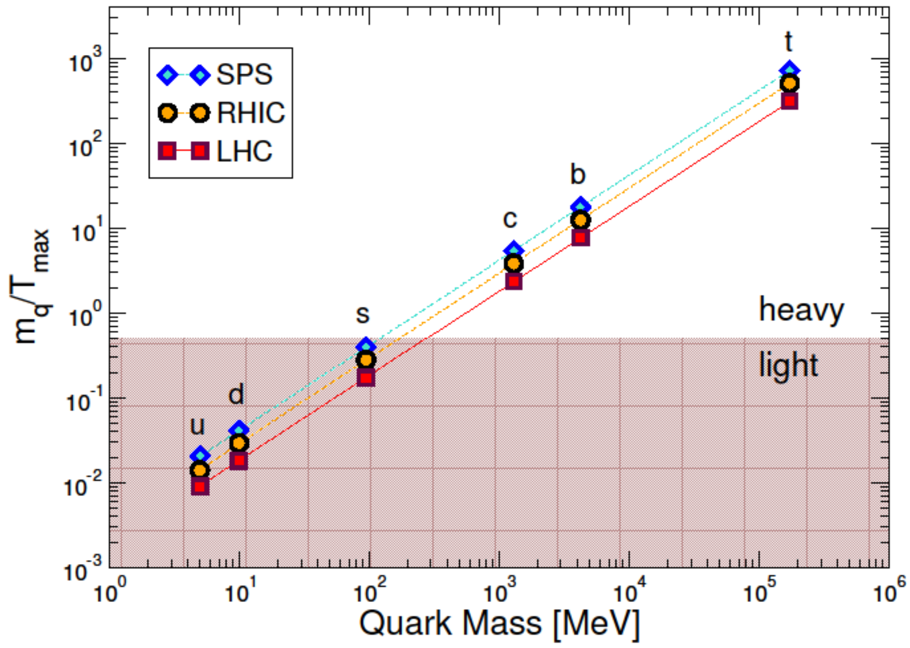
OUTLINE ……………

- Introduction
- Quark Gluon Plasma - the primordial fluid
- Heavy quark transport coefficients – R_{AA} and v_2
- Heavy quark momentum evolution and hadronization
- Initial stage effects – EM field, Angular momentum, Glasma
- Summary and outlook

Heavy Quark & QGP



SPS to LHC

$\sqrt{s} = 17.3 GeV \ to \ 2.76 TeV$ **~100 times**

$T_i = 200 \ MeV \ to \ 600 \ MeV$ **~3 times**

τ **relaxation time**

$$M_{c,b} >> \Lambda_{QCD}$$

Produced by pQCD process (before equilibrium)
(Early production)

$$\tau_{c,b} >> \tau_{QGP}$$

They go through all the QGP life time

$$M_{c,b} >> T_0$$

No thermal production

Boltzmann Kinetic equation

$$\left(\frac{\partial}{\partial t}+\frac{P}{E}\frac{\partial}{\partial x}+\mathrm{F}.\frac{\partial}{\partial p}\right)f\left(x,p,t\right)=\left(\frac{\partial f}{\partial t}\right)_{col}$$

- The plasma is uniform ,i.e., the distribution function is independent of x.
- In the absence of any external force, F=0

$$R(p,t)=\left(\frac{\partial f}{\partial t}\right)_{col}=\int d^3k\left[\omega(p+k,k)f(p+k)-\omega(p,k)f(p)\right]$$

$$\omega(p,k)=g\int\frac{d^3q}{(2\pi)^3}f'(q)v_{q,p}\sigma_{p,q\to p-k,q+k}$$

→ is rate of collisions which change the momentum of the charmed quark from p to p-k

$$\omega(p+k,k)f(p+k)\approx\omega(p,k)f(p)+k.\frac{\partial}{\partial p}(\omega f)+\frac{1}{2}k_ik_j\frac{\partial^2}{\partial p_i\partial p_j}(\omega f)$$

$$\frac{\partial \mathbf{f}}{\partial \mathbf{t}}=\frac{\partial}{\partial \mathbf{p_i}}\left[\mathbf{A_i(p)f}+\frac{\partial}{\partial \mathbf{p_j}}\left[\mathbf{B_{ij}(p)f}\right]\right]$$

B. Svetitsky PRD 37(1987)2484

where we have defined the kernels

,

$$\mathbf{A_i}=\int \mathbf{d^3k\,\omega(p,k)k_i}\quad\rightarrow \textbf{Drag Coefficient}$$

$$\mathbf{B_{ij}}=\int \mathbf{d^3k\,\omega(p,k)k_ik_j}\quad\rightarrow \textbf{Diffusion Coefficient}$$

Langevin Equation

The Fokker-Planck equation can be recast to Langevin equation:

$$\mathbf{dr} = \frac{p}{E}\,\mathbf{d}t$$

$$\frac{dp}{dt} = -\gamma(p)\,p + \zeta \qquad \textbf{with} \qquad <\zeta_i(t)\zeta_k(t')>= D\delta(t-t')\delta_{jk}$$

where γ **is the deterministic friction (drag) force**

ζ **is stochastic force**

For the bulk evolution: Hydrodynamics/Transport

Transport coefficients are connected by Fluctuation Dissipation Theorem.

Moore, Teaney, PRC 71 (2005) 064904

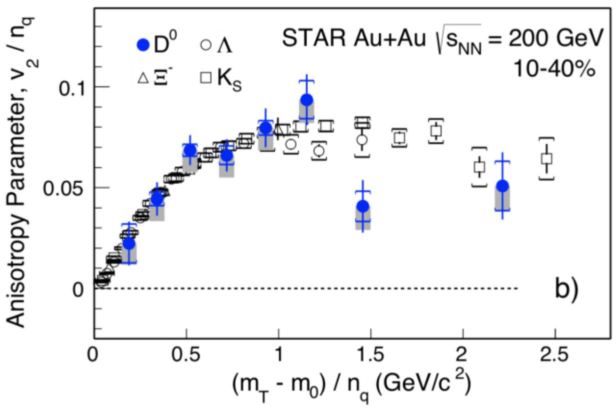
Van Hees, Greco, Rapp, PRC 73 (2006) 034913

Heavy quark initialization

- ✧ r-space: N_coll (Glauber mode)
- ✧ p-space: NLO (pQCD)

Heavy quark physics at different scales

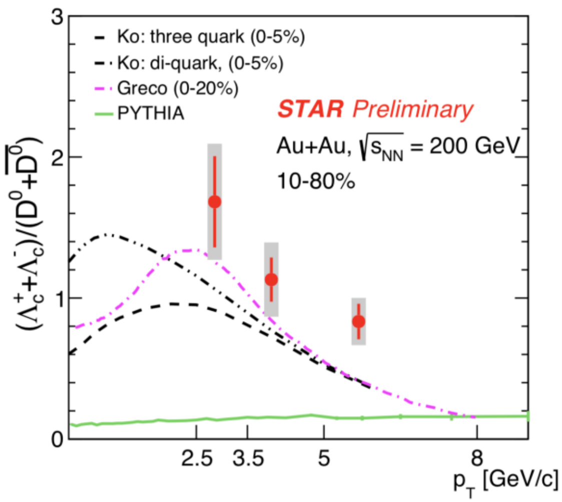
low p_T



Study thermalization process of HQ

Constrain diffusion coefficient D_s

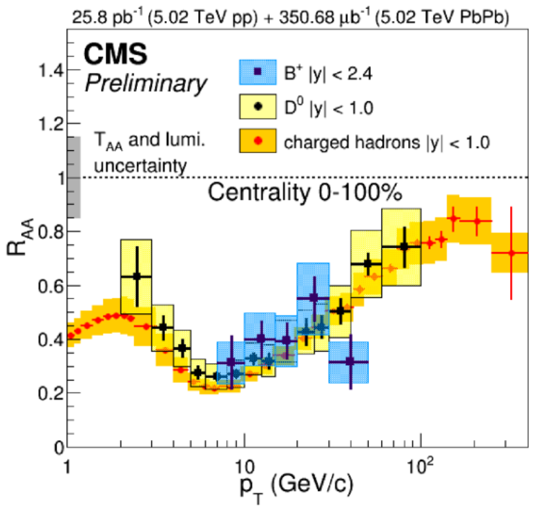
medium p_T



Study hadronization process of HQ

Constrain hadron wave-function

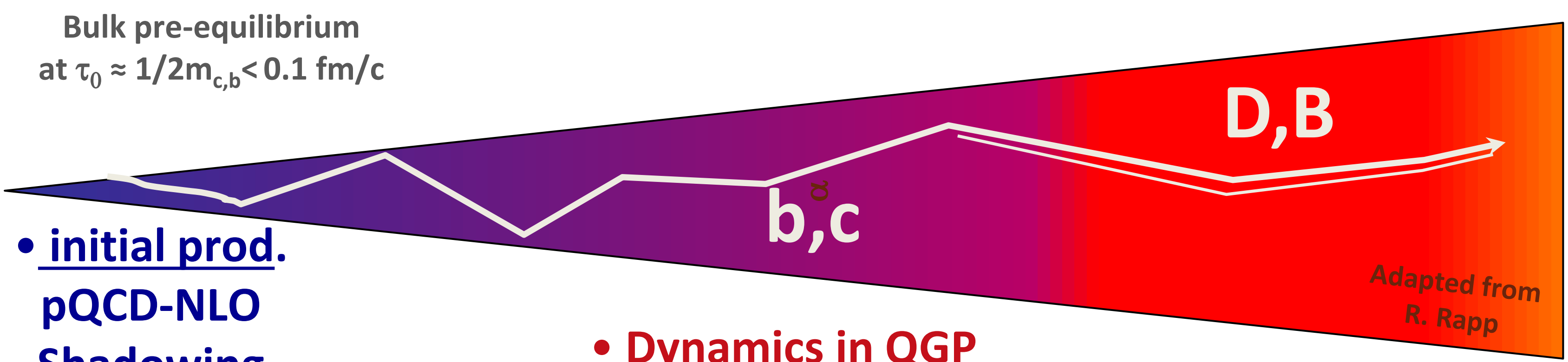
high p_T



Study parton energy loss and mass effect

Constrain jet transport parameter $\hat{q}$

Studying the HF at RHIC and LHC



- **initial prod.**

pQCD-NLO
Shadowing
Pre-equilibrium Effect/Glasma
Electromagnetic filed

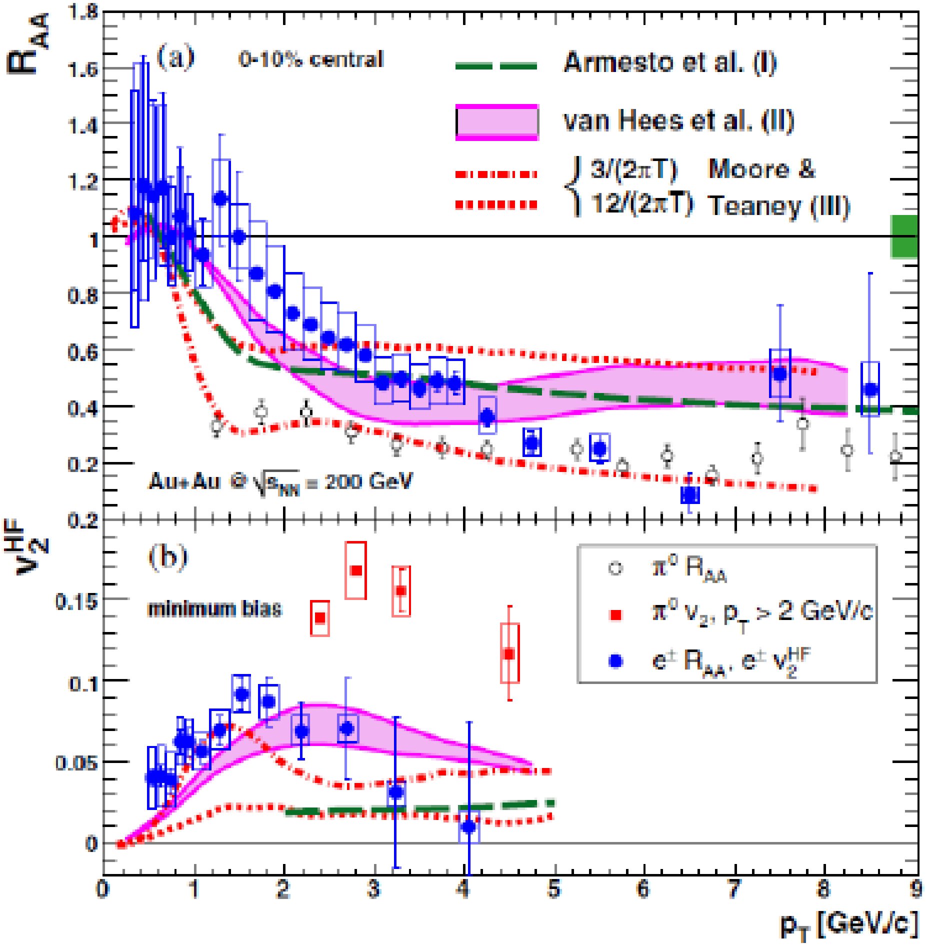
- **Dynamics in QGP**

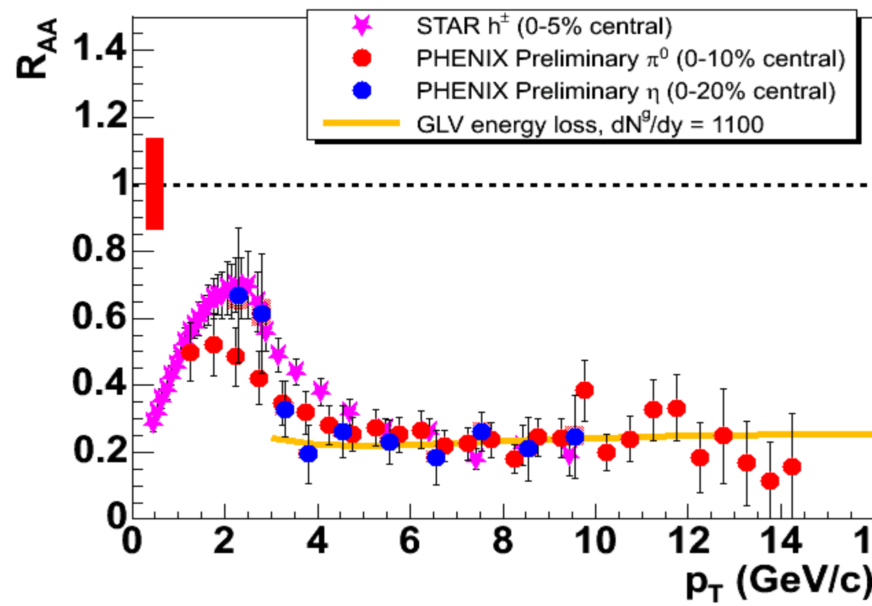
Heavy quark QGP interaction
Transp. coeff. of QCD matter
-> thermalization ?!
Mass & color in Jet quenching
Heavy quark momentum evol.
(Langevin/Boltzmann/E. loss model)

- **hadronization:**

coalescence and/or fragmentation.
Hadronic rescattering

Heavy flavor at RHIC (2007)

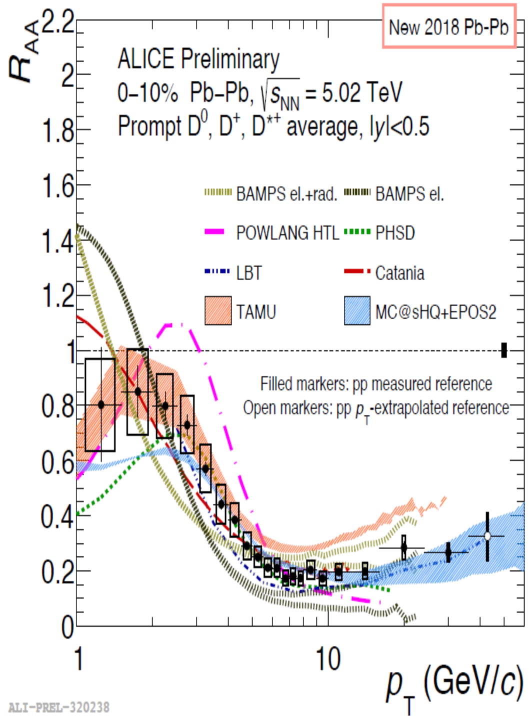


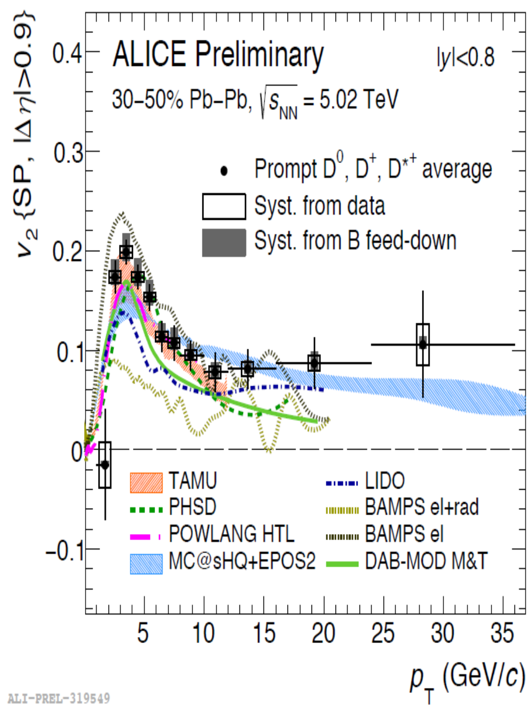


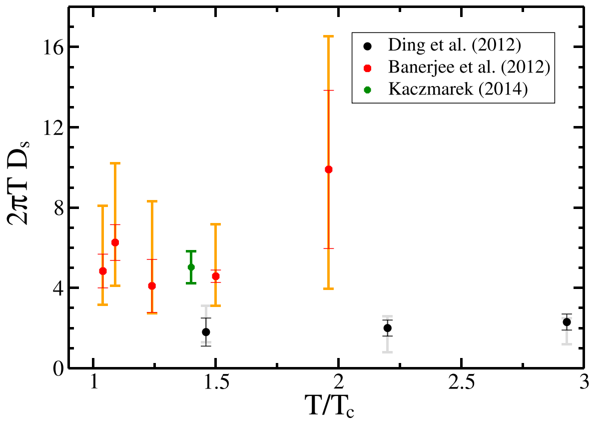
At RHIC energy heavy flavor suppression is similar to light flavor

Simultaneous description of RAA and v2 is a tough challenge for all the models.

R_{AA} and v_2
Comparison with models

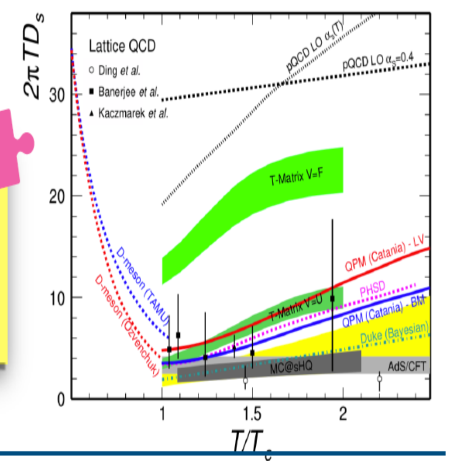






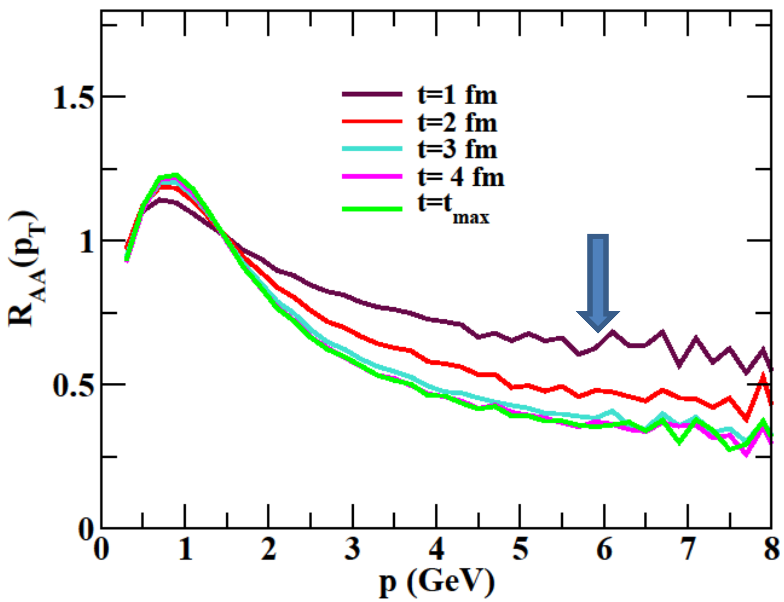
TAMU: PLB 735,445-450(2014), arXiv:1905.09216
PHSD: PRC 92, 014910 (2015)
POWLANG: EPJC 75,121(2015)
MC@sHQ+EPOS2: PRC 89 014905 (2014)
LBT: PLB 777 (2018) 255-259
LIDO: arXiv:1810.08177
BAMPS: JPG 42, 115106 (2016)
Djordevic: PRC 92, 024918 (2015)
CUJETS3.0: JHEP 02 (2016) 169
SCET: JHEP 03 (2017) 146
DAB-MOD: PRC 96 (2017) 064903
Catania: Eur. Phys. J. C (2018) 78: 348

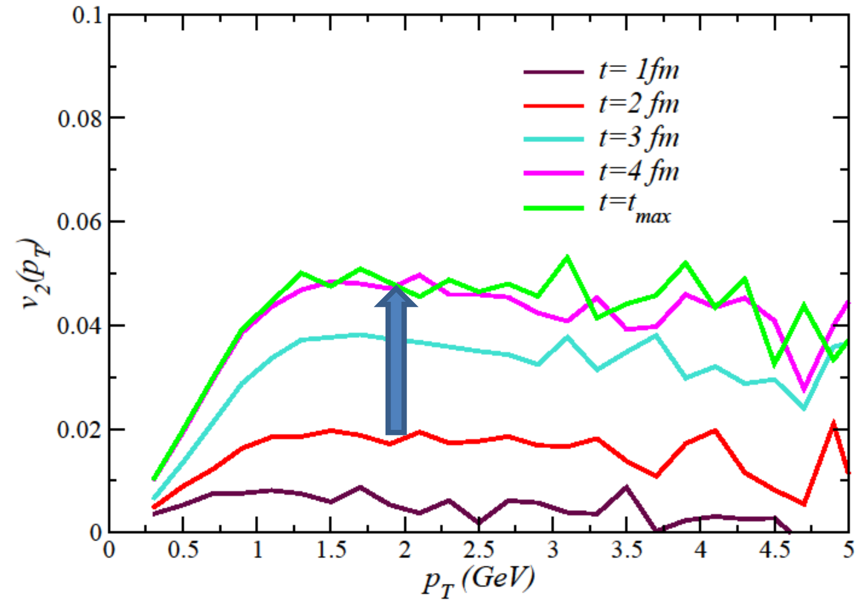
- ➡ Simultaneous description of R_{AA} **and** v_2 **is challenging** in the whole measured p_T range!
- ➡ Experimental measurements start to **provide constraint to the models** for the characterization of the charm and beauty interaction with the medium
  - ➡**constraints on plasma transport parameters**, such as the heavy-quark diffusion coefficient



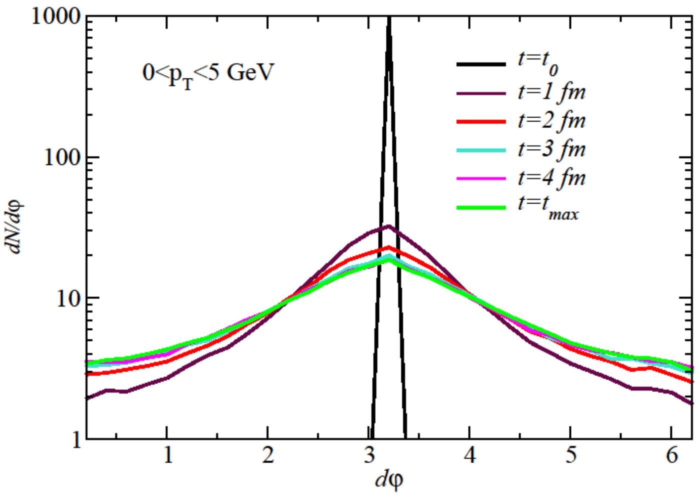
Terrevoli (SQM 2019)

Time evolution of Heavy quarks observables





Das, Scardina, Plumari, Greco
J. Phys. Conf. Ser. 668 (2016) 012051

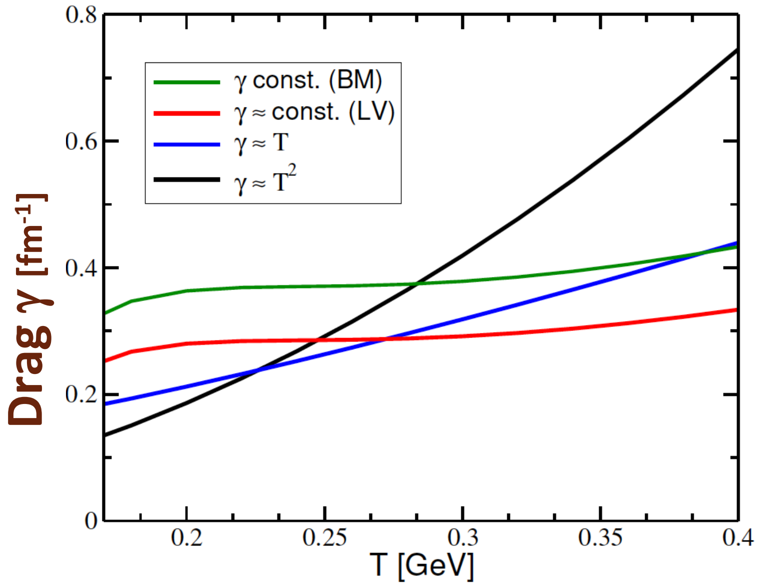


R_{AA} and $dN/d\Phi$ developed during the early stage of the evolution → T_i

V_2 developed duringing the later stage of the evolution → T_c

T dependence of the interaction i.e the transport Coefficients are the essential ingradiant for the symultanious description of HQ observabbles

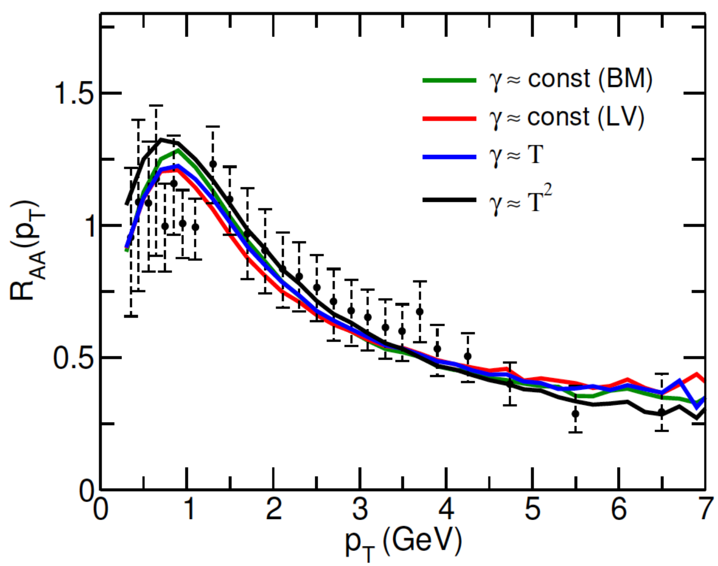
Impact of T dep. interaction on $R_{AA} - v_2$

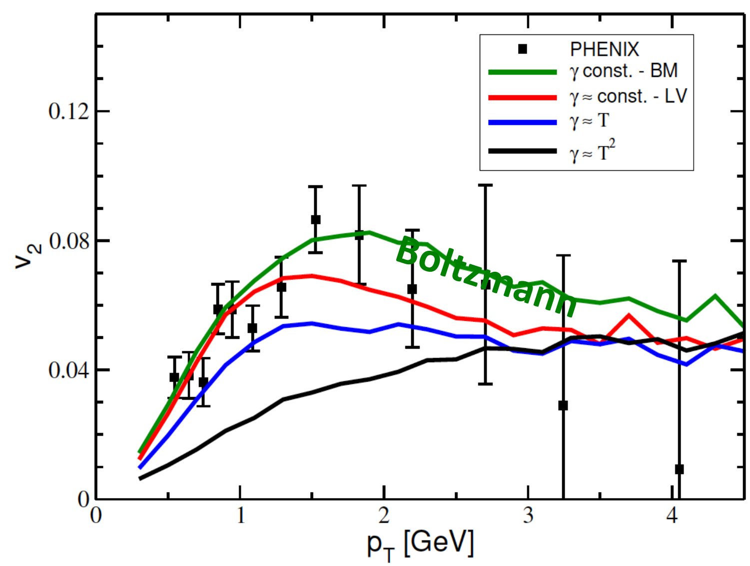


Looking at it beyond the specific modelings

- $\gamma \approx T^2$ [Ads/CFT, pQCD α_s=const]
- $\gamma \approx T$ [pQCD strong α_s running]
- $\gamma \approx$ const. [QPM, PHSD, T-matrix]

γ rescaled to fit $R_{AA}(p_T)$, D from FDT

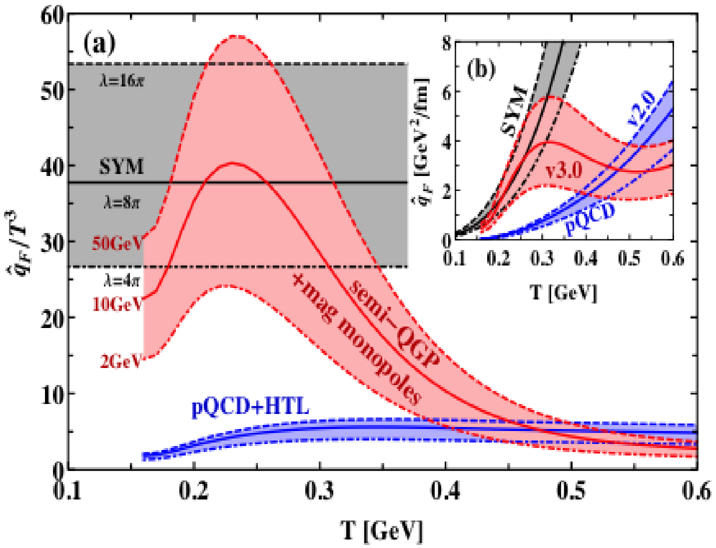


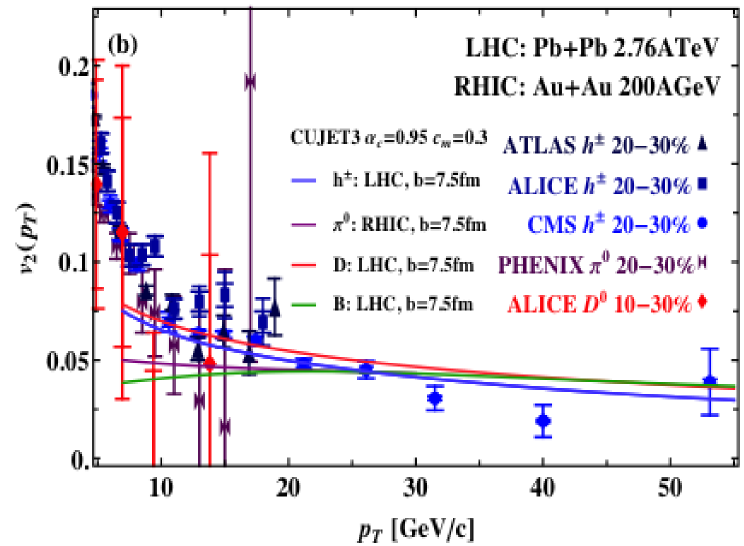


Das, Scardina, Plumari, Greco
Phys. Lett. B 747 (2016)260-264

R_{AA} vs. v_2 puzzle

Different temperature dependence of the interaction strength may lead to different v_2 for the same R_{AA}.





Semi-quark-gluon monopole plasma model increases $\hat{q}$ around T_c and enhances hard probes' v_2.

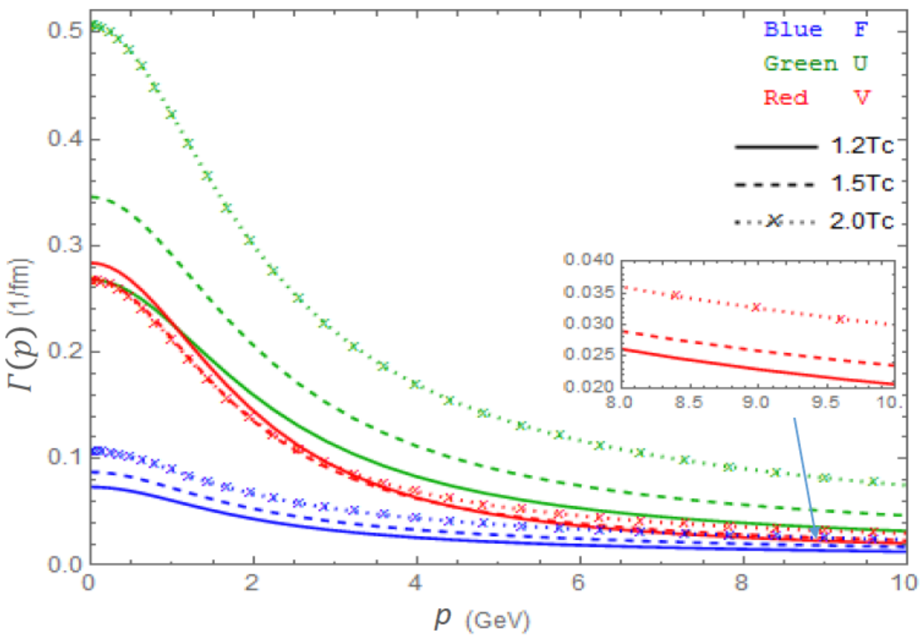
J. Xu, J. Liao and M. Guylassi
Chin. Phys. Lett. 32, 092501 (2015)

T-matrix developments [TAMU]:

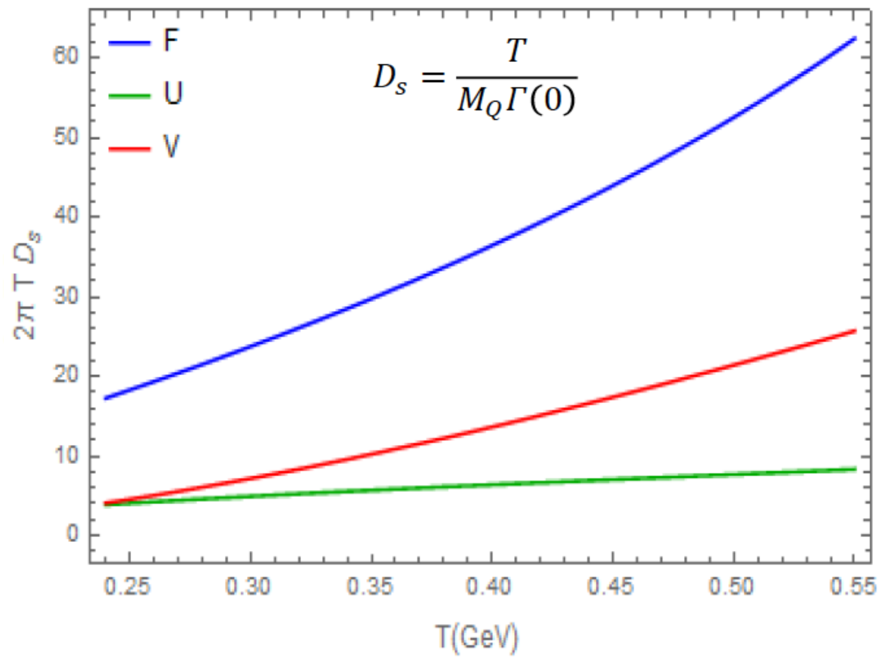
❖ Relaxation rate (drag coefficient)

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

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***

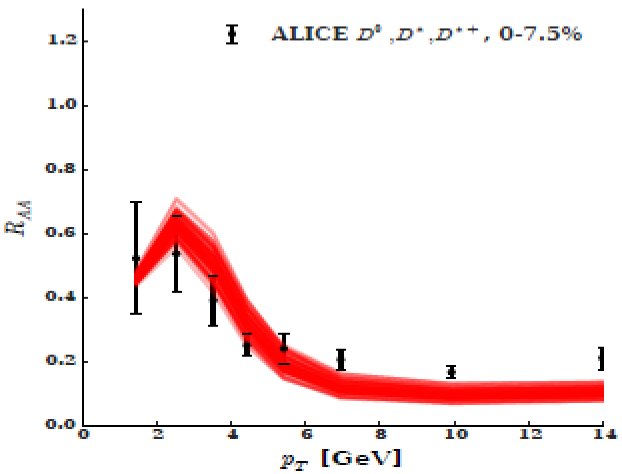
Radiative loss in T-matrix approach
Large suppression due to thermal mass
Impact on observables yet to see

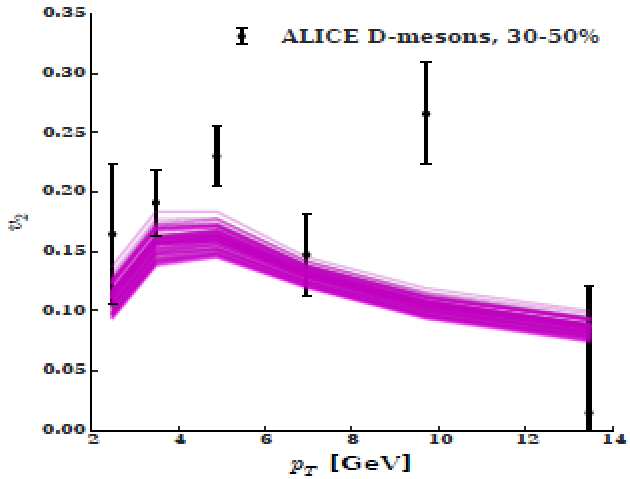
S. S. F. liu and R. Rapp
JHEP 08 (2020) 168

Bayesian model to data analysis [Duke]:

Simultaneously calibrate all model parameters through model-to-data comparison.

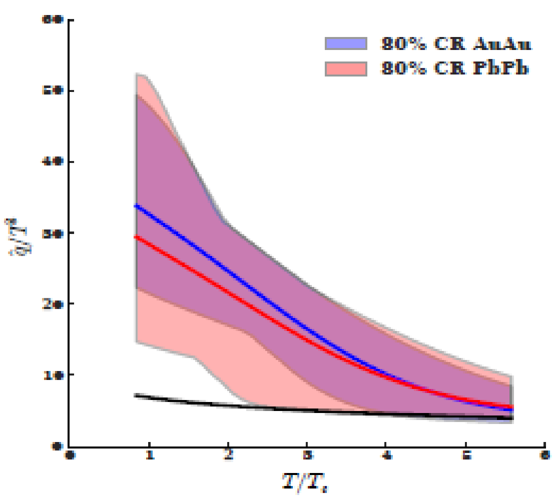
Extract the probability distribution of all parameters which best describe the data.

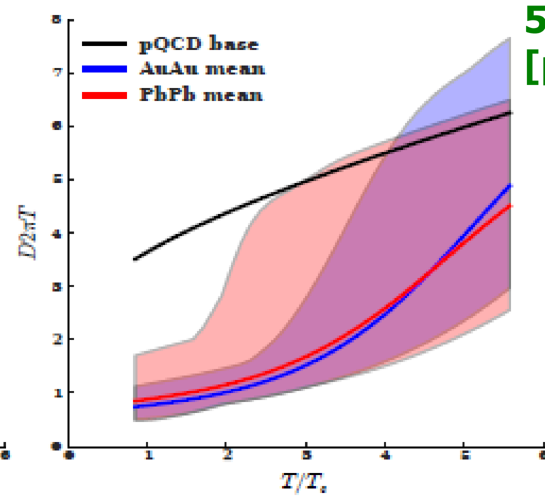




One can extract both the temperature and momentum dependence of heavy quark transport coefficients .

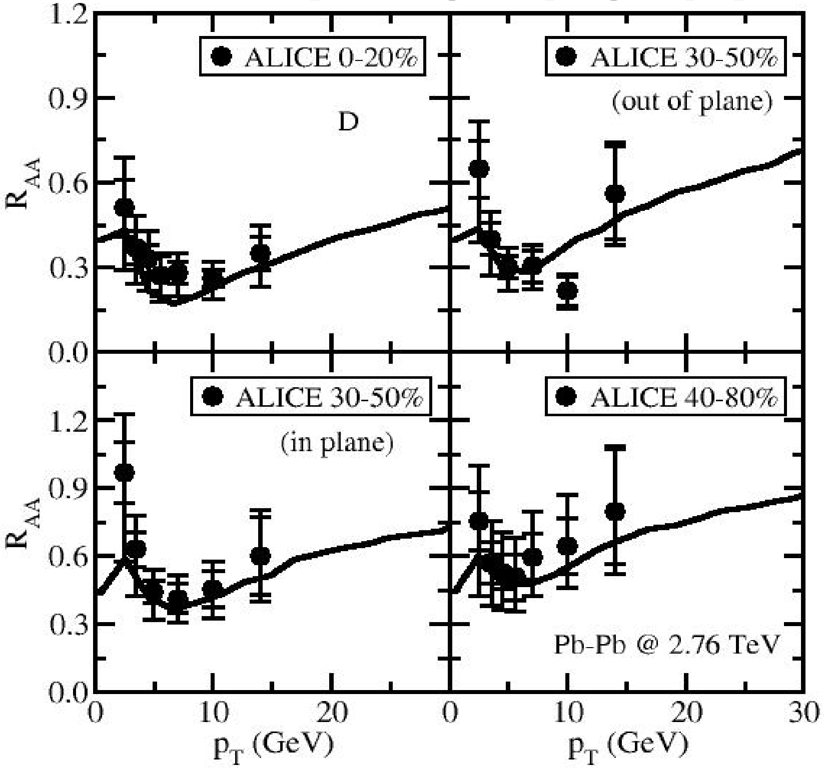
T,p-dependence: $\hat{q} = \hat{q}_{pQCD} * preK * (1 + K_p e^{-\frac{|p|^2}{2\sigma_p^2}}) * (1 + K_T e^{-\frac{(T-T_c)^2}{2\sigma_T^2}})$ $\quad D_s = T^2/\hat{q}$

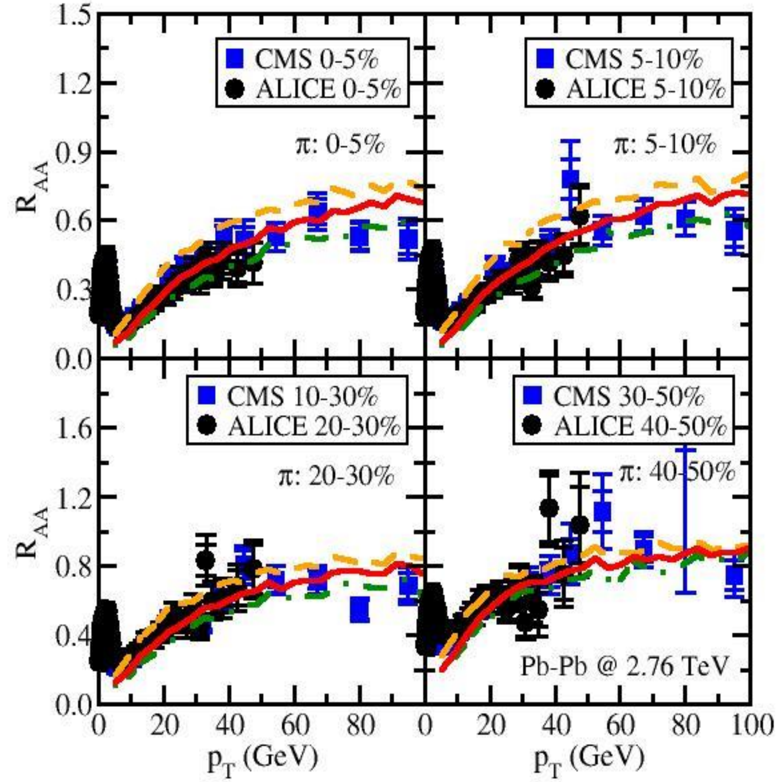




5 dimensional Parameter space: [pre$K$, K_p σ_p, K_T σ_T]

Approach from low to high pt
from heavy to light (high-pt) [LBL-CCNU]





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

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

Linearized Boltzmann transport model
Both collisional and radiative loss

$$K_p = 1 + A_p e^{-|\vec{p}|^2/2\sigma_p^2},$$

(T-matrix like featurs)

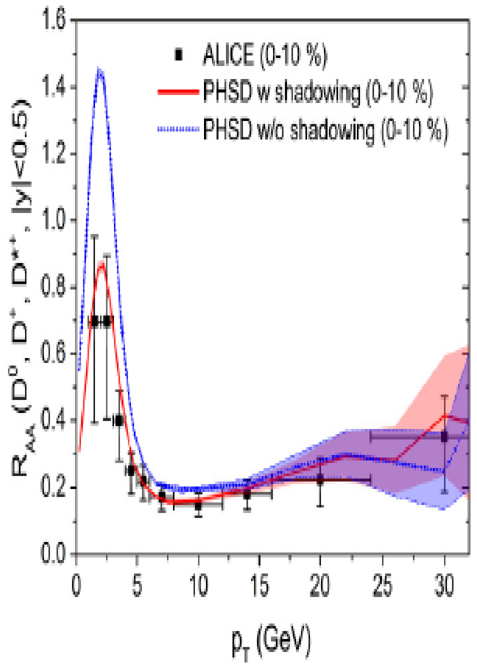
$$K_T = 1 + A_T e^{-(T-T_c)^2/2\sigma_T^2}$$

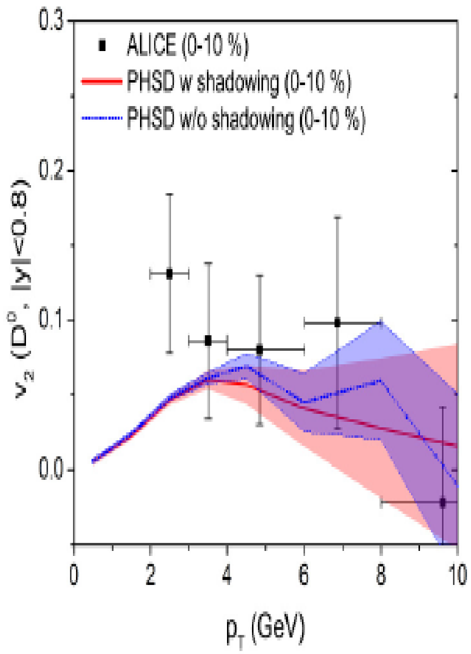
(Catania-QPM, PHSD, T-matrix)

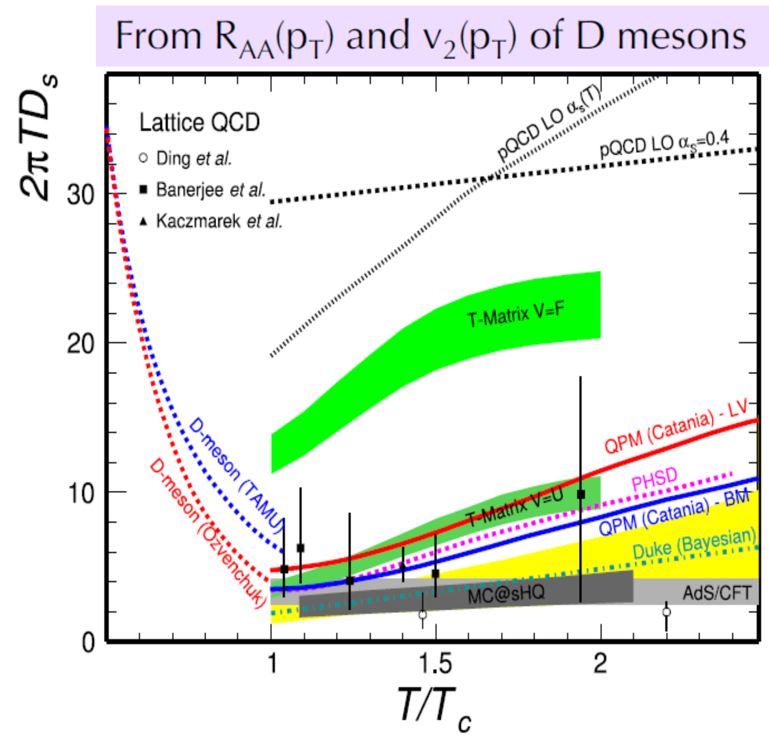
T and p dependent K factor needed starting from pQCD

Cao, Luo, Qin and Wang, PRC, 94, 014909 2016

RAA and v2 @PHSD







Dong, Greco, PPNP 104 (2019) 97-141

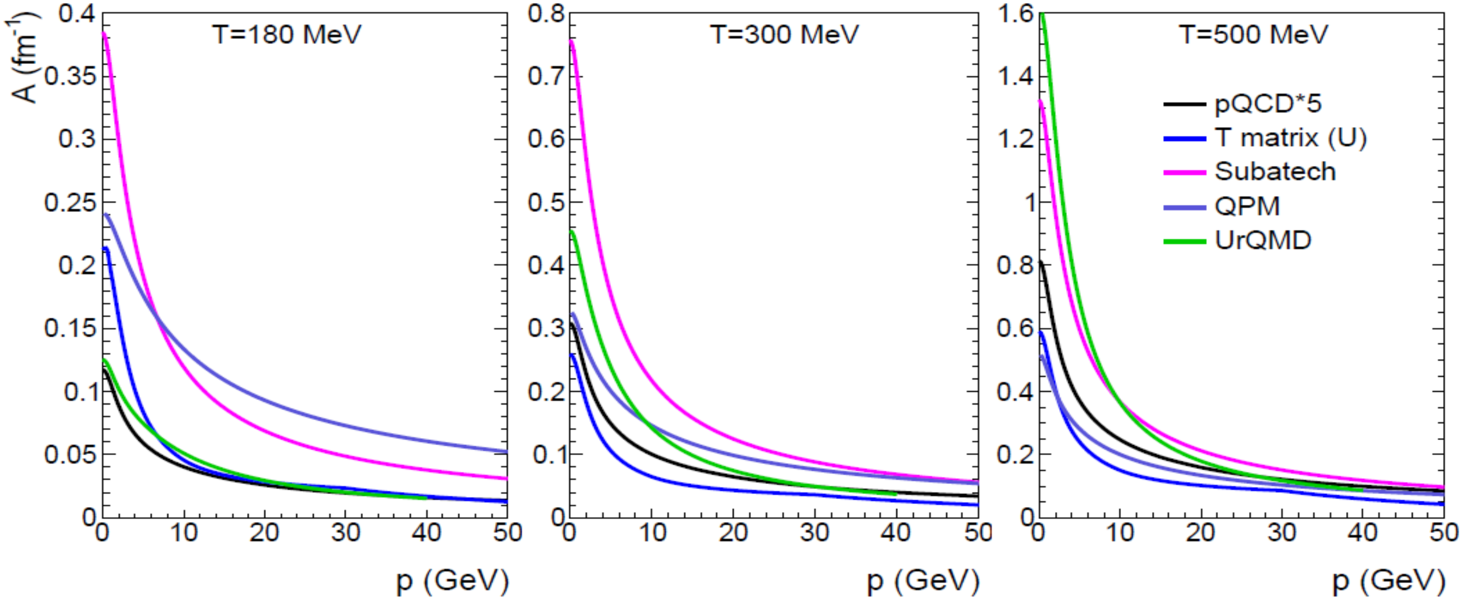
T. Song et al. PRC 93, 034906 (2016)

Brambilla et. al 2007.10078 [hep-lat]
Altenkort et al. 2009.13553 [hep-lat]

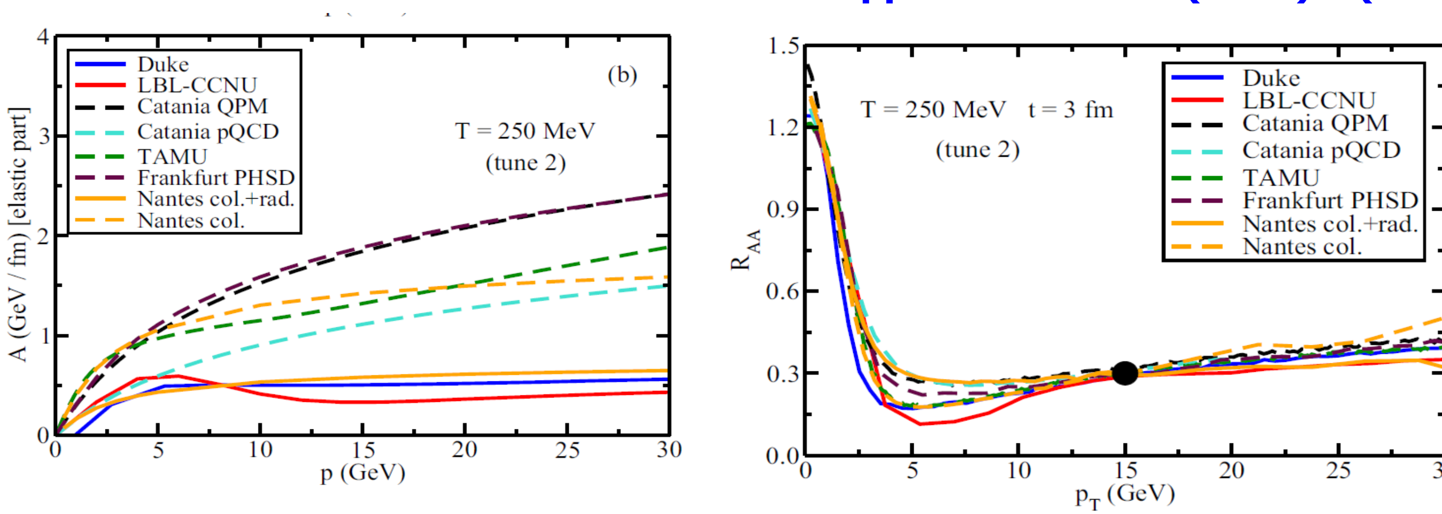
Heavy quark transport coefficients computed within Polyakov loop plasma showing similar T and p-dependence of heavy quark transport coefficients like T-matrix, QPM and PHSD.

Singh et al. PRD 100 (2019)114019

A systematic attempts are going on within the EMMI-RRTF and "JET-HQ" working groups to find a common agreement between different groups:



R. Rapp et.al NPA 979 (2018) (EMMI-RRTF)

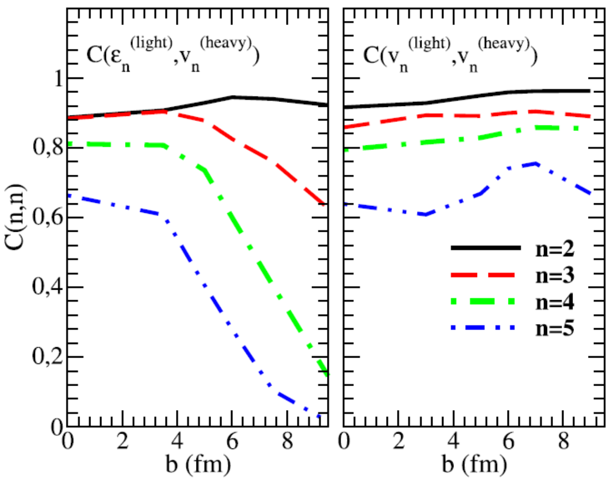


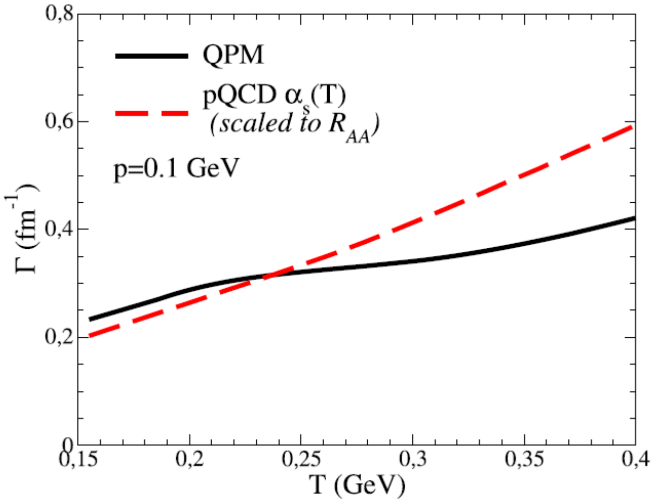
S. Cao et. al PRC 99, 054907 (2019) (JET-HQ)

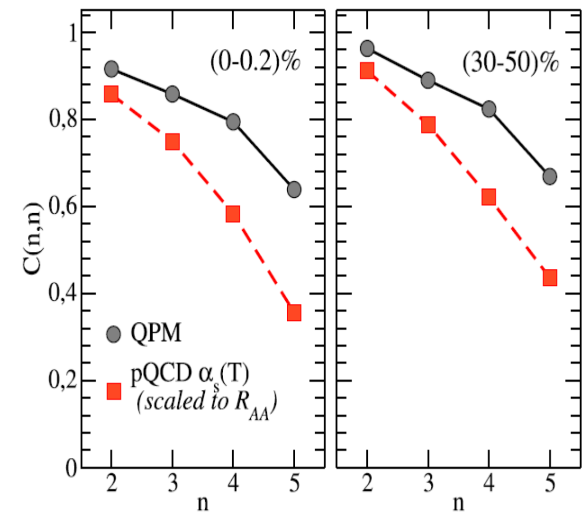
New observables:

Heavy-light event-by-event correlation

$$C(n,m) = \frac{\sum_i (v_n^{L,i} - \langle v_n^L \rangle)(v_m^{H,i} - \langle v_m^H \rangle)}{\sqrt{\sum_i (v_n^{L,i} - \langle v_n^L \rangle)^2 \sum_i (v_m^{H,i} - \langle v_m^H \rangle)^2}}$$







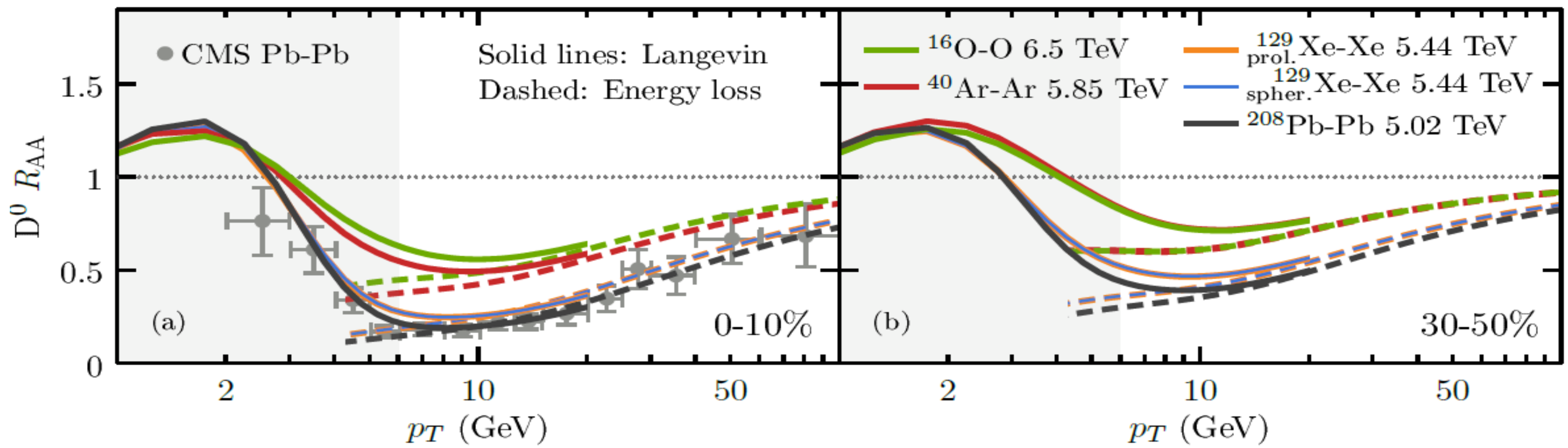
$V_n(D)$ more correlated to $v_n(N_{ch})$ than ε_n

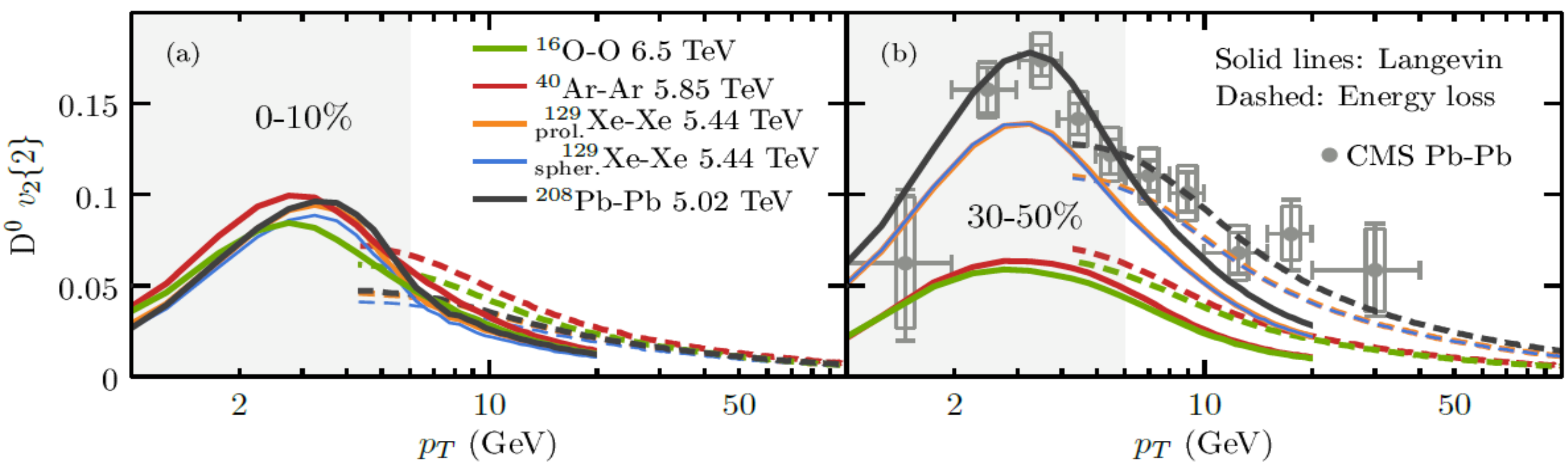
Very large sensitivity to T dep. of Ds

This can put further constrain on heavy quark transport coefficients

Plumari Coci, Minissale, Das, Sun, Greco
PLB 805 (2020) 135460

System size scan of D meson R_{AA} and v_2





In central collisions the v_2 is independent of system size.
System size vs Eccentricity

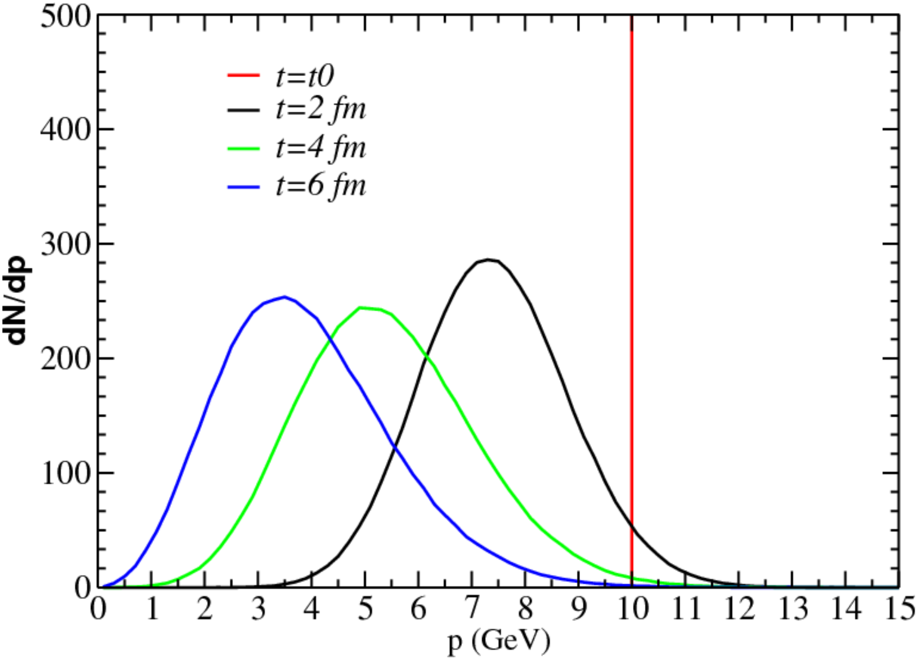
R. Katz et. al, arxiv:1907.03308

Evolution: Boltzmann vs Langevin (Charm)

Momentum evolution starting from a δ (Charm) in a Box

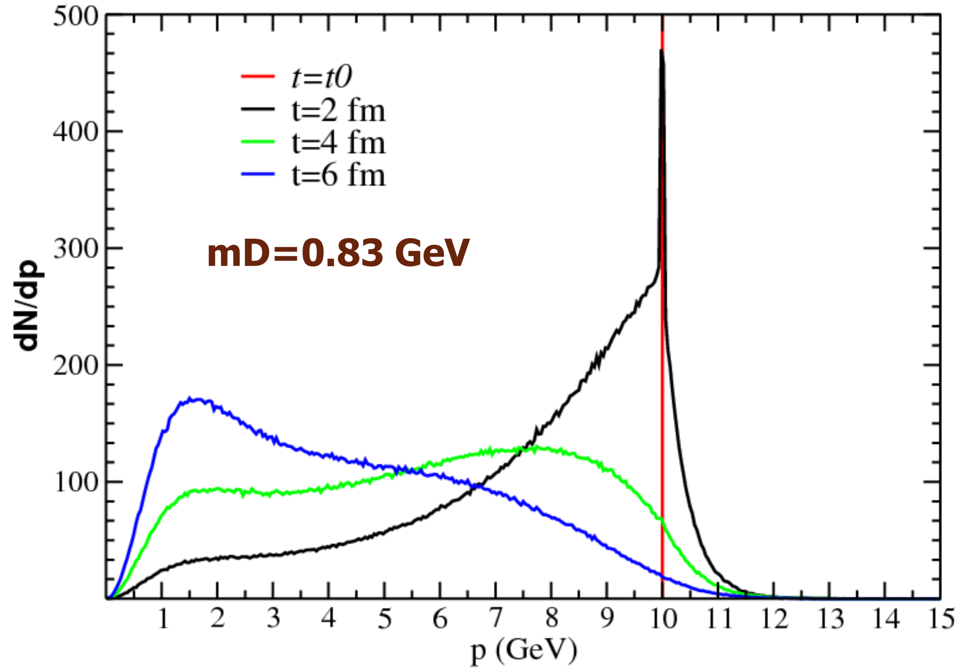
$$\left.\frac{dN}{d^3p}\right|_{initial} = \delta\left(p - 10GeV\right)$$

Langevin



In case of Langevin the distributions are Gaussian as expected by construction

Boltzmann



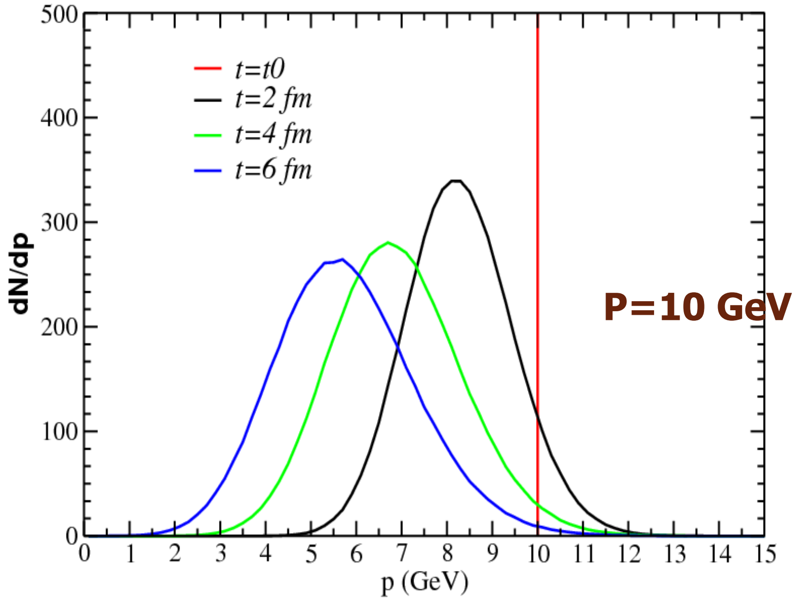
In case of Boltzmann the charm quarks does not follow the Brownian motion

Das, Scardina, Plumari and Greco PRC,90,044901(2014)

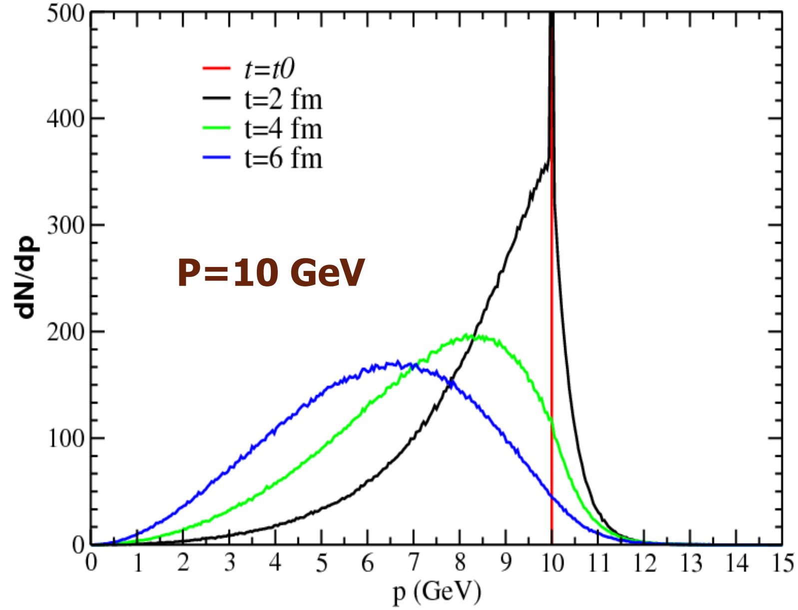
Momentum evolution starting from a δ (Bottom)

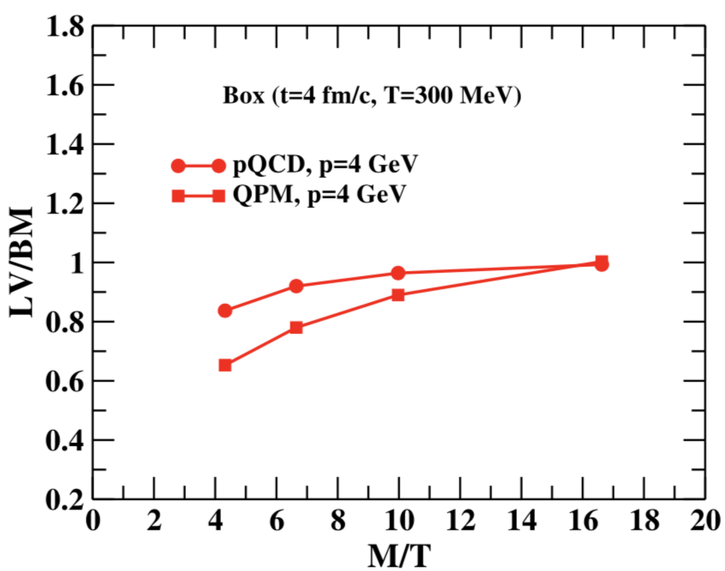
In a Box

Langevin



Boltzmann





Das, Scardina, Plumari and Greco
PRC,90,044901(2014)

Langevin dynamics overestimate the interaction
Boltzmann generate more v2 for the same RAA.

Rapp et. al. EMMI-RRTF, NPA 979 (2018)

Hadronization: Coalescence plus Fragmentation

Fragmentation function gives the probability to get a hadron from a parton:

$$f_H(p_T) = \sum_p f_p(p_T/z) \otimes D_{p\to H}(z)$$

<z>~0.9 for charm quark and <z>~0.5 for light quark

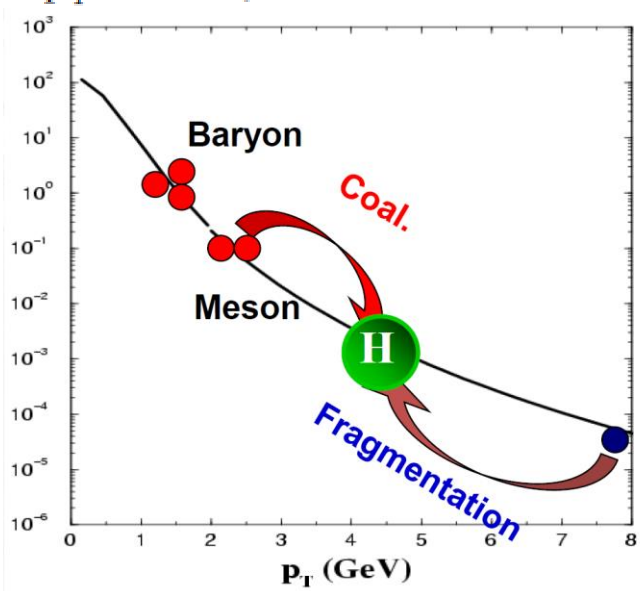
Coalescence is the convolution of two /three parton distribution folded by a wave function:

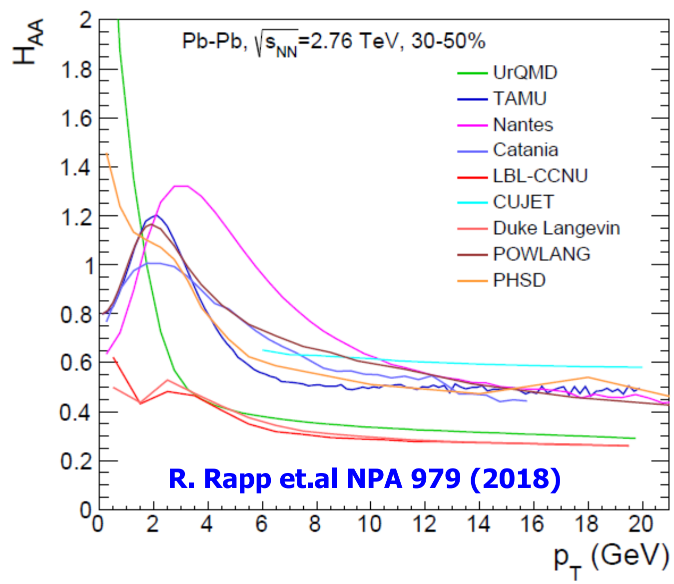
$$\frac{dN_{Meson}}{d^2p_T} = g_M \sum_{i,j} P_q(i) P_q(j) \delta^{(2)}(p_T - p_{iT} - p_{jT}) f_M(x_i, x_j; p_i, p_j)$$

V. Greco, C.M. Ko, and P. L´evai PRL 90 , 202302 (2003)

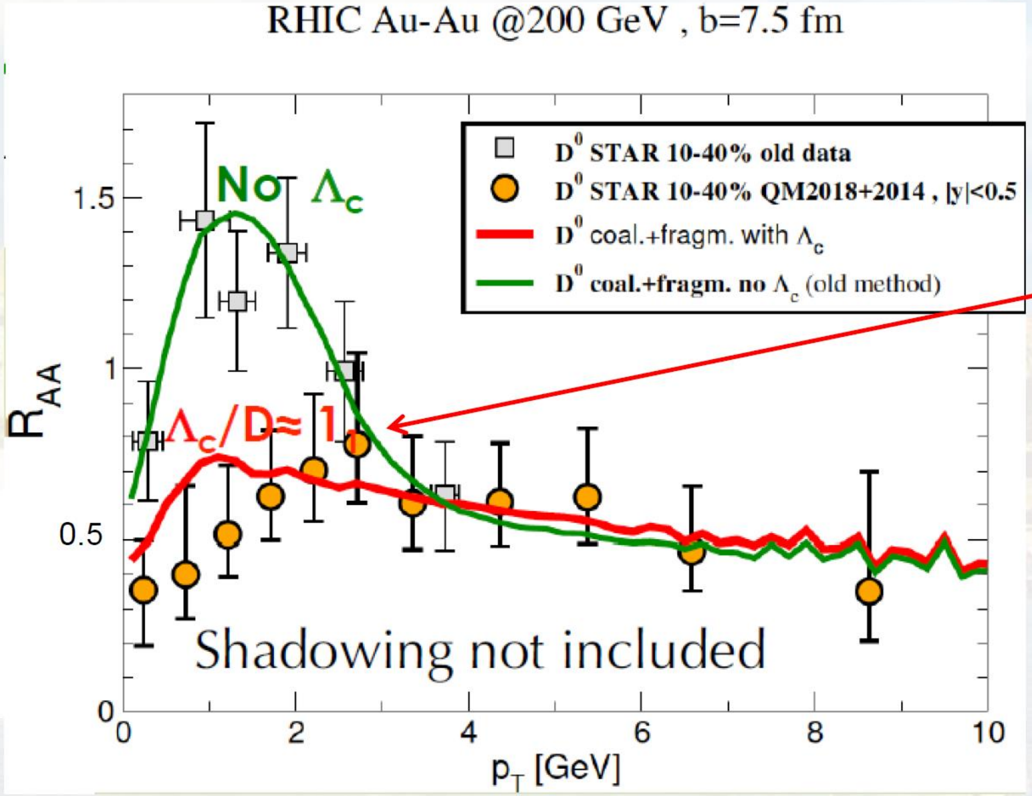
Hadron wave function

$$\frac{dN_{Baryon}}{d^2p_T} = g_B \sum_{i,j,k} P_q(i) P_q(j) P_q(k) \delta^{(2)}(p_T - p_{iT} - p_{jT} - p_{kT}) f_B(x_i, x_j, x_k; p_i, p_j, p_k)$$





Impact of heavy baryon to meson ratio on heavy quark suppressions



New STAR data in QM2018

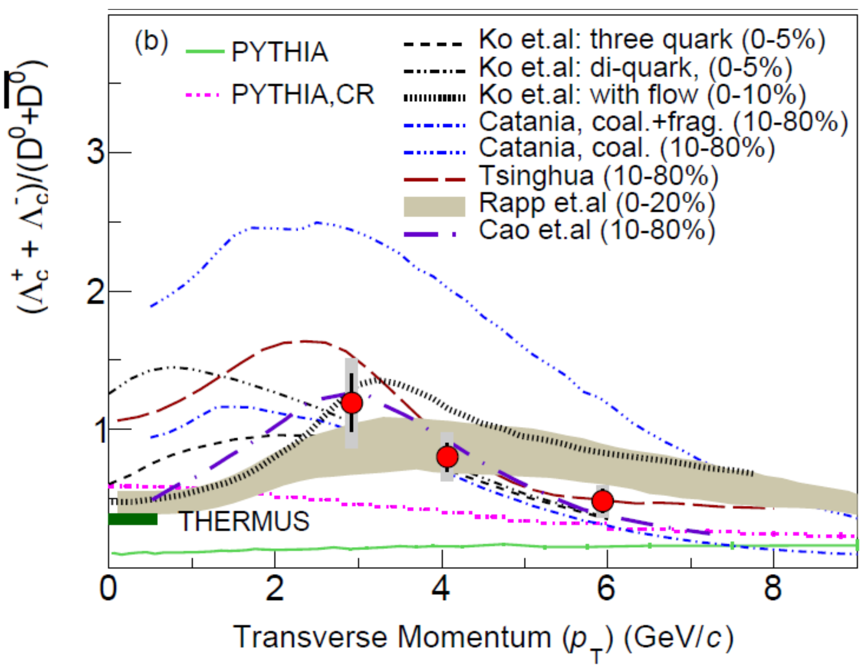
- Big effect at RHIC where coalescence dominates
- Smaller but still significant also at LHC

R_{AA} of D^o decreases because part of charm quark makes coalescence in charmed Lambdas, while in pp charm quarks fragment mainly in D mesons

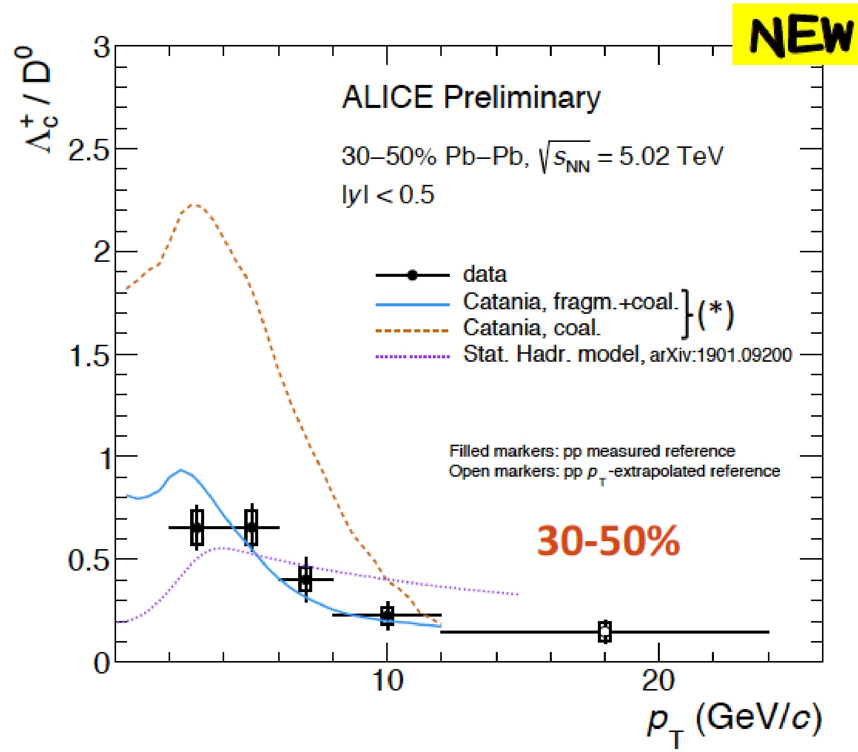
Minissale at.al (SQM-2019)

Heavy Baryon to meson ratio

(Serve as a tool to disentangle different hadronization mechanisms)



STAR, Phys. Rev. Lett. 124, 172301 (2020)



$P_{coal} = 1$ **to all hadron at p→0**

***Plumari et al. EPJC* 78 (2018) 4, 348**

Baryon in resonance recombination model

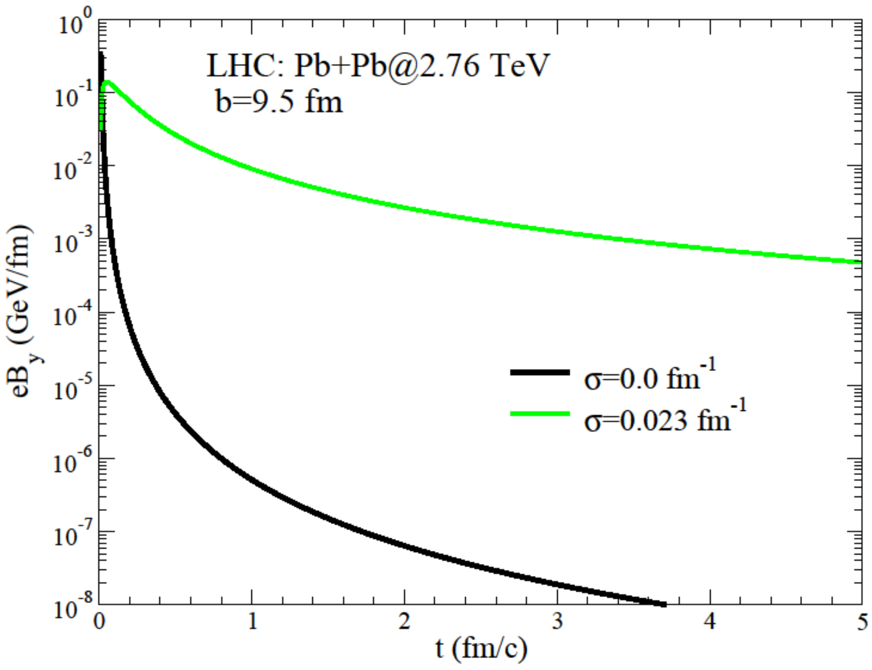
***He, Rapp, PRL* 124 (2020) 042301**

Impact of EM field on heavy quark dynamics at LHC

$$dp_j = -\Gamma p_j dt + \sqrt{dt} C_{jk}(t, p + \xi dp)\rho_k + F_{ext} dt$$

$$F_{ext} = q(E^{'} + v \times B^{'})$$

$$E' = \gamma (E + v \times B) - (\gamma - 1)(E \cdot \hat{v})\hat{v}$$
$$B' = \gamma (B - v \times E) - (\gamma - 1)(B \cdot \hat{v})\hat{v}$$



Gursoy, Kharzeev and Rajagopal
PRC 89, 054905 (2014)

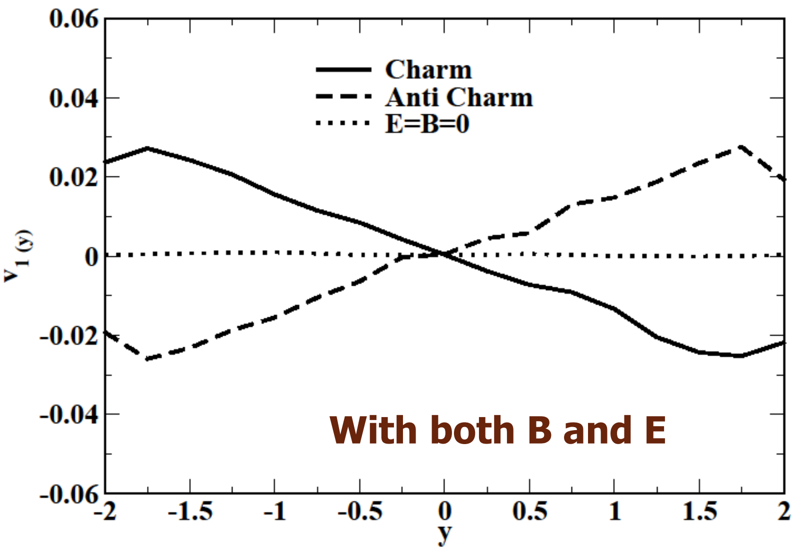
Electromagnetic field has been included in the Langevin equation as a external force.

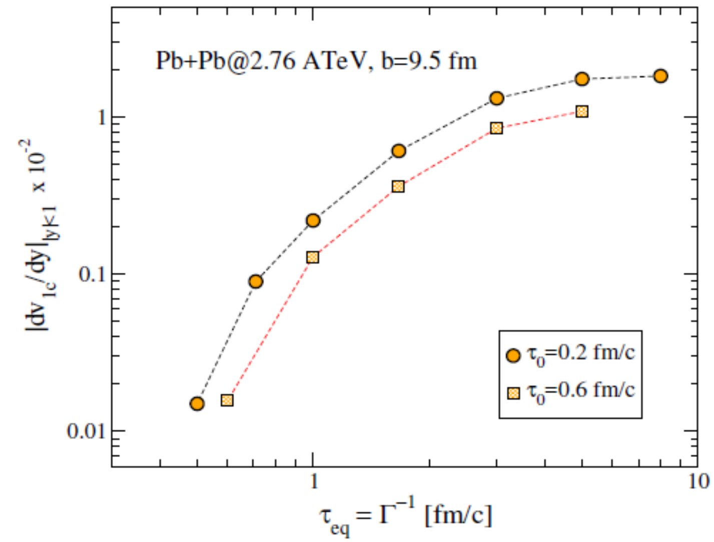
We consider both E and B.
Bx=Bz=0
And Ey=Ez=0

$$v_1 = < \frac{p_x}{p_T} >$$

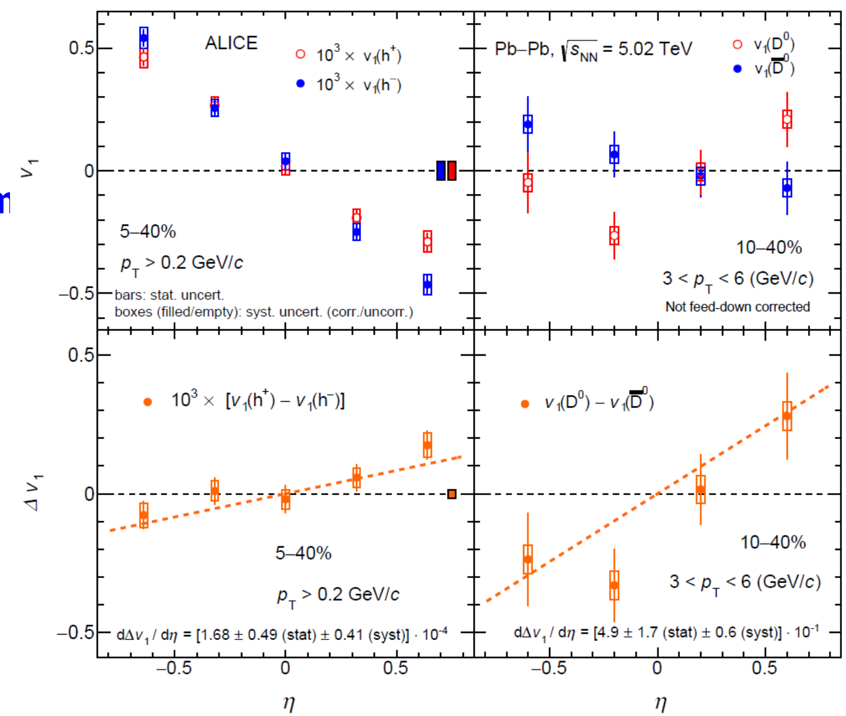
Das, Plumari, Chartarjee, Scardina, Greco, Alam
Phys. Lett. B, 768 (2017) 260

Heavy quark v_1@LHC





Das, Plumari, Chartarjee, Scardina, Greco, Alam
Phys. Lett. B, 768 (2017) 260

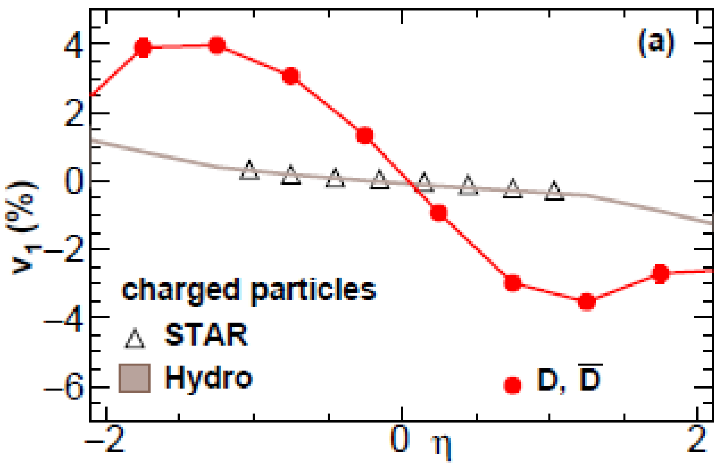


Heavy quark v_1 is larger than light quark v_1.

Recent data from ALICE indicates splitting in D and Dbar v_1.

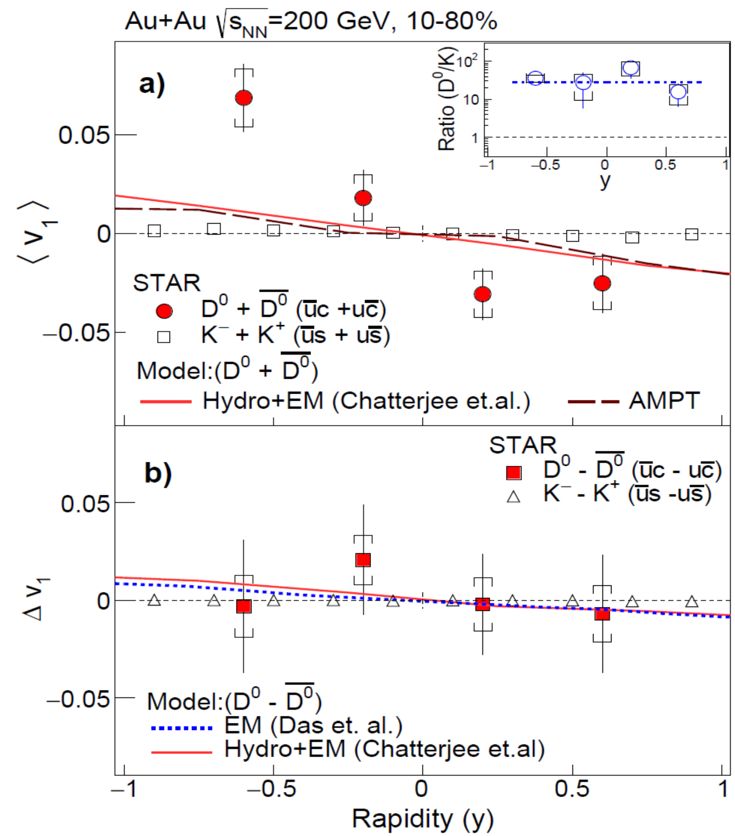
ALICE Collaboration, PRL 125 (2020) 2, 022301

Initial vorticities and electromagnetic field

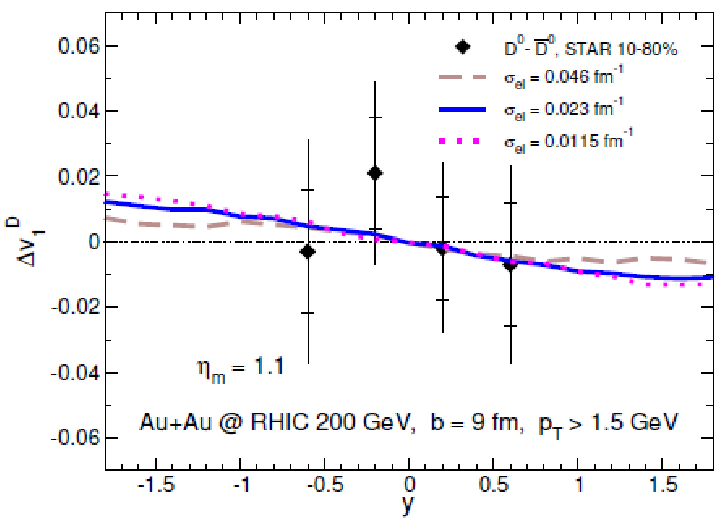


Impact of tilt bulk: Forward backward asymmetry

Chartarjee and Bozek, PRL 120 (2018) 192301



***STAR, PRL* 123 (2019) 16, 162301**

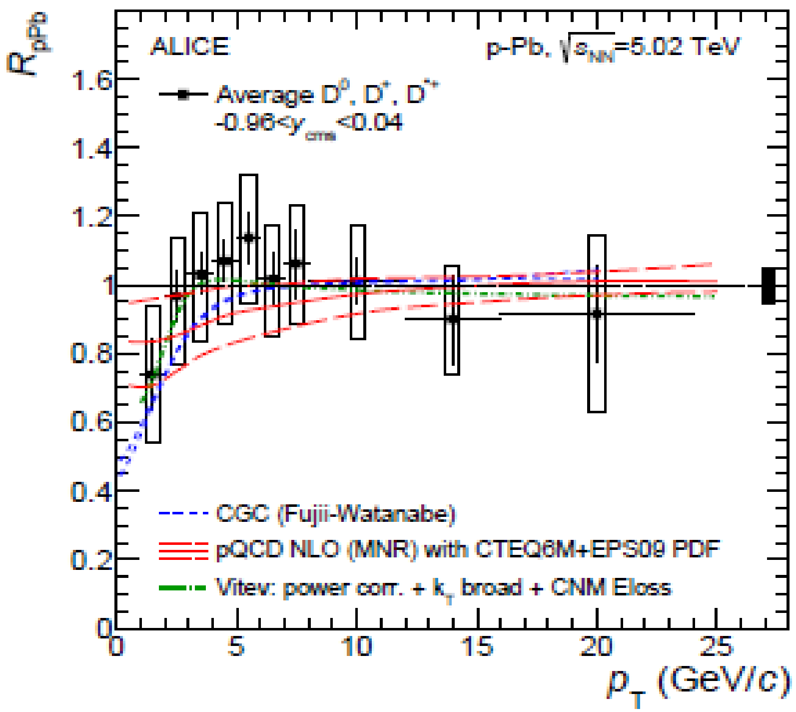


Oliva, Plumari, Greco, arxiv:2009.11077 [hep-ph]

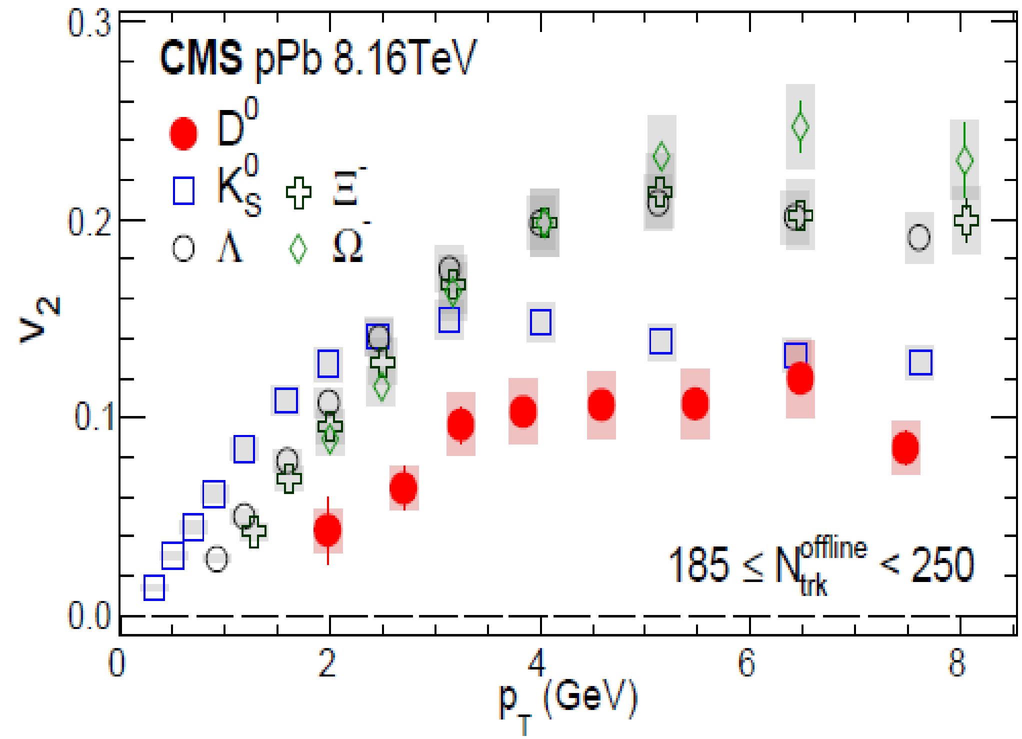
Heavy quark Transport coefficient in Magnetic field:

K. Fukushina at al. PRD,93 (2016) 074028
M. Kurin at al. PRD, 101 (2019) 074003
B. Singh at al. arXiv:2004.11092

Heavy quark in small system (p-nucleus)



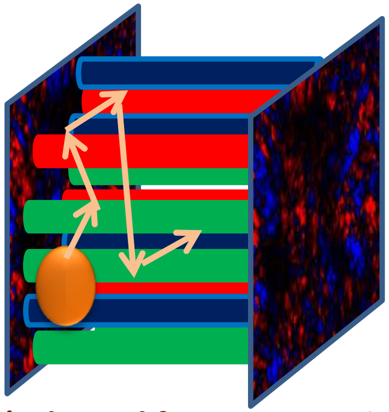
ALICE Collaboration
Phys. Rev. Lett. 113 (2014) 232301



CMS Collaboration
arXiv:1804.09767v2

What mechanism could build up v_2 without energy loss?

Heavy quarks as probes of the evolving Glasma

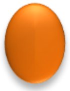


(Adapted from M. Ruggieri)

$$t_{\text{formation}} \approx \frac{1}{2m_c} \approx 0.06\ \text{fm/c}$$

[Talk by Mueller on Monday]

[Talk by Boguslavski on Tuesday]



HQs can probe the very early evolution of the Glasma fields

Hamilton equations of motion of *c*-quarks:

$$\frac{dx_i}{dt} = \frac{p_i}{E}$$

$$E = \sqrt{\boldsymbol{p}^2 + m^2}$$

$$\boldsymbol{v} \equiv \frac{\boldsymbol{p}}{E}$$ *(Relativistic) Velocity*

$$E\frac{dp_i}{dt} = gQ_a F^a_{i\nu} p^\nu \,,$$

$$\frac{d\boldsymbol{p}}{dt} = q\boldsymbol{E} + q\left(\boldsymbol{v} \times \boldsymbol{B}\right)$$ *Lorentz force*

$$E\frac{dQ_a}{dt} = -gQ_c \varepsilon^{cba} \boldsymbol{A}_b \cdot \boldsymbol{p}$$

Wong (1979)

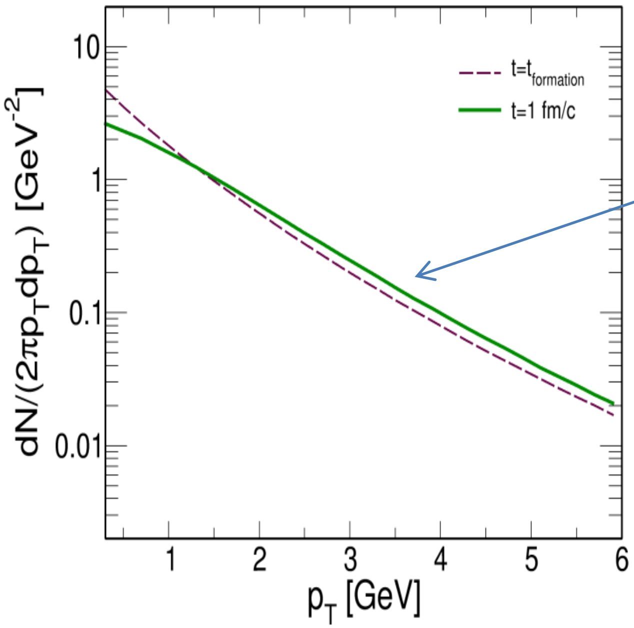
$$D_\mu J^\mu_a = 0$$

Gauge-invariant conservation of the color Current carried by charm quaks + gluons

$$J^\mu_a = \bar{c}\gamma^\mu T_a c$$

Equations of motion of heavy quarks are solved in the background given by the evolving Glasma fields p-Pb @ 5.02 TeV

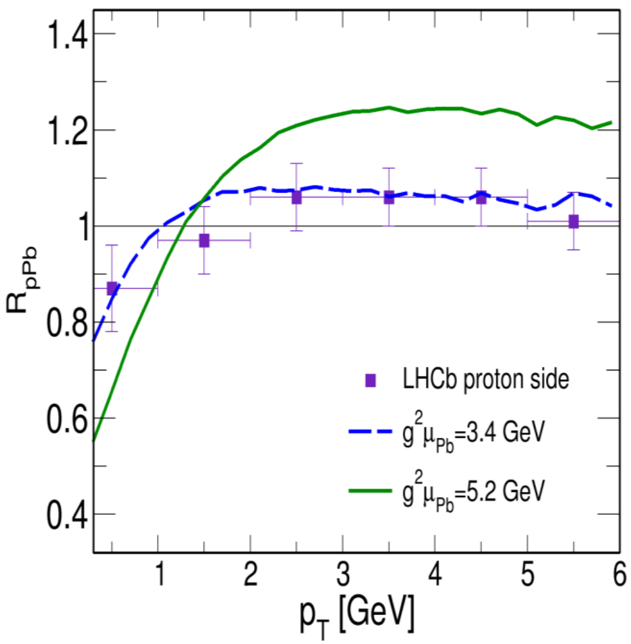
Nuclear modification factor (R_{pPb}) for p-Pb collisions

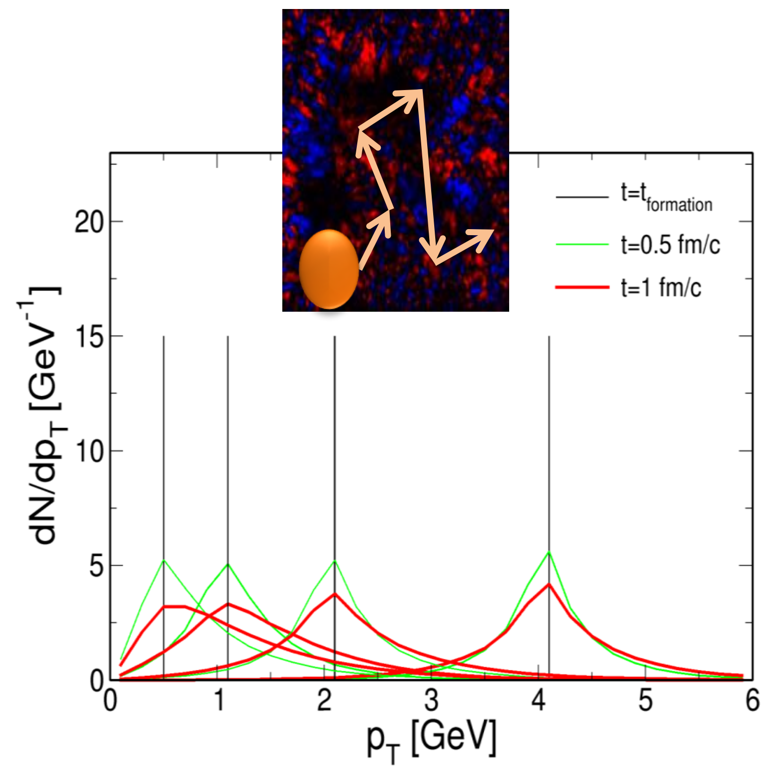


Initial distribution: from perturbative QCD
Evolution: interaction with the Glasma

$R_{pPb} \neq 1$

Interaction with the fields created by the collision

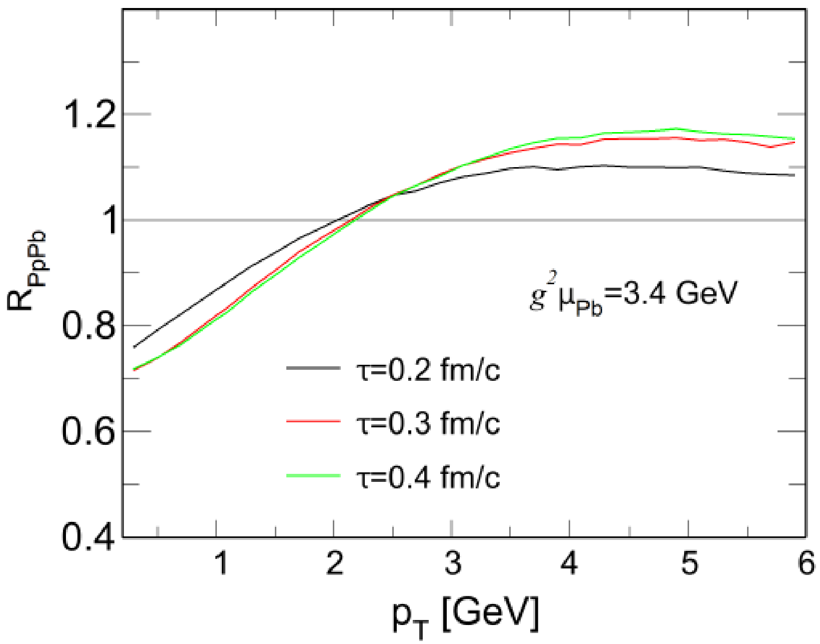


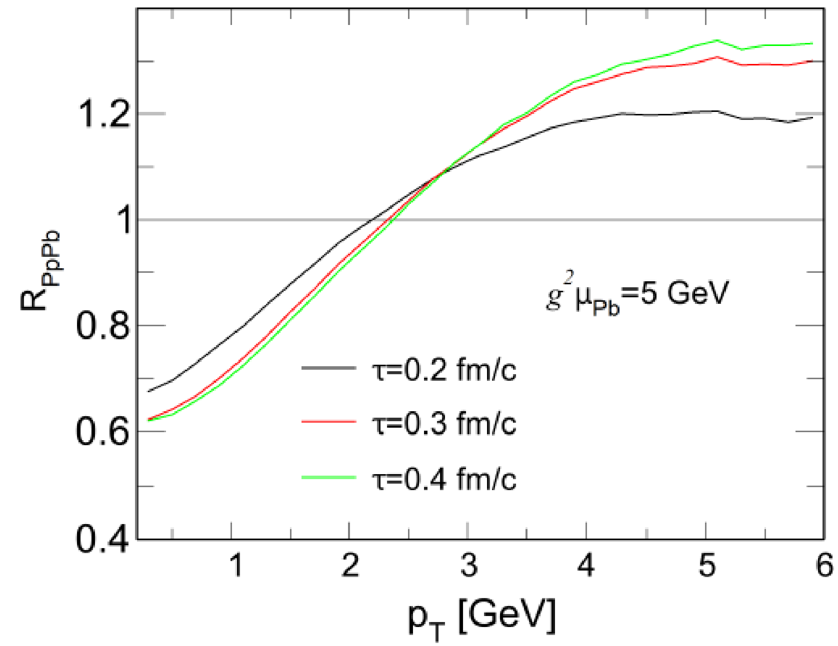


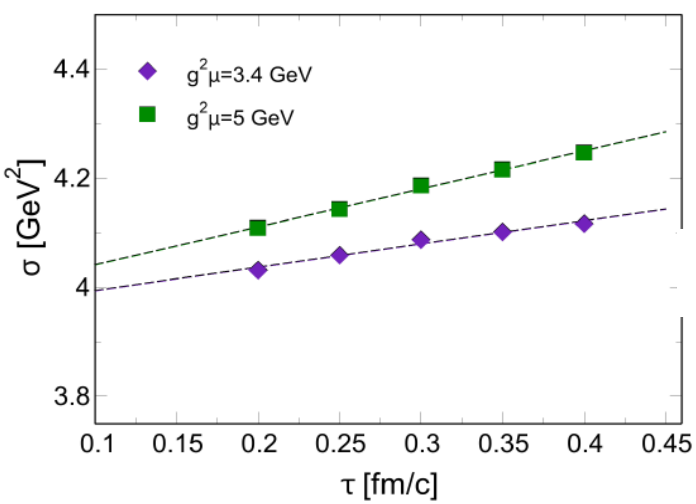
Ruggieri and Das
PRD, 98, 094024(2018)

HQ Diffusion in Glasma

Heavy quark dynamics in Expanding Glasma

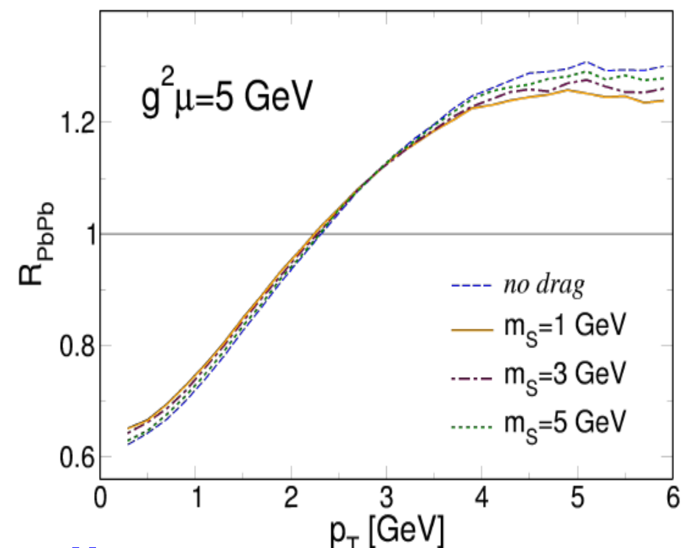






$$E\frac{dp_i}{dt} = Q_a F^a_{i\nu} p^\nu - E\Gamma p_i,$$

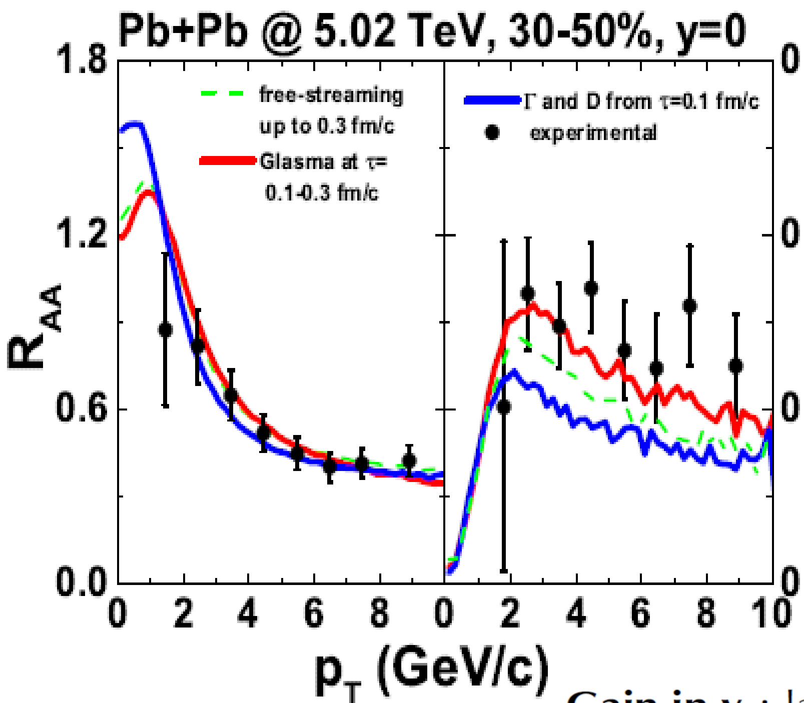
$$D = \Gamma E T,$$

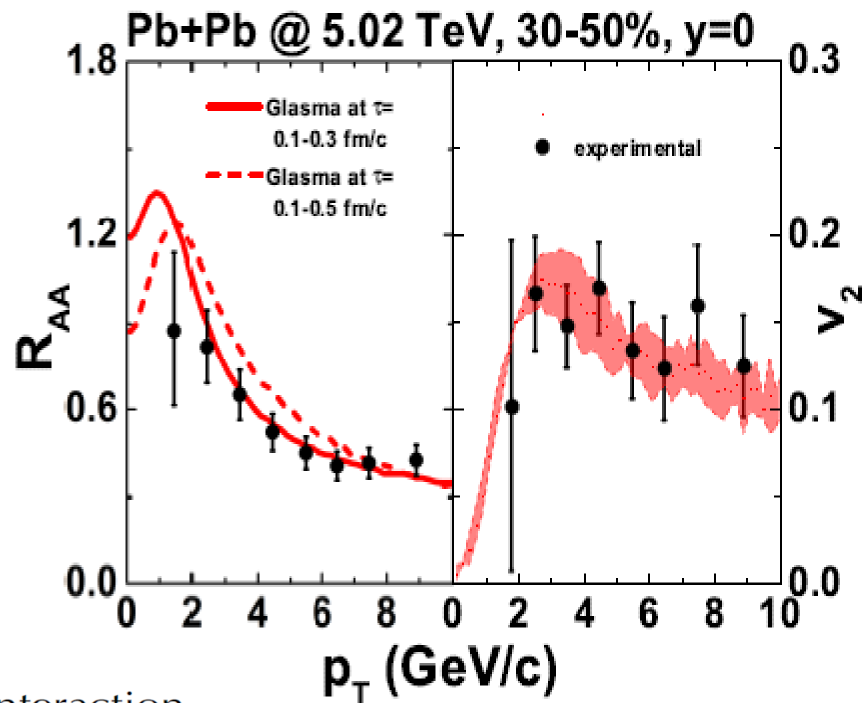


$$\sigma \equiv \langle (p_T - \langle p_T \rangle)^2 \rangle = 2D\tau \ + \ \text{constant}$$

Liu, Plumari, Das, Greco, Marco
PRC, in press

Impact of Glasma on a heavy quark observables at LHC
(Heavy quark dynamics in Glasma plus Plasma)





Gain in v_2: larger interaction in QGP stage to have same $R_{AA}(p_T)$

This indicates an initial pre-thermal stage is unlikely to be described in terms of a standard drag and diffusion dynamics, because even if one tune such coefficients to reproduce the same $R_{AA}(p_T)$ this would imply a significantly smaller v_2.

Sun, Coci, Das, Plumari, Ruggieri, Greco
PLB, 798 (2019) 134933

Few recent works on heavy quark diffusion in pre-equilibrium phase

S. Mrowczynski, EPJA 54 (2018) 3, 4

M. Carrington et al. NPA 1001 (2020) 121914

K. Boguslavski at. al. JHEP 09 (2020) 077

Talk by K. Boguslavski on Tuesday

A. IPP at al. 2009.14206 [hep-ph]

[Talk by D. Mueller on Monday]

Within Kinetic Theory:

S. K. Das et al. JPG, 44 (2017) 095112

T. Song et al. PRC, 101 (2020), 044901

Impact of pre-equilibrium phase is significant

Conclusions and Perspectives:

- **Open Heavy Flavor Physics at RHIC and LHC**

  R_{AA} and v_2 → $D_s(T)$→lQCD

- **More precision data and New Observables**

  V_n(HQ)-V_n(LQ), Λ_c, dN/dΦ, System size scan and bottom quark observables, will allows significant advantage to understand the hot QCD matter

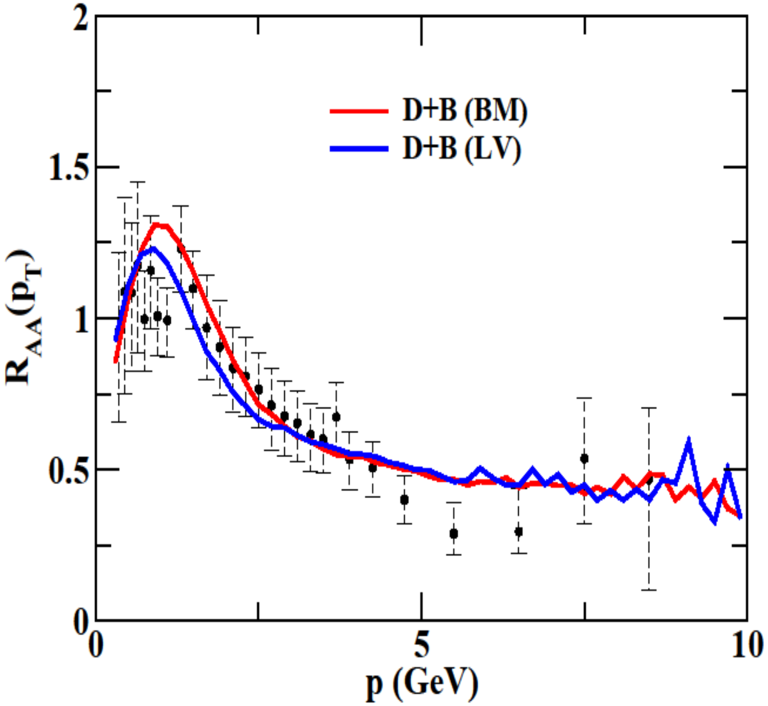
- **Heavy quark V_1 → EM field and Angular momentum**

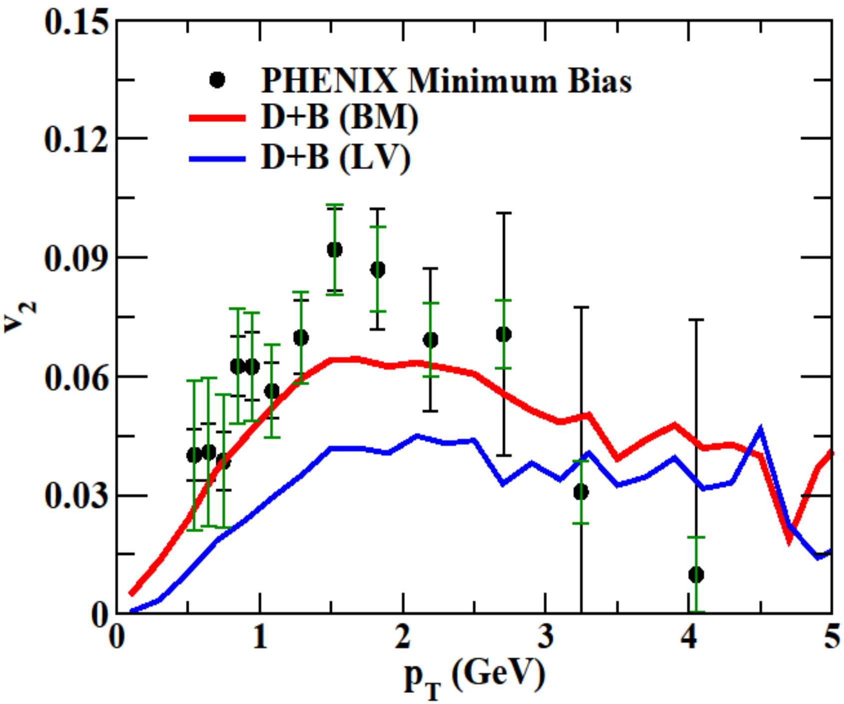
- **Heavy quark as a probe of the pre-equilibrium phase → Glasma**


Thank You

R_{AA} and v_2 at RHIC

(With near isotropic cross-section)



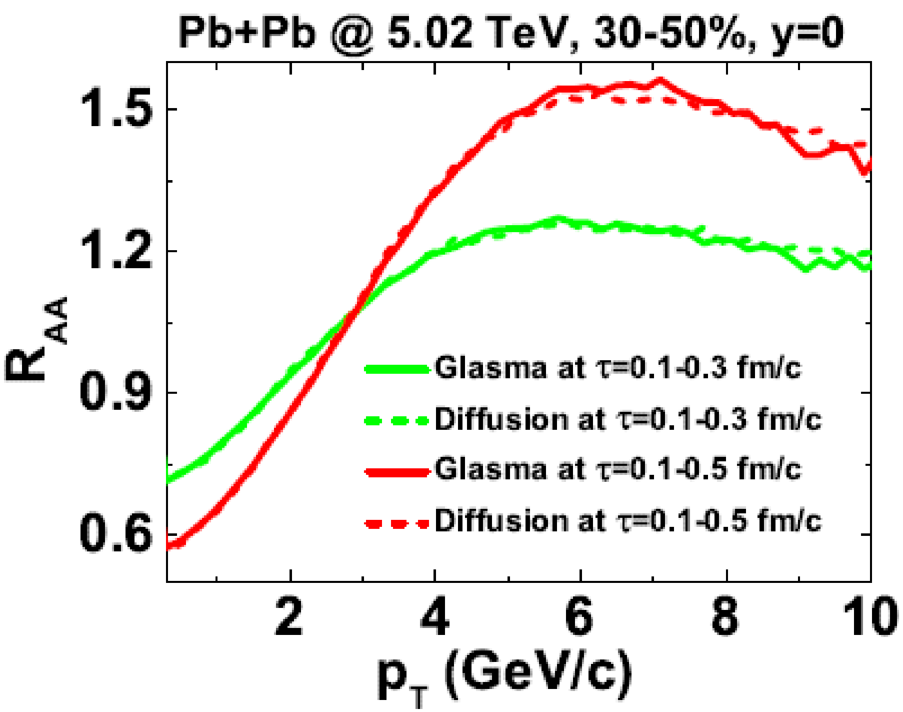


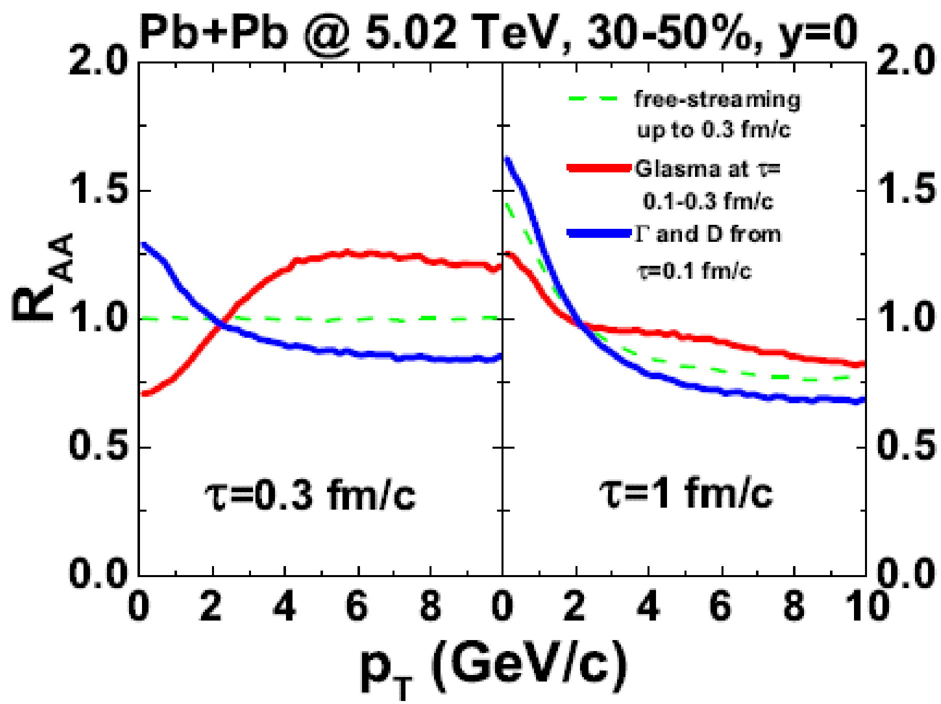
Das, Scardina, Plumari and Greco
PRC,90,044901(2014)

At fixed R_{AA} Boltzmann approach generate larger v_2 .
(depending on m_D and M/T)

With isotropic cross section one can describe both R_{AA} and V_2 simultaneously within the Boltzmann approach

Impact of Glasma on a heavy quark observables at LHC
(Glasma vs Plasma)

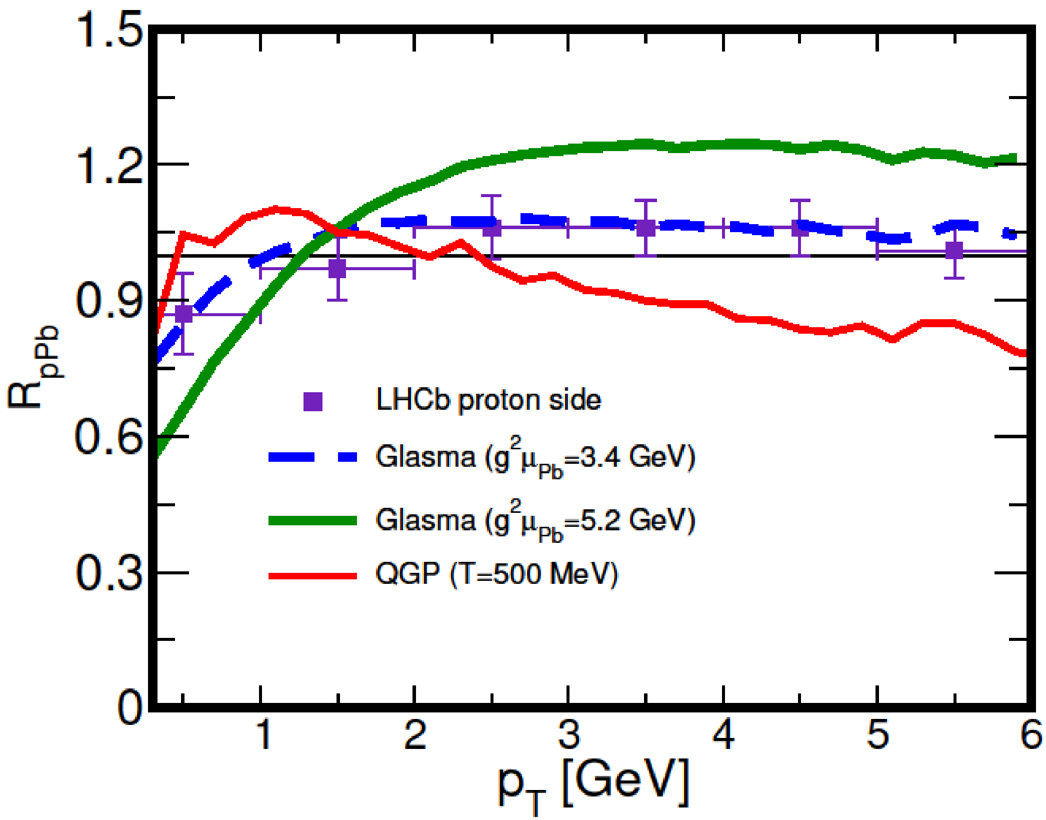




Glasma induce a diffusion of charm quarks in momentum space resulting in a tilt of their spectrum without a significant drag.

Sun, Coci, Das, Plumari, Ruggieri, Greco
PLB, 798 (2019) 134933

Heavy quark suppression in pPb: Glasma vs Plasma



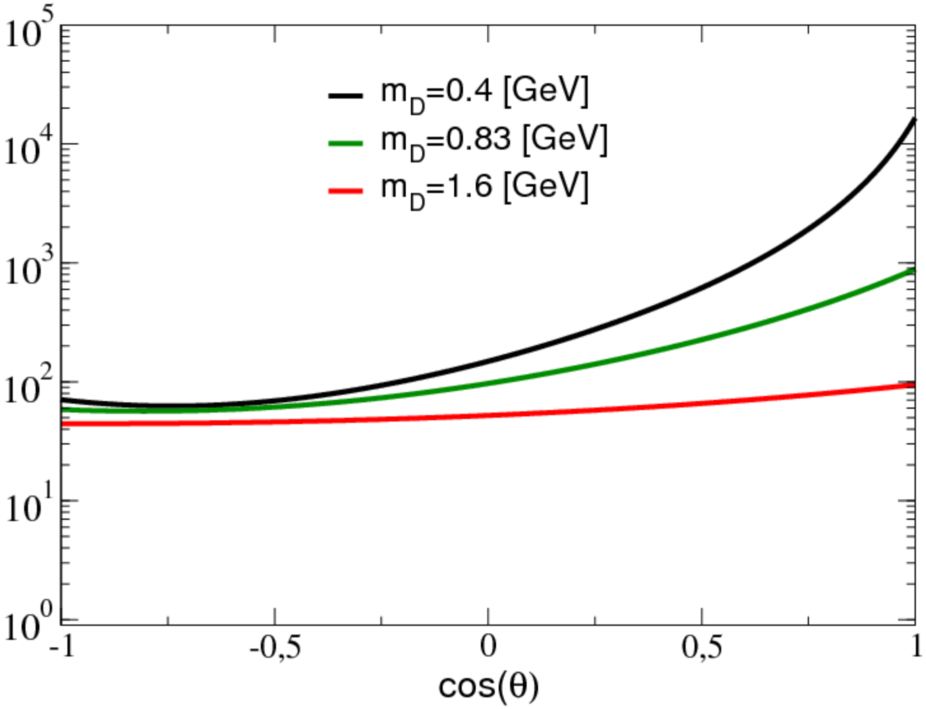
In Plasma: high momentum particle loose energy shifted to low momentum domain.
In Glasma: low momentum particle get accelerated and shifted to high momentum domain

Liu , Das, Ruggieri, Plumari, Greco
Under preparation

Boltzmann vs Langevin (Charm)

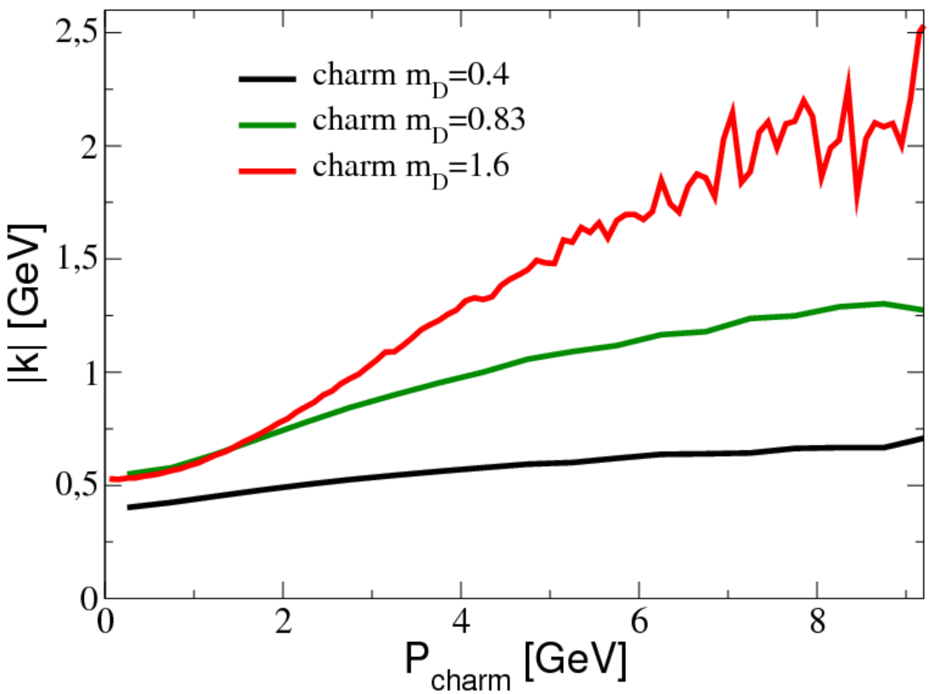
T=400 MeV

Angular dependence of σ



Decreasing m_D makes the σ more anisotropic

Mometum transfer vs P

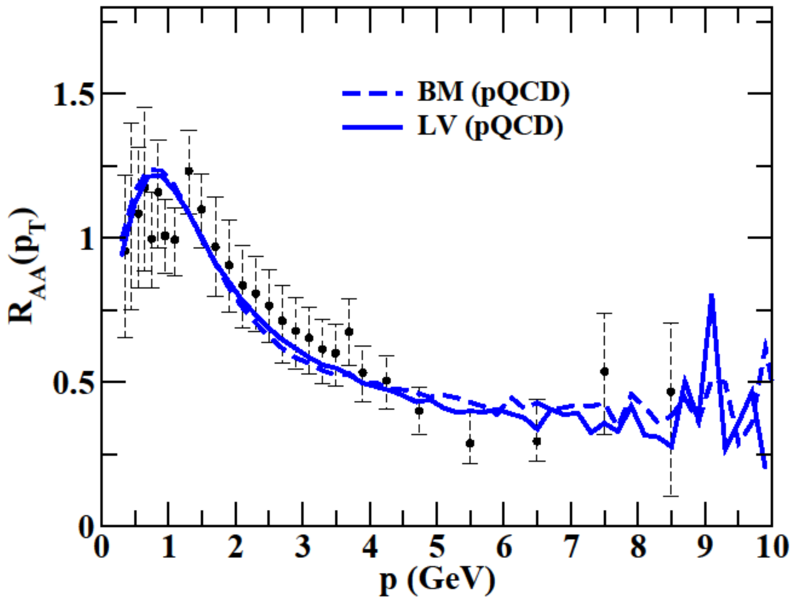


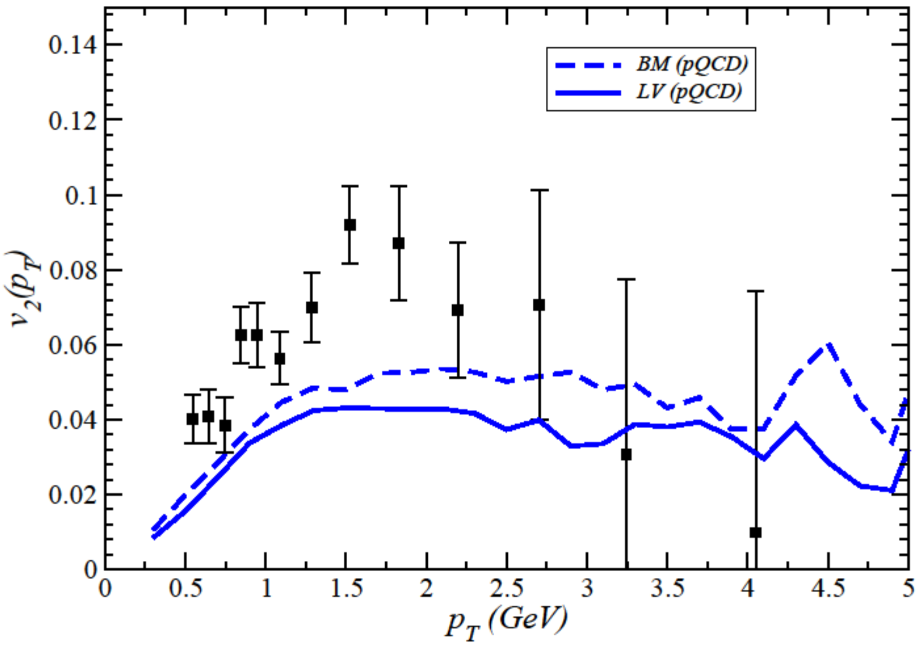
Smaller average momentum transfer

Hees,Greco,Rapp,PRC,73,034913 (2006)

Das, Scardina, Plumari and Greco PRC,90,044901(2014)

R_{AA} and v2 at RHIC at mD=gT

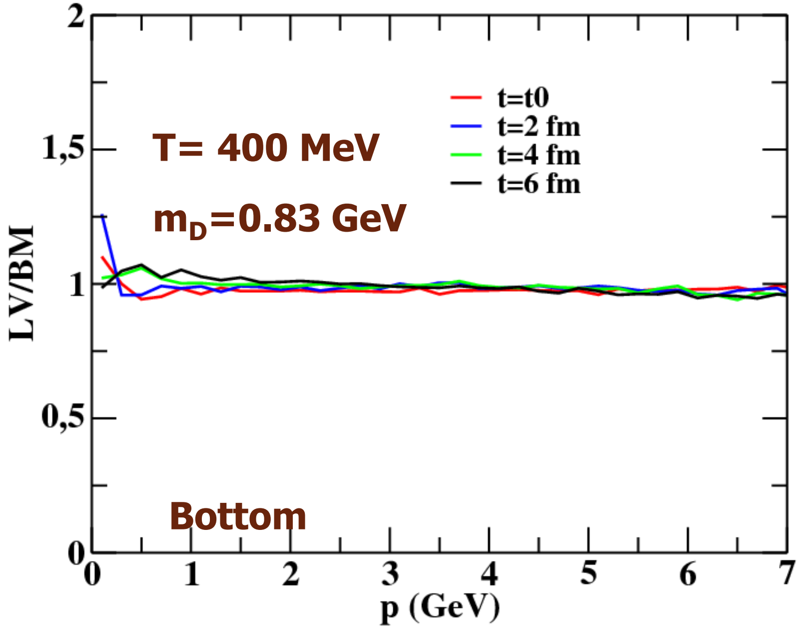


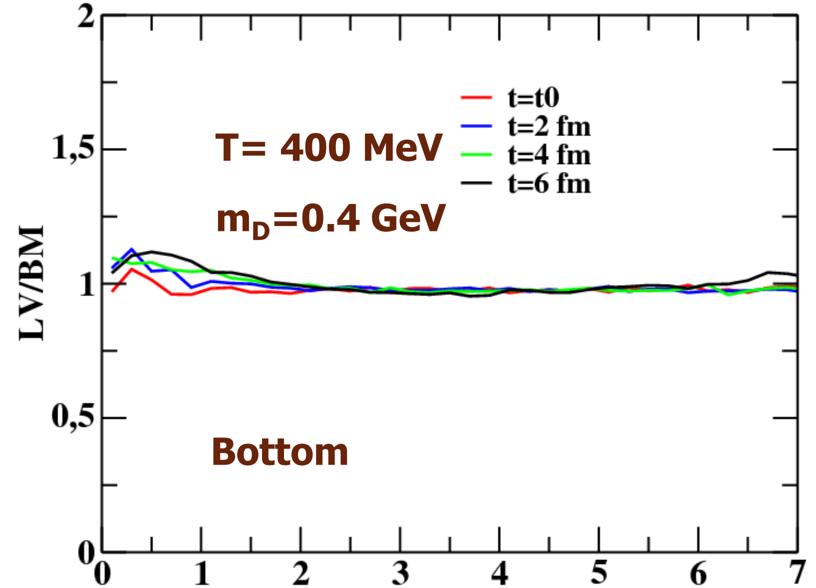


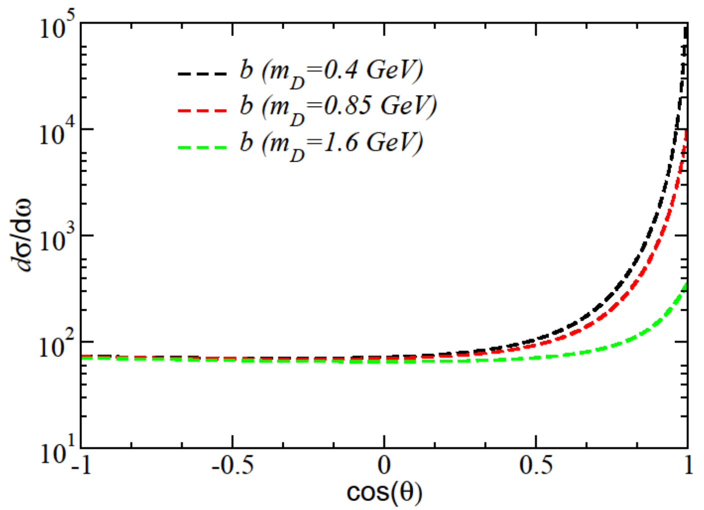
Das, Scardina, Plumari and Greco
PRC,90,044901(2014)

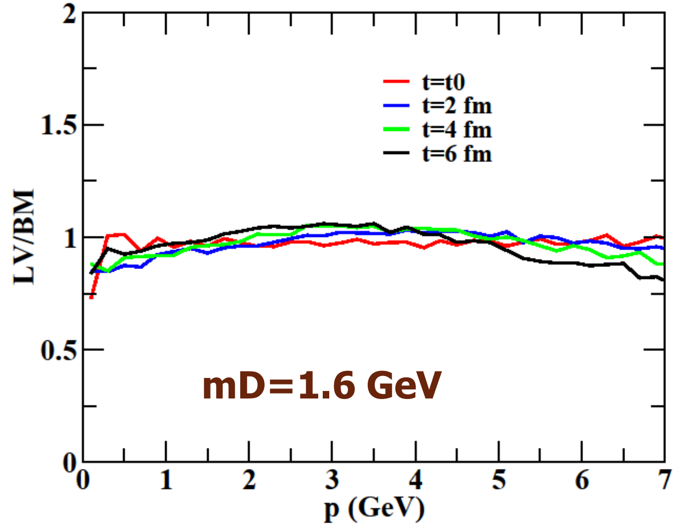
At fixed RAA Boltzmann approach generate larger v2 .
(depending on mD and M/T)

Bottom: Boltzmann = Langevin



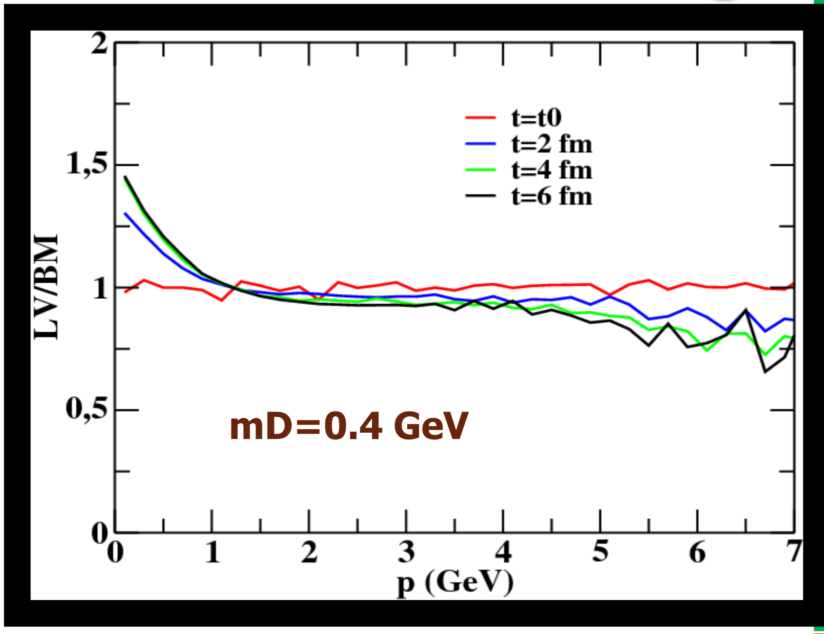


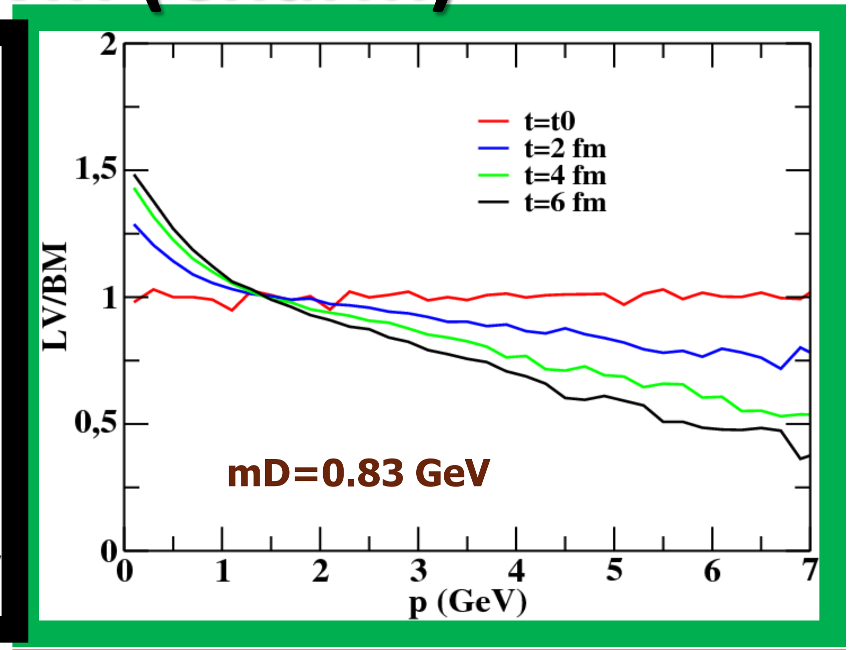


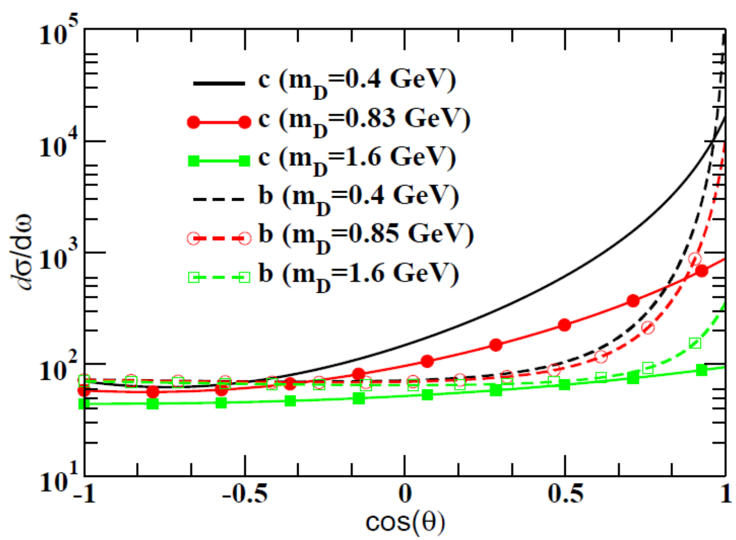


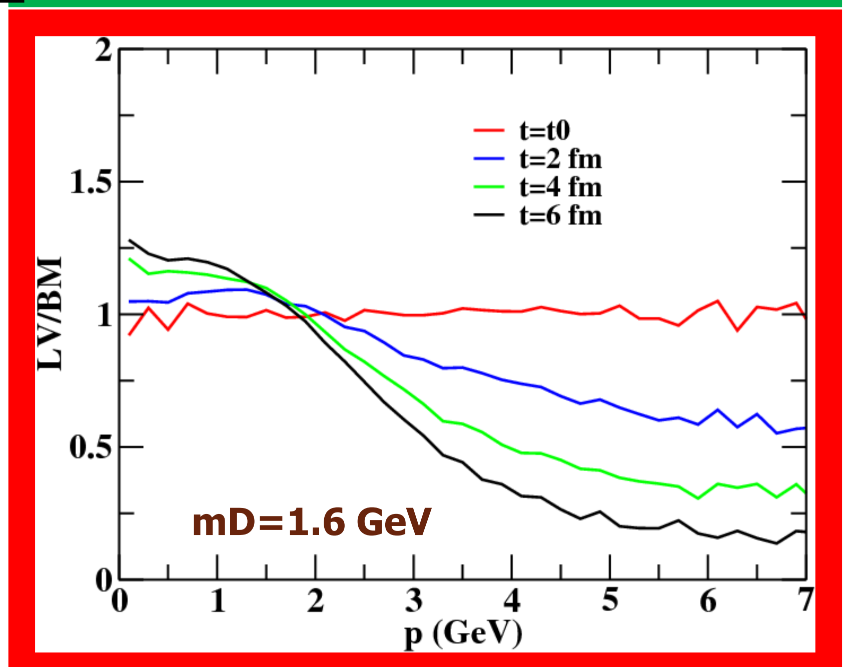
But Larger M_b/T (≈ 10) the better Langevin approximation works

Boltzmann vs Langevin (Charm)









Das, Scardina, Plumari and Greco
PRC,90,044901(2014)