Heavy quark transport and energy loss

S. Plumari

Dipartimento di Fisica e Astronomia 'E. Majorana',
Università degli Studi di Catania

INFN-LNS

Thanks to: V. Minissale, M.L. Sambataro,
M. Ruggieri , Y. Sun, L. Oliva, S. K. Das, V. Greco

QCD challenges from pp to AA collisions
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Outline

- **Heavy Flavor dynamical evolution in QGP:**

  - Direct access to transport coefficient ($p \rightarrow 0$)
    [R_{AA} and v_2] $\rightarrow$ $D_s(T)$

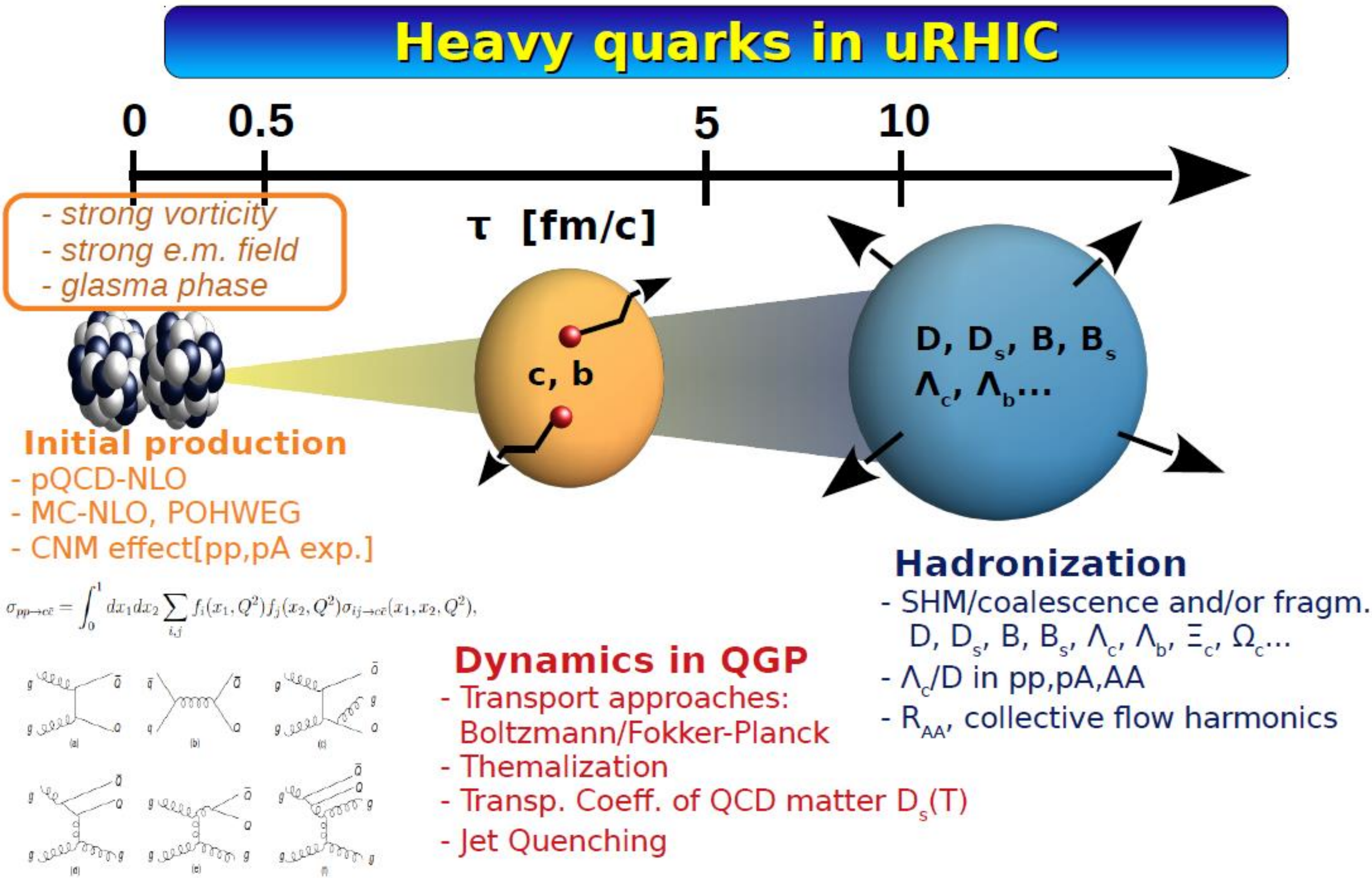
  - system size scan

  - Some recent development and exploration

- **Heavy Flavor as a probe of initial stage:**

  - first studies of the impact of **Glasma** dynamics

  - probe of vorticity and e.m field: v_1 of D meson and lepton from Z^0


Heavy quarks in uRHIC
0
0.5
5
10
τ [fm/c]
- strong vorticity
- strong e.m. field
- glasma phase
c, b
D, D_s, B, B_s
Λ_c, Λ_b...
Initial production
- pQCD-NLO
- MC-NLO, POHWEG
- CNM effect[pp,pA exp.]
$\sigma_{pp\to c\bar{c}} = \int_0^1 dx_1 dx_2 \sum_{i,j} f_i(x_1,Q^2) f_j(x_2,Q^2) \sigma_{ij\to c\bar{c}}(x_1,x_2,Q^2),$
Dynamics in QGP
- Transport approaches: Boltzmann/Fokker-Planck
- Themalization
- Transp. Coeff. of QCD matter $D_s(T)$
- Jet Quenching
Hadronization
- SHM/coalescence and/or fragm. D, D_s, B, B_s, Λ_c, Λ_b, Ξ_c, Ω_c...
- Λ_c/D in pp,pA,AA
- R_{AA}, collective flow harmonics

Transport approaches

Two main approaches:

1) Fokker-Planck ($T \ll m_q$ soft scattering)

[*TAMU, Duke, Nantes, Torino, Catania, ...*]

$$\frac{\partial}{\partial t} f_Q = \gamma \frac{\partial}{\partial p_i}[p_i f_Q] + D_p \nabla_p^2 [f_Q]$$

Background:
Hydro/transport expanding bulk

Drag coeff. (γ)
(thermalization rate)

momentum diffusion coeff. (D_p)

- **Fluctuation dissipation theorem** $D_p = E\,T\,\gamma$
- **Spatial diffusion coefficient** $D_s = \frac{T}{M\gamma} = \frac{T^2}{D_p} = \frac{T}{M}\tau_{th}$
  a measure of thermalization time

$$\langle x^2 \rangle - \langle x \rangle^2 = 6 D_s t$$

D_s from lQCD

2) Boltzman kinetic transport

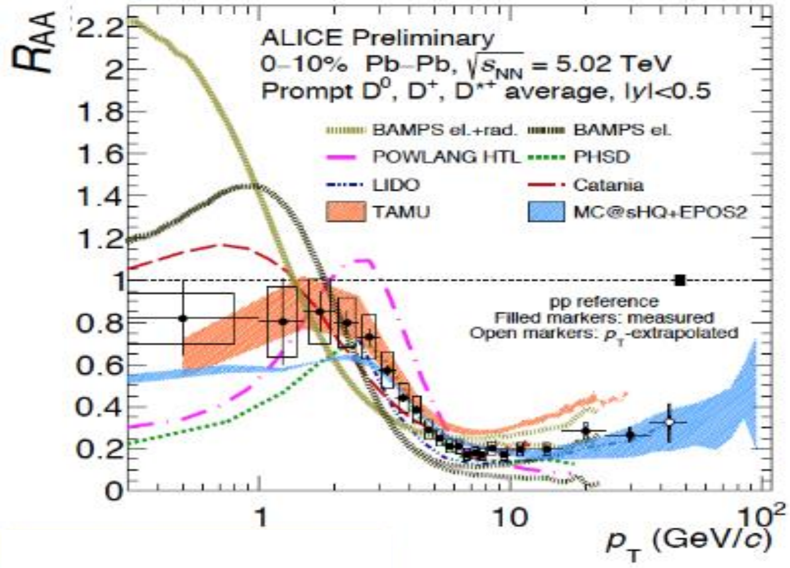
(...Kadanoff-Baym-PHSD)

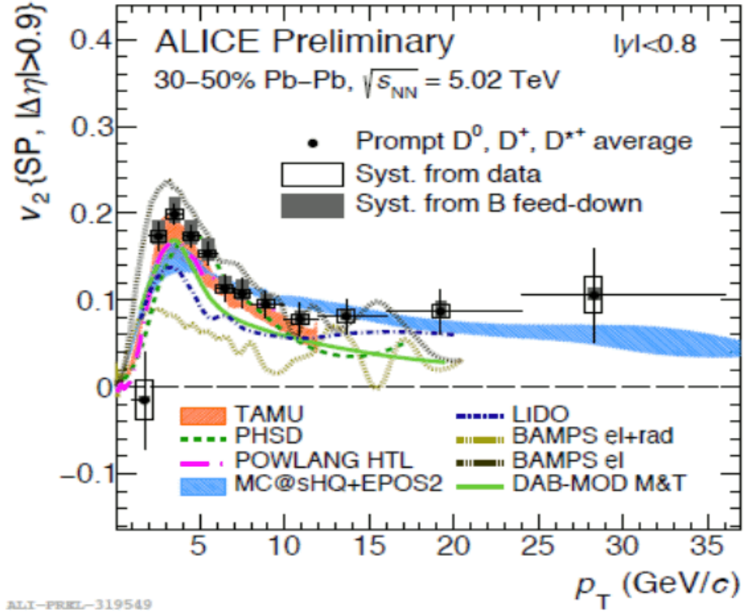
[*Catania, Nantes, Frankfurt, LBL,...*]

$$p^\mu \partial_\mu f_Q(x,p) = C[f_q, f_g, f_Q]$$

$$C[f_q, f_g, f_Q] = \frac{1}{2E_1}\int \frac{d^3 p_2}{2E_2(2\pi)^3}\int \frac{d^3 p_1'}{2E_1'(2\pi)^3}$$
$$\times [f_Q(p_1') f_{q,g}(p_2') - f_Q(p_1) f_{q,g}(p_2)]$$
$$\times |M_{(q,g)\to Q}(p_1 p_2 \to p_1' p_2')|$$
$$\times (2\pi)^4 \delta^4(p_1 + p_2 - p_1' - p_2')$$

Transport coefficient





Models not really tested at p→0

The new data → determine D_s(T) more properly,

i.e. p→0 where it is defined and computed in lQCD

	Catania	Duke	Frankfurt(PHSD)	LBL	Nantes	TAMU
Initial HQ (p)	FONLL	FONLL	pQCD	pQCD	FONLL	
Initial HQ (x)	binary coll.	binaryy coll.	binary coll.	binary coll.		binary coll.
Initial QGP	Glauber	Trento	Lund		EPOS	
QGP	Boltzm.	Vishnu	Boltzm.	Vishnu	EPOS	2d ideal hydro
partons	mass	m=0	m(T)	m=0	m=0	m=0
formation time QGP	0.3 fm/c	0.6 fm/c	0.6 fm/c (early coll.)	0.6 fm/c	0.3 fm/c	0.4 fm/c
interactions in between	HQ-glasma	no	HQ-preformed plasma	no		no

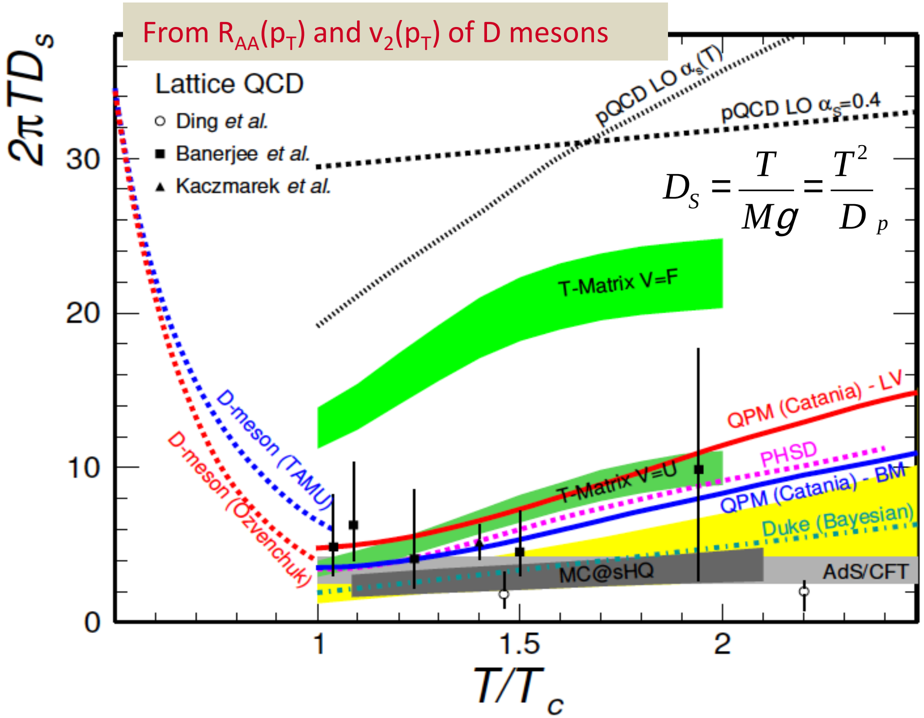
2018-2019

Several Collab. in joint activities:

- EMMI-RRTF:
  R. Rapp et al., Nucl. Phys. A 979 (2018)
- HQ-JETS:
  S. Cao et al.,Phys. Rev. C 99 (2019)
- Y. Xu et al., Phys. Rev. C 99 (2019)

Transport coefficient

X. Dong & VG, Progr. Part. Nucl. Phys.(2019)



Main Differences in models:

- impact of bulk evolution
- impact of hadronization
- momentum depedence of diffusion
- not all models describe data with the same quality [χ^2 and/or Bayesan analysis]

Future:

- Access low p & precision data (detector upgrade)
- Better insight into hadronization (Λ_c...)
- New observables: Extend to e-b-e: v_n , ESE q_2 selection & v_n(soft)-v_n(HQ) correlations + $v_1(y)$

  D-D triggered angular correlations
- Predictions & measurements for B mesons

Reviews:

- F. Prino and R. Rapp, JPG(2019)
- X. Dong and VG, Prog. Part. Nucl. Phys. (2019)
- X. Dong, Y.J. Lee and R. Rapp, Ann.Rev.Nucl.Part.Sci. 69 (2019)
- Jiaxing Zhao et al., Prog. Part. Nucl. Phys. 114 (2020)

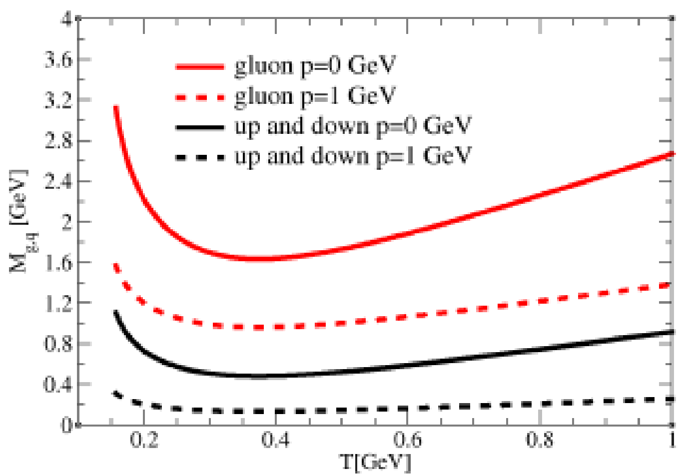
QPM extended – momentum dependence

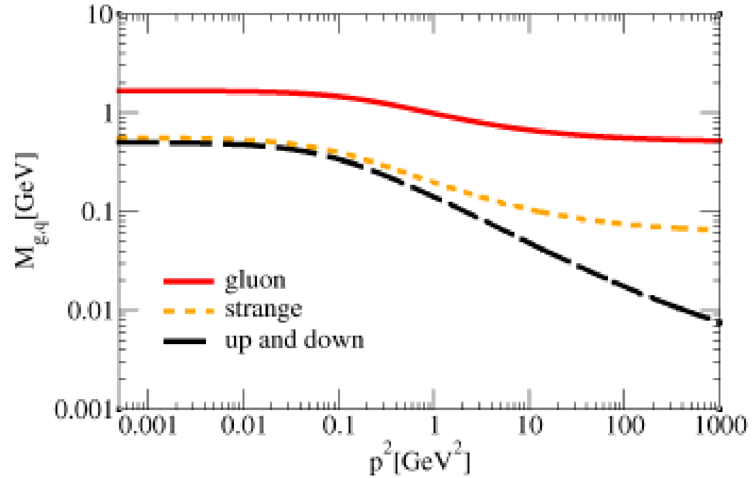
Dyson-Schwinger studies in the vacuum → following the model developed by PHSD group

$$M_g(T,\mu_q,p) = \left(\frac{3}{2}\right)\left(\frac{g^2(T^\star/T_c(\mu_q))}{6}\left[\left(N_c + \frac{1}{2}N_f\right)T^2 + \frac{N_c}{2}\sum\frac{\mu_q^2}{\pi^2}\right]\left[\frac{1}{1+\Lambda_g(T_c(\mu_q)/T^\star)p^2}\right]\right)^{1/2} + m_{\chi g}$$

$$M_{q,\bar{q}}(T,\mu_q,p) = \left(\frac{N_c^2-1}{8N_c}g^2(T^\star/T_c(\mu_q))\left[T^2 + \frac{\mu_q^2}{\pi^2}\right]\left[\frac{1}{1+\Lambda_q(T_c(\mu_q)/T^\star)p^2}\right]\right)^{1/2} + m_{\chi q}$$

Momentum dependent factors





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H. Berrehrah, W. et al., Phys.Rev.C 93, 044914 (2016).
C. S. Fischer, J. Phys. G 32, R253 (2006).

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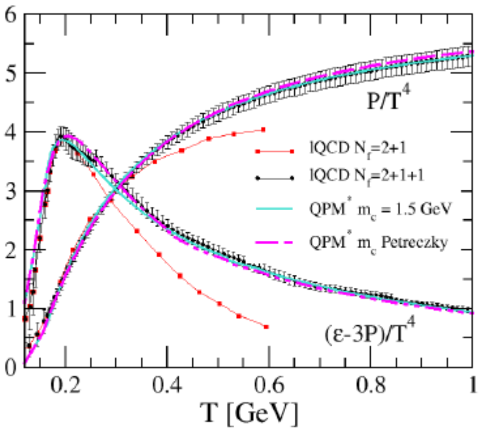
Momentum dependent factors

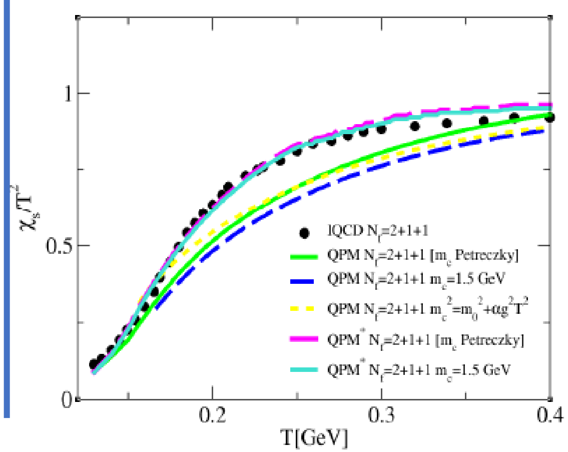
We correctly reproduce both **EoS** and **quark susceptibilities** which are understimated in the standard QPM approach.

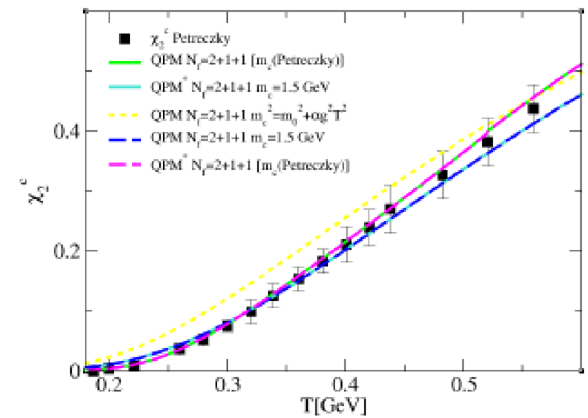


$$\chi_s = \frac{T}{V}\frac{\partial^2 lnZ}{\partial\mu_s^2}$$

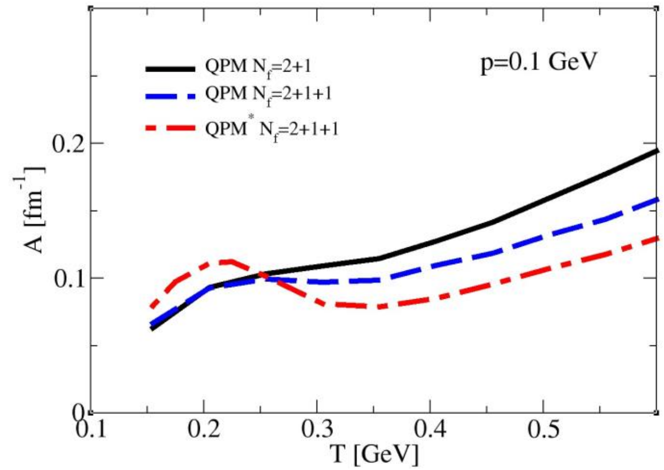
$$\chi_c = \frac{T}{V}\frac{\partial^2 lnZ}{\partial\mu_c^2}$$

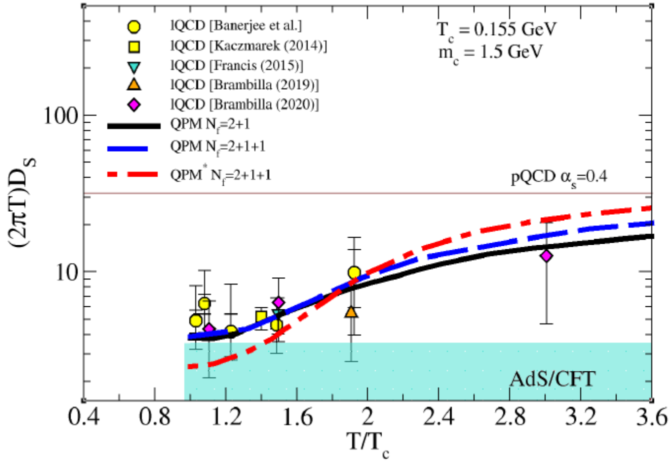
QUARK SUSCEPTIBILITIES





Drag and D_s in QPM extended





Drag coefficient → **standard QPM**
standard QPM including charm
extended QPM

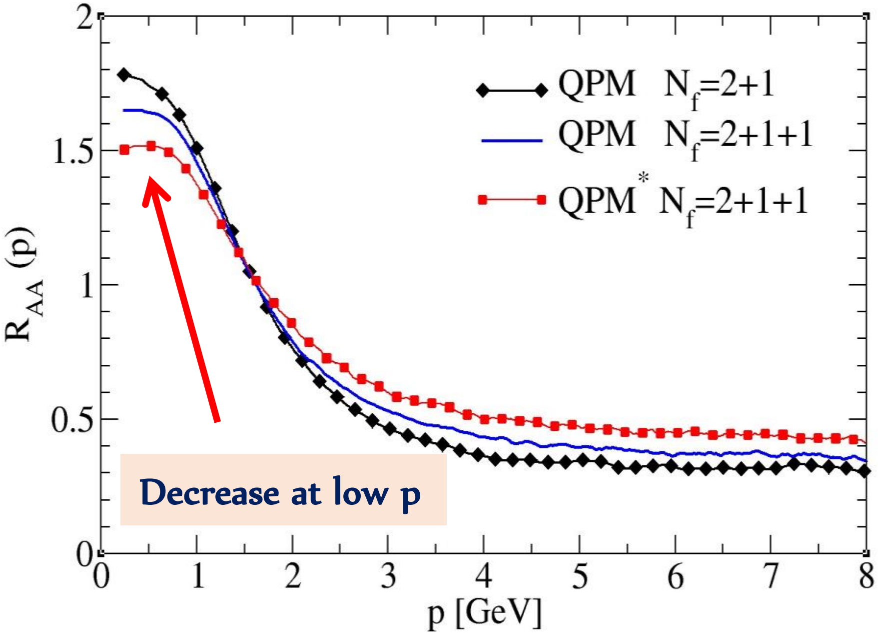
- **Increase** at low T consistent with the large enhancement of the coupling in the same T region
- **Decrease** at high T

Spatial diffusion coefficient D_s

$T/T_c < 2$ → strong non-perturbative behaviour near to T_c.

high T region → the D_S reaches the pQCD limit quickly than the standard QPM.

Preliminary:
Nuclear modification factor R_{AA}



$$R_{AA} = f_C(p, t_f) / f_C(p, t_0)$$

Initial momentum distribution function

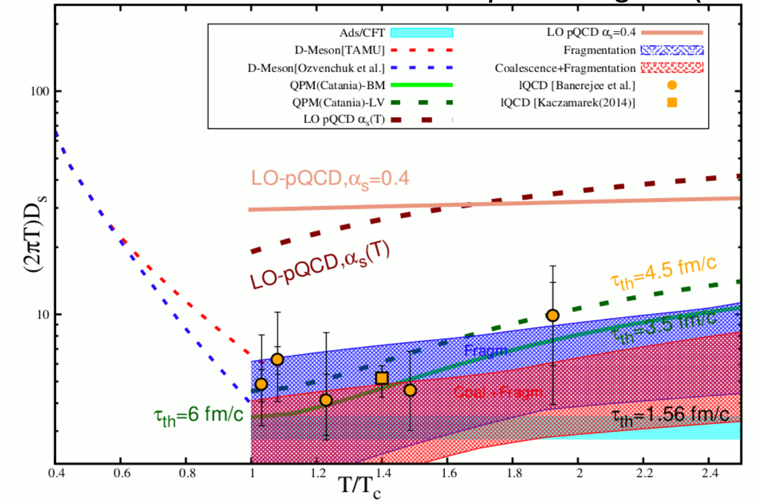
→ FONLL for charm quark

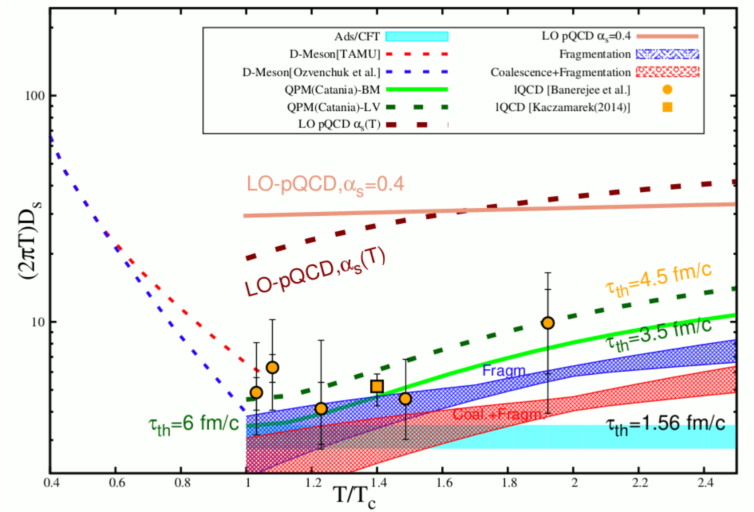
Momentum dependent QPM approach

- Better description of recent lQCD data.
- Effects on the global χ^2 coming from the comparison to the experimental data of R_{AA}, v_n?

Transport coefficient

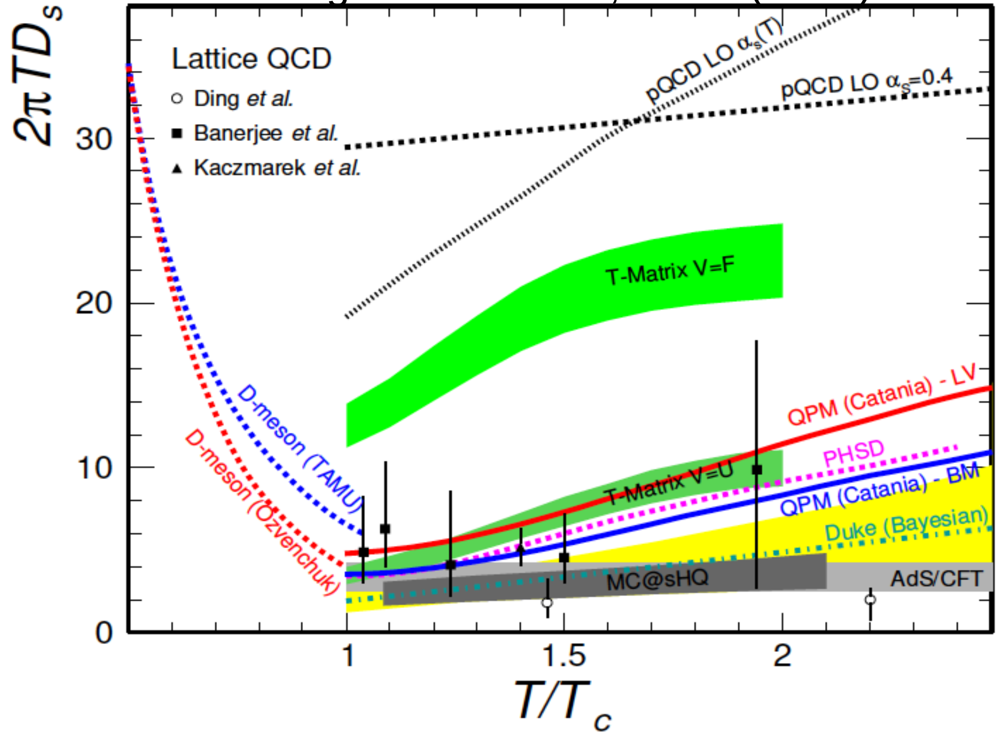
Z. Citron et al., CERN Yellow Rep. Monogr. 7 (2019) 1159





Different hadronization models can affect the extraction of the charm quark diffusion coefficient

X. Dong and V. Greco, PPNP(2019)



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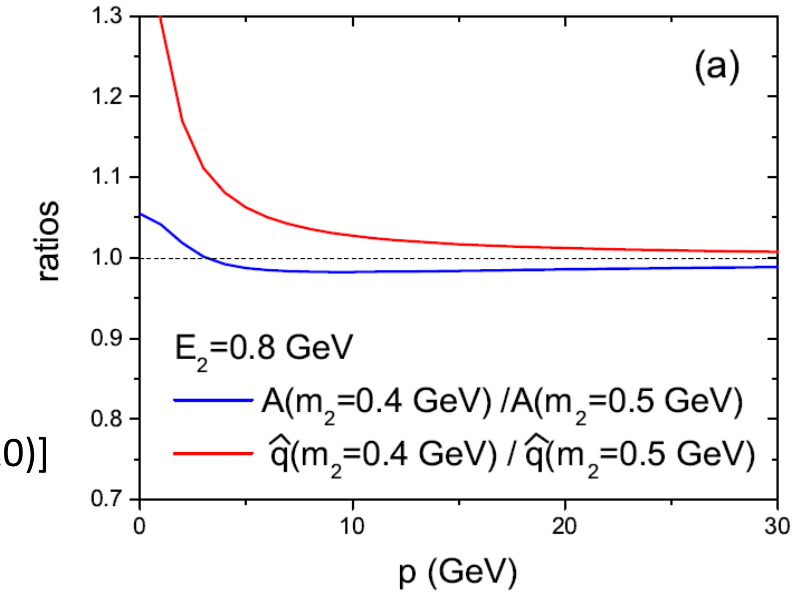
-Non-equilibrium in initial stage and bulk dynamics

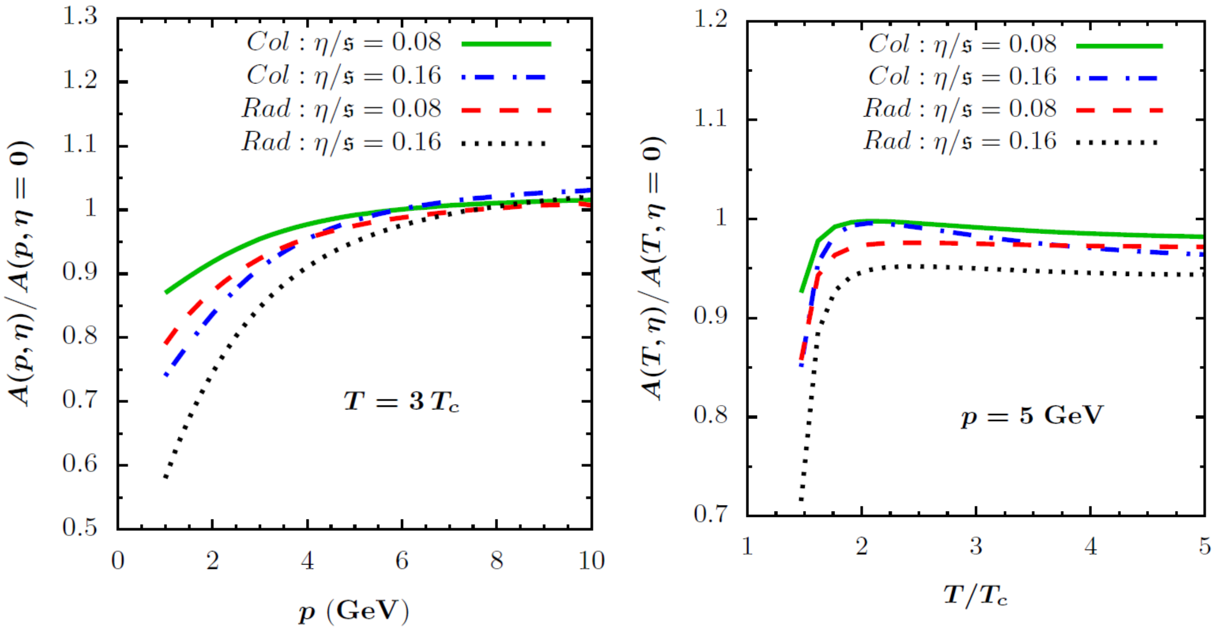
- anisotropic bulk distribution in initial stage P_L/P_T
- non-equilibrium energy/density ratio [fugacity,corona]
- shift in pole parton masses in the bulk

First study may be even more relevant to pA

[T. Song, P. Moreau, J. Aichelin, E. Bratkovskaya, PRC 101 (2020)]



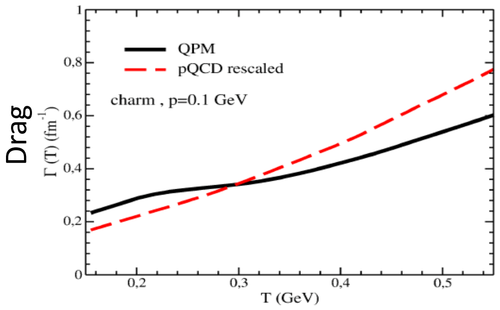
A. Shaikh et al., Phys.Rev.D 104 (2021) 3, 034017



At low T and low p viscous corrections on the drag coefficients are larger for the radiative process in comparison with collisional process

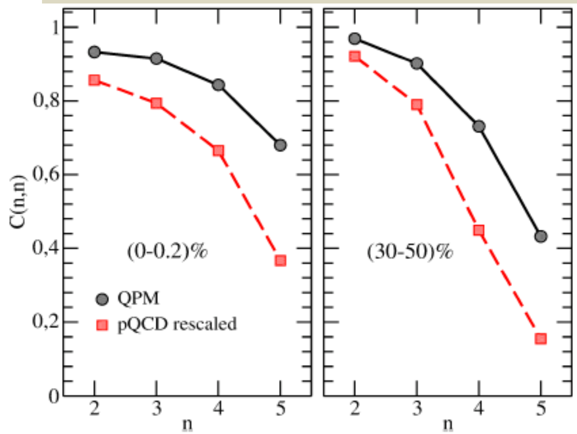
ESE: v2 and spectra

$$C\left(v_n^{light}, v_m^{heavy}\right) = \left\langle \frac{\left(v_n^{light} - \langle v_n^{light} \rangle\right)\left(v_m^{heavy} - \langle v_m^{heavy} \rangle\right)}{\sigma_{v_n^{light}} \sigma_{v_m^{heavy}}} \right\rangle$$

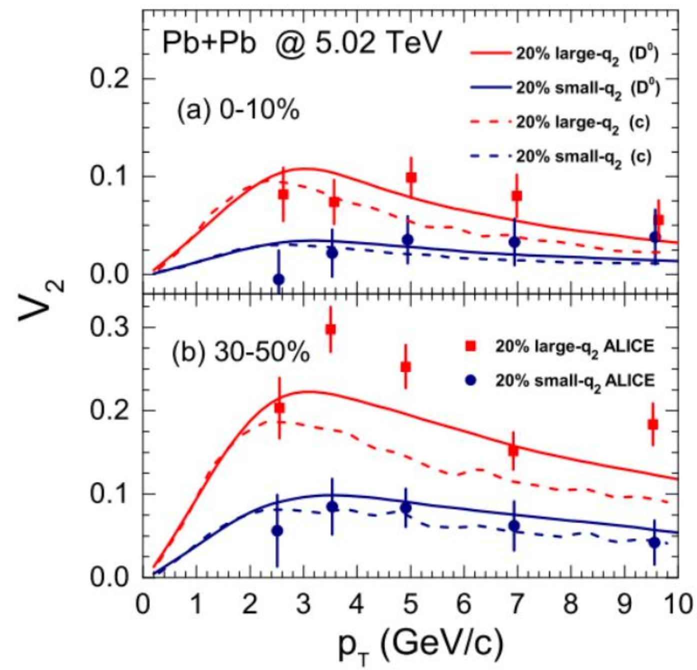


S. Plumari et al., Phys.Lett.B 805 (2020)
[Prado, JNH et al.,PRC 96(2017)

Very large sensitivity to T dep. of Ds



$q_2$selected $v_2(p_T)$



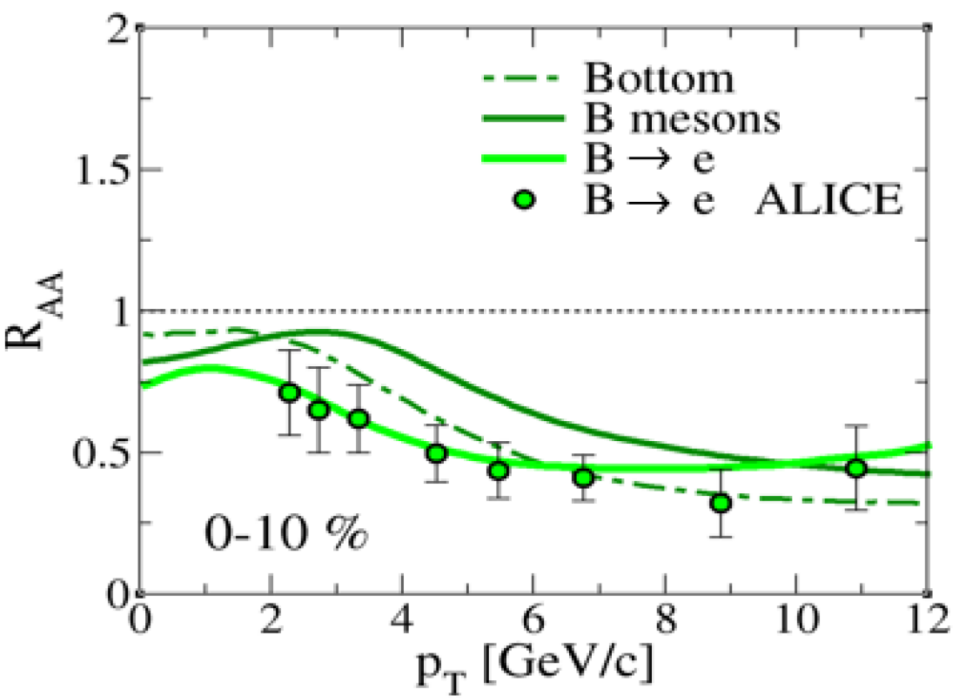
M.L. Sambataro et al., Eur.Phys.J.C 82 (2022) 9, 833
Data taken from ALICE coll.: *Phys.Lett.B* 813 (2021) 136054

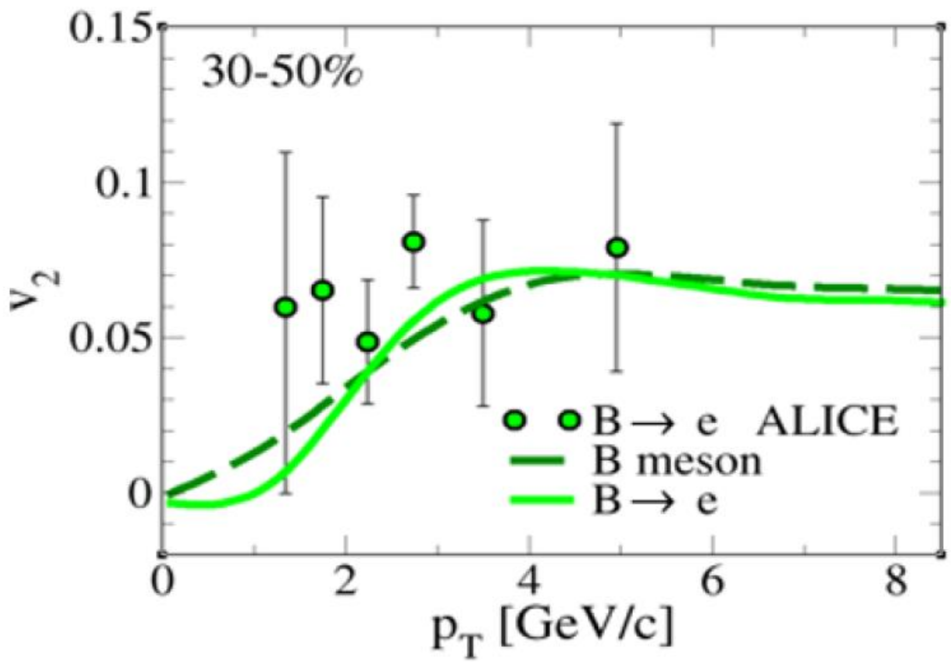
- v_2 (large- q_2 /small- q_2) $\gtrless$ v_2 (unbiased) of about 50% in both 0-10% and 30-50% central

What changes from c to b?

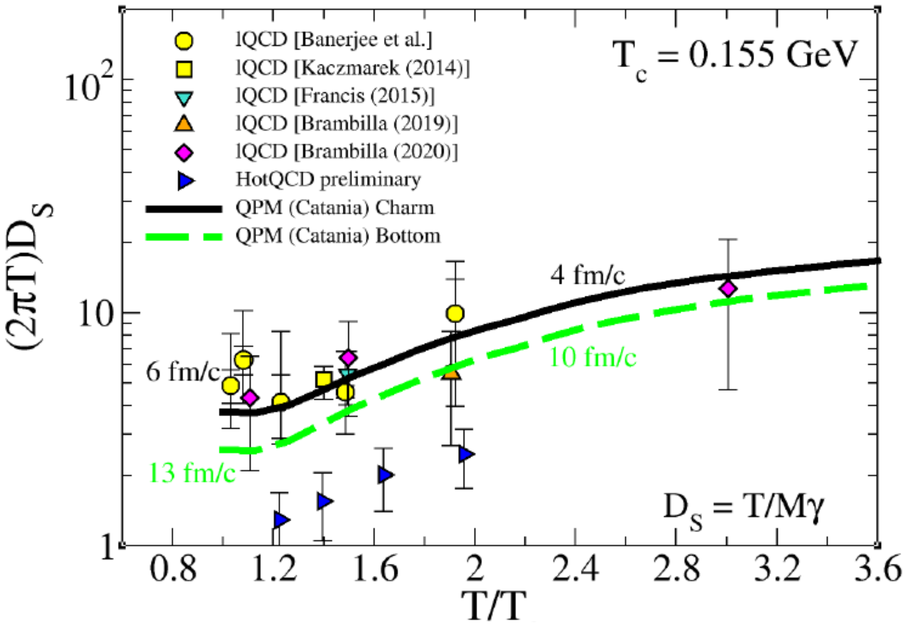
Prediction for B meson, electrons from semi-leptonic B meson decay within a coal.+ fragm. model

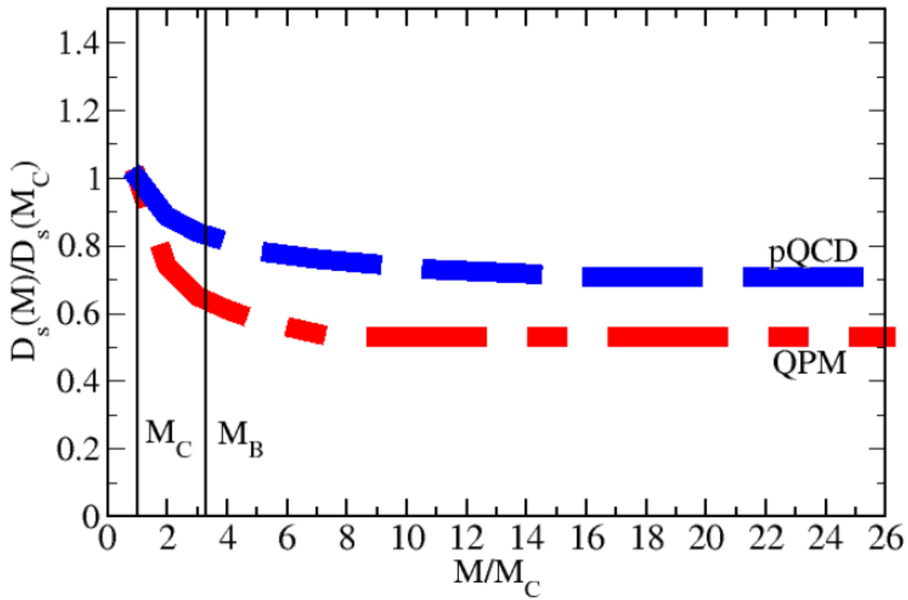
R_{AA} and v_2 data suggest a strong coupling of b quarks with bulk matter





What changes from c to b?





$$2\pi T D_s(T) = \frac{2\pi T^2}{M_{HQ} A(T, p \to 0)} = \frac{2\pi T^2}{M_{HQ}} \tau_{th}$$

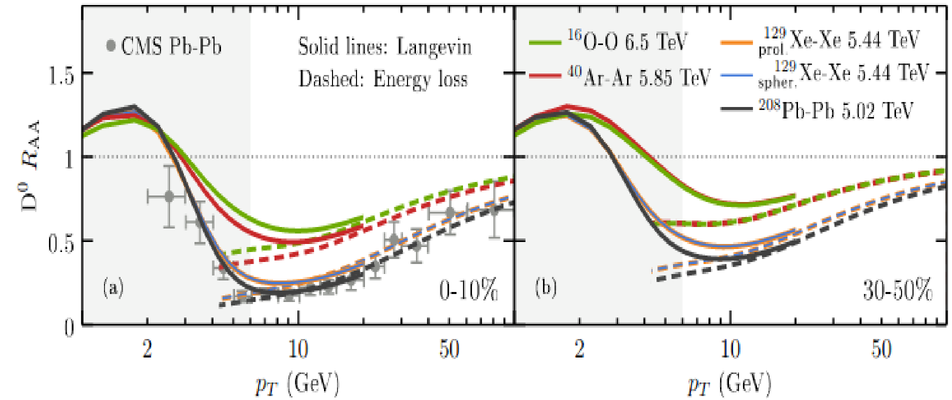
In QPM approach → D_s(c) is 30-40% larger than D_s(b)
M →∞ limit is not reached for charm

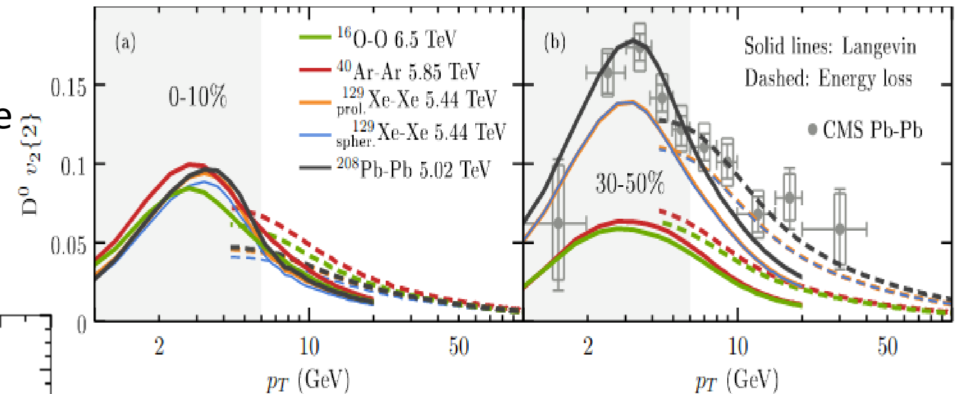
System size scan

Allows a focus only on system size effects.

- In mid-central collisions clear suppression of v_2 in small systems→role played by the system size.
- In central collisions v_2 constant across the system size scan. Decrease of system size compensated by increase of ε_2.

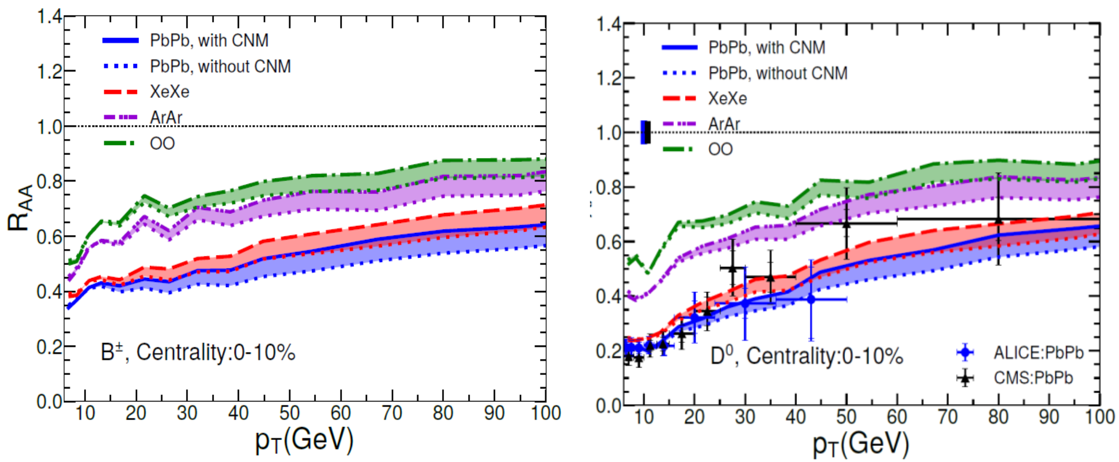
R. Katz et al., PRC 102 (2020) 4, 041901





- due to larger masses of b quarks, B meson RAA are larger than D meson.
- For B mesons, jet quenching effect on RAA is still sizable in central O+O collisions.

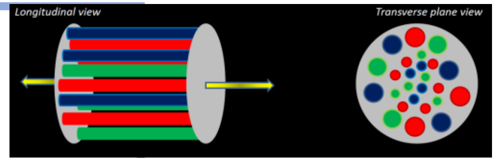
Yu-Fei Liu et al., *PRC* 105 (2022) 4, 044904



Impact of Glasma on HQ

Impact of Initial Stage

- **Impact of Glasma phase?!**
- **Huge vorticity**
- **Strong e.m. field**



Solving classical Yang-Mills

$$\frac{dA_i^a(x)}{dt} = E_i^a(x),$$

$$\frac{dE_i^a(x)}{dt} = \sum_j \partial_j F_{ji}^a(x) + \sum_{b,c,j} f^{abc} A_j^b(x) F_{ji}^c(x).$$

Heavy quark in the chromo magnetic field

$$\frac{dx_i}{dt} = \frac{p_i}{E}, \qquad E\frac{dQ_a}{dt} = -Q_c \varepsilon^{cba} A_b \cdot p,$$

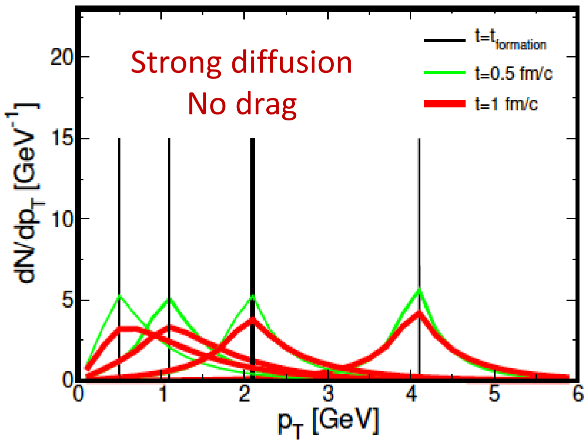
$$E\frac{dp_i}{dt} = Q_a F_{i\nu}^a p^\nu,$$

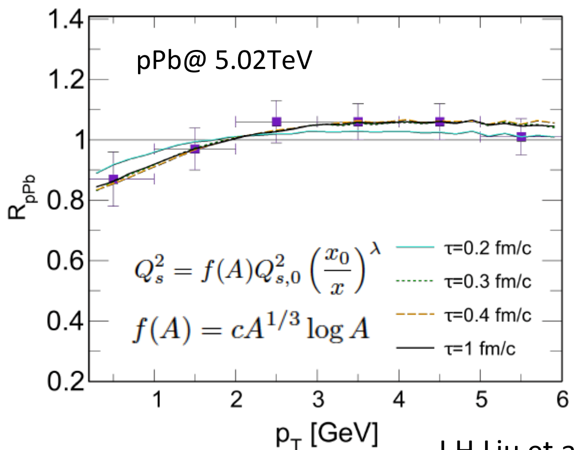
Strong and fast diffusion, see also in K. Boguslavski et al., arXiv:2005.02418 with correlator approach

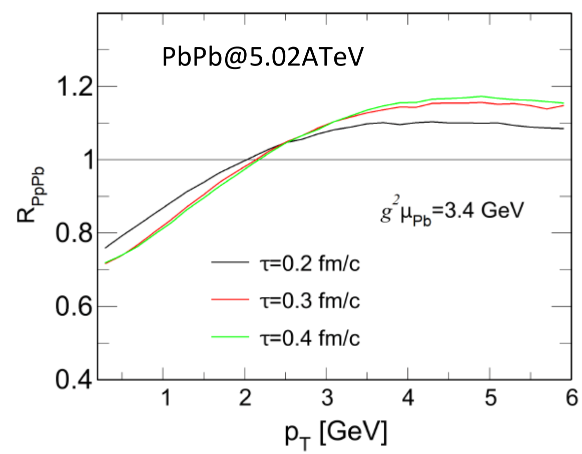
Initial Glasma in non-equilibrium can induce strong diffusion

- S. Mrowczynski, EPJA 54 (2018)
- M.Ruggieri and S.K. Das, PRD98 (2018)

Static box- SU(2)



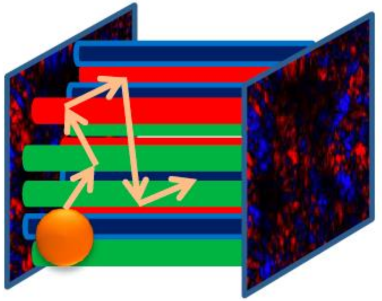




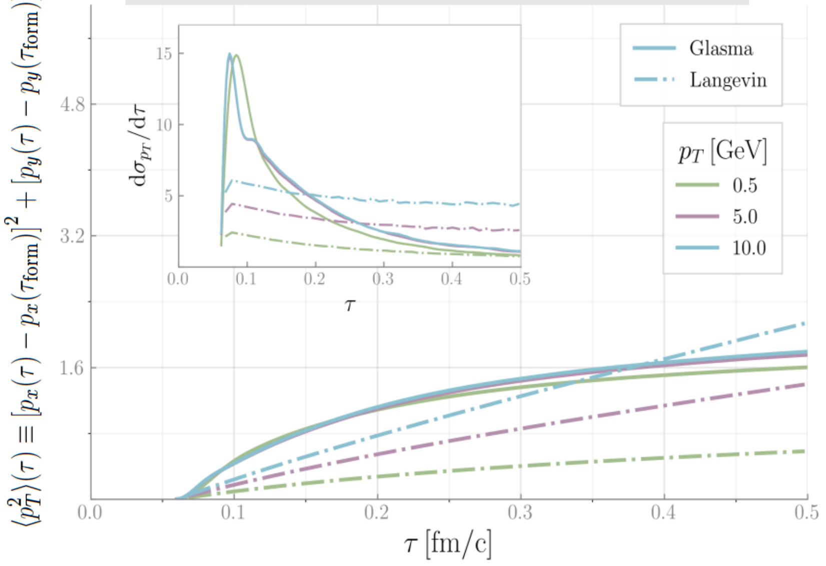
J.H.Liu et al., arXiv:1911.02480

Impact of Glasma on HQ

Charm in the Glasma and Langevin starting at t_{form}=0.08 fm/c
Same underlying bulk energy density (central PbPb@5.02ATeV)
LV: Drag & Diffusion tuned to R_{AA}



Evolution of momentum broadening



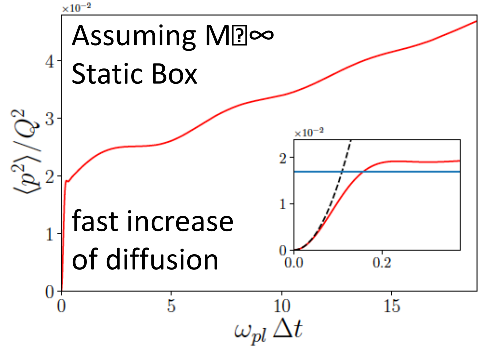
D. Avramescu QM2022

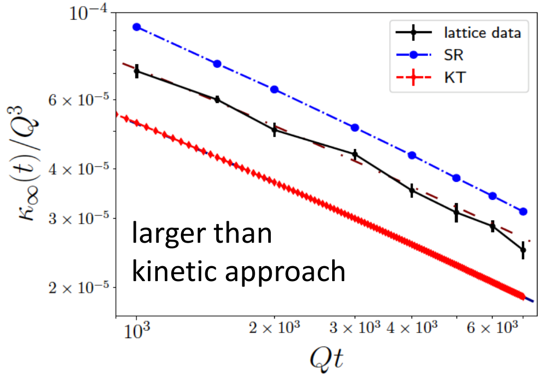
- Large initial broadening rate of Glasma at p_T < 5 GeV at $\tau \gtrsim 0.3$ fm/c LV (HQ scattering in QGP) becomes dominant
- Issue the transition from Glasma to QGP

❖ To quantify the phenomenological impact start from FONNL and compare HQ Wong's in Glasma bulk vs LV in hydro bulk starting at $\tau_{form}=1/2m_Q$ and/or τ_0=0.3-0.6 fm/c

Impact of Glasma on HQ

K. Boguslavski, A. Kurkela, T. Lappi and J. Peuron, arXiv:2005.02418





Correlator method

$$\langle \dot{p}_i(t)\dot{p}_i(t')\rangle = \frac{g^2}{2N_c}\langle E_i^a(t)E_i^a(t')\rangle \qquad 3\kappa\,(t,\Delta t) \equiv \frac{\mathrm{d}}{\mathrm{d}\Delta t}\langle p^2(t,\Delta t)\rangle$$

Link pA <-> AA

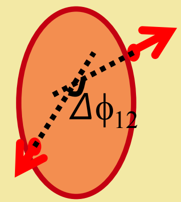
Using HQ as a probe of the Glasma

-> May have key role for

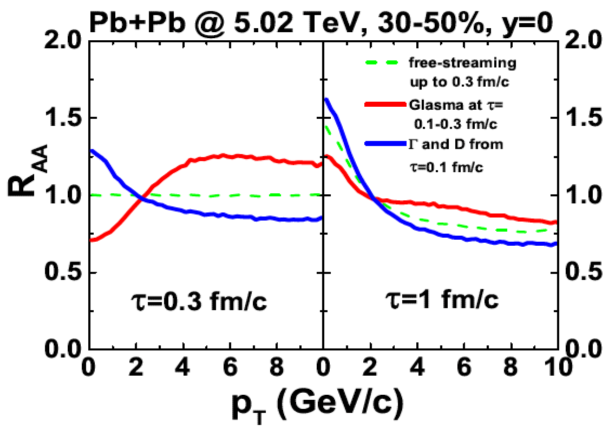
D-D angular correlation

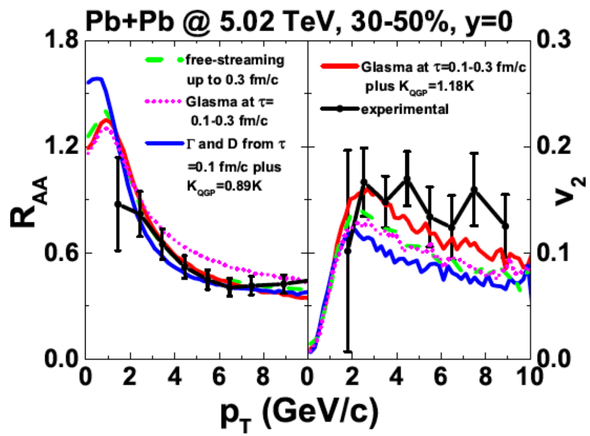
May affect the determination of Ds(T)

modify (improve) the relation R_{AA} & v_2



Impact on AA collisions observables (interacting at $\tau=\tau_{form}$)





- Dominance of diffusion-like **enhancement of $R_{AA}(p_T)$**
- **Gain in v_2**: larger interaction in QGP stage to have same $R_{AA}(p_T)$

Y. Sun et al., PLB 798 (2019)

Electro-Magnetic field in HIC

Start from point-like *Lienhard-Wiechart* retarded potentials (Biot-Savart law)

$$eB(t,\mathbf{r}) = \alpha_{em}\sum_a \frac{(1-v_a^2)(\mathbf{v}_a\times\mathbf{R}_a)}{R_a^3\left[1-(\mathbf{R}_a\times\mathbf{v}_a)^2/R_a^2\right]^{3/2}},$$

$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{B} = -\nabla\times\boldsymbol{J}_{ext},$$

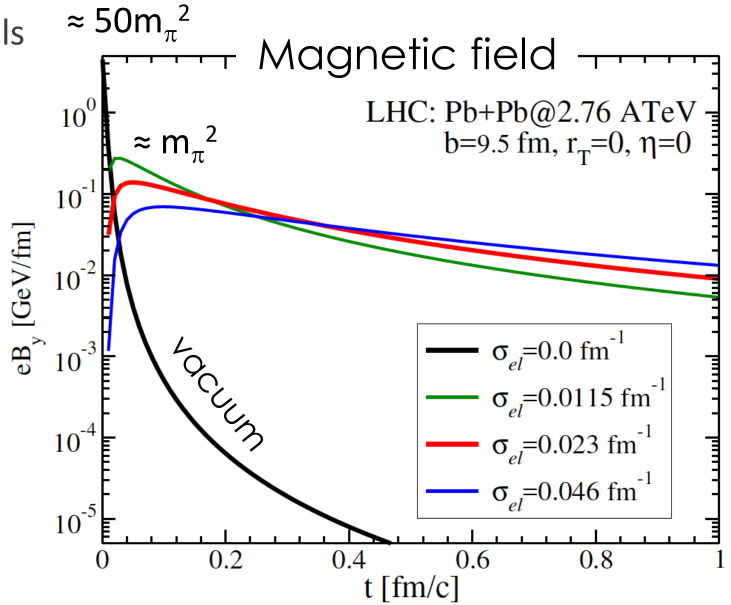
$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{E} = -\nabla\rho_{ext} + \partial_t\boldsymbol{J}_{ext},$$

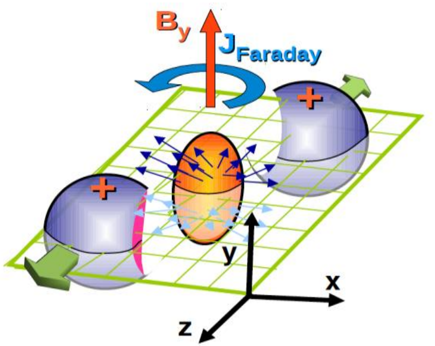
Fold them with the nuclear transverse density profile of the spectator nuclei and sum forward (+) and backward (-)

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

$$eE_x^+(\tau,\eta,x_\perp,\phi) = eB_y^+(\tau,\eta,x_\perp,\phi)\coth(Y_b-\eta)$$

Gursoy, Kharzeev, Rajagopal, PRC89(2014)
like in:
K. Tuchin, PRC 88, 024911 (2013).
K. Tuchin, Adv. High Energy Phys. 2013, 1 (2013).



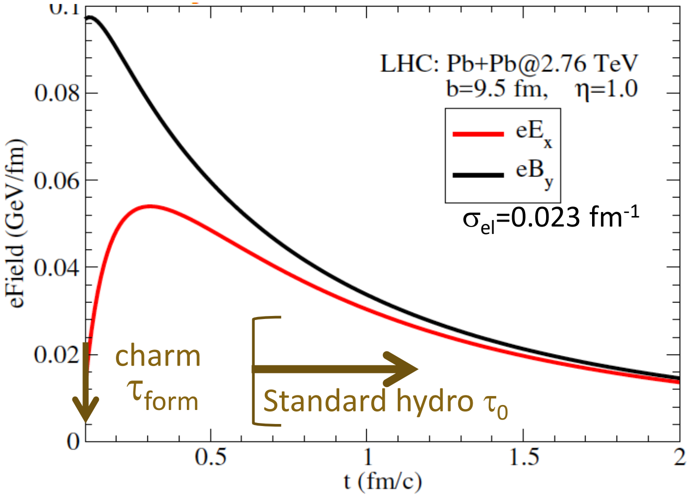


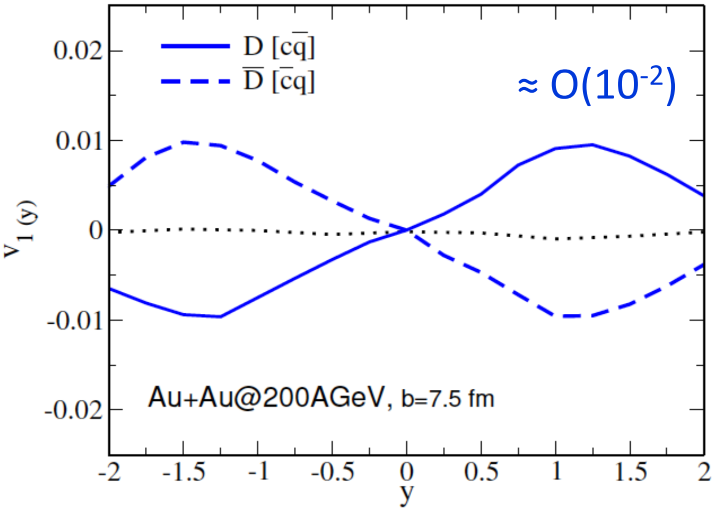
Assumptions:

- **Medium at t<0**
- **Electric Conductivity const. in T**
- **No back reactions in the bulk due to currents**
- **No e-b-e fluctuations**
- **Neglected finite size of colliding nuclei**

Electro-Magnetic field in HIC

S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scardina, V. Greco, PLB**768** (2017) 260-264.





For charm quark we find a sizeable v_1

$\approx O(10^{-2}) \approx$ 10-50 times larger than π^+/π^-!

Using the same E-B field evolution in U. Gursoy et al, PRC(2014)

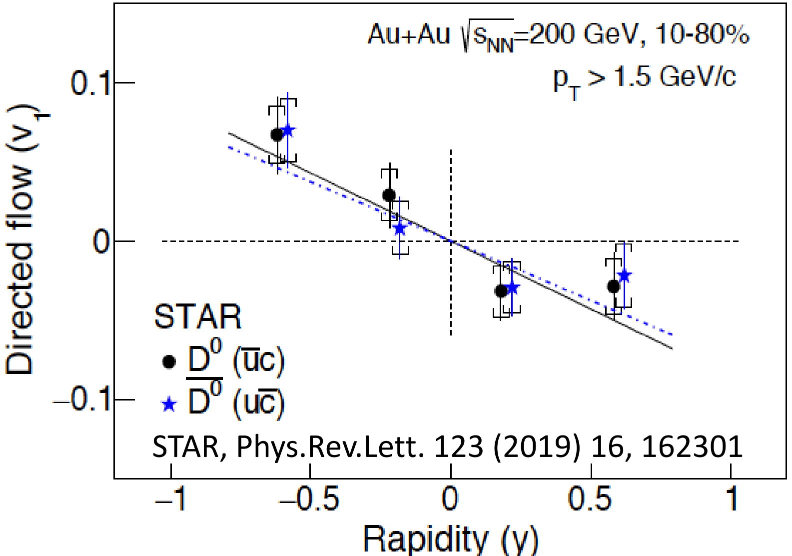
Huge v_1 about **30 times larger** than the kaon one

Excellent qualitative prediction of

Chatherjee and Bozek, PRL 120 (2018)

$dv_1/dy \approx 0.02\text{-}0.04$ (≈ 10-15 times larger than light-charged)

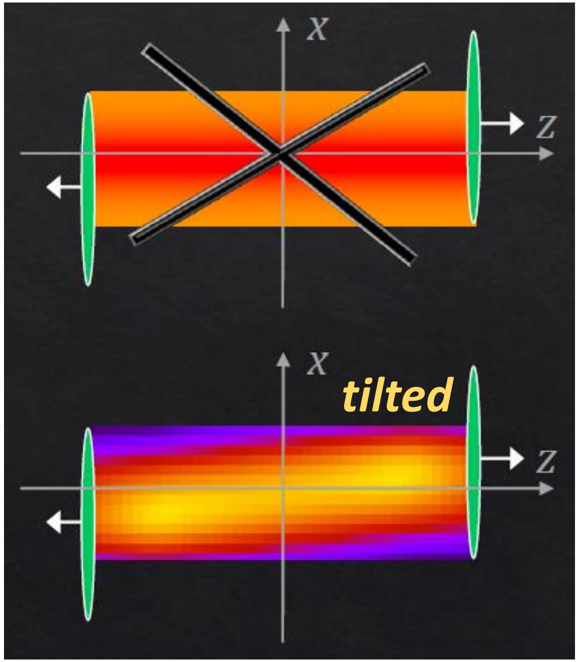
Very surprising that v_1 heavy quark >> v_1 light quarks

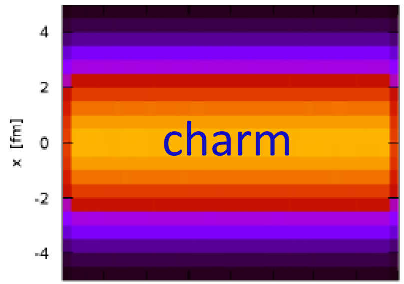


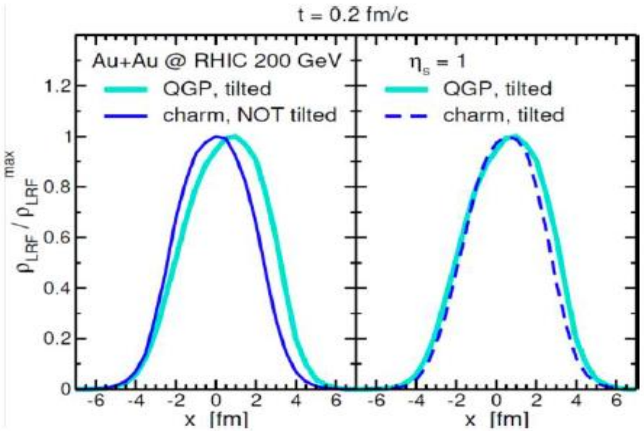
$dv_1/dy = -0.080 \pm 0.017(\text{stat}) \pm 0.016(\text{syst})$

v_1 of D mesons: quantitative study

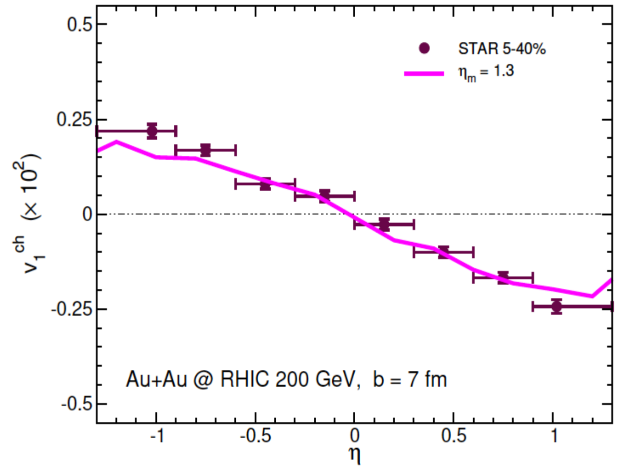
Oliva, Plumari, V.G., JHEP05 (2021) 034







“Tilt” fix bulk v_1



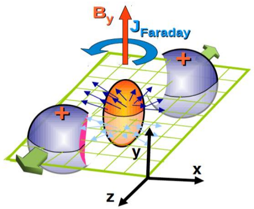
$$W(x_\perp, \eta_s) = 2\left(N_A(x_\perp) f_-(\eta_s) + N_B(x_\perp) f_+(\eta_s)\right)$$

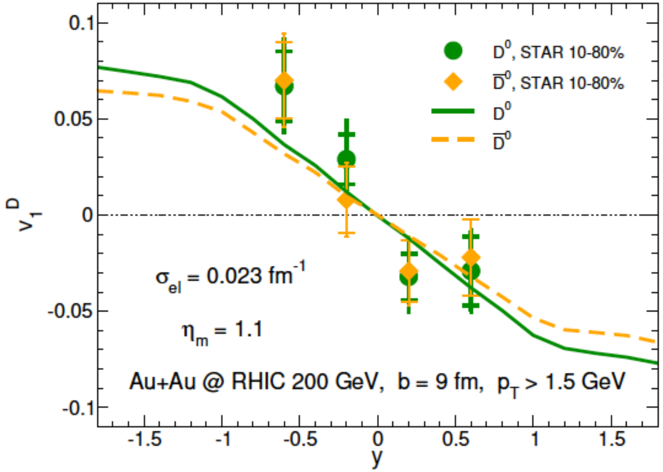
$$f_+(\eta_s) = f_-(-\eta_s) = \begin{cases} 0 & \eta_s < -\eta_m \\ \dfrac{\eta_s + \eta_m}{2\eta_m} & -\eta_m \le \eta_s \le \eta_m \\ 1 & \eta_s > \eta_m \end{cases}$$

P. Bozek and I. Wyskiel, PRC 81(2010) 054902

Δv_1 from e.m. field?

Oliva, Plumari, V.G., JHEP 05 (2021)





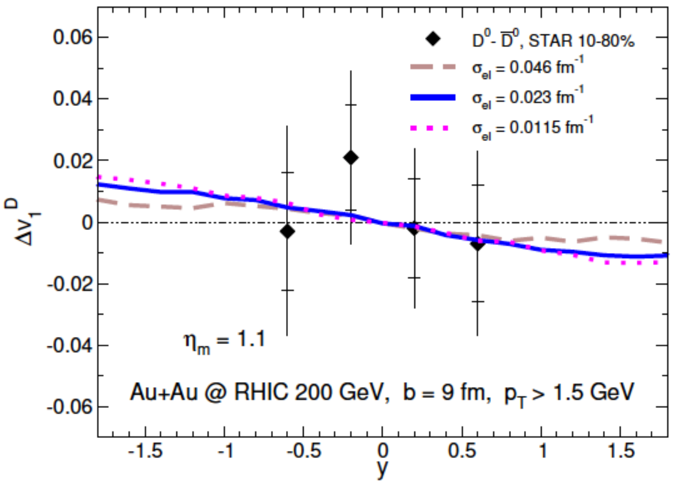
$d(\Delta v_1)/dy|_{exp}$= – 0.011 ±0.024(stat)±0.016(syst)

$d(\Delta v_1)/dy|_{th.}$= – 0.01, L. Oliva et al.

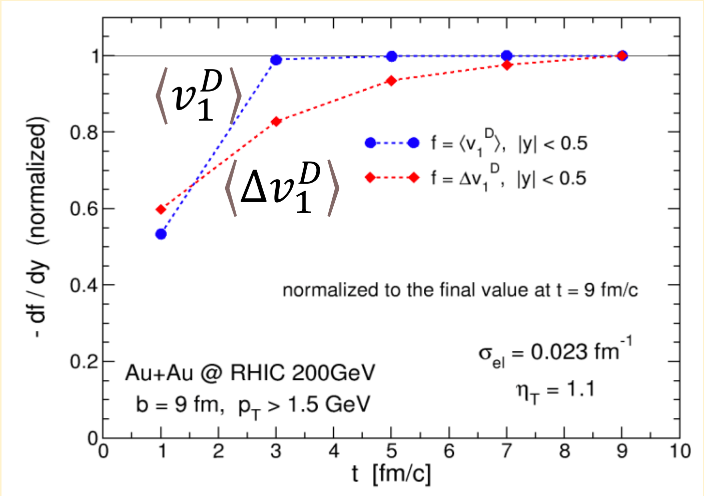
≈ 10 times larger than charged,

similar to S. Das et al., PLB768 (2017)

but could be **also consistent with 0!**



Time evolution

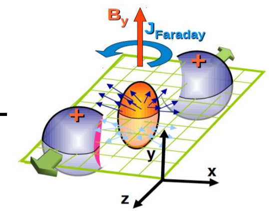


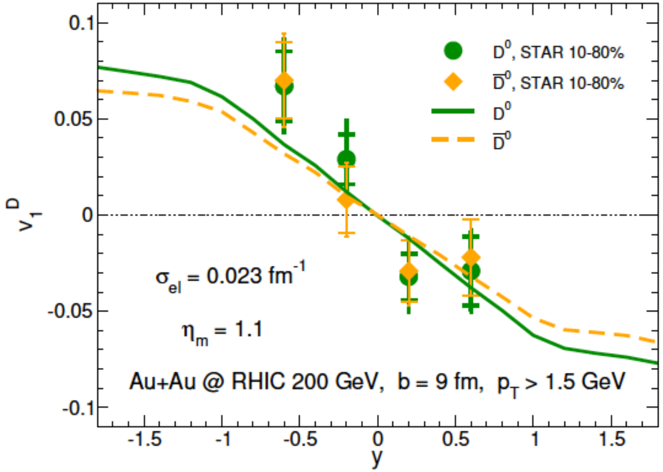
v_1 expected to be more sensitive than v_2 to high T (early time) $D_s(T)$!

Unexplored…

Δv_1 from e.m. field?

Oliva, Plumari, V.G., JHEP 05 (2021)





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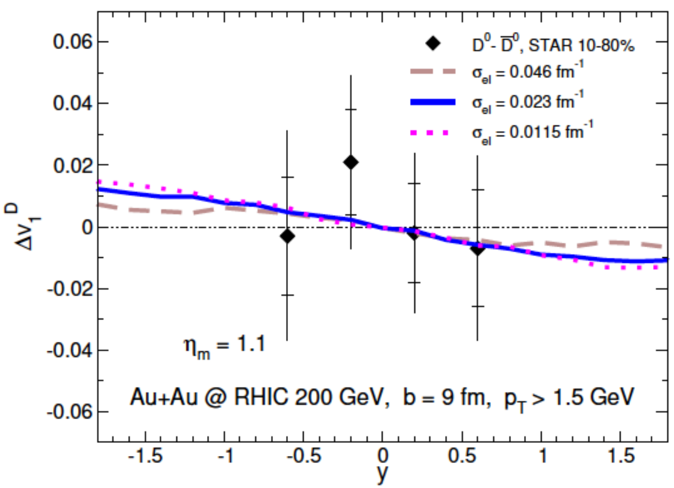
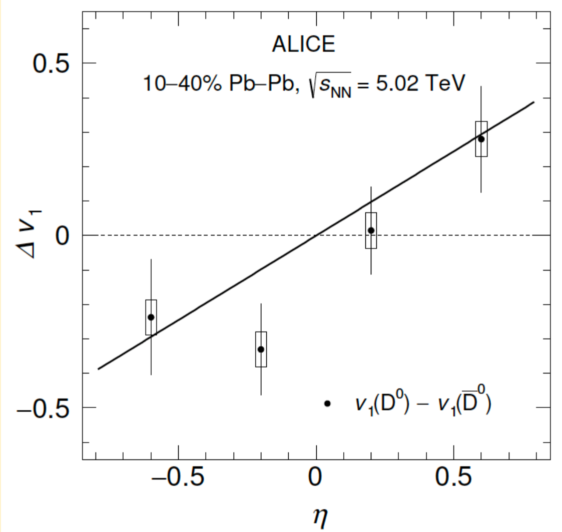




$d(\Delta v_1)/dy$ for D^0 50 times larger RHIC

$d(\Delta v_1)/dy \approx 10^{-4}$ for charged particles

Opposite sign & magnitude

≈ 40 times larger than model predictions

Δv_1 (RHIC) ≈ Δv_1 (LHC)

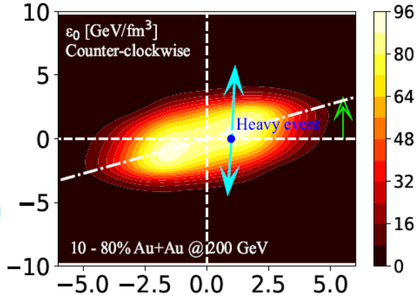
What's going on?

V1 HEAVY FLAVOUR

The heavy quark dynamics is described using a modified Langevin

- Thermal diffusion of heavy quarks inside the QGP
- Medium-induced gluon emission
- Lorentz force due to the electromagnetic field.

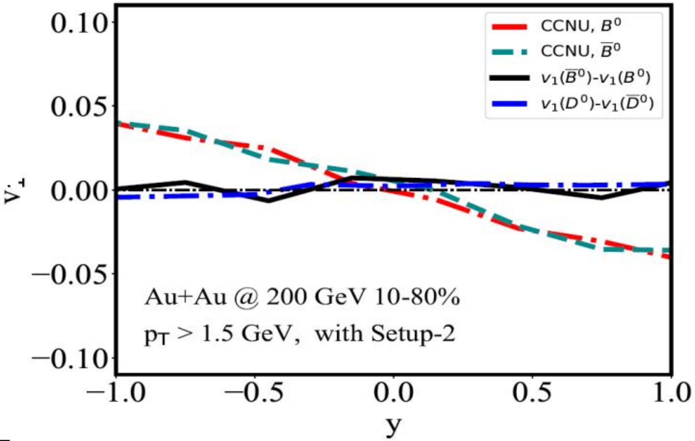
$$\frac{d\vec{p}}{dt} = -\eta_{\mathrm{D}}(\vec{p})\vec{p} + \vec{\xi} + \vec{f}_g + q(\vec{E} + \vec{v} \times \vec{B})$$

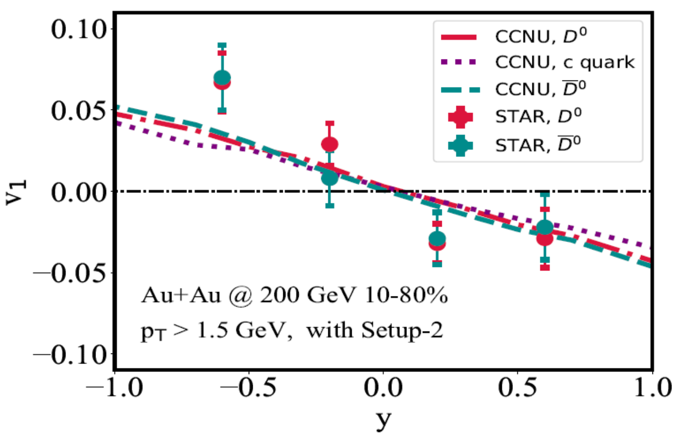


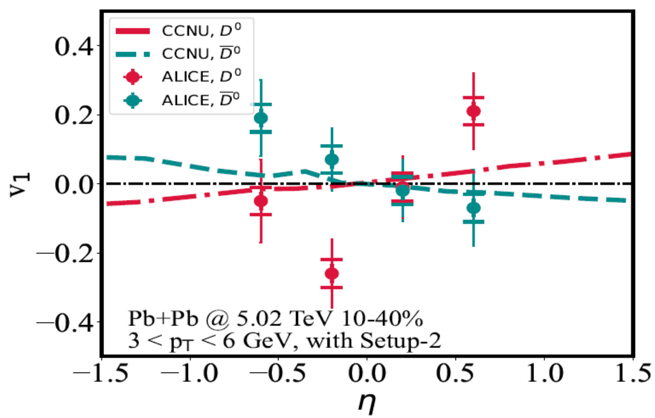
QGP evolution simulated with the (3+1)-D viscous hydrodynamic including the tilted geometry of the initial energy density distribution with respect to the longitudinal direction

Ze-Fang Jiang et al., *Phys.Rev.C* 105 (2022) 5, 054907

B meson v1 splitting smaller than D meson v1 splitting which results from the smaller electric charge







Conclusions

- Estimate of $D_s(T)$ [non –perturbative] from R_{AA} & v_2 successful:

  - v_1 should be added to efforts for $D_s(T)$: more sensitive to high (initial) T

  - Glasma impact: link pA and AA

- Charm ΔV_1 can allow to <u>access the initial strong E-B field and vorticity :</u>

  * splitting in $\Delta v_1(l^+, l^-)$ from Z^0 decay can clarify the e.m. origin of $\Delta v_1(D^0 - \bar{D}^0)$@LHC

  * Bottom can supply info on the evolution of $B_y(t)$ at earlier t≈0.03fm/c