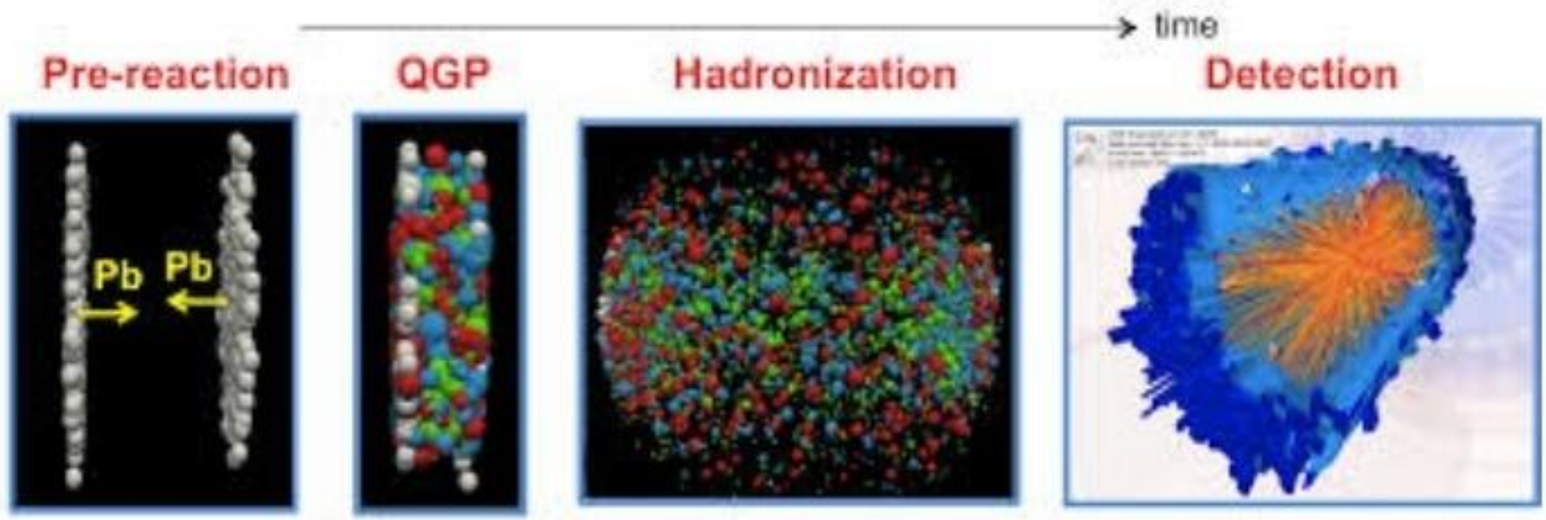
Probing the hot QCD matter with heavy quarks



Santosh Kumar Das

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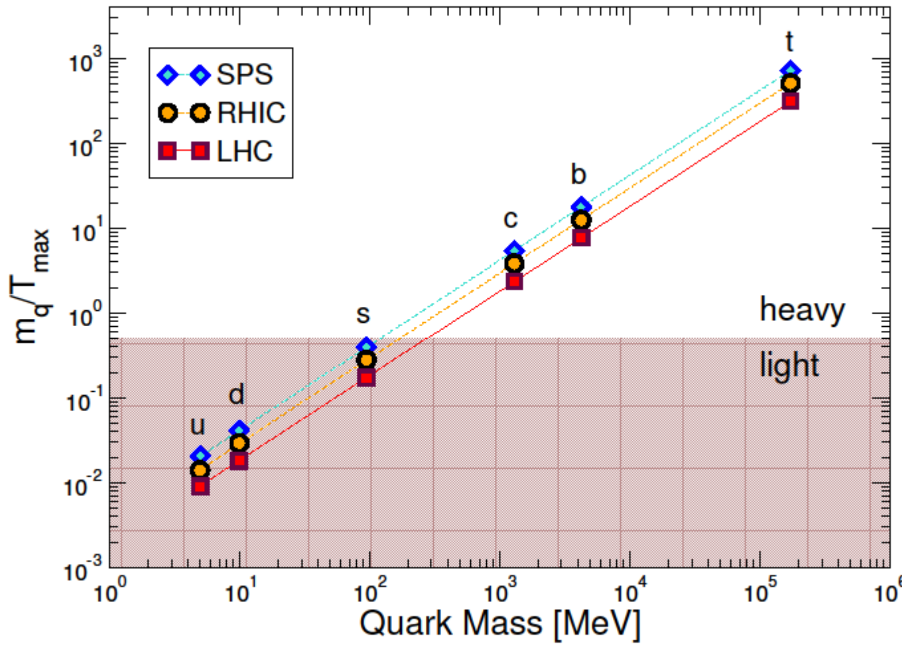
Goa, India

Heavy Quark & Quark Gluon Plasma



SPS to LHC

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

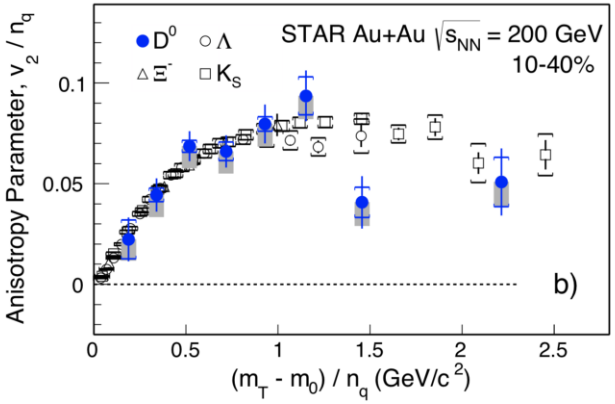
$T_i = 200 \ MeV \ to \ 600 \ MeV$ **~3 times**

- $m_{c,b} >> \Lambda_{QCD}$ pQCD initial production
- $m_{c,b} >> T_{RHIC,LHC}$ negligible thermal production (not @FCC)
- $\tau_0 < 0.08$ fm/c $<< \tau_{QGP}$ witness of all the QGP evolution
- $\tau_{th} \approx \tau_{QGP} >> \tau_{q,g}$ carry more information of their evolution
- $m_{c,b} >> gT_{RHIC,LHC}$ soft scatterings → Brownian motion (low p charm)

Das, Torres-Rincon, Rapp, Phys. Rept. 1129-1131 (2025)

Heavy quark physics at different scales

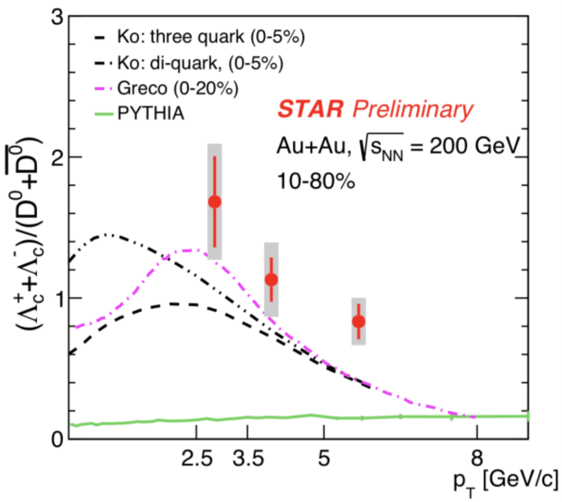
low p_T



Study thermalization process of HQ

Constrain diffusion coefficient D_s

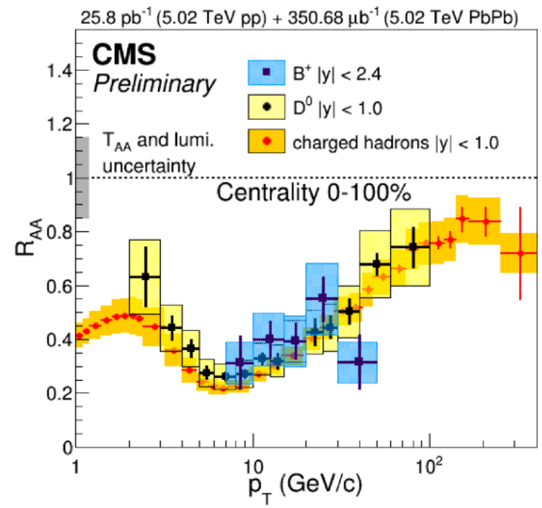
medium p_T



Study hadronization process of HQ

Constrain hadron wave-function

high p_T



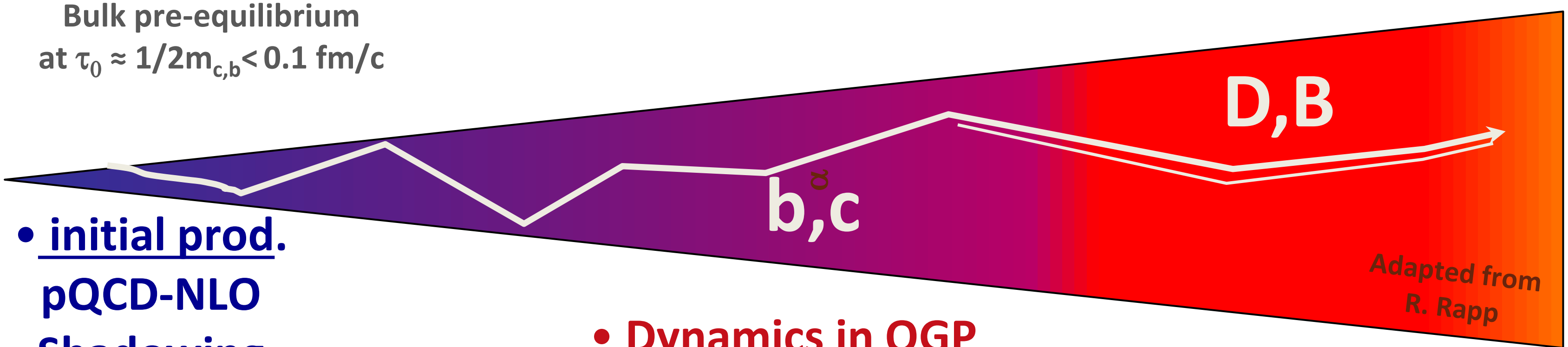
Study parton energy loss and mass effect

Constrain jet transport parameter $\hat{q}$

S. Cao (HP 2018)

Studying the heavy quark dynamics in HIC

Bulk pre-equilibrium
at $\tau_0 \approx 1/2m_{c,b} < 0.1$ fm/c



• initial prod.
pQCD-NLO
Shadowing
Pre-equilibrium
Effect
Electromagnetic
field

• 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

Boltzmann Kinetic equation

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

- 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

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

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

B. Svetitsky PRD 37(1987)2484

where we have defined the kernels

,

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

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

Heavy quark momentum evolution: Langevin vs Boltzmann

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

Boltzmann Equation **Fokker Planck**

It will be interesting to study both the equation in a identical environment to ensure the validity of this assumption at different momentum transfer and their subsequent effects on RAA and v2.

Langevin dynamics:

$$dx_i = \frac{p_i}{E}dt,$$
$$dp_i = -Ap_i dt + C_{ij}\rho_j\sqrt{dt}$$

Das, Scardina, Plumari and Greco
Phys. Rev. C,90,044901(2014)

A is the deterministic friction (drag) force

C_{ij} **is stochastic force.**

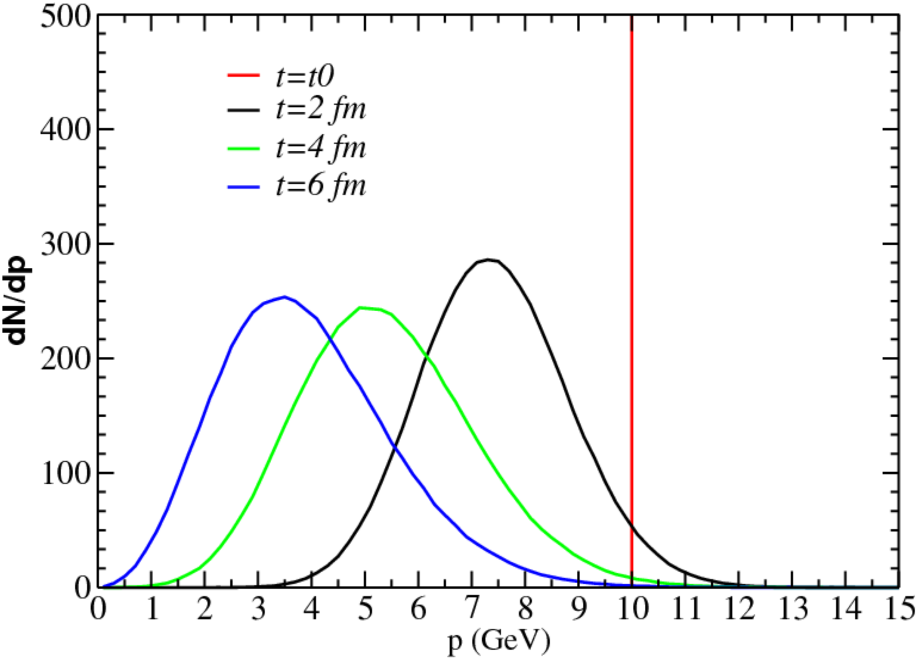
Evolution: Boltzmann vs Langevin (Charm)

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

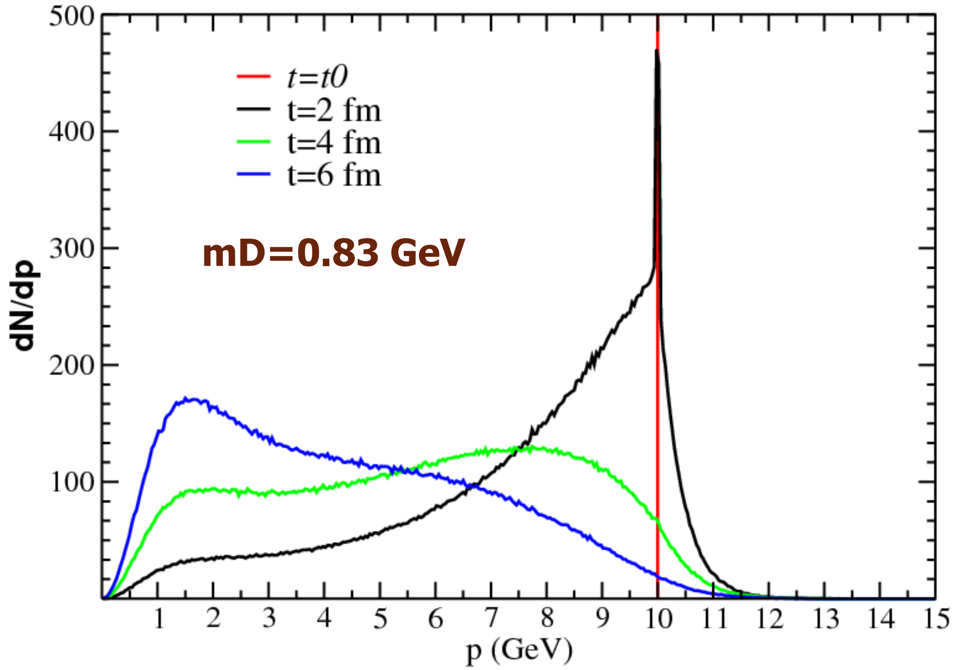
$$\left.\frac{dN}{d^3p}\right|_{initial} = \delta(p - 10GeV)$$

T=400 MeV

Langevin



Boltzmann



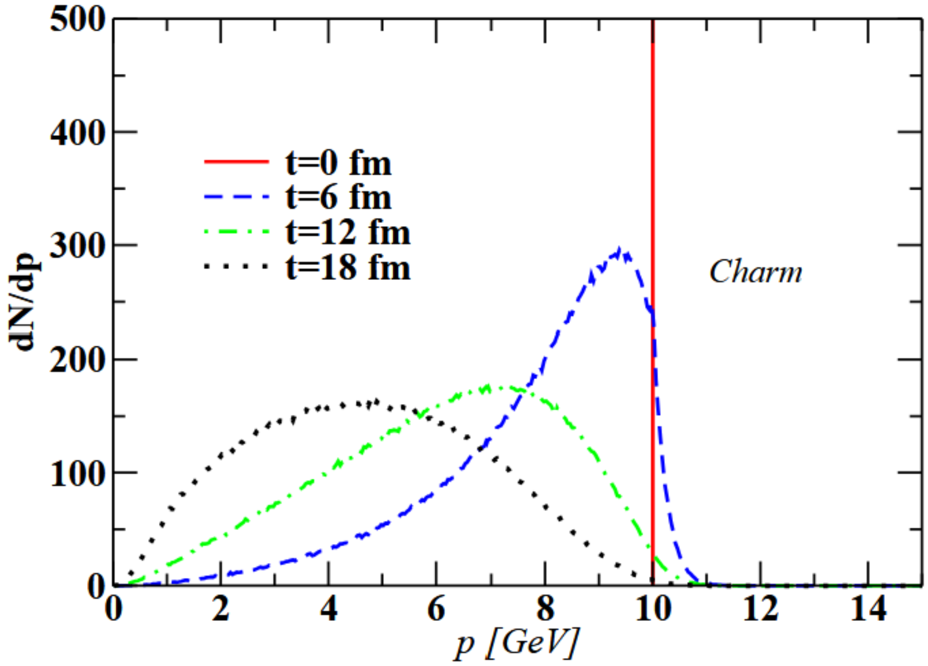
In case of Langevin the distributions are Gaussian as expected by construction

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

Evolution: Boltzmann (Charm)

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

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



T=200 MeV

Evolution: Boltzmann vs Langevin (Charm)

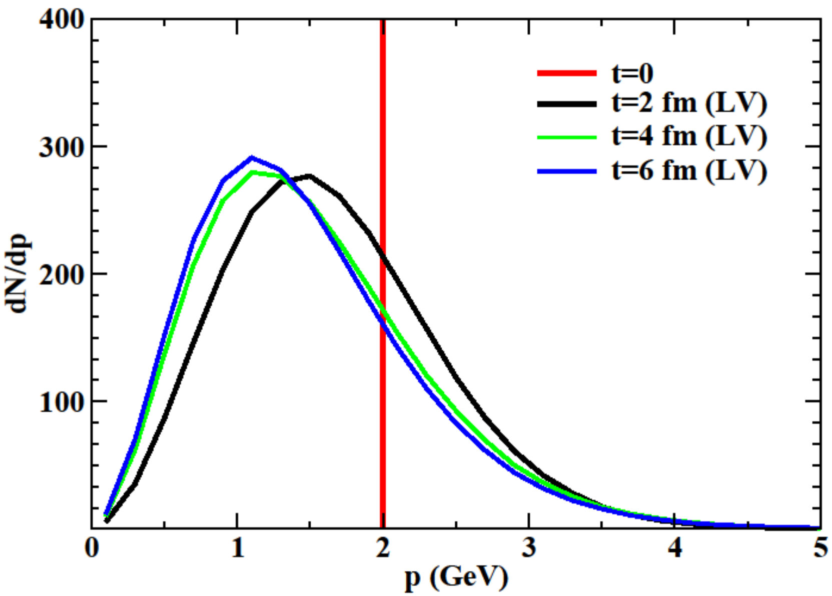
Momentum evolution starting from a δ (Charm) in a Box

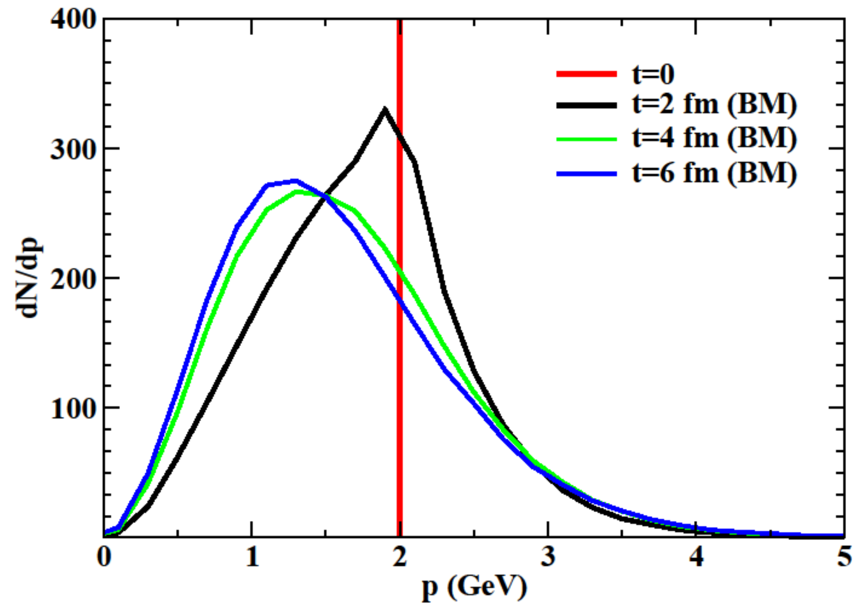
$$\left.\frac{dN}{d^3p}\right|_{initial} = \delta(p - 2GeV)$$

Langevin

Boltzmann

T=400 MeV





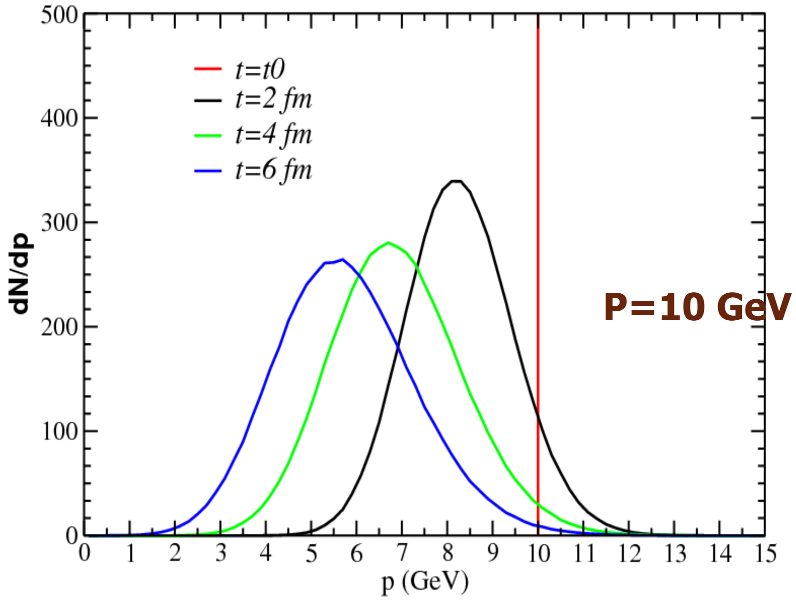
In case of Langevin the distributions are Gaussian as expected by construction

In case of Boltzmann the charm quarks follow the Brownian motion: At Low Momentum.

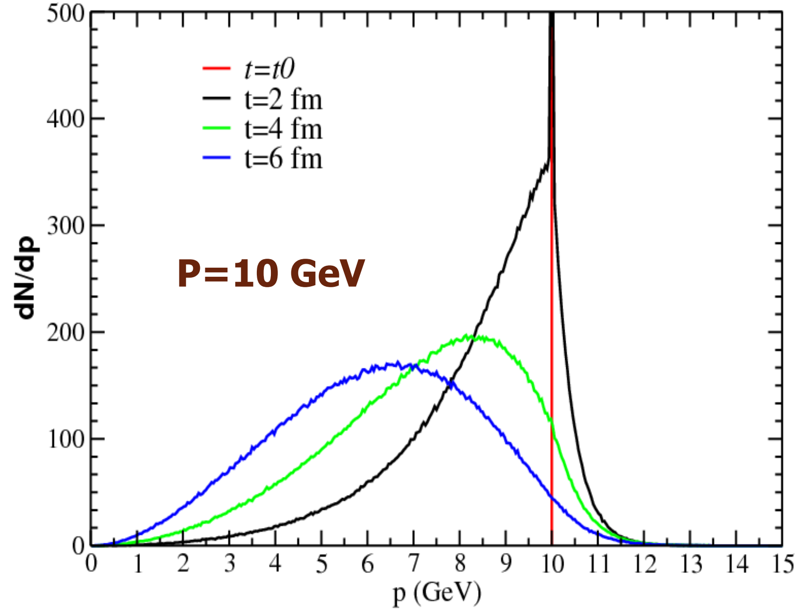
Momentum evolution starting from a δ (Bottom)

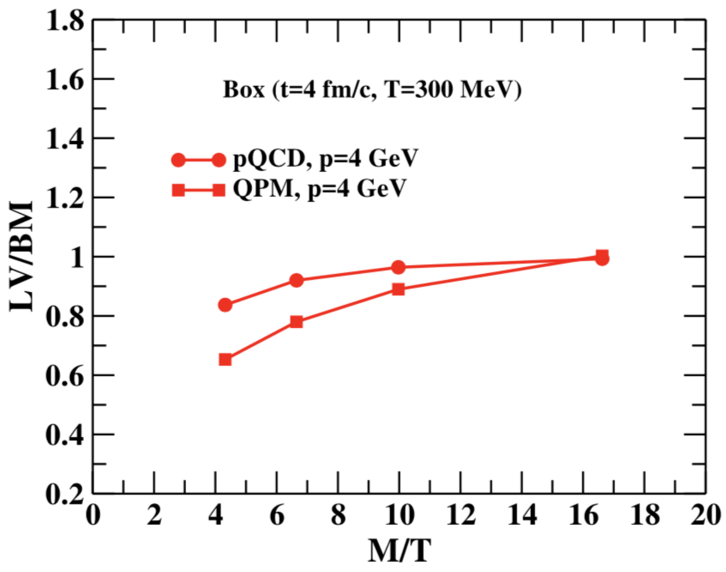
In a Box

Langevin



Boltzmann **T=400 MeV**





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

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

EMMI-RRTF, NPA 979 (2018)

Langevin Equation

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

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

$$\frac{dp}{dt} = -\gamma(p)p + \zeta$$

with $< \zeta_i(t)\zeta_k(t') >= D\delta(t-t')\delta_{jk}$

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.

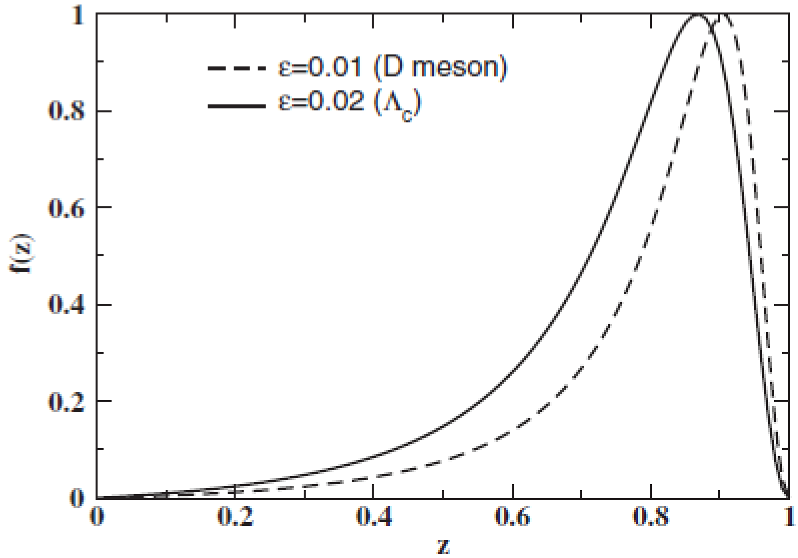
Heavy quark initialization

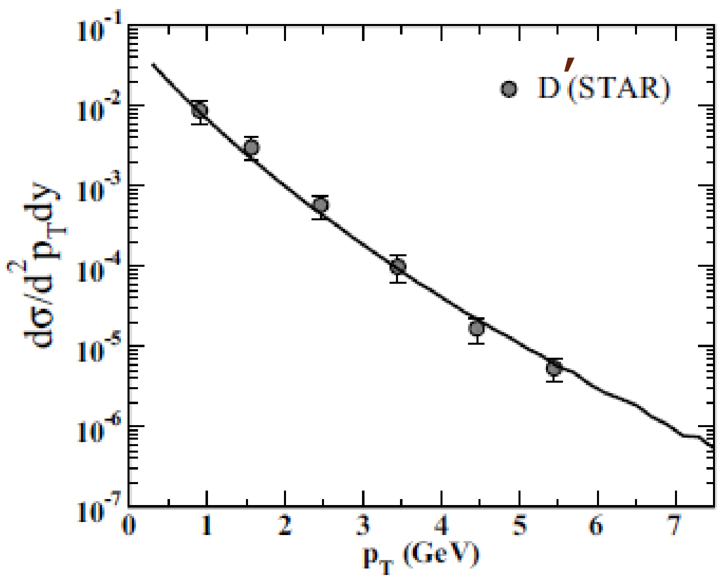
- ✧ r-space: N_coll (Glauber mode)
- ✧ p-space: NLO (pQCD)

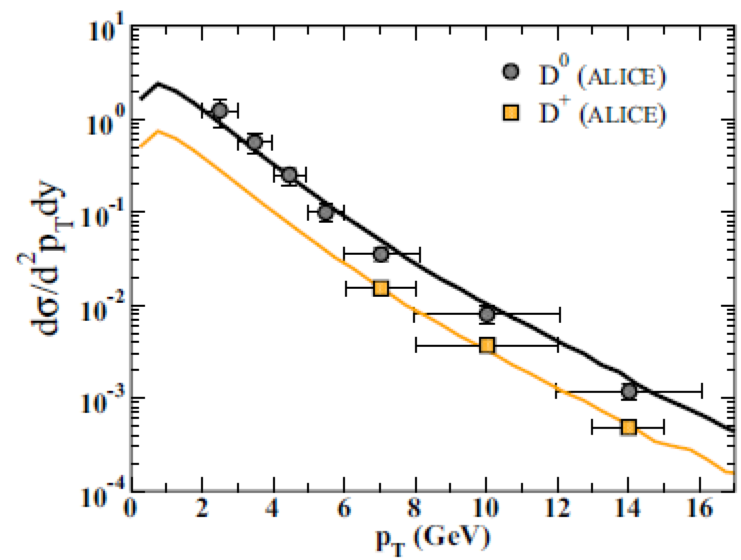
Heavy Quark Production pp collisions

$$f(z) \propto \frac{1}{z[1-\frac{1}{z}-\frac{\epsilon_c}{1-z}]^2} \qquad z = p_D/p_c$$

Peterson fragmentation function:







Scardina, Das, Minissale, Plumari, Greco
PRC, 96,044905 (2017)

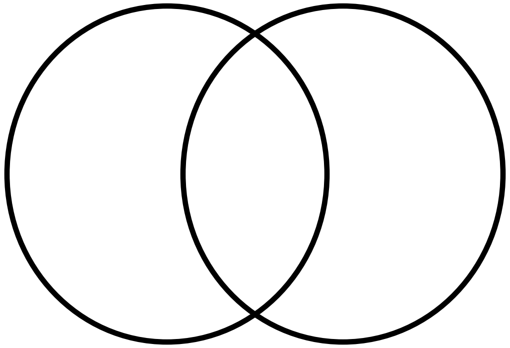
Nuclear Modification Factor (R_{AA}) and Elliptic Flow (v2)

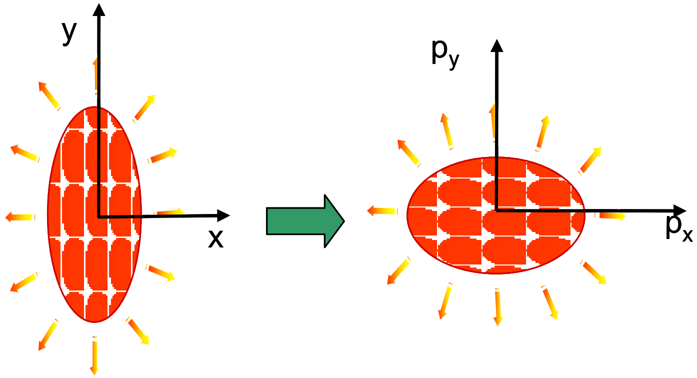
$$R_{AA} = \frac{\left(\frac{dN}{d^2 p_T dy}\right)^{Au+Au}}{N_{coll}\left(\frac{dN}{d^2 p_T dy}\right)^{p+p}} = \frac{f^{FP}_{final}}{f^{FP}_{initial}}$$

If R_{AA} = 1 → **No medium/ No interaction**

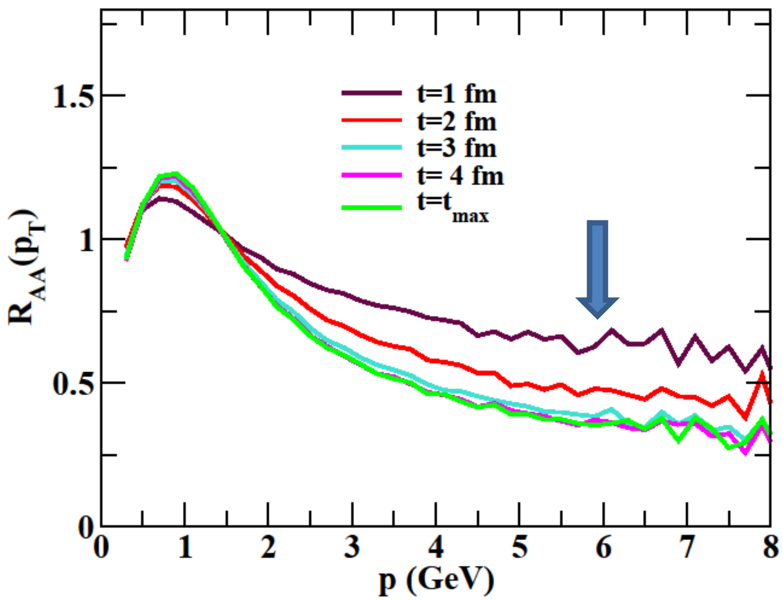
If R_{AA} < 1 → **Medium/Interaction**

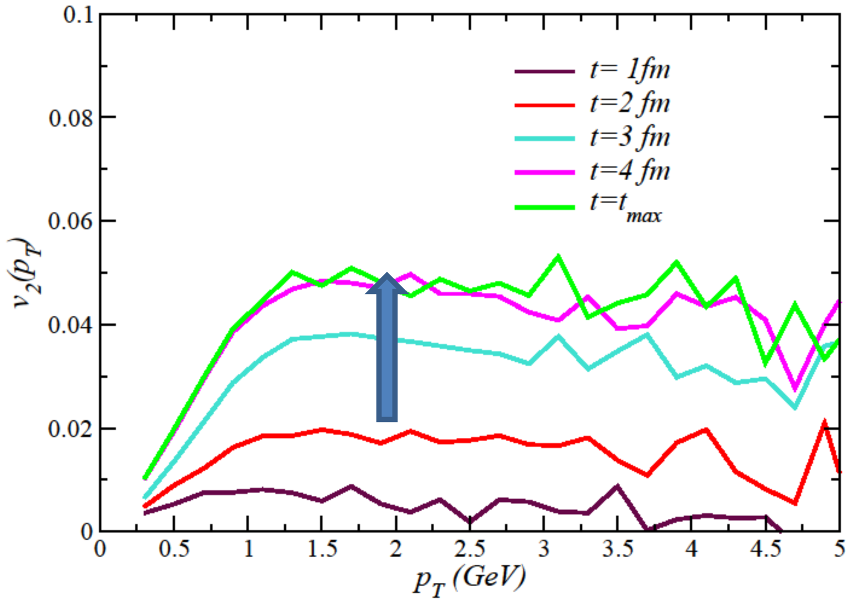
$$v_2^{HF}(p_T) = \langle \cos(2\phi) \rangle = \frac{\int d\phi \frac{dN}{dy dp_T d\phi} \cos(2\phi)}{\int d\phi \frac{dN}{dy dp_T d\phi}}$$





Time evolution of Heavy quarks observables





Das, Scardina, Plumari, Greco (2015)

Hadronic phase impact
Non-perturbative effect

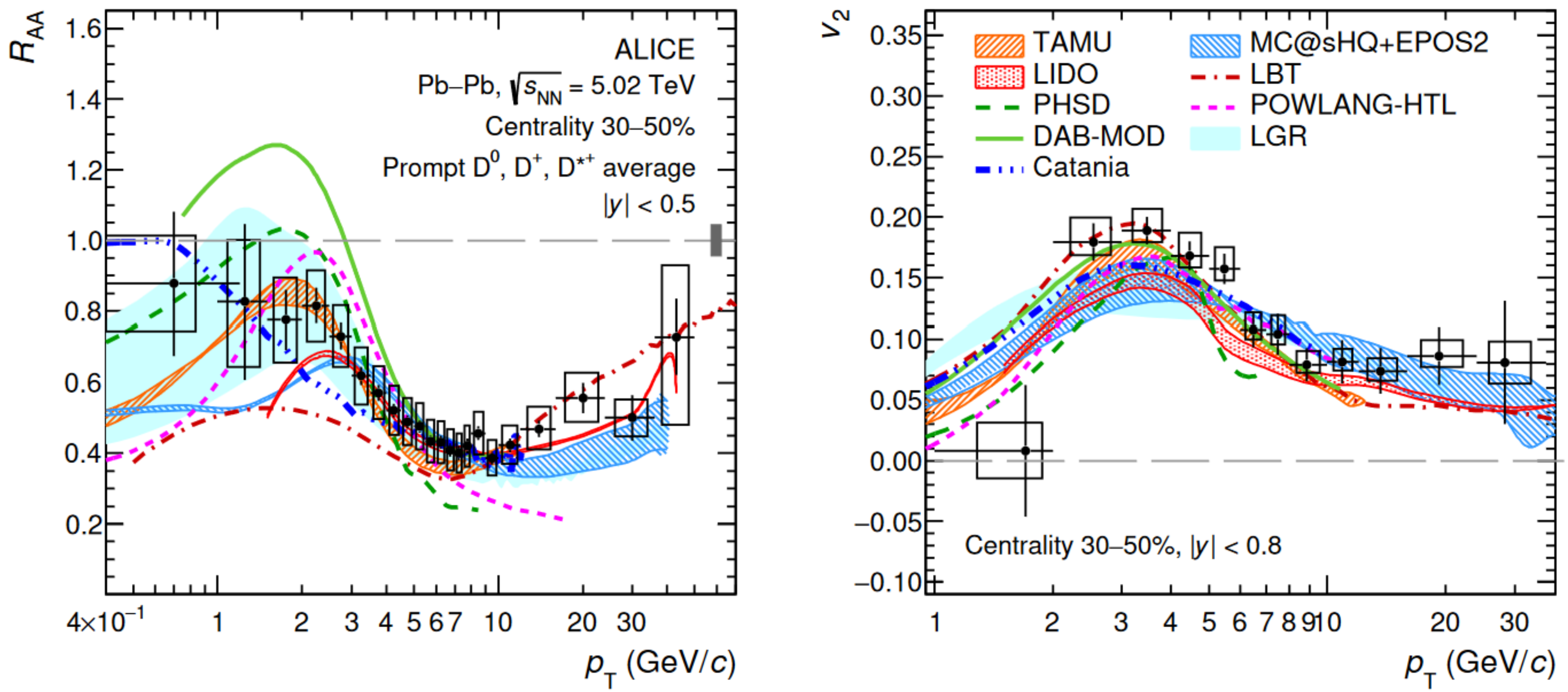
Rapp, van Hees (2008)

RAA developed during the early stage of the evolution → T_i

V2 developed duringing the later stage of the evolution → T_c

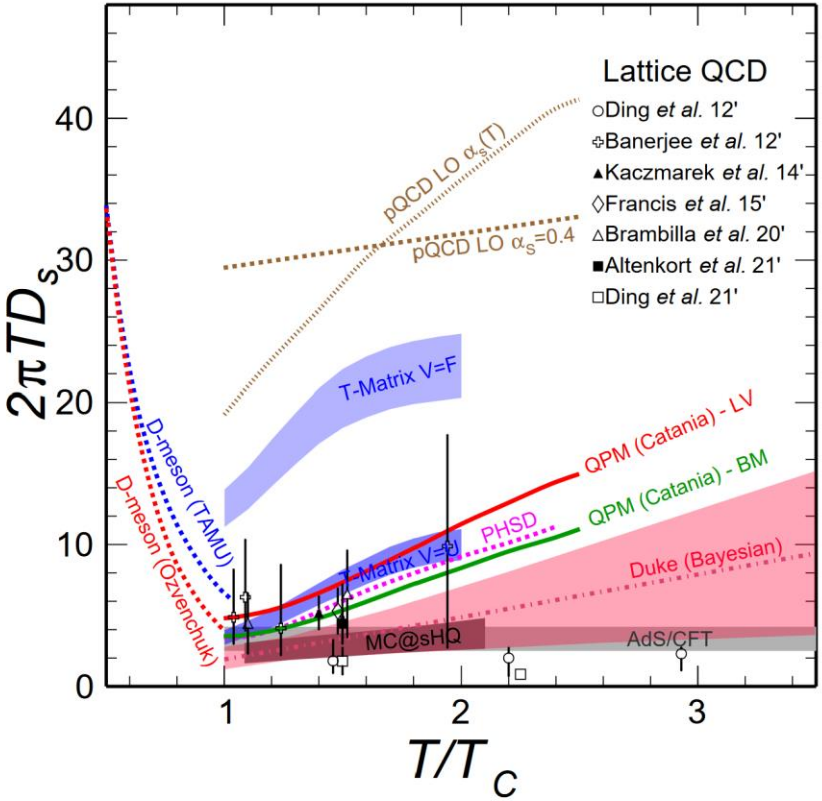
T dependence of the interaction i.e the transport coefficients are the essential ingredient for the simultaneous description of HQ observables.

Comparison with models at LHC energy



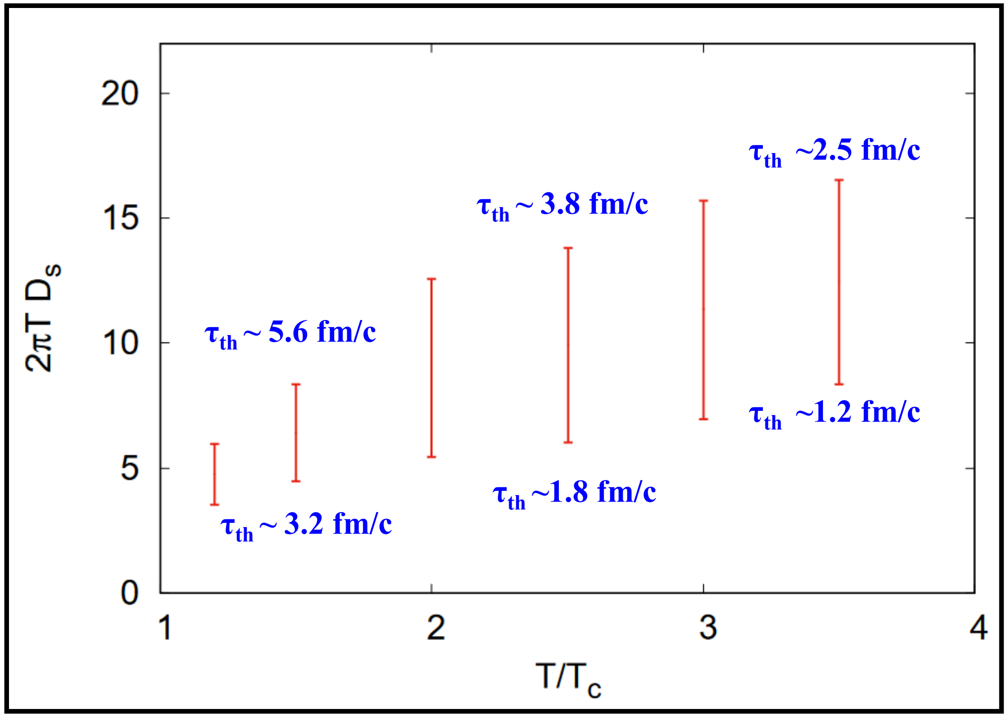
ALICE, JHEP 01 (2022) 174

Heavy quark diffusion



$$D_s = T/M * \gamma(p \to 0)$$

He, Fries, Rapp, PRL,110, 112301 (2013)

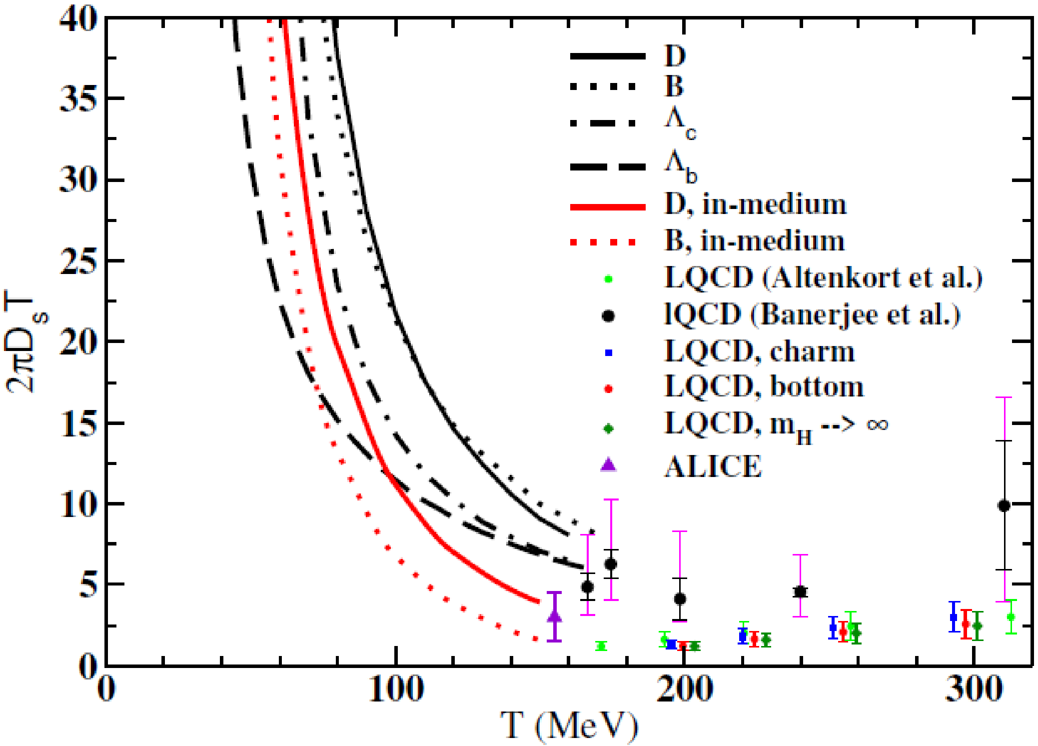


Banerjee, Datta, Gavai, Majumdar
arxiv: 2206.15471 [hep-ph]

$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8 \frac{2\pi T D_s}{(T/T_c)^2} \text{ fm/c}$$

Scardina, Das, Minissale, Plumari, Greco
PRC,96, 044905 (2017)

Heavy quark diffusion



Das, Torres-Rincon, Rapp, Phys. Rept. 1129-1131 (2025)

$$1.5 \leq (2\pi T)D_s \leq 4.5$$

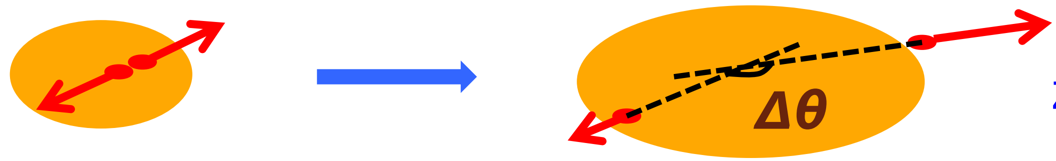
ALICE JHEP, 01:174, 2022.

. Quark Mass Dependence of Heavy Quark Diffusion Coefficient from Lattice QCD.

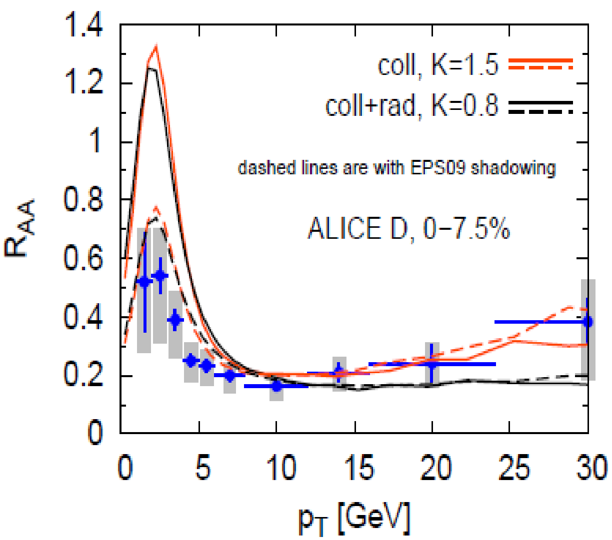
Banerjee, Datta, Laine, *JHEP*, 08:128, 2022

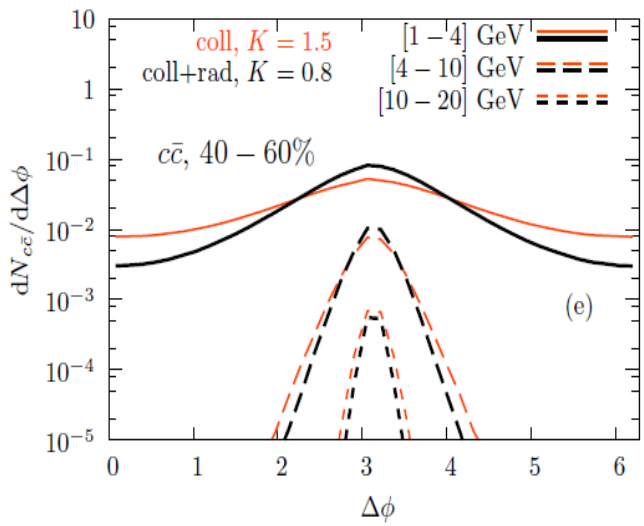
Altenkort at el, *PRL* 132, 051902, 2024

Angular De-correlation of *c*cbar:



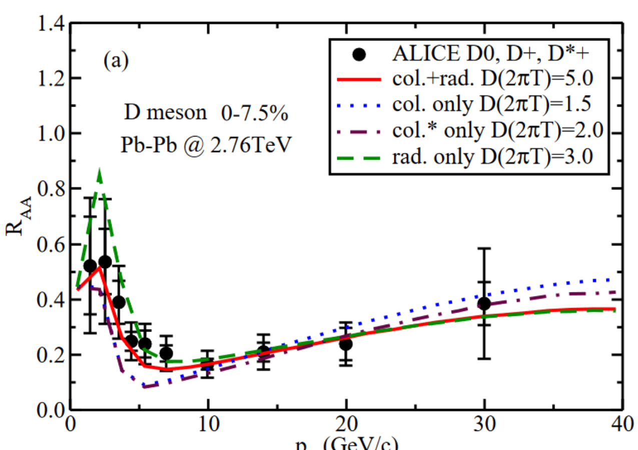
Zhu ,Xu, Zhuang, PRL100, 152301 (2008)

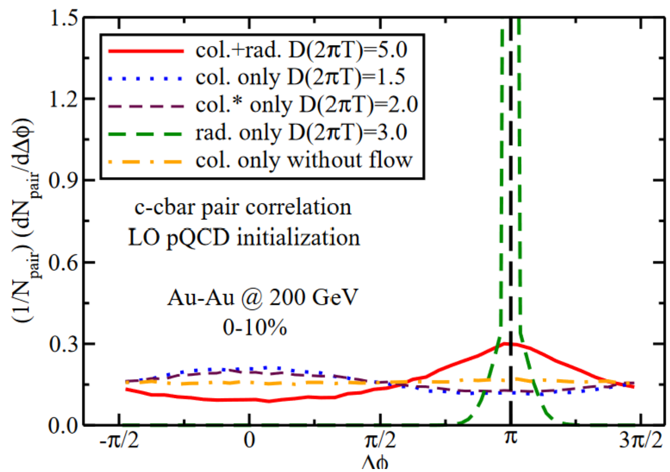




DDbar correlation is sensitive to energy loss mechanism

Nahrgang, Aichelin, Gossiaux, Werner PRC,90, 024907 (2014)

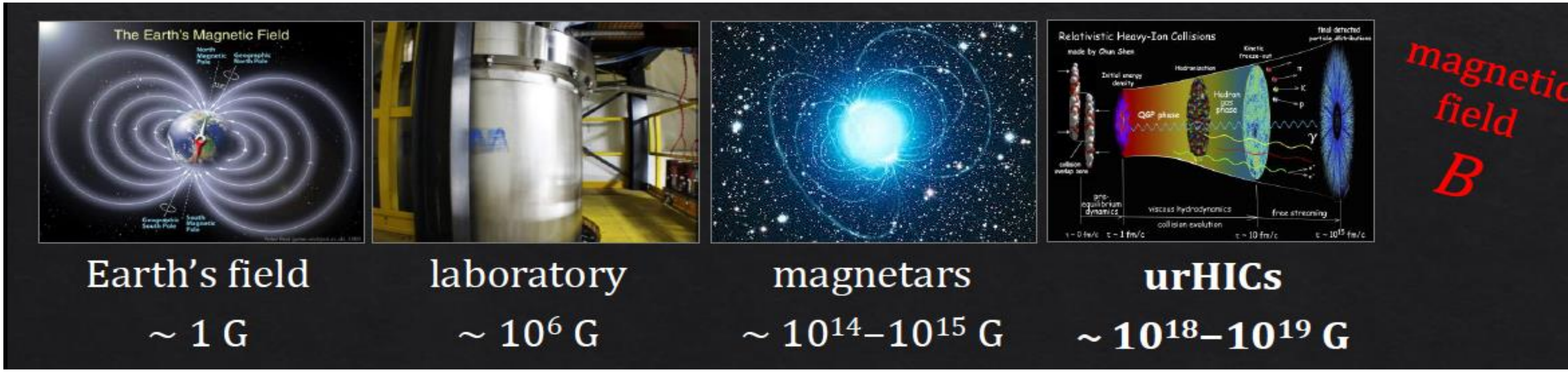


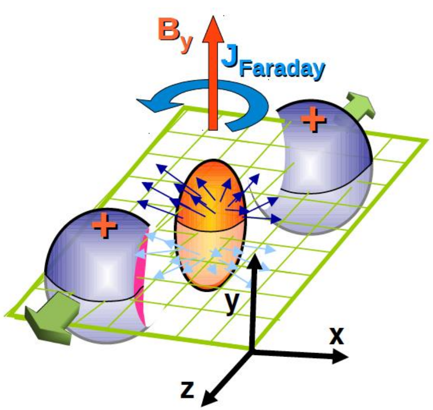


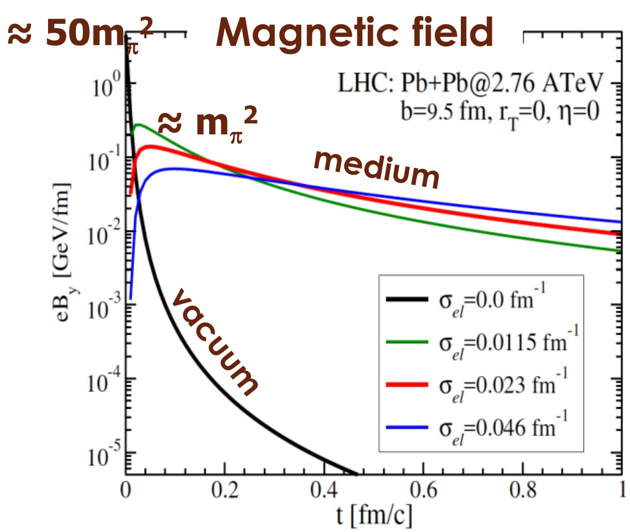
DDbar correlation can disentangle different Energy loss mechanism

Cao, Qin, Bass PRC, 95 (2015)

Charm quark as a probe of the magnetic field in HIC

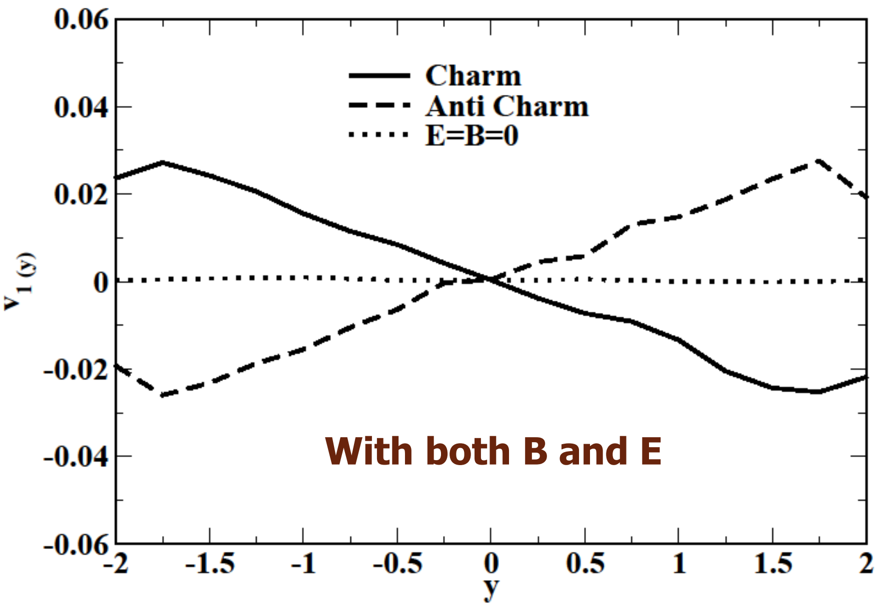


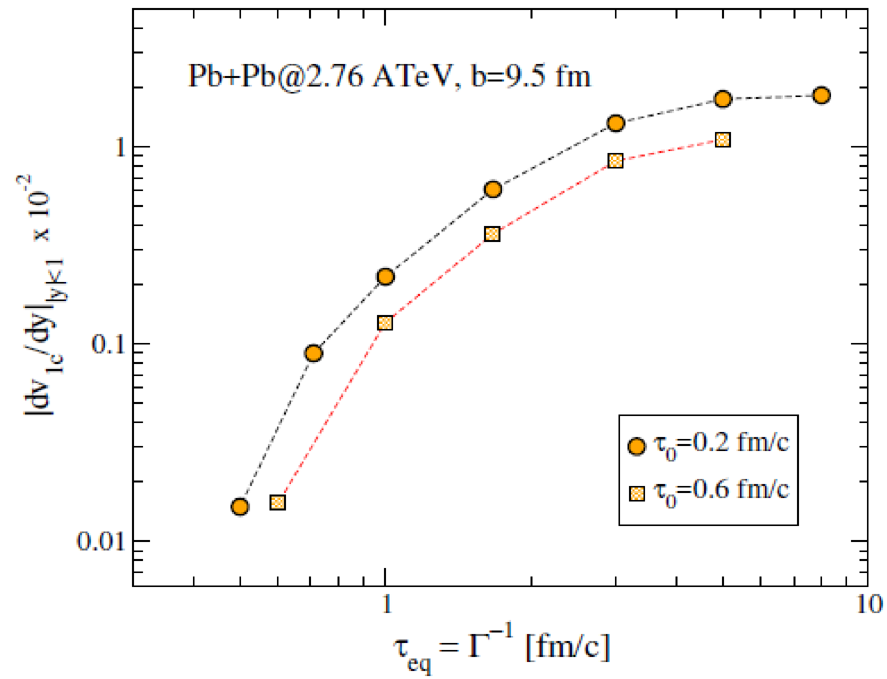




Schematic calculation: early time behavior quite uncertain theoretically

Heavy quark directed flow (v1) @LHC





$$dp_i = -\Gamma(p)\, p_i\, dt + C_{ij}(p)\, \rho_j \sqrt{dt} + F_{\rm ext}\, dt$$

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

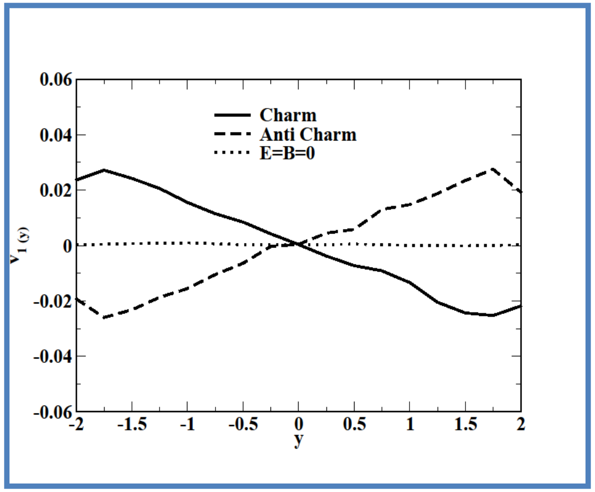
$$v_1 = < \frac{p_x}{p_T} >$$

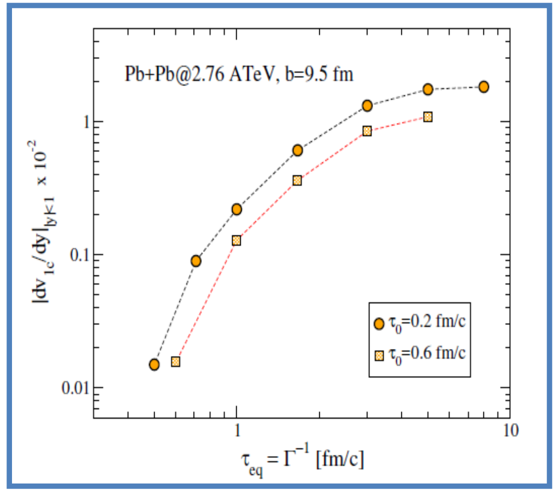
Das, Plumari, Chartarjee, Scardina, Greco, Alam
PLB, 768 (2017) 260

For Light quarks predicted $v_1 \approx 10^{-4}$
[Gursoy et al., PRC89 (2014)]

For heavy quarks $v_1 \approx 10^{-2}$
100 times larger than light quarks v1 !

Heavy quark directed flow@ RHIC and LHC



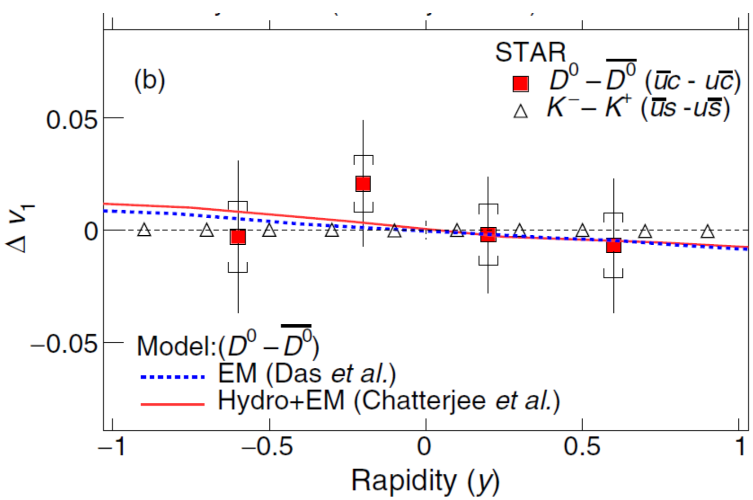


Das, Plumari, Chartarjee, Scardina, Greco, Alam
Phys. Lett. B, 768 (2017) 260

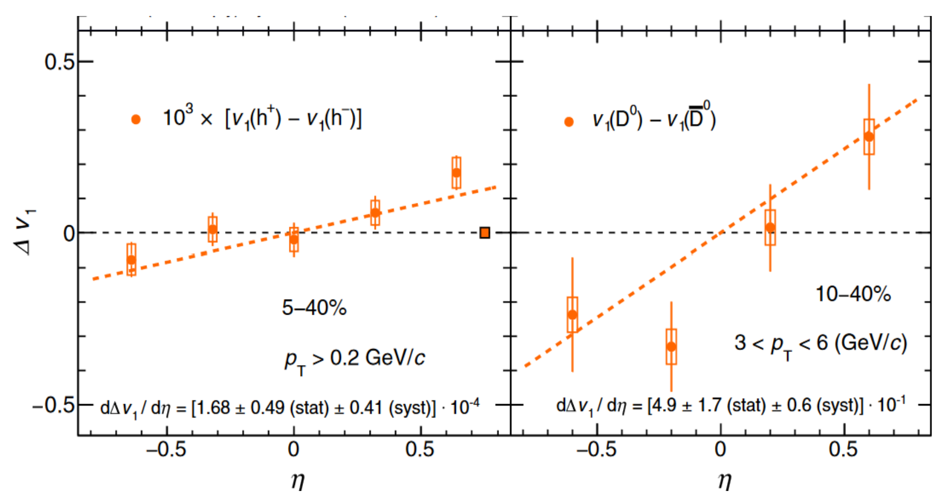
- ❖ **Order of magnitude larger than light hardon v_1**
- ❖ **Opposite v_1 for charm and anti-charm**

$$\Delta v_1(\mathrm{D}) = \mathrm{v}_1(\mathrm{D}^0) - \mathrm{v}_1(\overline{\mathrm{D}}^0)$$

Heavy meson directed flow at RHIC & LHC:



STAR Collaboration PRL 123, 162301 (2019)



ALICE Collaboration PRL 125, 022301 (2020)

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

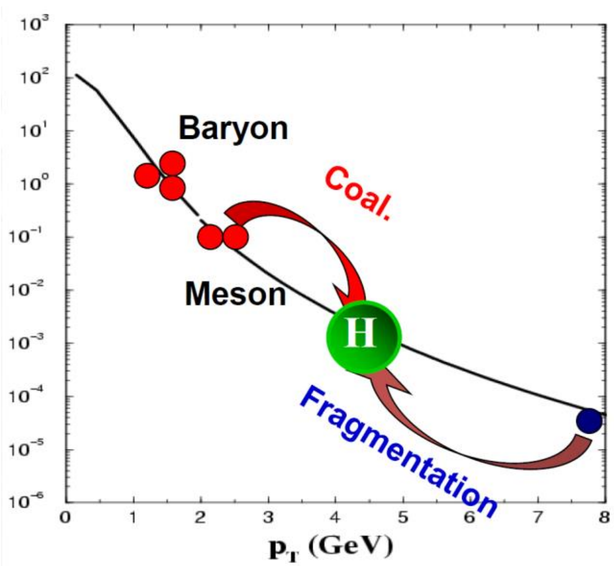
Coalescence is the convolution of two /three parton distribution folded by a wave function:

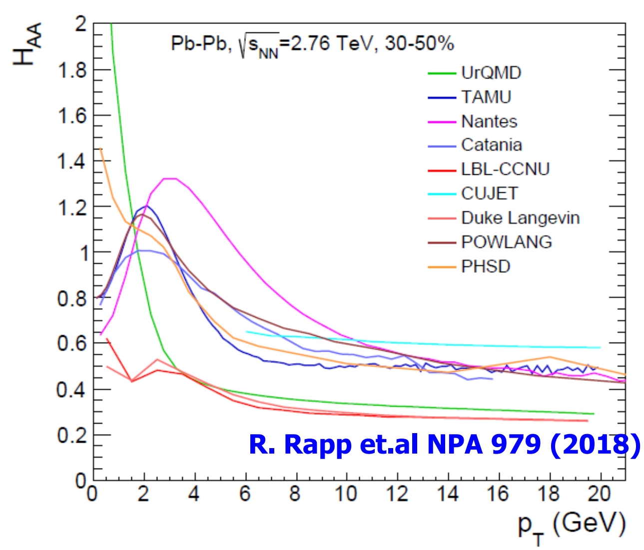
$$\frac{dN_{Meson}}{d^2 p_T} = g_M \sum_{i,j} P_q(i) P_q(j) \delta^{(2)}(p_T - p_{iT} - p_{jT}) f_M(x_i, x_j; p_i, p_j)$$

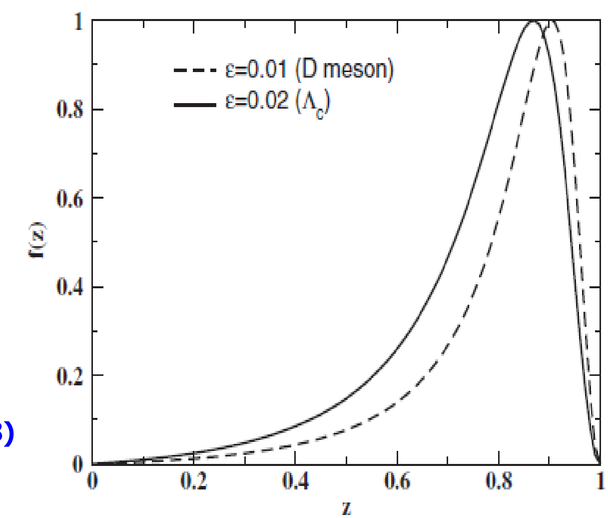
V. Greco, C.M. Ko, and P. L´evai PRL 90 , 202302 (2003)

Hadron wave function

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

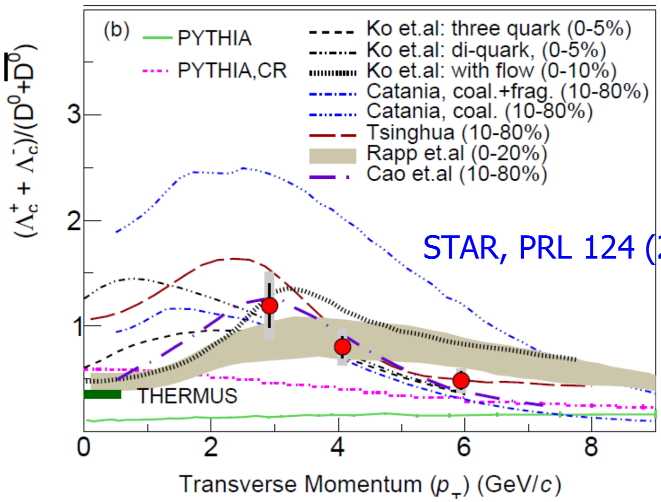




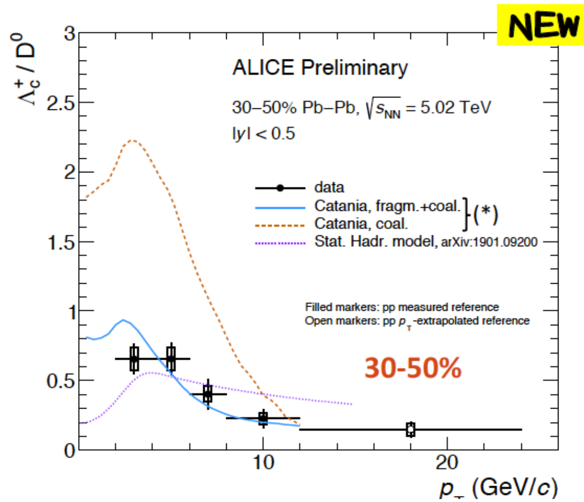


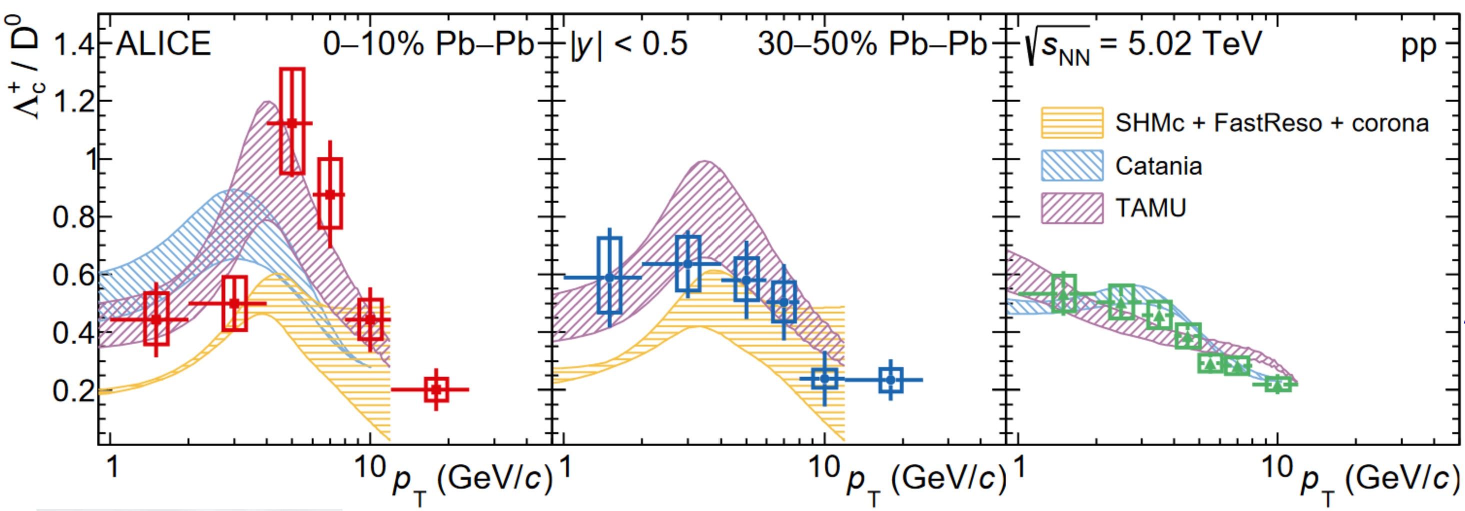
Heavy Baryon to meson ratio

(Serve as a tool to disentangle different hadronization mechanisms)



STAR, PRL 124 (2020)





ALICE:PLB 839 (2023)

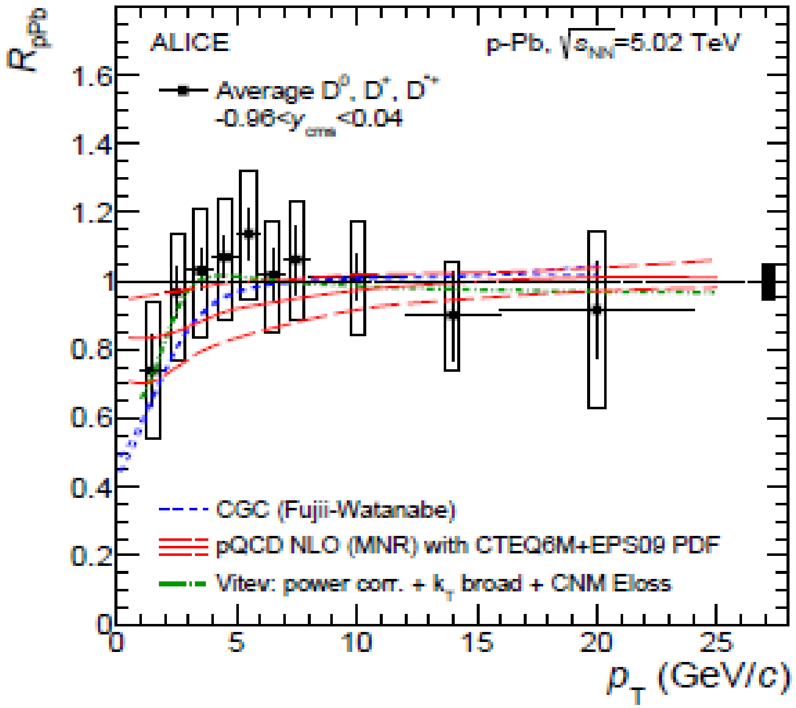
$P_{coal}=1$ **to all hadron at p→0**

Baryon in resonance recombination model

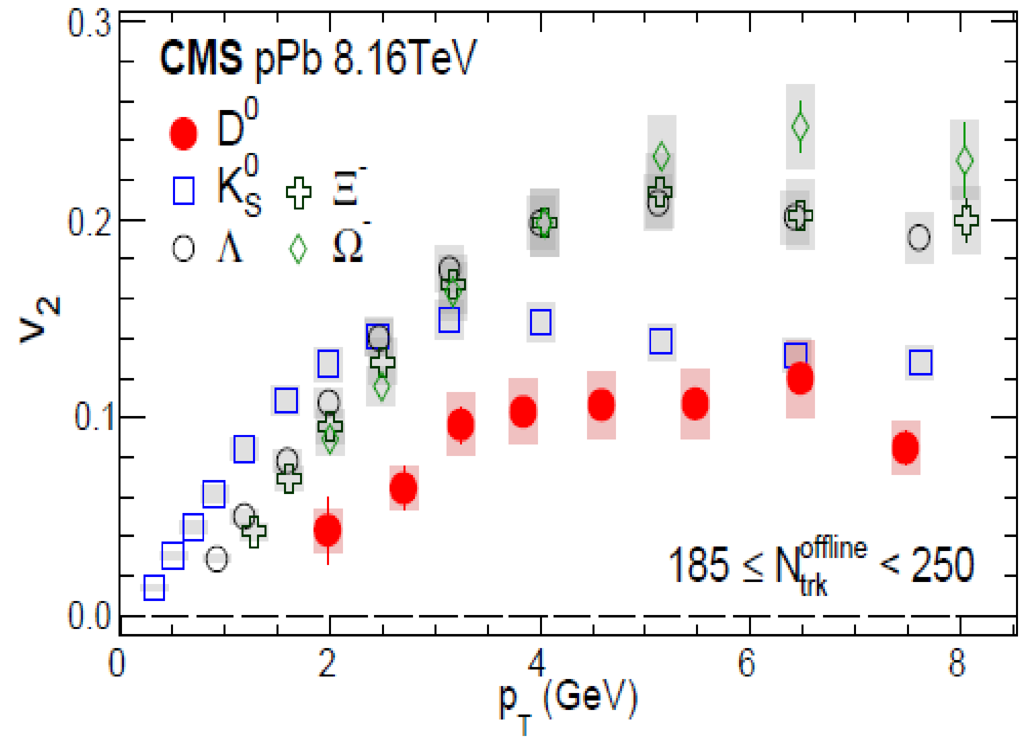
Plumari, Minissale, Das, Cosi, Greco
EPJC 78 (2018) 4, 348

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

Heavy quark in small system (p-nucleus)



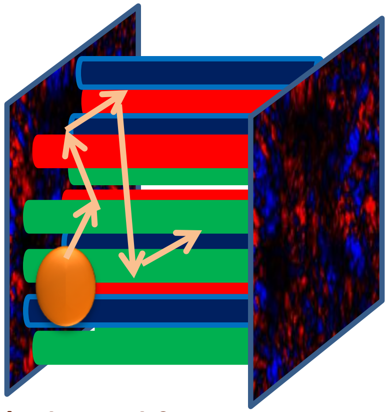
ALICE Collaboration
Phys. Rev. Lett. 113 (2014) 232301



CMS Collaboration
arXiv:1804.09767v2

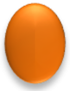
What mechanism could build up v_2 without energy loss?

Heavy quarks as probes of the pre-equilibrium phase



(Adapted from M. Ruggieri)

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



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)

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

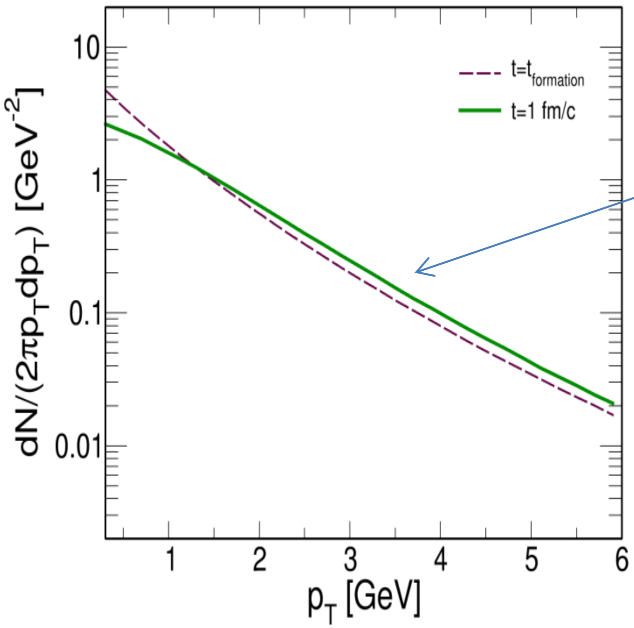
$$J^\mu_a = \bar{c}\gamma^\mu T_a c$$

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

Equations of motion of heavy quarks are solved in the background given by the evolving Glasma fields

p-Pb @ 5.02 TeV

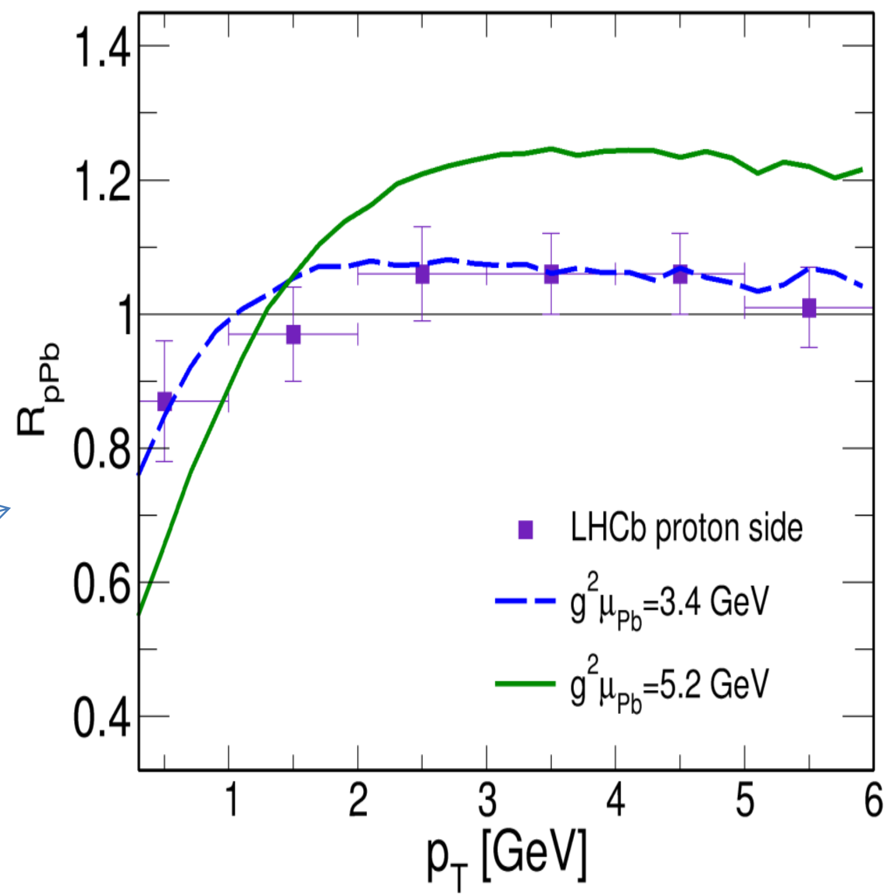
Nuclear modification factor (R_{pPb}) for p-Pb collisions



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

D-mesons R_{pPb}

Standard fragmentation [Peterson *et al.*(1983)]



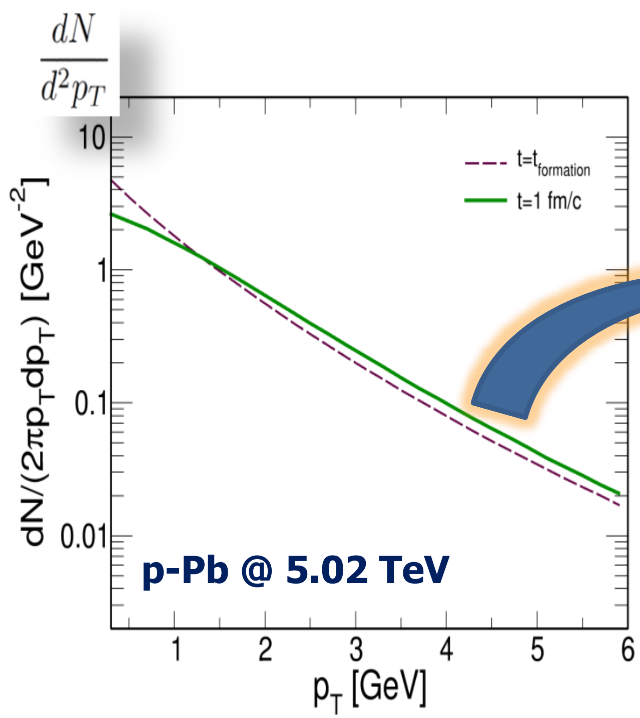
$$R_{\mathrm{pPb}} = \frac{(dN/d^2p_T)_{\mathrm{final}}}{(dN/d^2p_T)_{\mathrm{pQCD}}}$$

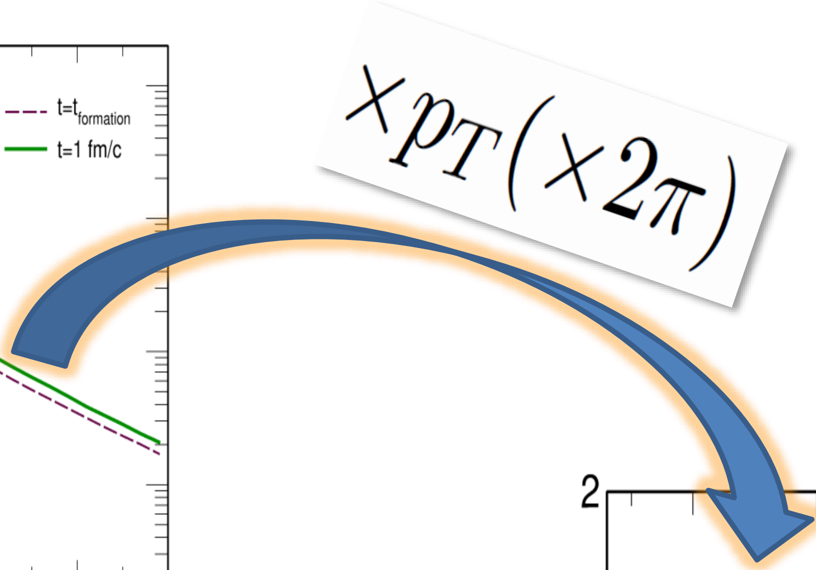
$R_{pPb} \neq 1$

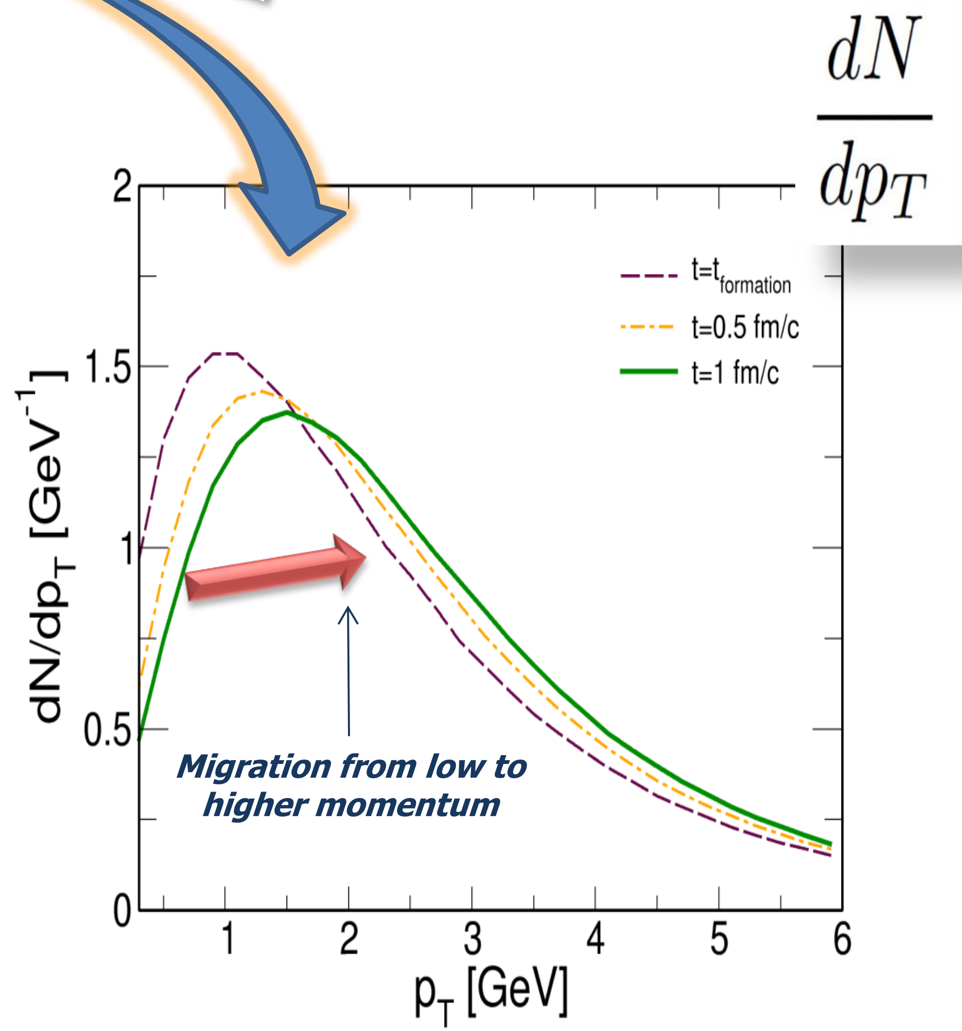
Interaction with the fields created by the collision

Ruggieri and Das
PRD, 98, 094024(2018)

Diffusion results in acceleration





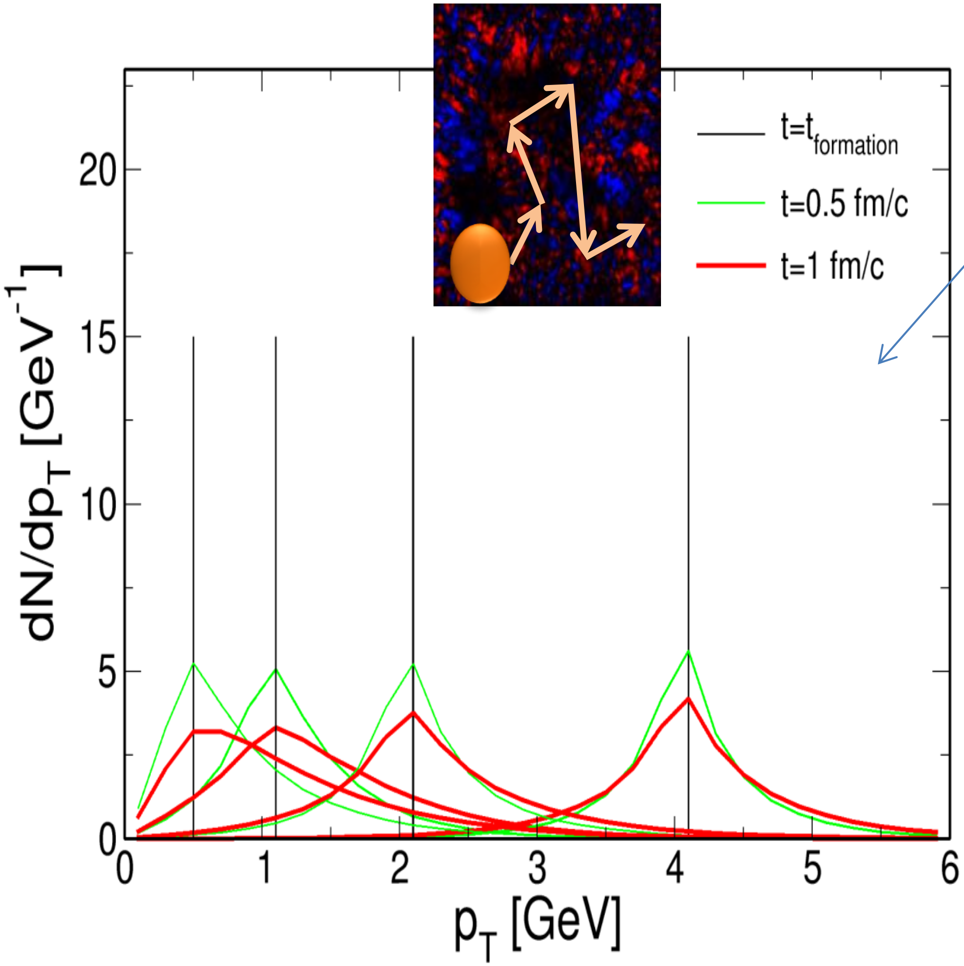


Heavy quarks seem to be accelerated by the (color-)electric field

We called it cathode tube effect

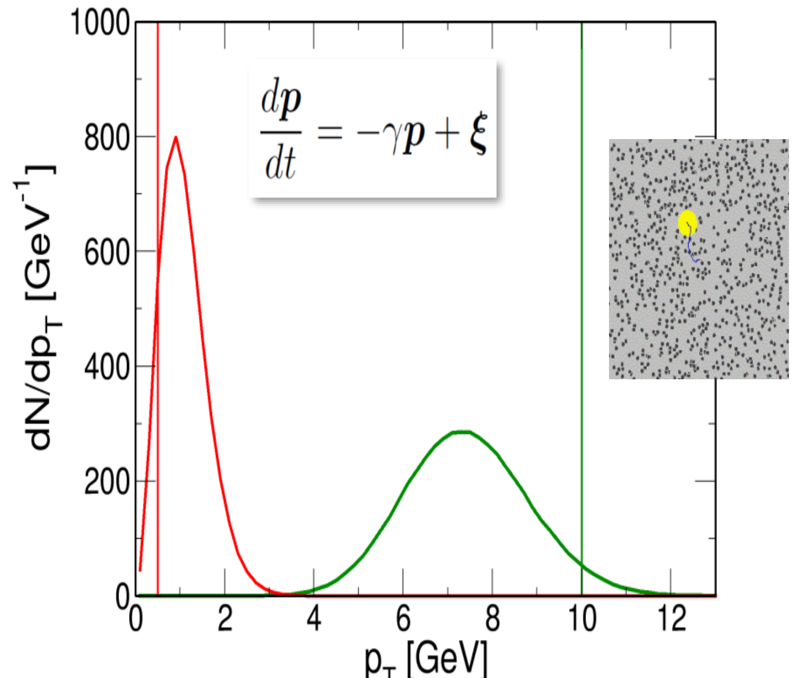
Ruggieri and Das
PRD, 98, 094024(2018)

HQs in Glasma



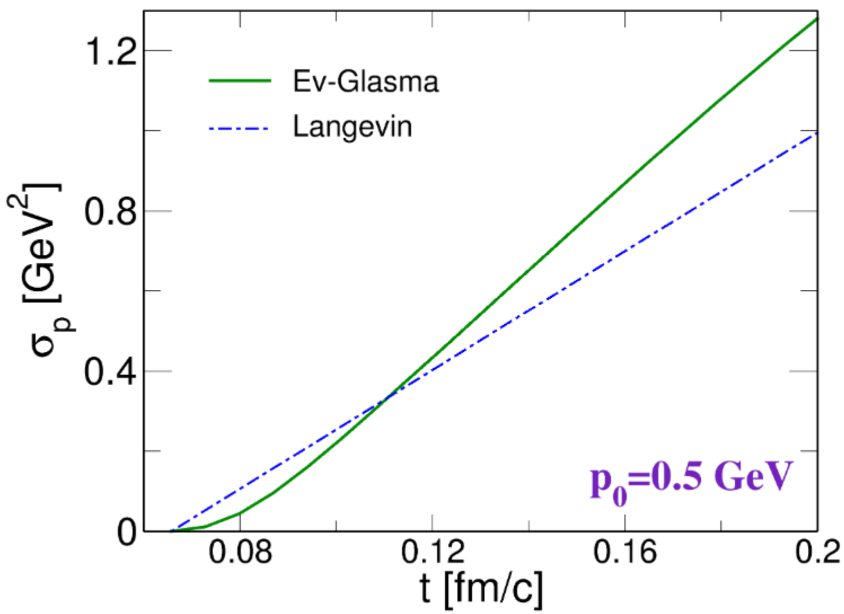
Diffusion in momentum space

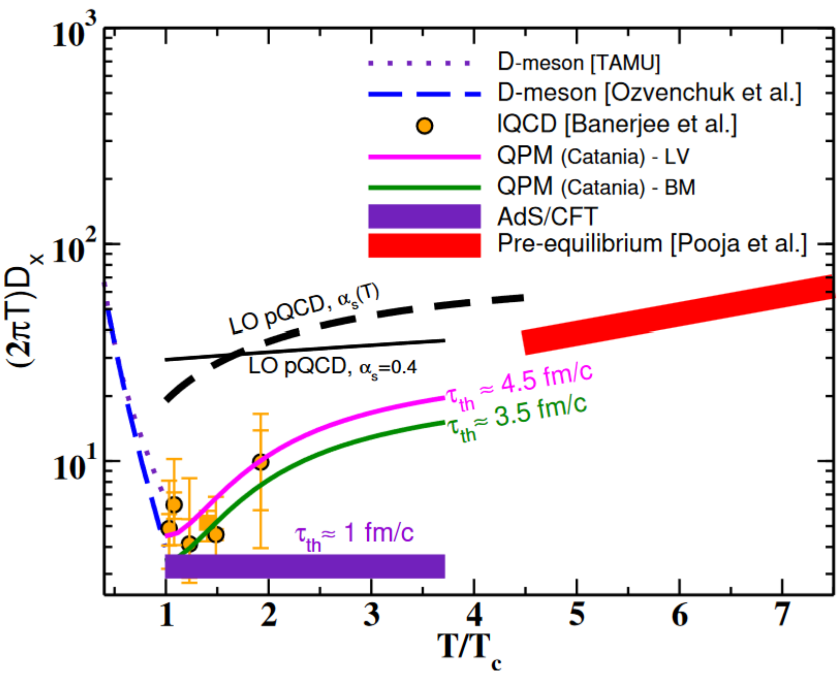
T=500 MeV ***HQs in hot plasma***



Ruggieri and Das
PRD, 98, 094024(2018)

Heavy quark diffusion in the pre-equilibrium phase





$$\sigma_p = \frac{1}{2}\langle (p_x(t) - p_{0x})^2 + (p_y(t) - p_{0y})^2 \rangle$$

Das, Hard Probes (2023)

Diffusion in pre-equilibrium phase is Ballistic. Memory effect.

Liu, Das, Greco, Ruggieri,
PRD 103, 034029 (2021)

Ruggieri, Das, PRD, 98(2018)
Mrowczynski, EPJA 54 (2018)
Boguslavski, Kurkela, Lappi and J. Peuron, JHEP (2020)
Pandey, Schlichting, Sharma, PRL 132 (2024)
Avramescu, Greco, Lappi, Maentysaar, Mueller, PRL, 134, (2025)

Brownian Motion: Quark to Corona

Transmission of airborne virus through sneezed and coughed droplets

Cite as: Phys. Fluids 32, 097102 (2020); doi: 10.1063/5.0022859
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Note: This paper is part of the Special Topic, Flow and the Virus.
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ABSTRACT

The spread of COVID19 through droplets ejected by infected individuals during sneezing and coughing has been considered a matter of key concern. Therefore, a quantitative understanding of the propagation of droplets containing the virus assumes immense importance. Here, we investigate the evolution of droplets in space and time under varying external conditions of temperature, humidity, and wind flow by using laws of statistical and fluid mechanics. The effects of drag, diffusion, and gravity on droplets of different sizes and ejection velocities have been considered during their motion in air. In still air, we found that bigger droplets traverse a larger distance, but smaller droplets remain suspended in air for a longer time. Therefore, in still air, the horizontal distance that a healthy individual should maintain from an infected one is based on the bigger droplets, but the time interval to be maintained is based on the smaller droplets. We show that in places with wind flow, the lighter droplets travel a larger distance and remain suspended in air for a longer time. Therefore, we conclude that both temporal and geometric distance that a healthy individual should maintain from an infected one is based on the smaller droplets under flowing air, which makes the use of a mask mandatory to prevent the virus. Maintenance of only stationary separation between healthy and infected individuals is not substantiated. The quantitative results obtained here will be useful to devise strategies for preventing the spread of other types of droplets containing microorganisms.

Brownian Motion: Quark to Corona

Airborne virus transmission under different weather conditions

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ABSTRACT

The COVID19 infection is known to disseminate through droplets ejected by infected individuals during coughing, sneezing, speaking, and breathing. The spread of the infection and hence its menace depend on how the virus-loaded droplets evolve in space and time with changing environmental conditions. In view of this, we investigate the evolution of the droplets within the purview of the Brownian motion of the evaporating droplets in the air with varying weather conditions under the action of gravity. We track the movement of the droplets until

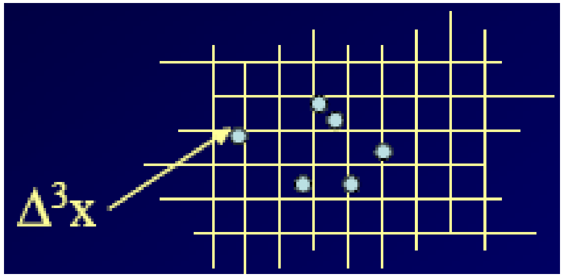

Thank You . . . .

Transport theory

$$p^{\mu}\partial_{\mu} f(x,p) = C_{22}$$

We consider two body collisions

$$C_{22} = \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2} f'_1 f'_2 |\mathcal{M}_{1'2'\to 12}|^2 (2\pi)^4 \delta^{(4)}(p'_1 + p'_2 - p_1 - p_2)$$
$$- \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p'_1}{(2\pi)^3 2E'_1}\frac{d^3p'_2}{(2\pi)^3 2E'_2} f_1 f_2 |\mathcal{M}_{12\to 1'2'}|^2 (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p'_1 - p'_2)$$



$$\Delta t \to 0$$
$$\Delta^3 x \to 0$$

Exact solution

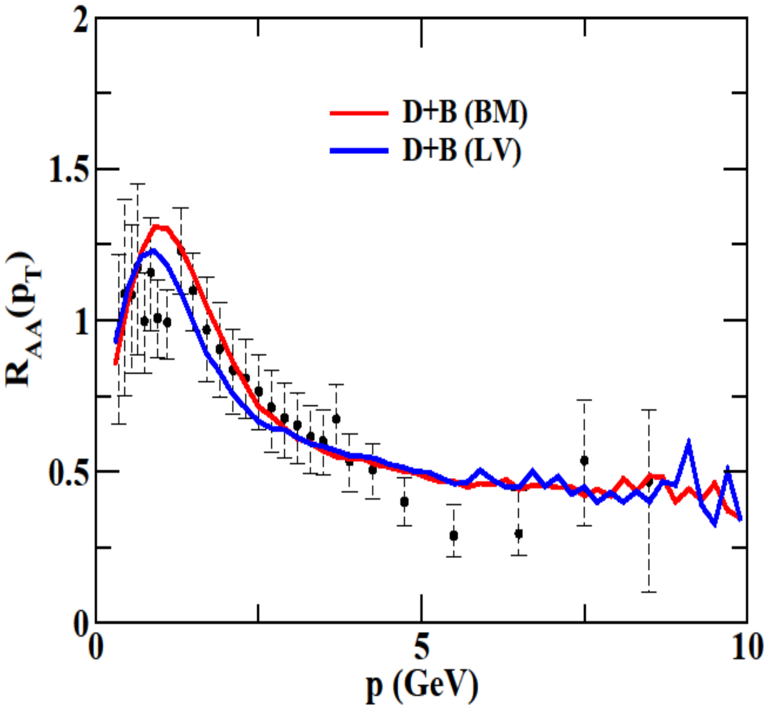
Collision integral is solved with a local stochastic sampling

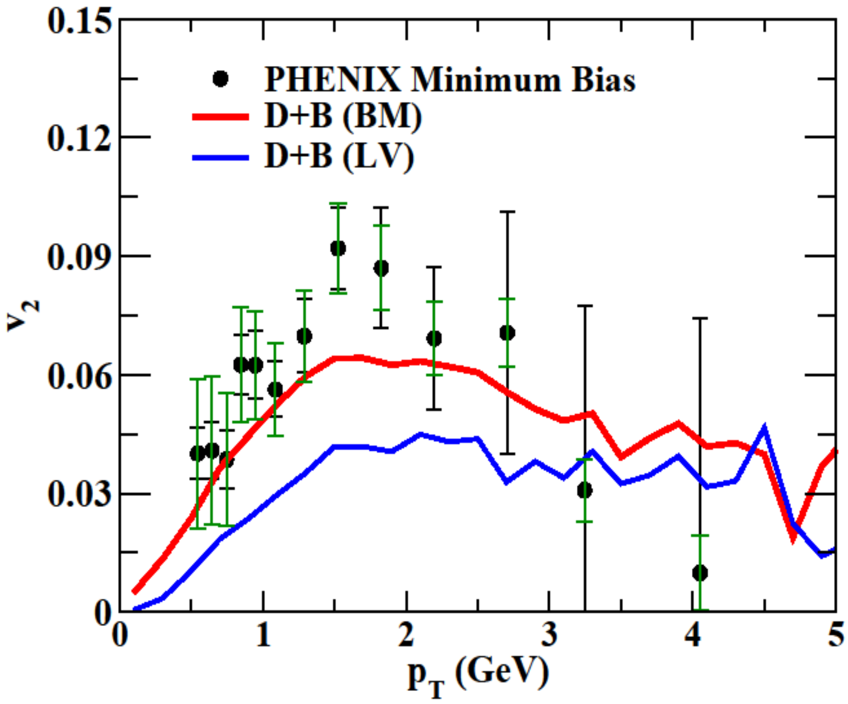
Das, Scardina, Plumari and Greco
Phys. Rev. C,90,044901(2014)

$$P_{22} = \frac{\Delta N^{2\to 2}_{coll}}{\Delta N_1 \Delta N_2} = v_{rel}\sigma_{22}\frac{\Delta t}{\Delta^3 x}$$

R_{AA} and v2 at RHIC

(With near isotropic cross-section)



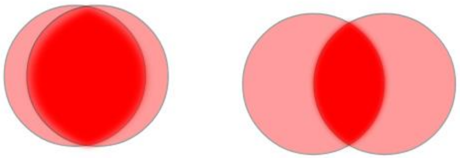


Das, Scardina, Plumari and Greco
Phys. Rev. C,90,044901(2014)

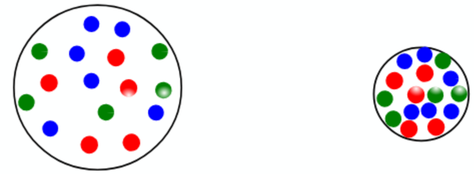
At fixed RAA Boltzmann approach generate larger v2 .
(depending on mD and M/T)

With isotropic cross section one can describe both RAA and V2 simultaneously within the Boltzmann approach !

Heavy quark radial flow: collective outward expansion



$v_2 < v_2$

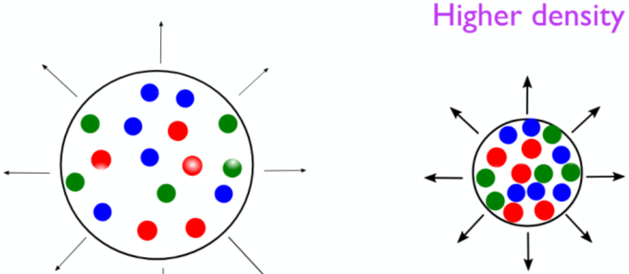


$[p_T] < [p_T]$

Particles fly outward from the centre due to pressure gradient: motion is organized, particles moves collectively outwards, not random. Examples: Explosion of fireworks, ballon bursting.

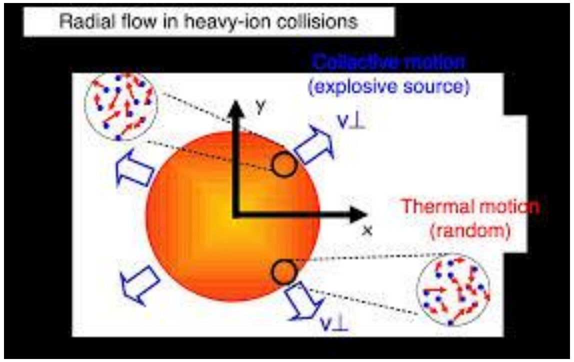
Higher temperature

Higher density

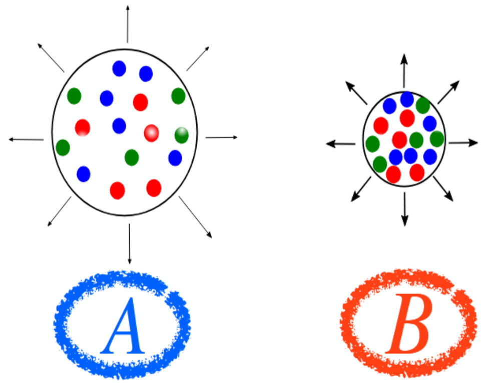


$\langle v_\perp \rangle < \langle v_\perp \rangle$

$$\frac{dN}{p_T dp_T} \sim e^{\frac{-m_T}{T_s}}$$

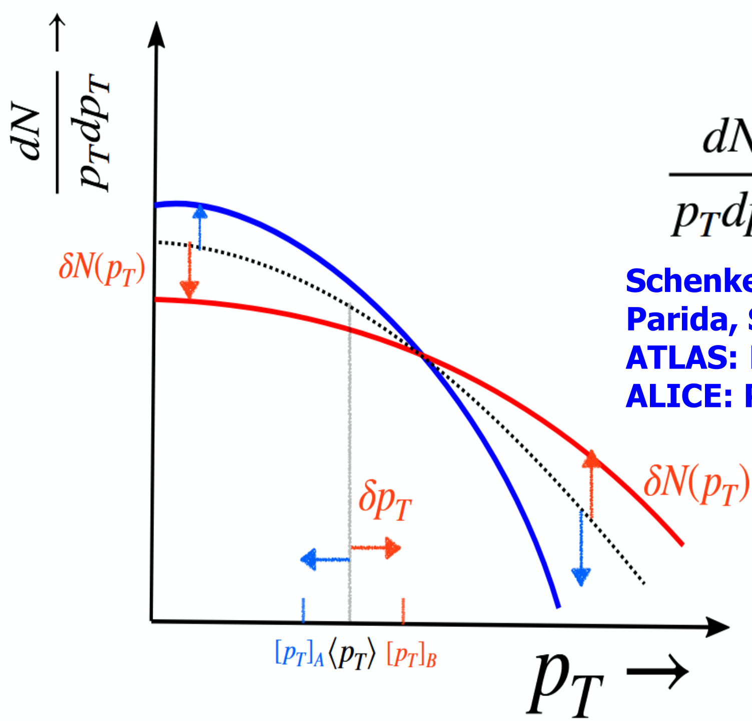


What happens due to Size fluctuation ?



$$v_0(p_T) \equiv \frac{\langle \delta N(p_T)\delta p_T \rangle}{N_0(p_T)\sigma_{p_T}}$$

$v_0(p_T)$ quantifies the change in spectra induced by change in average radial velocity $\langle v_\perp \rangle$.



$$\frac{dN}{p_T dp_T} \sim e^{\frac{-m_T}{T_s}}$$

Schenke, Shen,Teaney, PRC 102,034905 (2020)
Parida, Samanta, Ollitrault, PLB, 857, 138985 (2024)
ATLAS: PRL, 136, 032301 (2026)
ALICE: PRL, 136, 032302 (2026)

Probe of radial flow.

Adopted from T. Parida

$$v_0(p_T) \equiv \frac{\langle \delta N(p_T)\delta p_T \rangle}{N_0(p_T)\sigma_{p_T}}$$

$$v_0(p_T) \sim \langle \delta N(p_T)\delta p_T \rangle$$

correlation between the fluctuation of p_T spectra and fluctuation of $[p_T]$

$\delta N(p_T)$ **deviation of the particle spectrum from the mean spectrum**

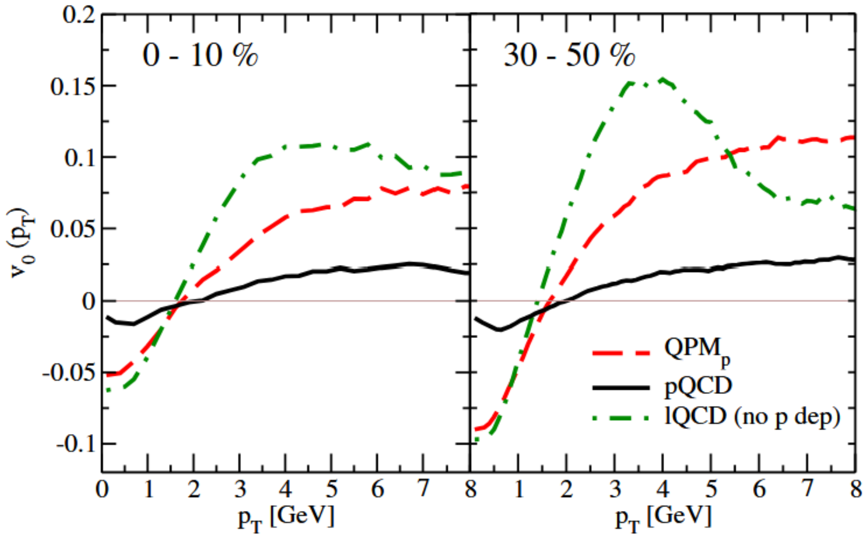
δp_T **change in the pT induced by the radial flow fluctuation**

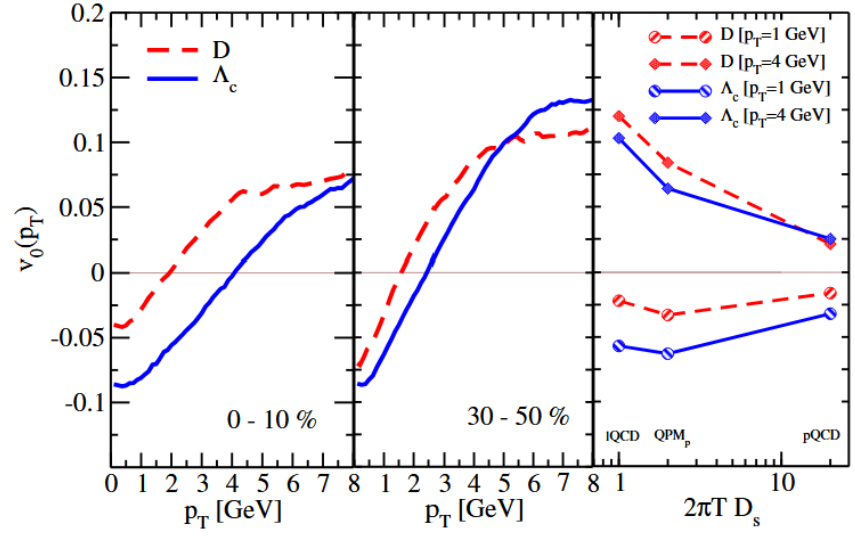
σ_{p_T} **standard deviation of the pT fluctuation**

Momentum fluctuation normalized by standard deviation
Yield fluctuation normalized by mean

$N_0(p_T)\sigma_{p_T}$

Heavy quark radial flow





The v0(pT) of heavy-flavor has a strong and distinct sensitivity to both transport coefficients and hadronization mechanisms. In particular, the hadronization effect for the v0 at low pT is as large as about a factor of two.

Sambataro, Plumari, Das, Greco
2510.19448 [hep-ph]