Terzo incontro sulla fisica con ioni pesante alle alte energie

Padova, 25th November 2021

ADVANCES IN HEAVY-FLAVOUR THEORY

Open heavy-flavour dynamics within transport approaches

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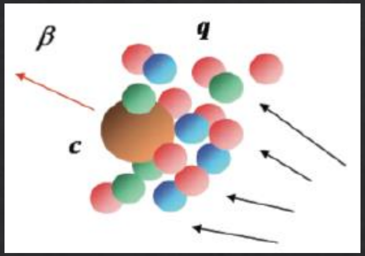
Picture credit: https://www.etnafriends.it/img/notizie/eruzione_etna_20_04_13.jpg

Heavy quarks (HQs)

The Quark-Gluon Plasma (QGP) in relativistic Heavy-Ion Colisions (HICs) is mostly made of light quarks plus few heavy **charm** ($m_c \approx 1.3$ GeV) and **bottom** ($m_b \approx 4.5$ GeV) quarks



- **$m_{HQ} \gg \Lambda_{QCD}$** → HQ produced in pQCD initial hard scatterings
- **$m_{HQ} \gg T_{HICs}$** → negligible thermal production of HQs

HQ production points symmetric in the forward-backward hemispheres

- **$\tau_0^{HQ} < 0.08$ fm/c $\ll \tau_0^{QGP}$** → HQ production much earlier than QGP formation
- **$\tau_{th}^{HQ} \approx \tau^{QGP} \approx$ 5-10 fm/c $\gg \tau_{th}^{QGP}$** → HQ thermalization time comparable to QGP life

HQ final states keep a better memory of both initial stage and QGP evolution

- **$q < m_{HQ}, p_{HQ}$; $m_{HQ} \ll gT_{HICs}$** (*b* or low momentum *c*) → Brownian motion of HQs in QGP

BOLTZMANN (BM) EQ.

$$p^\mu \partial_\mu f_{HQ}(x,p) = \mathcal{C}[f_g, f_q, f_{HQ}]$$

soft-scattering approximation

FOKKER-PLANCK (FP) EQ.

$$\frac{\partial f_{HQ}}{\partial t} = \gamma \frac{\partial (p f_{HQ})}{\partial p} + D_p \frac{\partial^2 f_{HQ}}{\partial p^2}$$

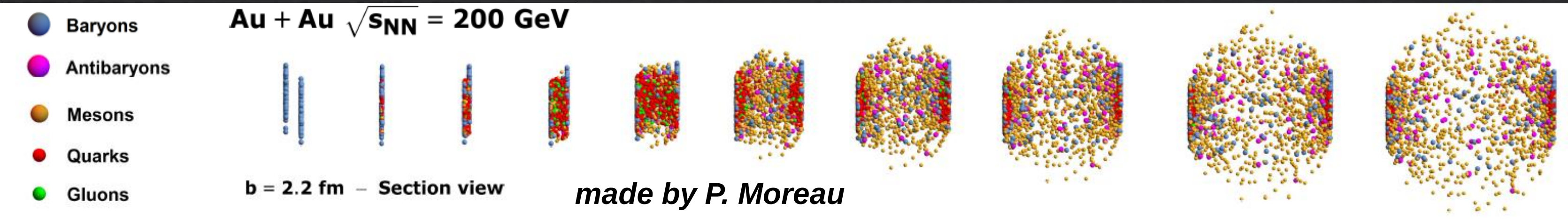
[Catania, PHSD, BAMPS, Nantes, Duke, CCNU-LBNL (LBT), …]

solved through a **LANGEVIN (LV) eq.** [TAMU, Torino (POWLANG), Duke, Nantes, Catania, …]

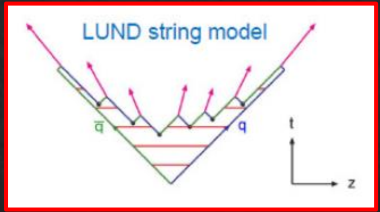
Background: transport [Catania, PHSD, BAMPS, …] or hydro [Nantes, Duke, CCNU-LBNL (LBT),…] expanding bulk

Parton-Hadron-String Dynamics – PHSD

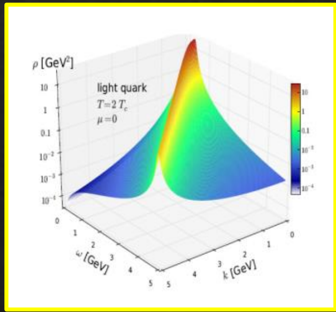
non-equilibrium off-shell transport approach to describe HICs and small systems to study the phase transition from hadronic to partonic matter and the QGP properties from a microscopic origin



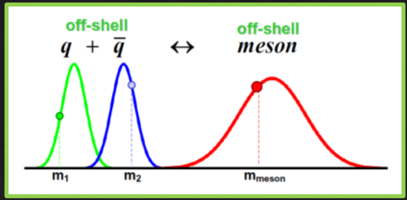
- INITIAL A+A COLLISIONS: nucleon-nucleon collisions lead to the formation of strings that decay to pre-hadrons



- FORMATION OF QGP: if energy density $\varepsilon > \varepsilon_C$ pre-hadrons dissolve in massive off-shell quarks and gluons + mean-field potential



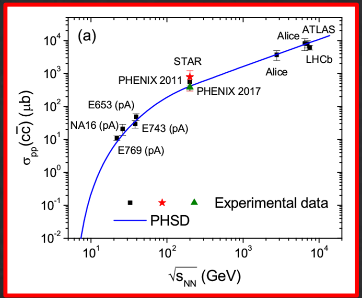
- PARTONIC STAGE: evolution based on off-shell transport equations with the Dynamical Quasi-Particle Model (DQPM) defining parton spectral functions
- HADRONIZATION: massive off-shell partons with broad spectral functions hadronize to off-shell baryons and mesons



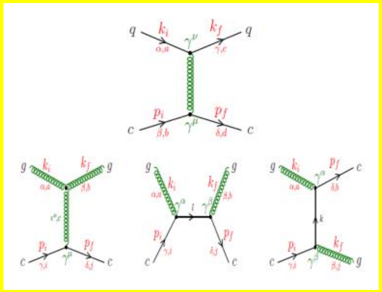
- HADRONIC PHASE: evolution based on the off-shell transport equations with hadron-hadron interactions

Cassing and Bratkovskaya, Phys. Rev. C 78, 034919 (2008); Nucl. Phys. A 831, 215 (2009)

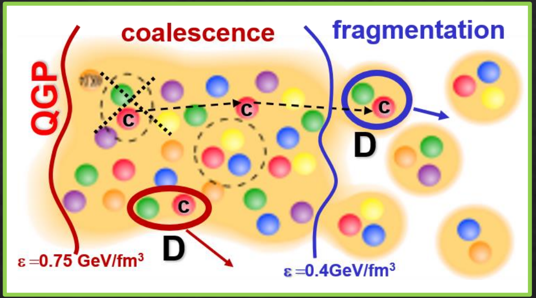
Heavy quark dynamics in PHSD



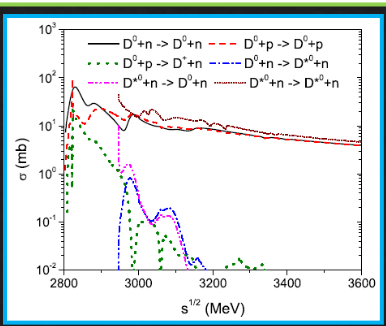
- INITIAL PRODUCTION: heavy quarks produced in initial binary collisions according to FONLL calculations taking into account shadowing and Cronin effects



- PARTONIC STAGE: interaction in the non-perturbative QGP according to DQPM describing the collisional energy loss



- HADRONIZATION: dynamical hadronization scenario of heavy quarks and antiquarks to heavy-flavored hadrons through coalescence and fragmentation



- HADRONIC PHASE: hadronic rescattering of heavy quarks based on G-matrix and effective chiral Lagrangian approaches

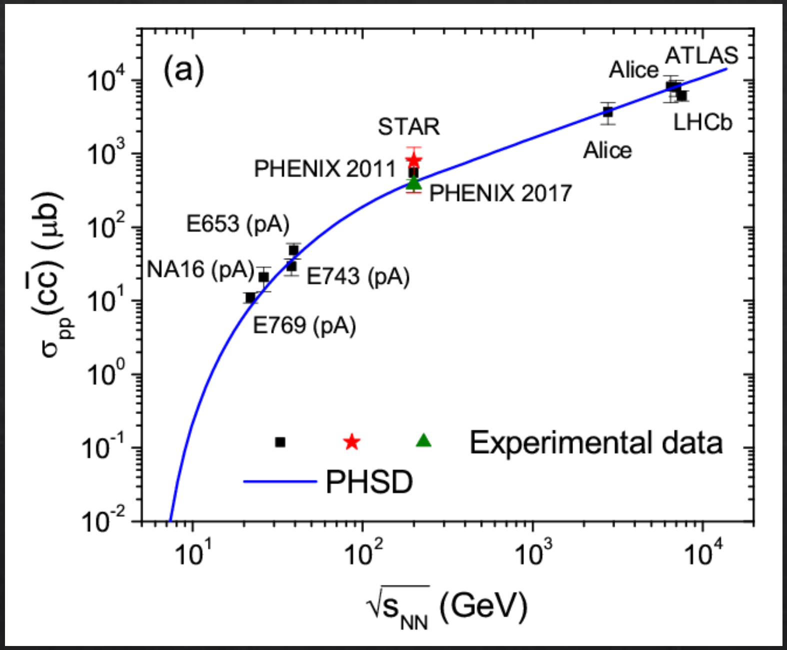
Berrehrah et al, Phys. Rev. C 89, 054901 (2014); Phys. Rev. C 90, 051901 (2014); Phys. Rev. C 90, 064906 (2014).
Song et al., Phys. Rev. C 92, 014910 (2015); Phys. Rev. C 93, 034906 (2016); Phys. Rev. C 96, 014905 (2017); Phys. Rev. C 97, 064907 (2018); Phys. Rev. C 101, 044901 (2020); Phys. Rev. C 101, 044903 (2020).

Initial production of HQs

In PHSD charm quark-antiquark pairs are produced through initial hard nucleon-nucleon scattering according to the probability $P = \sigma(c\bar{c})/\sigma_{NN}^{inel}$ with energy-momenta given by PYTHIA event generator tuned to reproduce the FONLL (fixed-order next-to-leading log) results at RHIC and LHC energies

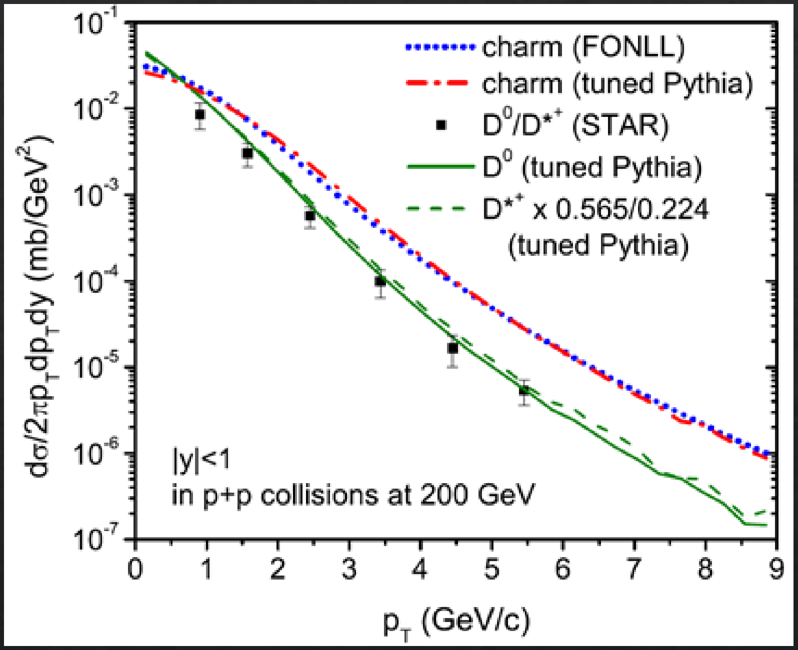
Cacciari, Nason and Vogt, Phys. Rev. Lett. 95, 122001 (2005)

CHARM PRODUCTION CROSS SECTION



Song et al., Phys. Rev. C 97, 064907 (2018)

CHARM MOMENTUM DISTRIBUTION



Song et al., Phys. Rev. C 92, 014910 (2015)

+ Cold Nuclear Matter (CNM) modifications: **SHADOWING** and **CRONIN** effects

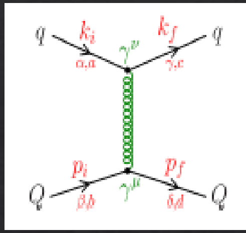
Song et al., Phys. Rev. C 93, 034906 (2016);
Phys. Rev. C 96, 014905 (2017)

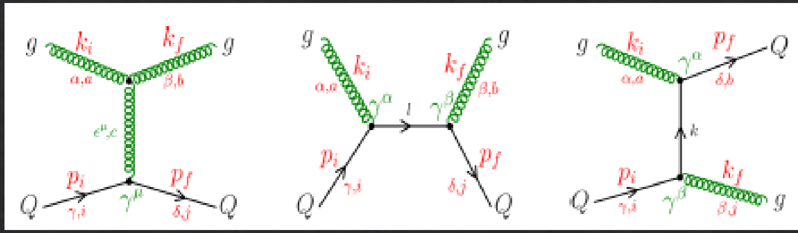
$$\sigma_{c\bar{c}}^{N^*N^*}(s) = \sum_{i,j} \int dx_1 dx_2 R_i^A(x_1, Q) R_j^A(x_2, Q) \times f_i^N(x_1, Q) f_j^N(x_2, Q) \sigma_{c\bar{c}}^{ij}(x_1 x_2 s, Q)$$

Scattering of HQs in the QGP

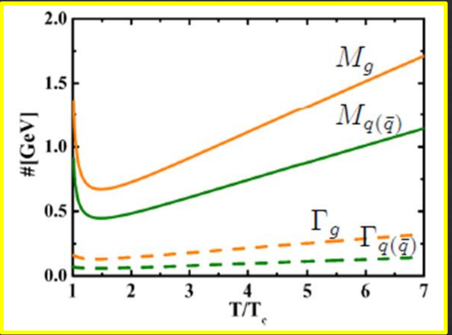
In PHSD the HQ interaction with non-perturbative QGP is described by elastic scatterings with off-shell massive partons according to DQPM

$Q + q \rightarrow Q + q$ $\qquad$ $Q + g \rightarrow Q + g$





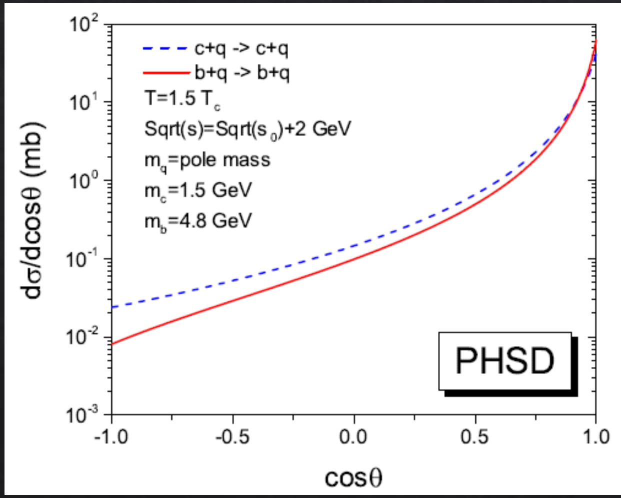
COLLISIONAL ENERGY LOSS



Berrehrah et al, PRC 89, 054901 (2014); PRC 90, 051901 (2014); PRC 90, 064906 (2014)

$m_{q,g} = m_{q,g}(T)$
fit to lQCD

ELASTIC CROSS SECTION

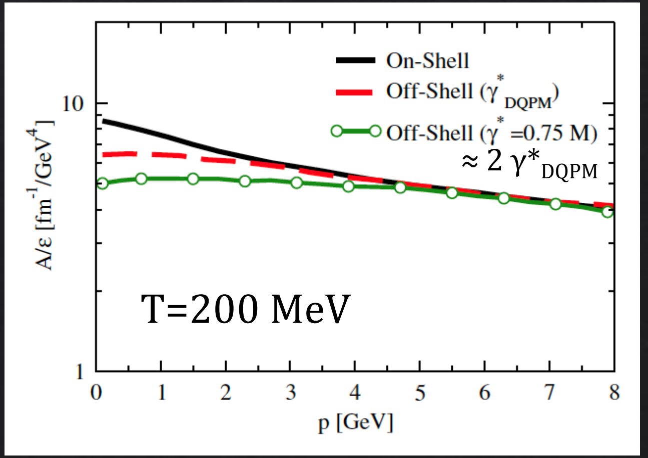


Song et al., Phys. Rev. C 96, 014905 (2017)

Non perturbative dynamics
cross sections in Quasi-Particle Model (QPM) are less forward peaked than pQCD ones leading to more efficient momentum transfer

Off-shell dynamics
breaking of drag coefficient scaling with energy density in the low *p* region leads to 30-40% decreasing

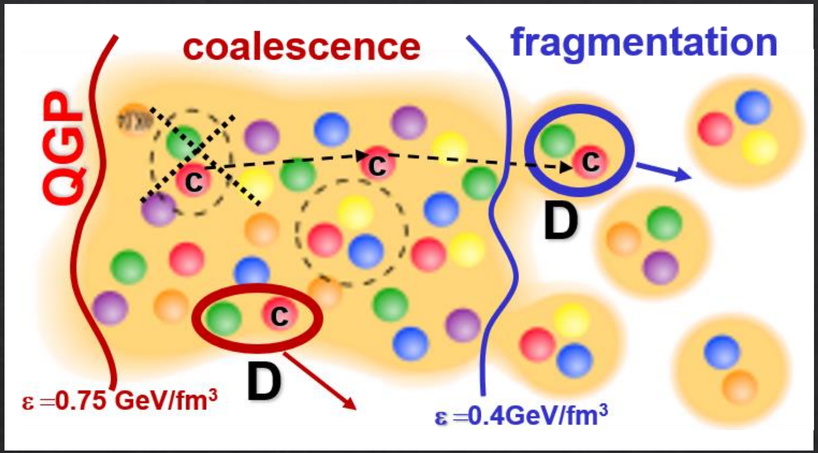
DRAG OVER ENERGY DENSITY



RADIATIVE ENERGY LOSS
not implemented yet in PHSD
included in BAMPS, Nantes, Duke, CCNU-LBLN

Sambataro et al., Eur. Phys. J C 80, 1140(2020)

Hadronization of HQs in A+A



If the local energy density goes below the critical value heavy quarks and antiquarks hadronized to heavy-flavour hadrons

Dynamical hadronization scenario for HQs

COALESCENCE $0.4 < \varepsilon < 0.75$ GeV/fm^3

+

FRAGMENTATION $\varepsilon < 0.4$ GeV/fm^3

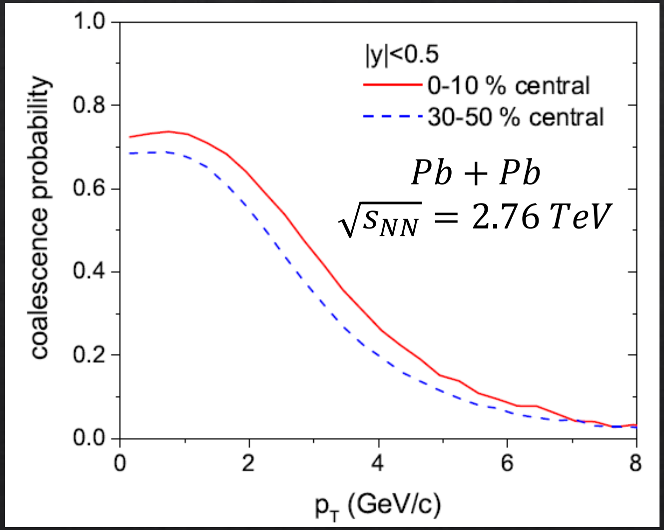
Coalescence probability

$$f(\boldsymbol{\rho}, \mathbf{k}_\rho) = \frac{8 g_M}{6^2} \exp\left[-\frac{\boldsymbol{\rho}^2}{\delta^2} - \mathbf{k}_\rho^2 \delta^2\right]$$

$\langle r \rangle$=0.9 fm

$$\boldsymbol{\rho} = \frac{1}{\sqrt{2}}(\mathbf{r}_1 - \mathbf{r}_2) \qquad \mathbf{k}_\rho = \sqrt{2}\,\frac{m_2 \mathbf{k}_1 - m_1 \mathbf{k}_2}{m_1 + m_2} \qquad \langle r^2 \rangle = \frac{3}{2}\frac{m_1^2 + m_2^2}{(m_1 + m_2)^2}\delta^2$$

Song et al., Phys. Rev. C 92, 014910 (2015)



Song et al., Phys. Rev. C 93, 034906 (2016)

The HQ that does not succeed to hadronize by coalescence then fragments as in p+p collisions according to the fragmentation function

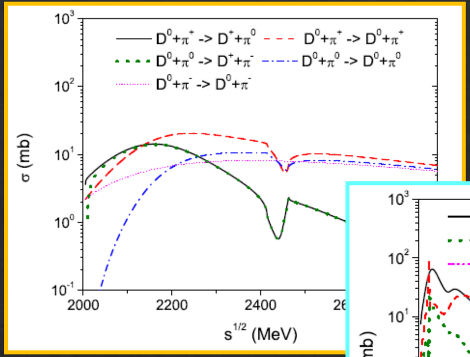
$$D_Q^H(z) \sim \frac{1}{z[1 - 1/z - \epsilon_Q/(1-z)]^2}$$

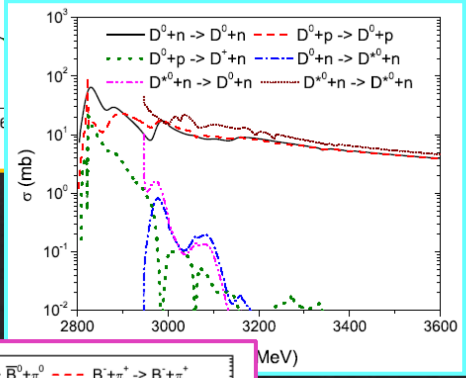
Peterson, Schlatter, Schmitt and Zerwas, Phys. Rev. D 27, 105 (1983)

ϵ_Q = 0.01 (0.004) for c (b)

Rescattering of heavy-flavour hadrons

The *D* and *D** mesons produced through coalescence or fragmentation interact with the surrounding hadrons in PHSD





D-meson scattering with mesons

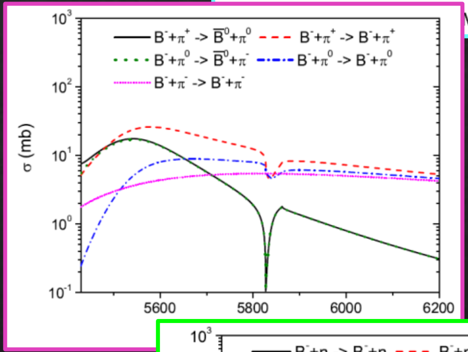
based on effective chiral Lagrangian approach:
interaction of $D=(D^0,D^+,D^+_s)$ and $D^*=(D^{*0},D^{*+},D^{*+}_s)$ with the octet $(\pi, K, \overline{K}, \eta)$

Abreu, Cabrera, Llanes-Estrada and Torres-Rincon, Annals Phys. 326, 2737 (2011)

D-meson scattering with baryons

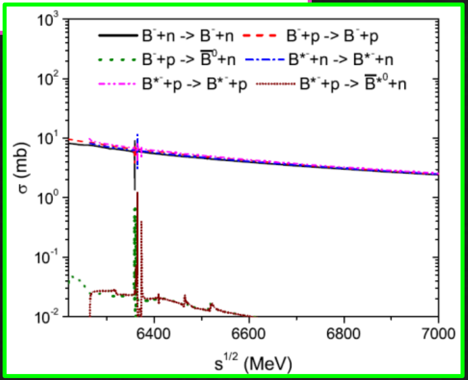
based on G-matrix approach:
interactions of $D=(D^0,D^+,D^+_s)$ and $D^*=(D^{*0},D^{*+},D^{*+}_s)$ with nucleon octet and Delta decuplet

Garcia-Recio, Nieves, Romanets, Salcedo and Tolos, Phys. Rev. D 87, 074034 (2013)



Similarly for **B-meson scattering with mesons** and **B-meson scattering with baryons**

Tolos and Torres-Rincon, Phys. Rev. D 88, 074019 (2013)
Torres-Rincon, Tolos and Romanets, Phys. Rev. D 89, 074042 (2014)



More than 200 hadronic channels implemented in PHSD

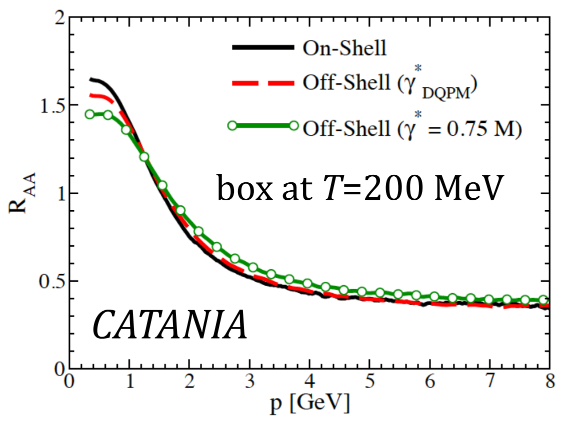
Song et al., Phys. Rev. C 92, 014910 (2015); Phys. Rev. C 96, 014905 (2017)

Some highlights on HF observables

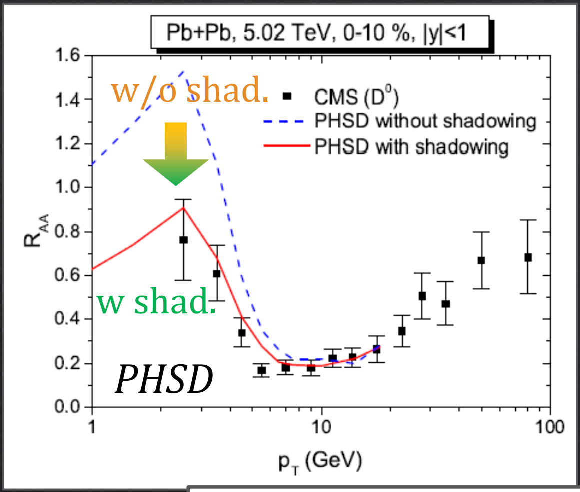
NUCLEAR MODIFICATION FACTOR

$$R_{AA}(p_T) \equiv \frac{dN_{AA}/dp_T}{N^{AA}_{binary} \times dN_{pp}/dp_T}$$

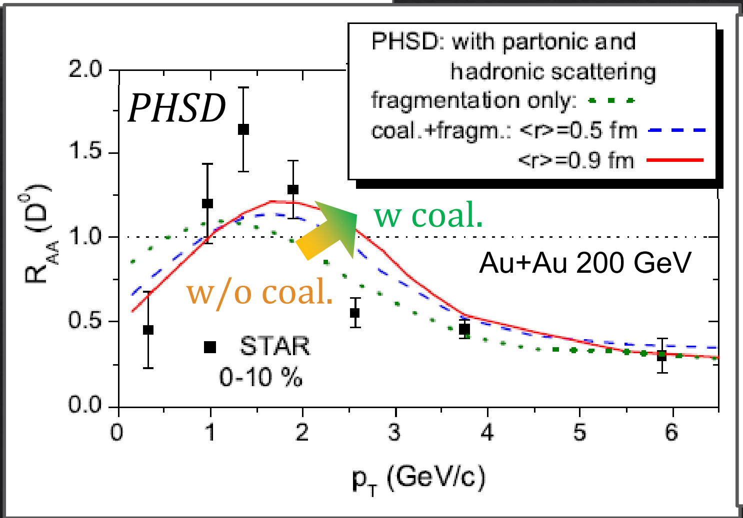
Sambataro et al., EPJ C 80, 1140(2020)

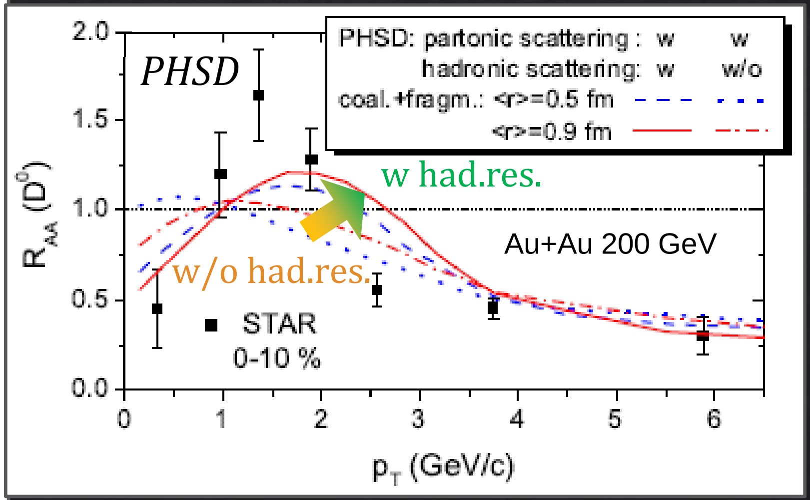


Song et al., PRC 97, 064907 (2018)



- Shadowing effect suppresses R_{AA} at low p_T
- Off-shell effect slightly descreases R_{AA} at low p_T
- Coalescence and hadronic rescattering shift R_{AA} to larger p_T
- The energy loss of D-mesons at high p_T can be dominantly attributed to partonic scattering





Song et al., PRC 92, 014910 (2015)

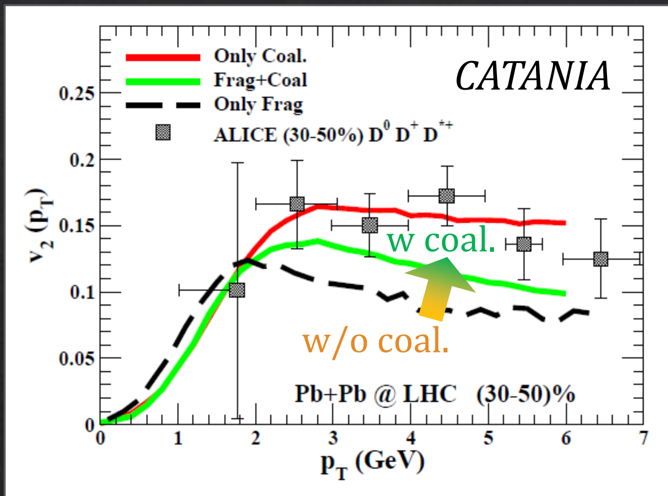
Some highlights on HF observables

ELLIPTIC FLOW

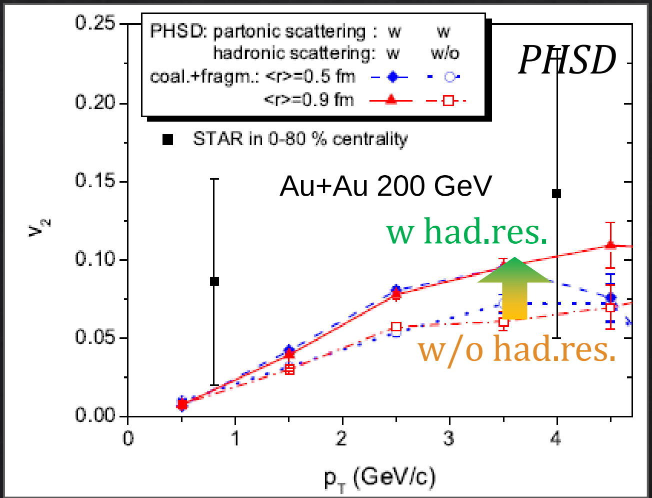
$$v_2(\mathrm{p_T}) \equiv \frac{\int d\phi \cos 2\phi (dN_{\mathrm{AA}}/d\mathrm{p_T} d\phi)}{2\pi dN_{\mathrm{AA}}/d\mathrm{p_T}}$$

- Coalescence and hadronic rescattering substantially increases v_2 at larger p_T
- About 60-80% of D-meson v_2 comes from the HQ diffusion within the QGP (HQ-bulk interaction)

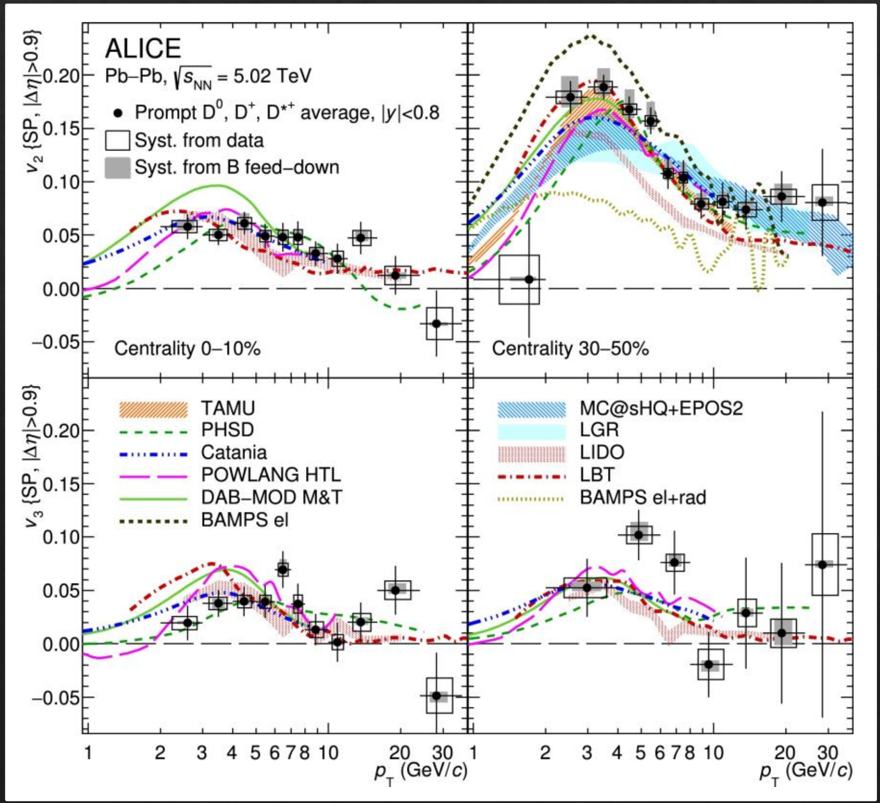
Das, Scardina, Plumari and Greco, Phys Lett. B 747, 260 (2015)



Scardina et al., Phys. Rev. C 96, 044905 (2017)



Song et al., Phys. Rev. C 92, 014910 (2015)



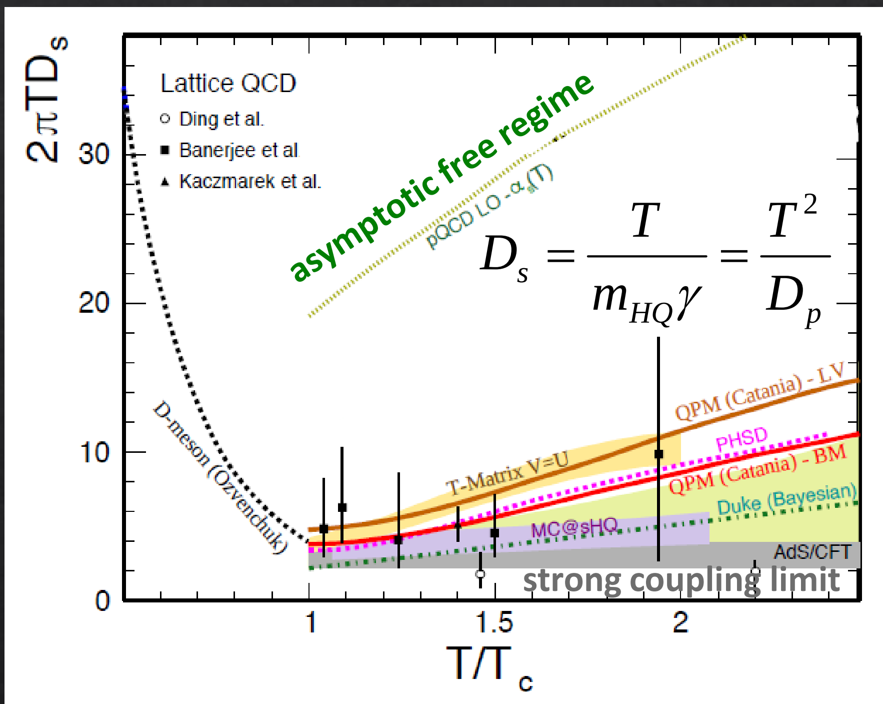
ALICE Collaboration, Phys. Lett. B 813, 136054 (2021)

HQ spatial diffusion coefficient

$R_{AA}(p_T)$ and $v_2(p_T)$ of D meson have been the main observables for determining the **transport properties of HQs in hot QCD matter**: **DRAG** and **DIFFUSION** coefficients

$$\frac{\partial f_{c,b}}{\partial t} = \gamma \frac{\partial (p f_{c,b})}{\partial p} + D_p \frac{\partial^2 f_{c,b}}{\partial p^2}$$

Greco, PoS HardProbes2020, 018 (2020)



CHARM-QUARK SPATIAL DIFFUSION COEFFICIENT

QGP diffuses charm quarks like an almost perfect fluid with a very low $2\pi TD_s$

$$2\pi T D_s \approx 2-5 \quad \text{at } T \sim T_c$$

HQ interaction in QGP largely NON-PERTURBATIVE

The sources of uncertainties in the D_s determination may be clarified through

- access to low p_T and precision data
- more exclusive observables
- better insight into hadronization
- predictions and measurements for B mesons

reviews

Prino and Rapp, J. Phys. G 43, 093002 (2019)
Dong and Greco, Prog. Part. Nucl. Phys. 104, 97 (2019)

Intense fields and heavy flavor transport

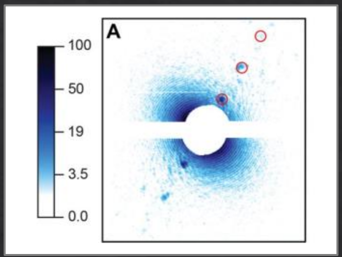
✓ HUGE ANGULAR MOMENTUM GENERATING A STRONG **VORTICITY**

tornado cores

$\sim 10^{-1}\ s^{-1}$

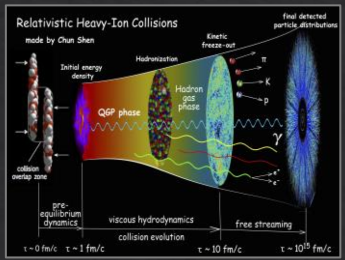
Jupiter's spot

$\sim 10^{-4}\ s^{-1}$



He nanodroplets

$\sim 10^{7}\ s^{-1}$



urHICs

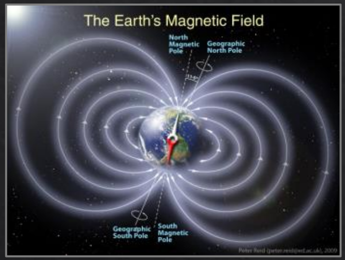
$\sim \mathbf{10^{22}\text{–}10^{23}}\ \boldsymbol{s^{-1}}$

since 2017

impact on HQ transport coefficients and D meson directed flow

vorticity ω

✓ INTENSE **ELECTROMAGNETIC FIELDS**



Earth's field

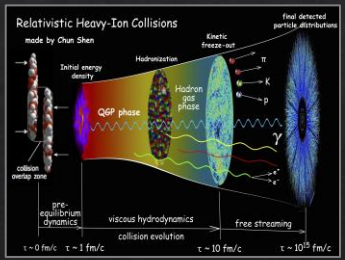
~ 1 G

laboratory

$\sim 10^{6}$ G

magnetars

$\sim 10^{14}\text{–}10^{15}$ G



urHICs

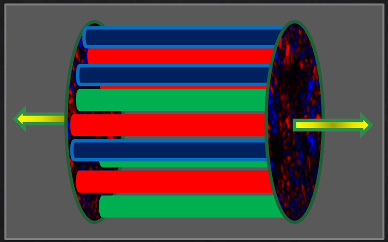
$\sim \mathbf{10^{18}\text{–}10^{19}}$ **G**

since 2016

impact on D meson directed flow

magnetic field B

✓ INTENSE **COLOR FIELDS** IN THE EARLY STAGE OF URHICS



since 2018

impact on HQ transport coefficients and D meson R_{AA} and v_2

The vortical quark-gluon plasma

Huge **orbital angular momentum** of the colliding system up to **J ≈ 10^5 - 10^6 ħ**

- ➢ dominated by the y component
- ➢ partly transferred to the plasma

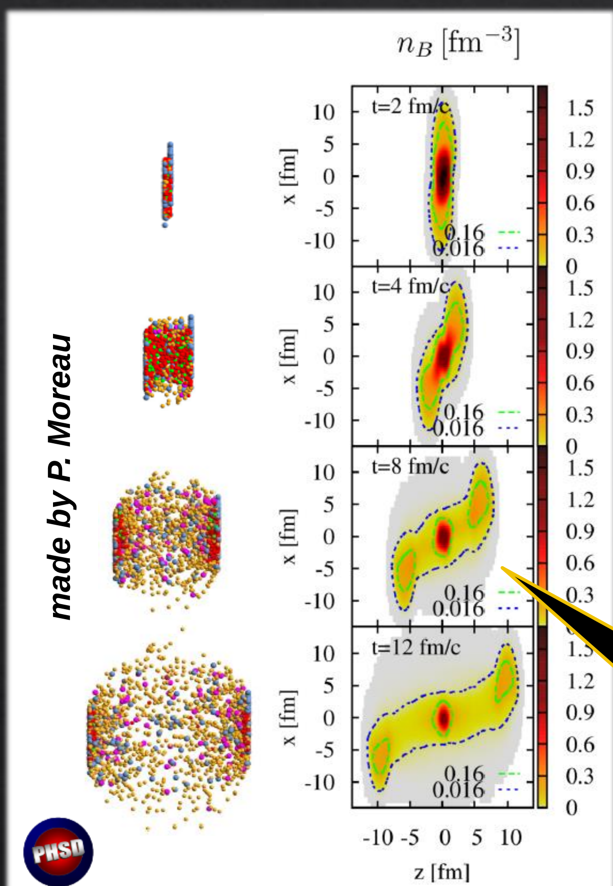
→ asymmetry in local participant density from forward and backward going nuclei

Bozek and Wyskiel, Phys. Rev. C 81, 054902 (2010)

$$\rho(x_\perp,\eta_s) = \rho_0 \frac{W(x_\perp,\eta_s)}{W(0,0)} \exp\left[-\frac{(|\eta_s|-\eta_{s0})^2}{2\sigma_\eta^2}\theta(|\eta_s|-\eta_{s0})\right]$$

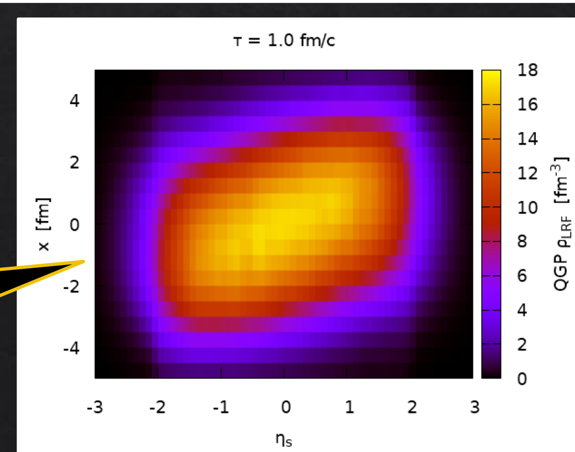
$$W(x_\perp,\eta_s) = 2\left(N_A(x_\perp)f_-(\eta_s) + N_B(x_\perp)f_+(\eta_s)\right)$$

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



Not a symmetric energy distribution…

tilted fireball on the reaction plane



Cassing and Bratkovskaya, Nucl. Phys. A 831, 215 (2009)

Kolomeitsev, Toneev and Voronyuk, Phys. Rev. C 97, 064902 (2018)

Oliva, Plumari and Greco, JHEP 05, 034 (2021)

The vortical quark-gluon plasma

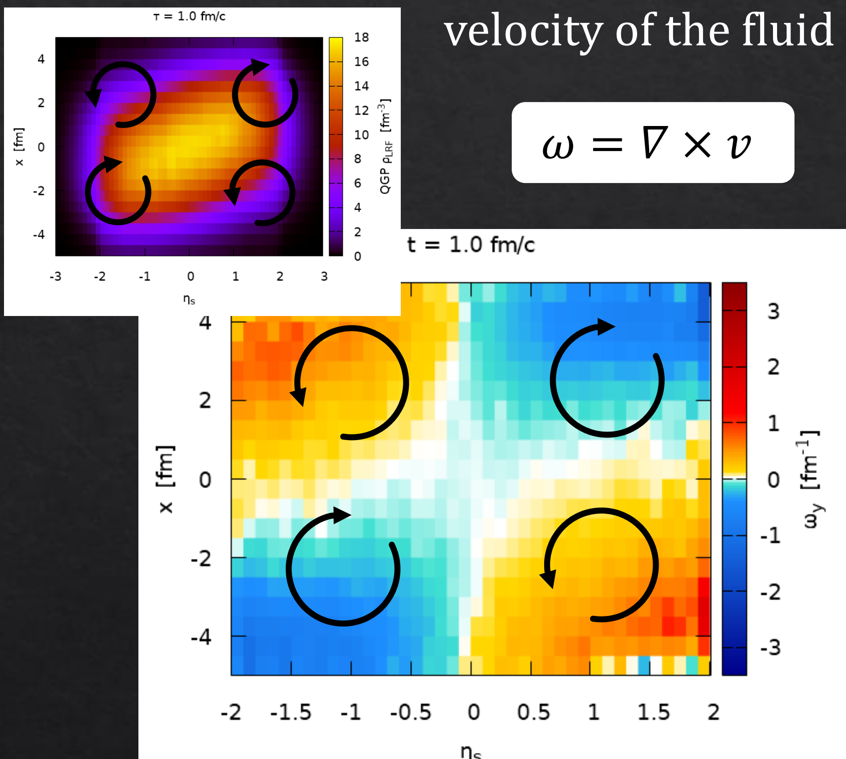
Oliva, Plumari and Greco, JHEP 05, 034 (2021)

The huge angular momentum and the tilt of the fireball induce in the QGP

an intense <u>VORTICITY</u>

measure of the local angular velocity of the fluid

$$\omega = \nabla \times v$$



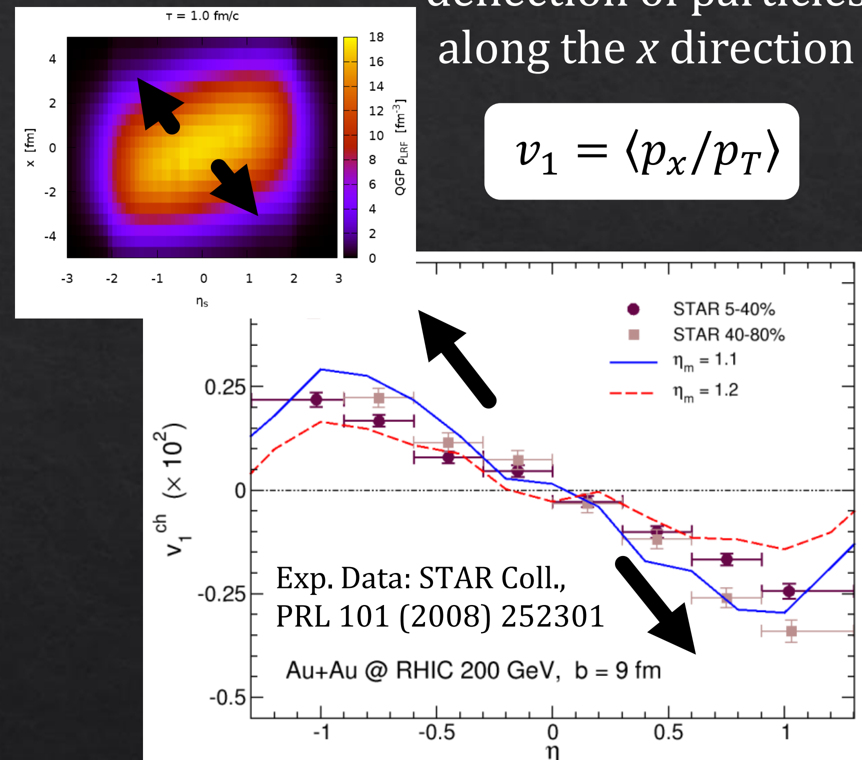
NONRELATIVISTIC VORTICITY

QGP as the most vortical fluid: $\omega_y \approx 3$ c/fm in agreement with the ongoing research on Λ hyperon polarization

a <u>DIRECTED FLOW</u>

collective sidewards deflection of particles along the *x* direction

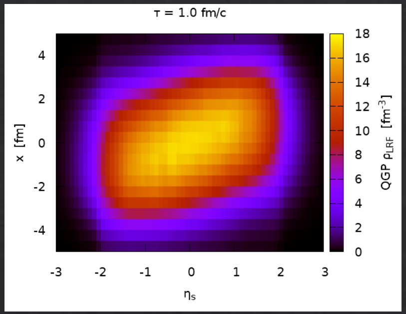
$$v_1 = \langle p_x / p_T \rangle$$



CHARGED PARTICLES DIRECTED FLOW

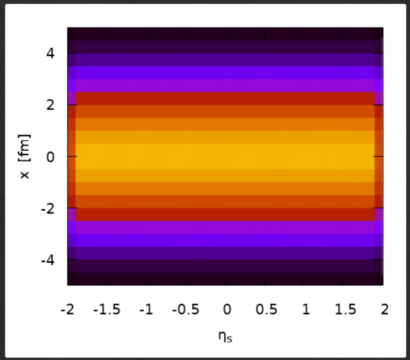
Negative slope in the η dependence of the v_1 of bulk particles due to the "tilt" ($v_1 = 0$ if the fireball is not tilted)

Directed flow of neutral D mesons



Do the initial tilt of the fireball and the directed flow of bulk medium affect <u>HEAVY QUARKS</u>?

production points symmetric in the forward-backward hemispheres

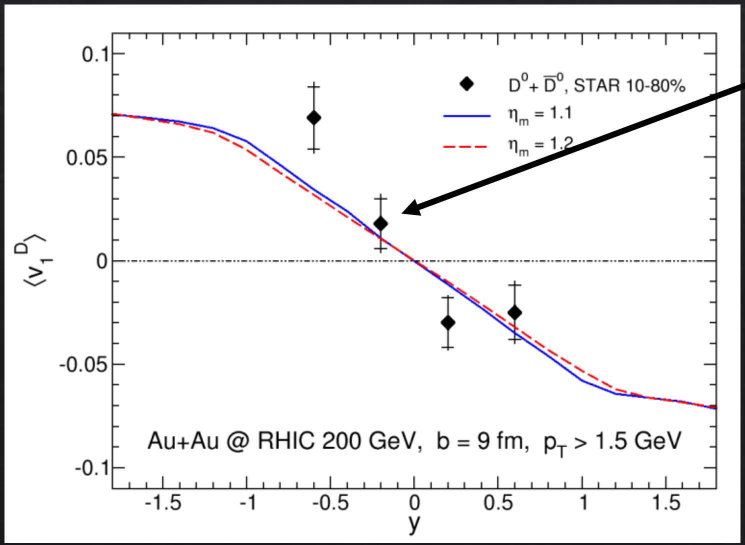


Excellent qualitative prediction with LV approach

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

Chatterjee and Bozek, Phys. Rev. Lett. 120, 192301 (2018)

DIRECTED FLOW OF NEUTRAL D MESONS



Oliva, Plumari and Greco, JHEP 05, 034 (2021)

First exp. measurement from STAR

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

The directed flow of neutral D mesons is about 30 times larger than that of kaons

STAR Collaboration, Phys. Rev. Lett. 123, 162301 (2019)

CATANIA APPROACH

relativistic BM equations for both QGP and HQs

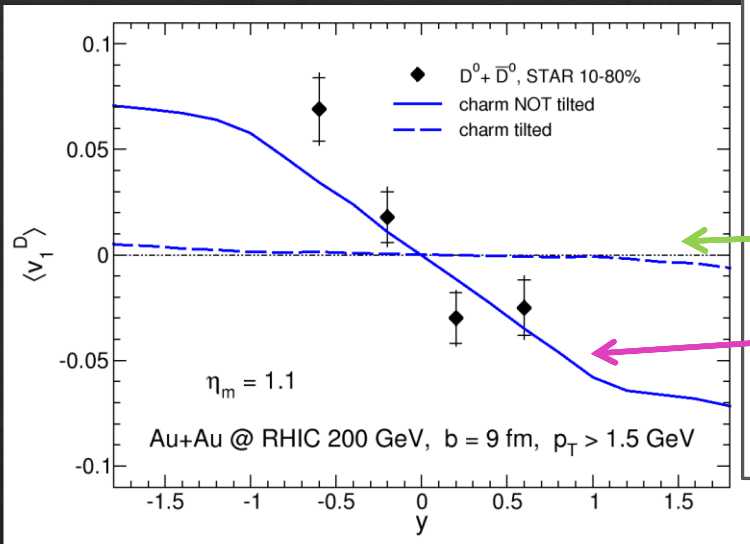
$dv_1^D/dy = -\,0.065$ (25-30 times larger than charged)

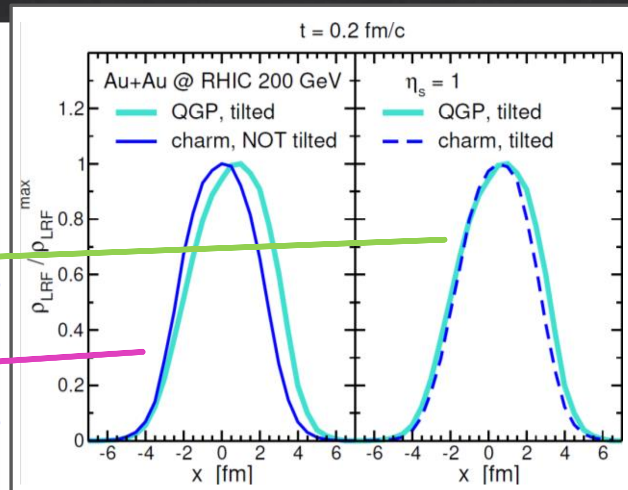
v_1 (HQs) $\gg$ v_1 (QGP)

origin of the large directed flow of HQs different from the one of light particles

Origin of D meson directed flow

Oliva, Plumari and Greco, JHEP 05, 034 (2021)

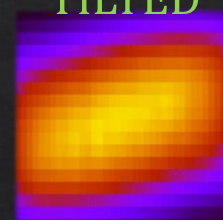




longitudinal asymmetry leads to pressure push of the bulk on the HQs

CHARM **NOT** TILTED

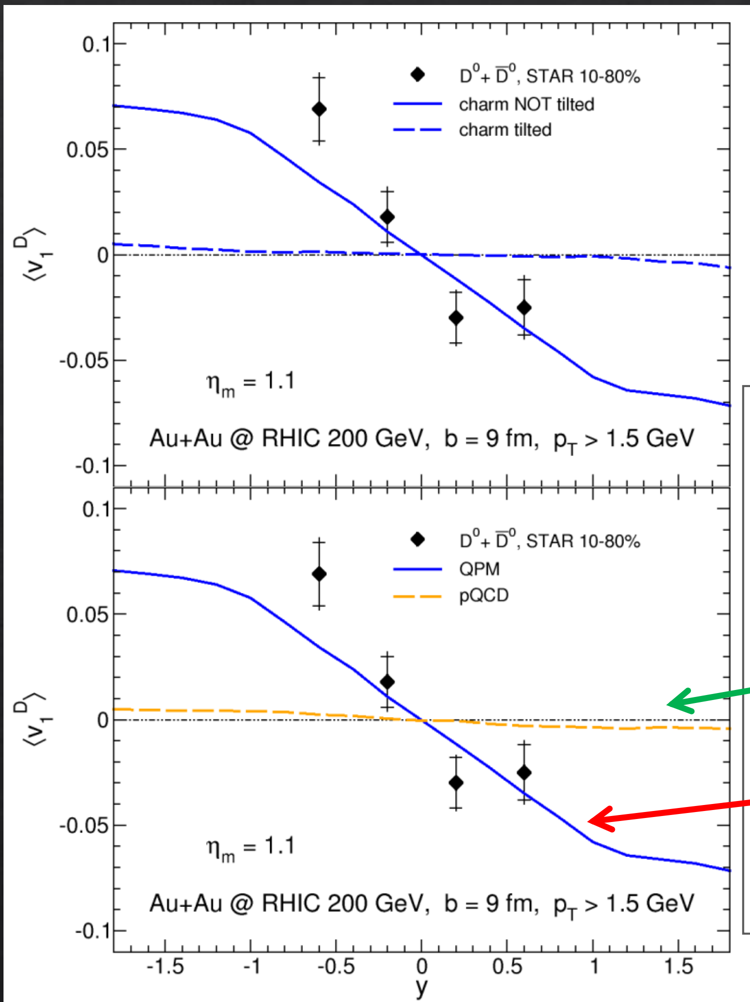
CHARM TILTED



QGP tilted in both cases

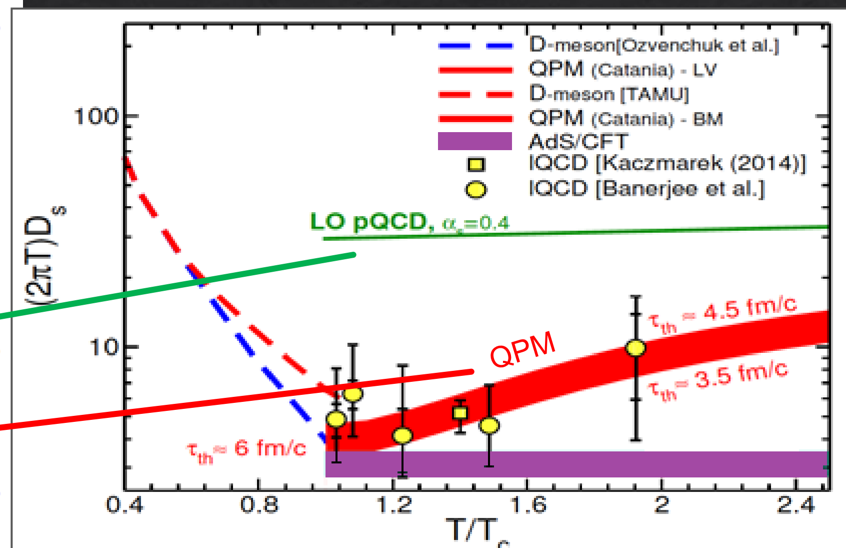
Origin of D meson directed flow

Oliva, Plumari and Greco, JHEP 05, 034 (2021)



longitudinal asymmetry leads to pressure push of the bulk on the HQs

effective because the HQ interaction in QGP is largely non-perturbative



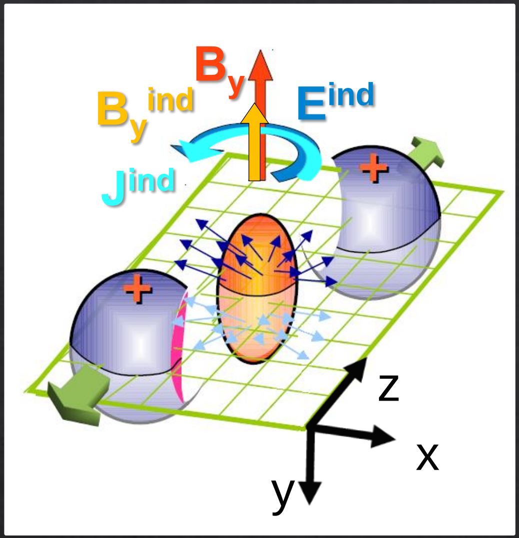
Greco, NPA 967, 200 (2017)

Similar conclusions with POWLANG approach

Beraudo, De Pace, Monteno, Nardi and Prino, JHEP 05, 279 (2021)

strict connection between the magnitude of the D-meson v_1 and the HQ diffusion coefficient

Electromagnetic (EM) fields in HICs



Huge **magnetic field** in the overlap area up to **eB ≈ 5-50 m_π^2**

- dominated by the y component
- mainly produced by spectators protons
- intense electric field generated by Faraday induction
- charged currents induced in the conducting QGP generates a magnetic field pointing towards the initial one

induced current from Ohm's law

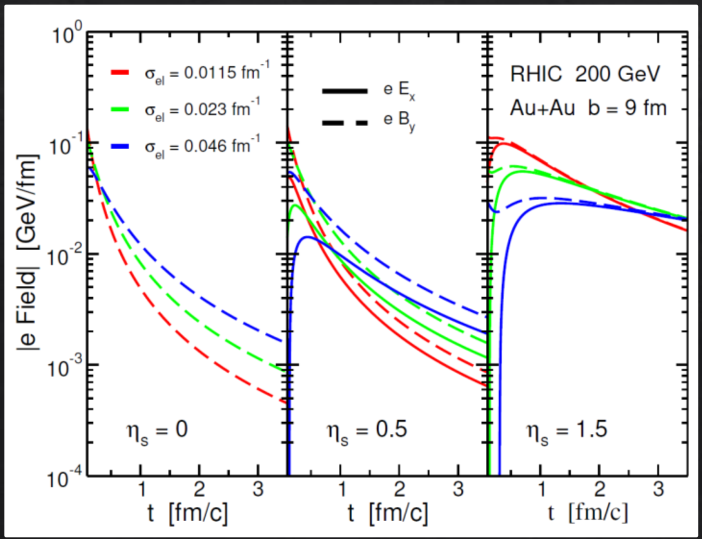
$$J_{ind} = \sigma_{el} E$$

external charge and current produced by a point-like charge in longitudinal motion

$$\rho = \rho_{ext} \qquad J = J_{ext} + J_{ind}$$

$$\rho_{ext} = e\delta(z - \beta t)\delta(x_\perp - x'_\perp)$$

$$J_{ext} = \hat{z}\beta e\delta(z - \beta t)\delta(x_\perp - x'_\perp)$$



Oliva, Plumari and Greco, JHEP (2021), 2009.11066

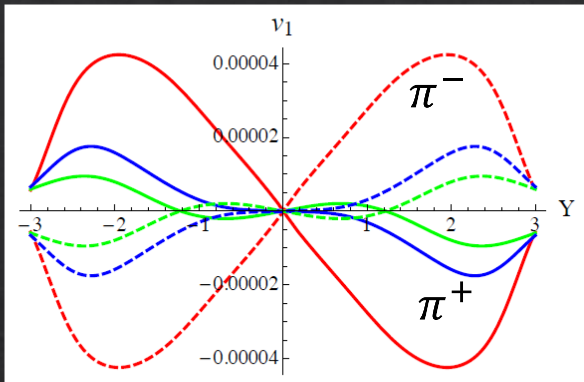
Maxwell equations can be solved analytically for a medium with **constant electric conductivity**

Tuchin, Adv. High Energy Phys. 2013, 1 (2013)
Gursoy, Kharzeev, Rajagopal, Phys. Rev. C 89, 054905 (2014)

$$p^\mu \partial_\mu f(x,p) + qF^{\mu\nu}_{ext} p_\nu \partial^p_\mu f(x,p) = \mathcal{C}[f]$$

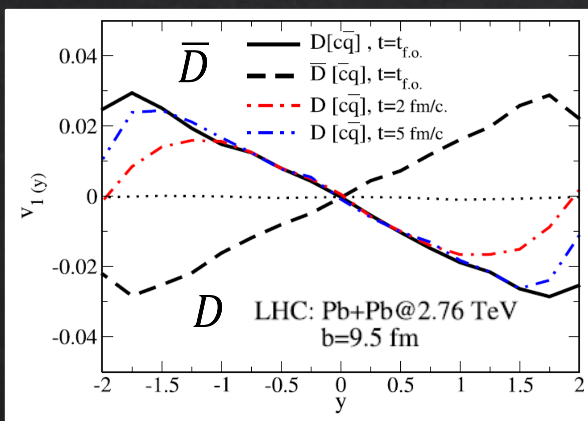
BM eq. with EM interaction term

EM fields and directed flow splitting



The huge EM fields induce a splitting in the DIRECTED FLOW of particles with the same mass and opposite charge

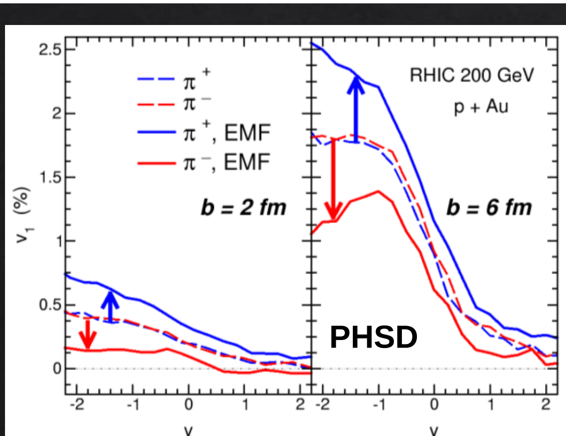
- difference in the v_1 of light hadrons in AA: $O(10^{-4}–10^{-3})$
  Gursoy, Kharzeev and Rajagopal, Phys. Rev. C 89, 054905 (2014)
  Toneev, Voronyuk, Kolomeitsev and Cassing,
  Phys. Rev. C 95, 034911 (2017)



- difference in the v_1 of heavy mesons in AA: $O(10^{-2})$
  Das, Plumari, Chatterjee, Alam, Scardina and Greco,
  Phys. Lett. B 768, 260 (2017)
  Chatterjee and Bozek, Phys. Lett. B 798, 134955 (2019)

Δv_1 (HQ) ≫ Δv_1 (QGP)

charm quarks are more sensitive to the EM fields due to the early production



- difference in the v_1 of light mesons in pA: $O(10^{-2})$
  Oliva, Moreau, Voronyuk and Bratkovskaya,
  Phys. Rev. C 101, 014917 (2020)

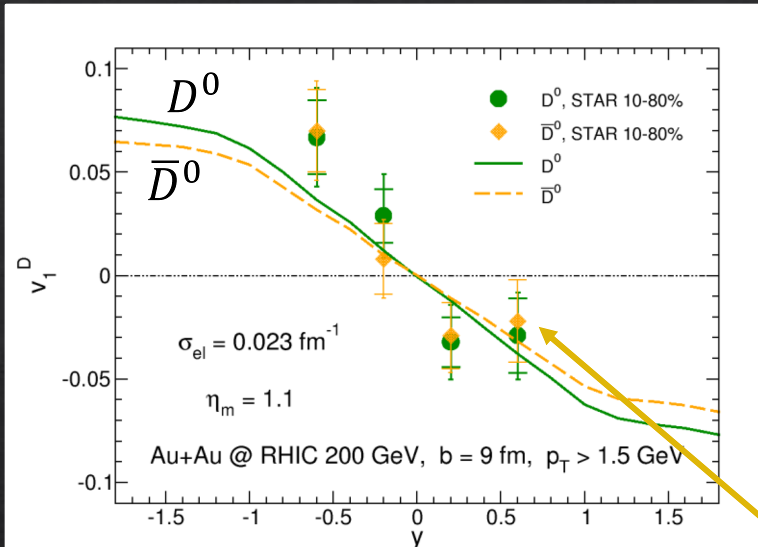
reviews

Oliva, Eur. Phys. J. A 56, 255 (2020)
Dubla, Gursoy and Snellings,
Mod. Phys. Lett. A 35, 2050324 (2020)

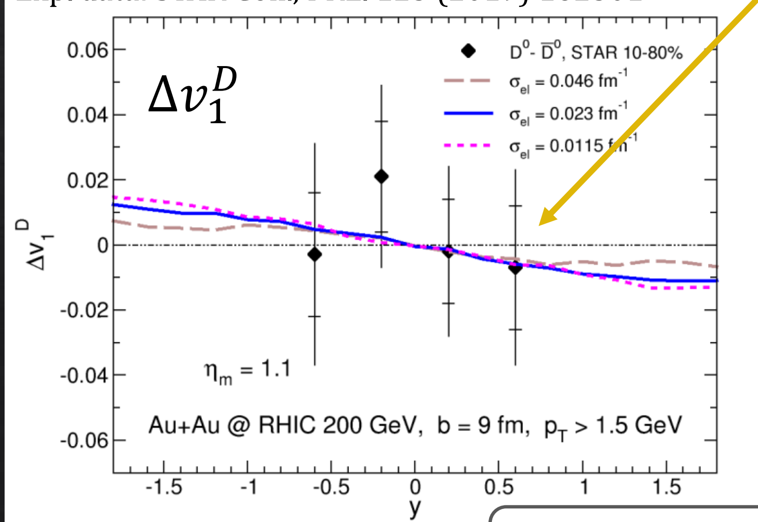
Directed flow in A+A at RHIC energy

Oliva, Plumari and Greco, JHEP 05, 034 (2021)

The electromagnetic fields induce a large splitting in the directed flow of HEAVY QUARKS



Exp. data: STAR Coll., PRL. 123 (2019) 162301



DIRECTED FLOW OF NEUTRAL D MESONS

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

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

$d(\Delta v_1)/dy|_{th}$ = – 0.01

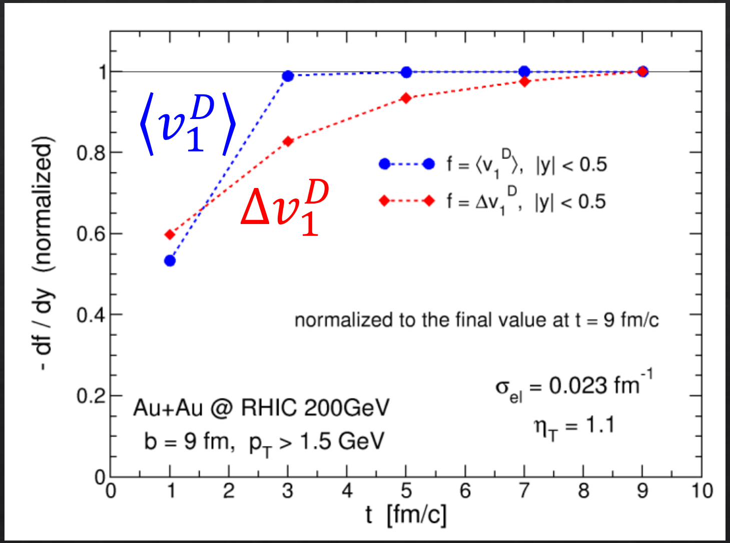
≈ 10 times larger than charged,

in agreement with Das et al., Phys. Lett. B 768, 260 (2017)

BUT

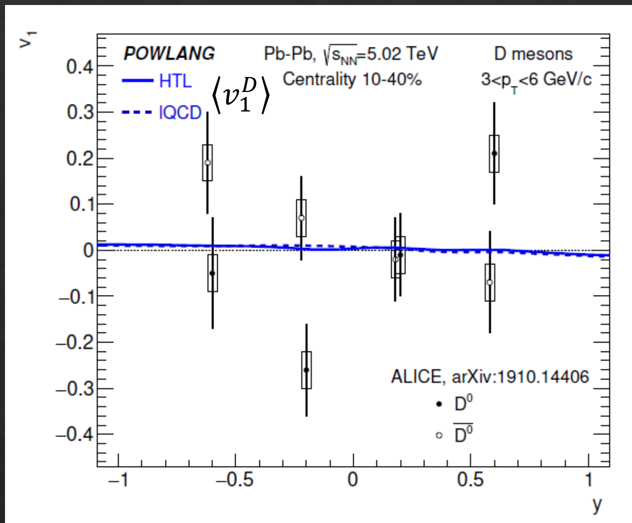
exp. Δv_1^D still consistent with zero due to the large errors

SLOPE TIME EVOLUTION



v_1^D more sensitive to the early QGP evolution when T is higher, while v_2^D probes more $T \sim T_c$
→ include v_1^D in Bayesian fits

Directed flow in A+A at LHC energy



Beraudo et al., JHEP 05, 279 (2021)

ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)

ALICE exp. measurements:

- the slope of $\langle v_1^D \rangle$ is ~ 50 times smaller than that at RHIC (in line with model predictions) and is consistent with 0
- the $\Delta v_1{}^D$ has opposite sign and magnitude ~ 40 times larger than model predictions (Δv_1^D(LHC) ≈ Δv_1^D(RHIC))

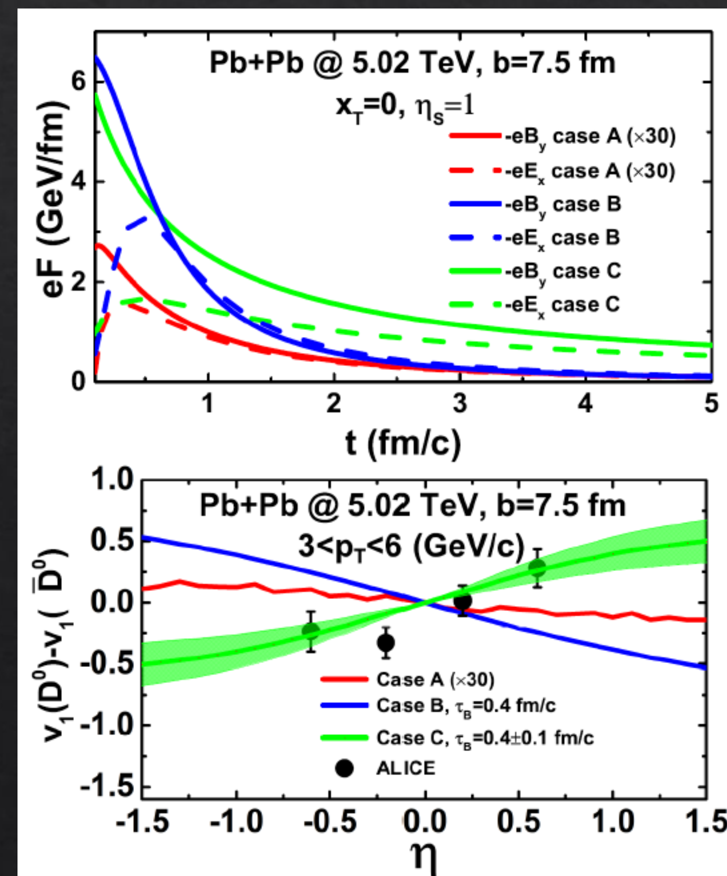
Sun, Plumari and Greco, Phys. Lett. B 816, 136271 (2021)

❖ Analytic solution of EM fields with constant σ_{el} case A

❖ Magnetic field parametrization between in-vacuum and in-medium decay: $B(\tau) = B_0/[1+(\tau/\tau_B)^n]$

case B n=2 case C n=1

Electric field from Faraday law



case C reproduces the ALICE data for the Δv_1 (D^0,$\overline{D}^0$) but it is really a slow time decay of B

if the Δv_1 of neutral D mesons is confirmed to be of electromagnetic origin it is a proof of QGP formation

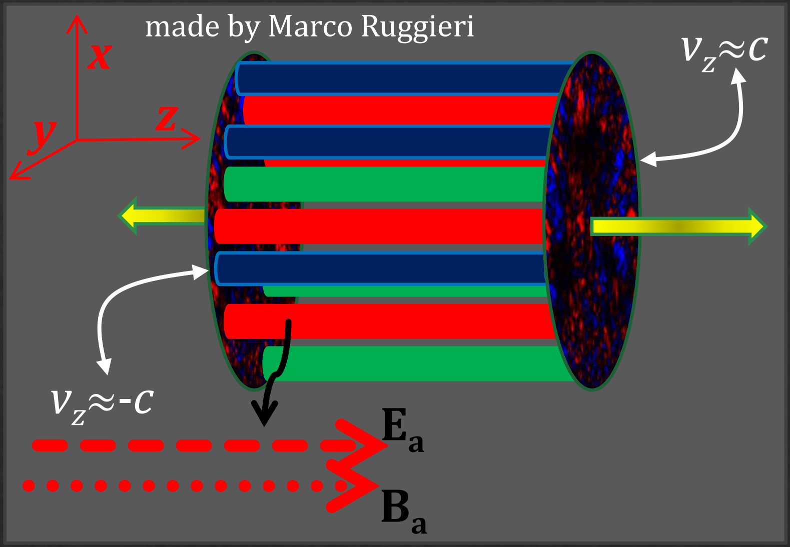
Heavy quarks in the glasma

What happens for 0<t<0.3 fm/c?
Has the very early stage left some imprints on heavy flavor transport?

McLerran-Venugopalan (MV) model for the initial conditions of the classical gluon field

McLerran and Venugopalan, Phys. Rev. D 49, 2233 (1994); Phys. Rev. D 49, 3352 (1994); Phys. Rev. D 50, 2225 (1994)

$$\langle \rho_A^a(x_T)\rho_A^b(y_T)\rangle = (g^2\mu_A)^2\delta^{ab}\delta^{(2)}(x_T - y_T)$$



Classical Yang-Mills (CYM) equations for the dynamical evolution of glasma

$$E^i = \tau\partial_\tau A_i, \qquad \partial_\tau E^i = \frac{1}{\tau}D_\eta F_{\eta i} + \tau D_j F_{ji},$$
$$E^\eta = \frac{1}{\tau}\partial_\tau A_\eta, \qquad \partial_\tau E^\eta = \frac{1}{\tau}D_j F_{j\eta}.$$

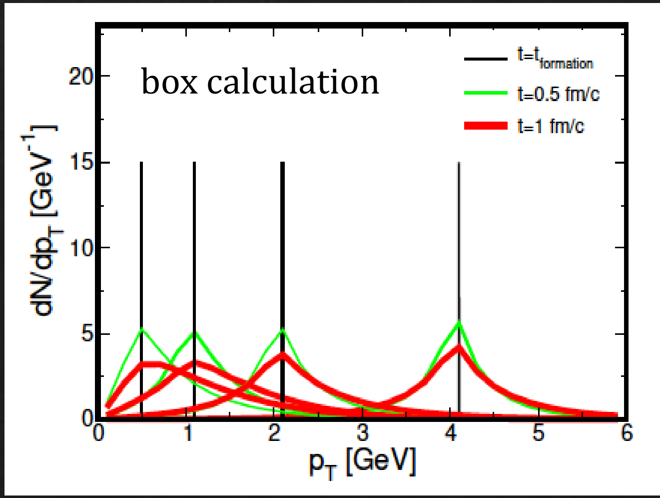
solved in SU(2)

interaction with the initial glasma induce strong diffusion of charm quarks

Mrowczynski, Eur. Phys. J. A 54, 43 (2018)
Ruggieri and Das, Phys. Rev. D 98, 094024 (2018)

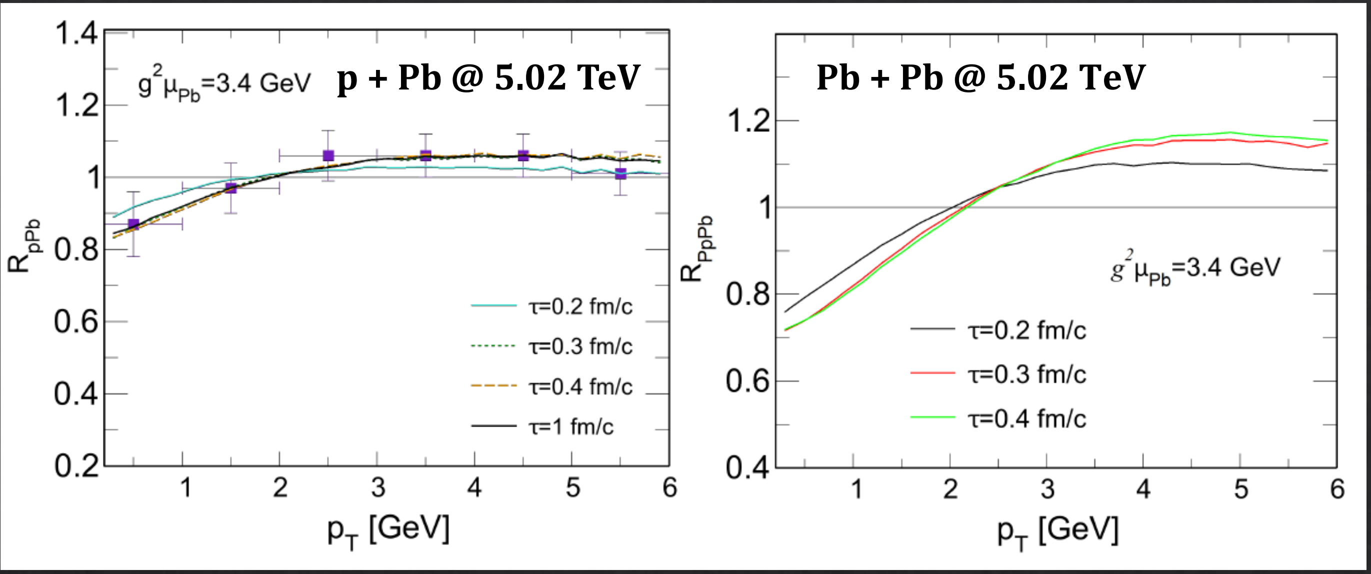
Wong equations for the dynamics of a heavy quark in the evolving glasma

$$\frac{dx_i}{dt} = \frac{p_i}{E} \qquad E\frac{dQ_a}{dt} = -Q_c\varepsilon^{cba}A_b\cdot p$$
$$E\frac{dp_i}{dt} = Q_a F^a_{i\nu}p^\nu$$



Heavy quarks in the glasma

Liu, Plumari, Das, Greco and Ruggieri, Phys. Rev. C 102, 044902 (2020)

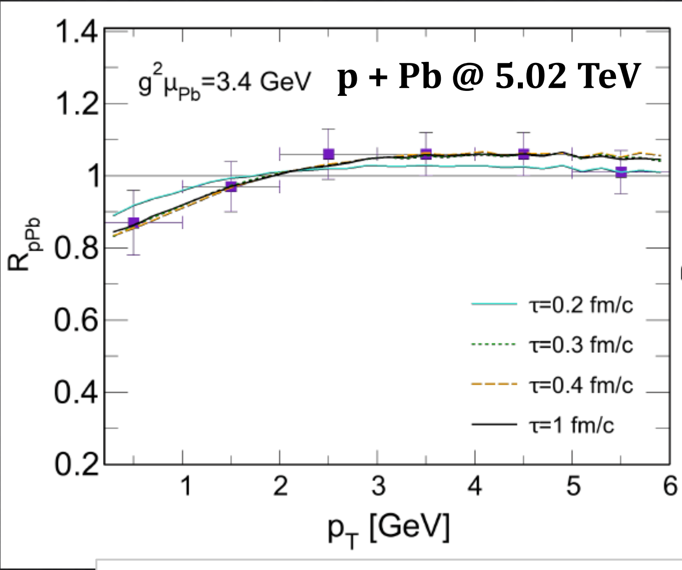


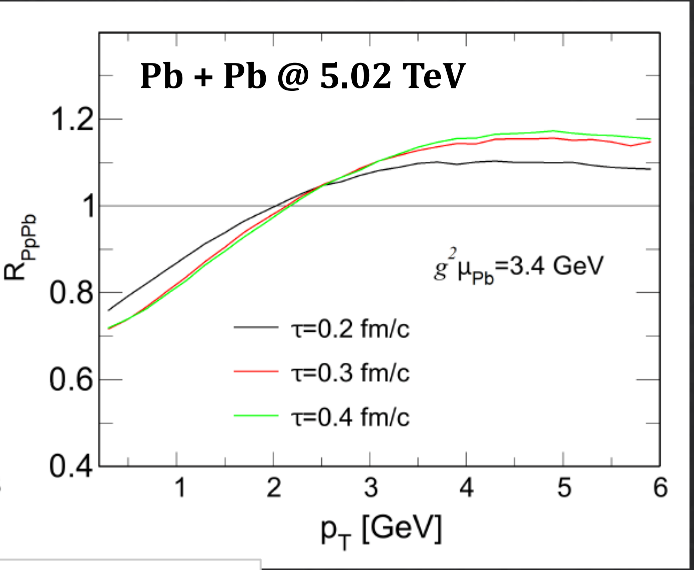
Strong and fast diffusion of HQs in the glasma

The dominance of diffusion-like dynamics leads to an **enhancement of R_{AA} at high p_T**

Heavy quarks in the glasma

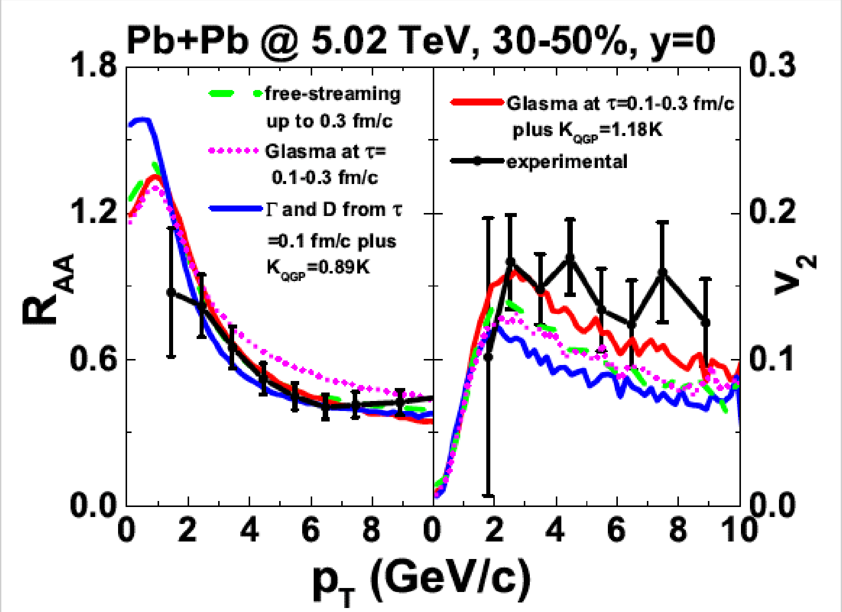
Liu, Plumari, Das, Greco and Ruggieri, Phys. Rev. C 102, 044902 (2020)





Strong and fast diffusion of HQs in the glasma

The dominance of diffusion-like dynamics leads to an **enhancement of R_{AA} at high p_T**



HQ spectrum in the glasma phase as initialization of HQs in the QGP for studying the impact on D-meson observables in AA collisions

The inclusion of the glasma phase leads to a **gain in $v_2(p_T)$:** larger interaction in QGP stage to have the same $R_{AA}(p_T)$

Sun, Coci, Das, Plumari, Ruggieri and Greco, Phys. Lett. B 798, 134933 (2019)

CONCLUSIONS

Balance among many ingredients for reproducing R_{AA} and v_2 of D meson at RHIC and LHC energies: cold nuclear matter effects, HQ in-medium interaction, fragmentation and coalescence hadronization processes, hadronic rescattering.

→ Successful estimate of $D_s(T)$ of hot QCD medium from R_{AA} and v_2 in comparison to lattice QCD data.

Future perspectives on $D_s(T)$ determination: extension to new observables, system size scan, extension to b quark, more precision data and low p_T access.

Intense fields in ultra-relativistic collisions influence transport coefficients and observables of heavy-flavor particles: vorticity, EM fields, glasma.

→ The very large v_1 for D mesons can be generated only if there is a longitudinal asymmetry between the bulk matter and the c quarks and if the latter have a large non-perturbative interaction in the QGP medium.

→ The Δv_1 of neutral D mesons is well described at RHIC energy but still a challenge at LHC. If confirmed to be of EM origin it is a proof of QGP formation and can constrain EM field evolution.

→ Heavy-flavor particles can play a role in spotting the glasma dynamics and linking pA and AA collisions.

Future perspectives: inclusion of v_1 (more sensitive to the initial high temperature) for $D_s(T)$ estimate, investigate the impact of glasma (link pA and AA collisions)

Thank you for your attention!

Many thanks to my collaborators

Vincenzo Greco, Salvatore Plumari, Yifeng Sun (Catania)

Elena Bratkovskaya, Taesoo Song (Frankfurt, Darmstadt)

Jun-Hong Liu, Marco Ruggieri (Lanzhou)

Santosh K. Das (Goa)

Catania transport approach

The temporal evolution of the QGP fireball and the heavy quarks (HQ) in relativistic HICs is described by solving the **relativistic Boltzmann transport equation** for the parton distribution function **f(x,p)**

QGP

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

$$p^\mu \partial_\mu f_q(x,p) + qF^{\mu\nu}_{ext} p_\nu \partial^p_\mu f_q(x,p) = \mathcal{C}[f_g, f_q]$$

HEAVY QUARKS

$$p^\mu \partial_\mu f_{HQ}(x,p) + qF^{\mu\nu}_{ext} p_\nu \partial^p_\mu f_{HQ}(x,p) = \mathcal{C}[f_g, f_q, f_{HQ}]$$

RELATIVISTIC BOLZTMANN EQUATIONS

Collision integral

change of **f** due to collision processes responsible for deviations from ideal hydro (η/s ≠ 0)

$$\mathcal{C}[f] = \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\frac{1}{\nu}\int \frac{d^3p_1'}{(2\pi)^3 2E_1'}\frac{d^3p_2'}{(2\pi)^3 2E_2'}(f_1' f_2' - f_1 f_2) \times |\mathcal{M}_{12\to 1'2'}|(2\pi)^4 \delta^{(4)}(p_1' + p_2' - p_1 - p_2),$$

Field interaction

change of ***f*** due to interactions of the partonic plasma with the external electromagnetic field

Ferini, Colonna, Di Toro and Greco, Phys. Lett. B 670, 325 (2009)
Ruggieri, Scardina, Plumari and Greco, Phys. Rev. C 89, 054914 (2014)

Catania transport approach

The temporal evolution of the fireball produced in relativistic HICs is described by solving the **relativistic Boltzmann equation** for the parton distribution function **f(x,p)**

$$\left(p_\mu \partial^\mu + gQF^{\mu\nu} p_\mu \partial_\nu^p\right) f = \mathcal{C}[f]$$

collision integral

$\eta/s \neq 0$

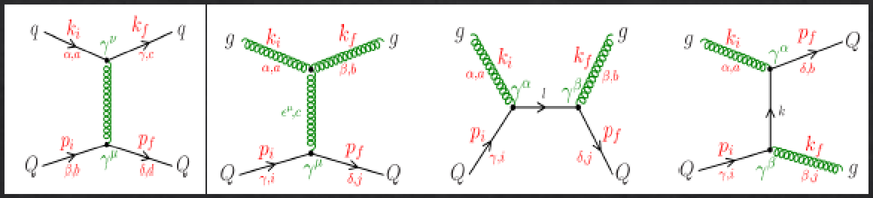
Instead of starting from cross sections we simulate a fluid at **fixed η/s**

CHAPMAN-ENSKOG EQUATION

$$\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho} \frac{1}{\sigma}$$

Plumari, Puglisi, Scardina and Greco, PRC 86 (2012) 054902

Boltzmann transport equivalent to viscous hydro at **$\eta/s \approx 0.1$**



$$\begin{aligned}\mathcal{C}[f_Q] \; = \; & \frac{1}{2E_1} \int \frac{d^3 p_2}{2E_2 (2\pi)^3} \int \frac{d^3 p_1'}{2E_{1'} (2\pi)^3} \\ & \times [f_Q(p_1') f_{q,g}(p_2') - f_Q(p_1) f_{q,g}(p_2)] \\ & \times |\mathcal{M}_{(q,g)+Q}(p_1 p_2 \to p_1' p_2')|^2 \\ & \times (2\pi)^4 \delta^4 (p_1 + p_2 - p_1' - p_2') \; ,\end{aligned}$$

Non perturbative dynamics → M scattering matrices (q,g → Q) evaluated by Quasi-Particle Model (QPM) fit to lQCD thermodynamics

$$m_g^2(T) = \frac{2N_c}{N_c^2 - 1} g^2(T) T^2 \qquad g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f) \ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$

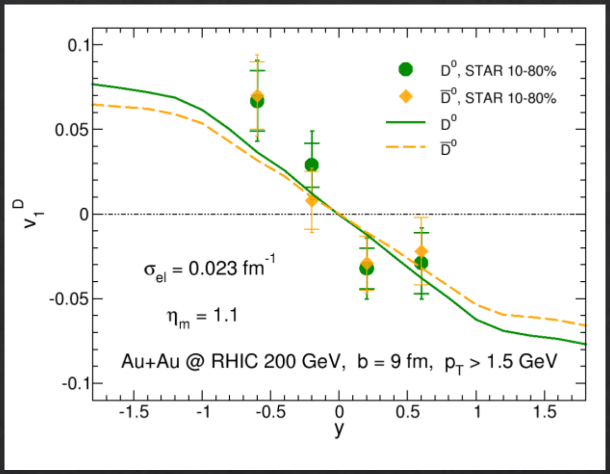
$$m_q^2(T) = \frac{1}{N_c} g^2(T) T^2$$

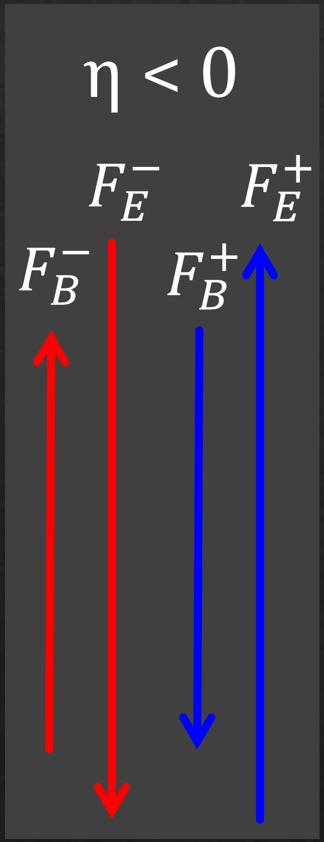
EMF and directed flow in A+A

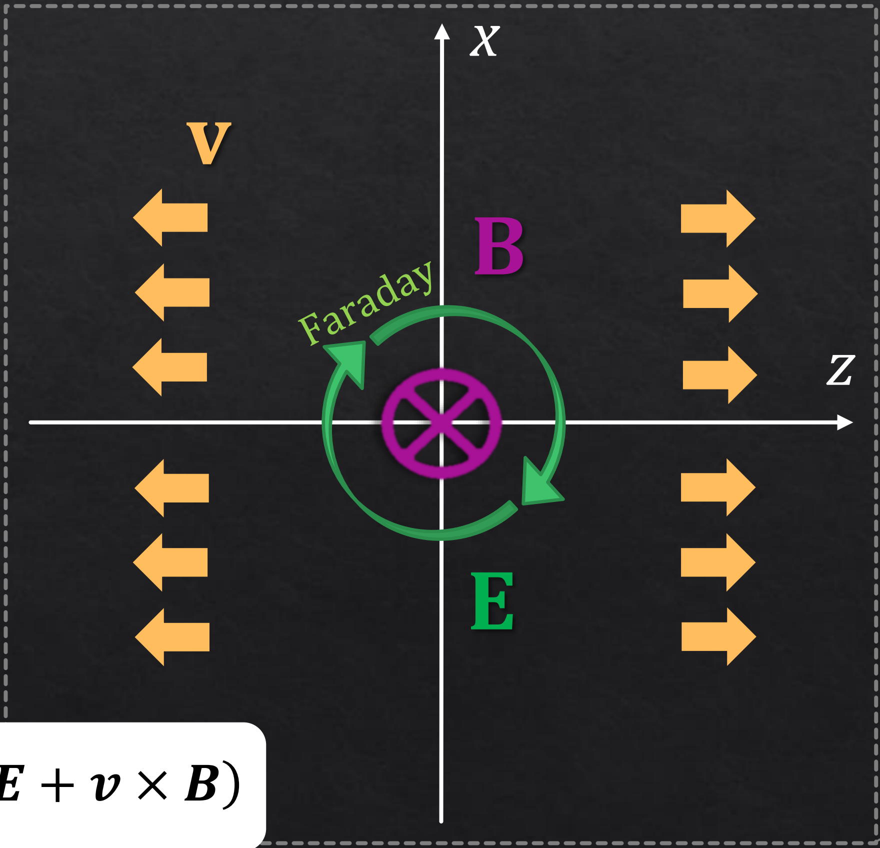
rapidity dependence of the DIRECTED FLOW

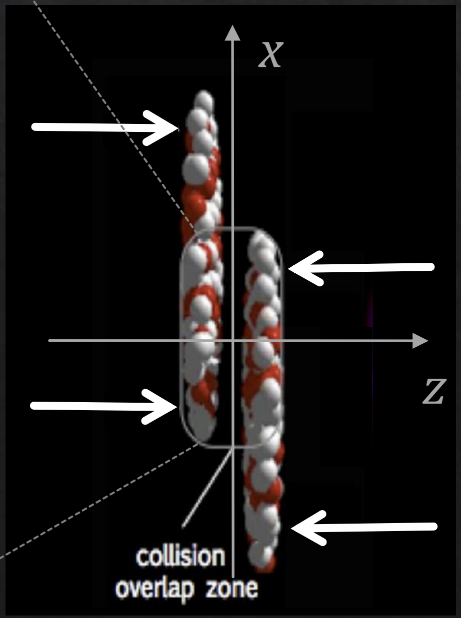
collective sidewards deflection of particles

$$v_1 = \langle \cos\varphi \rangle = \langle p_x/p_T \rangle$$



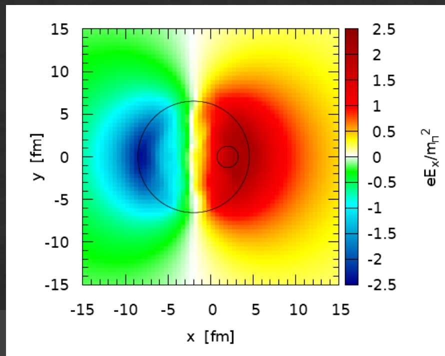


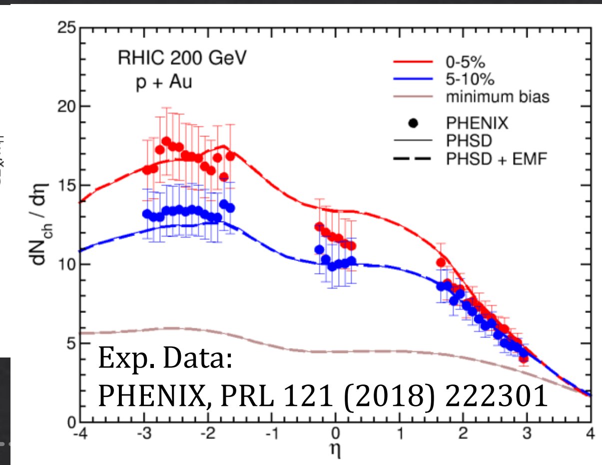




$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

EMF and directed flow in p+A

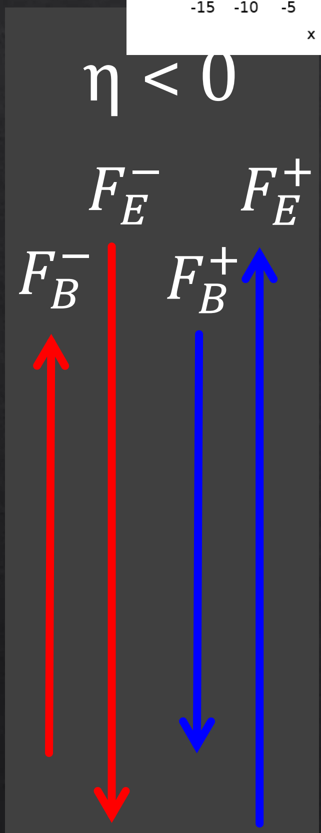


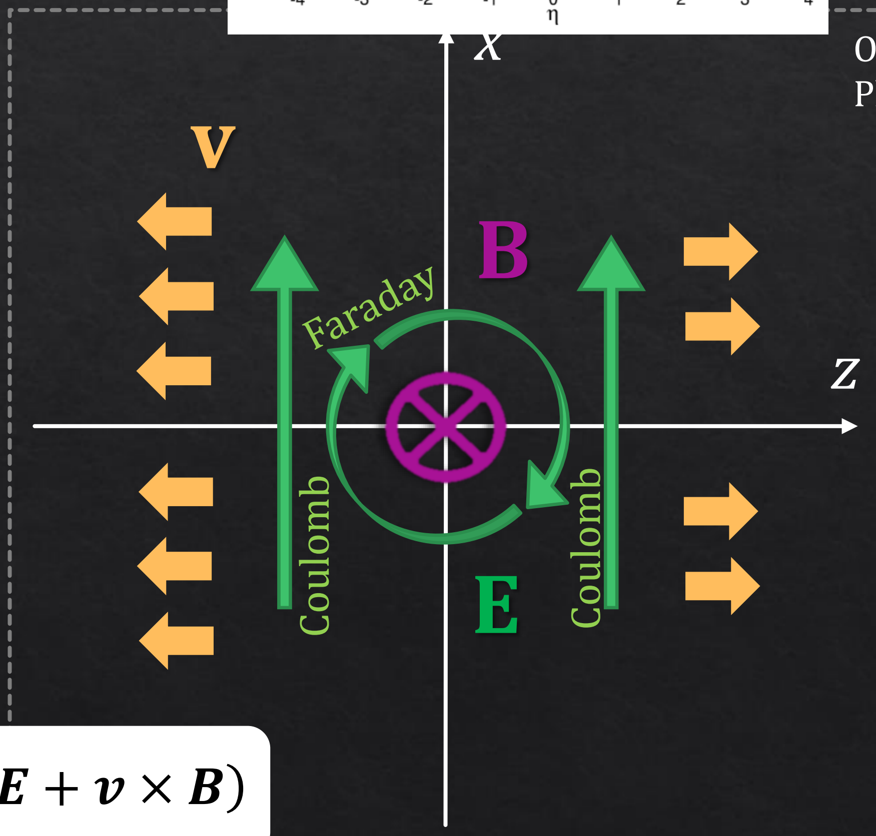


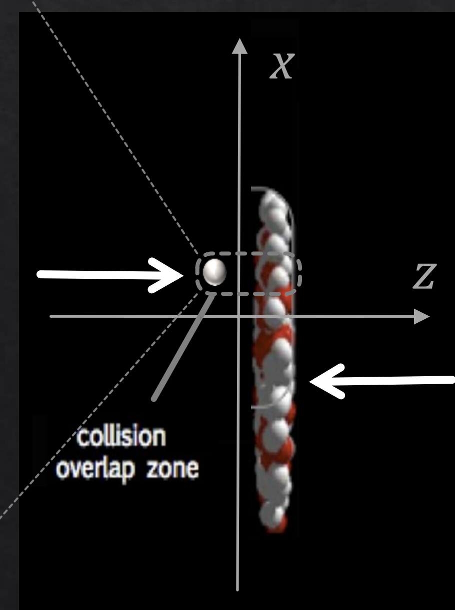
Asymmetry in charged particle and electric field profiles in p+Au

- enhanced particle production in the Au-going direction
- electric field directed from the heavy ion to the proton

Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)





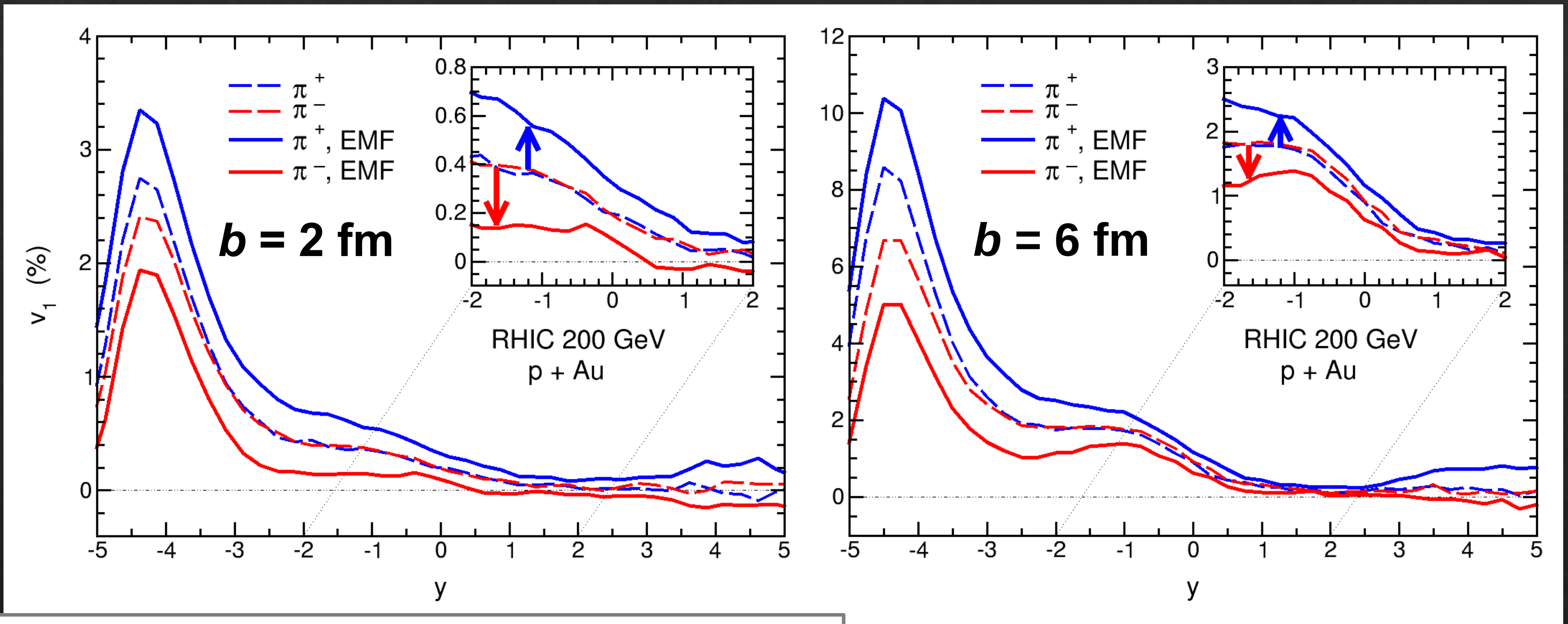


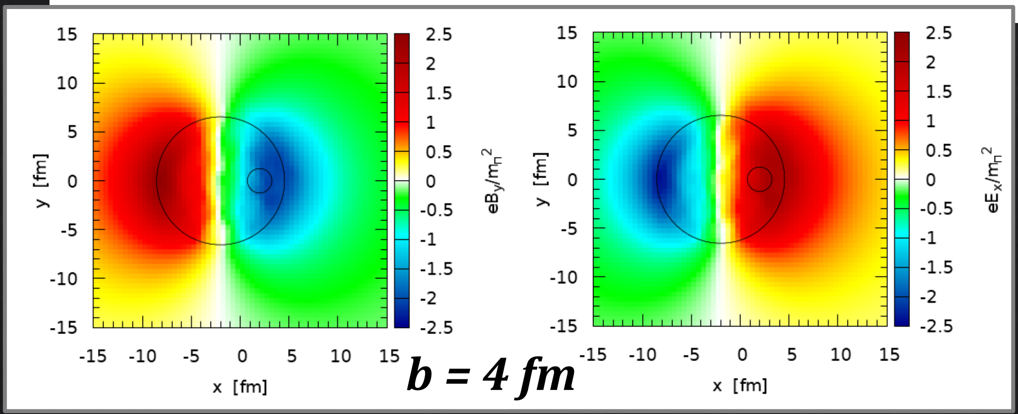
$$F_{Lorentz} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Directed flow in p+A

rapidity dependence of the
DIRECTED FLOW OF PIONS

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$





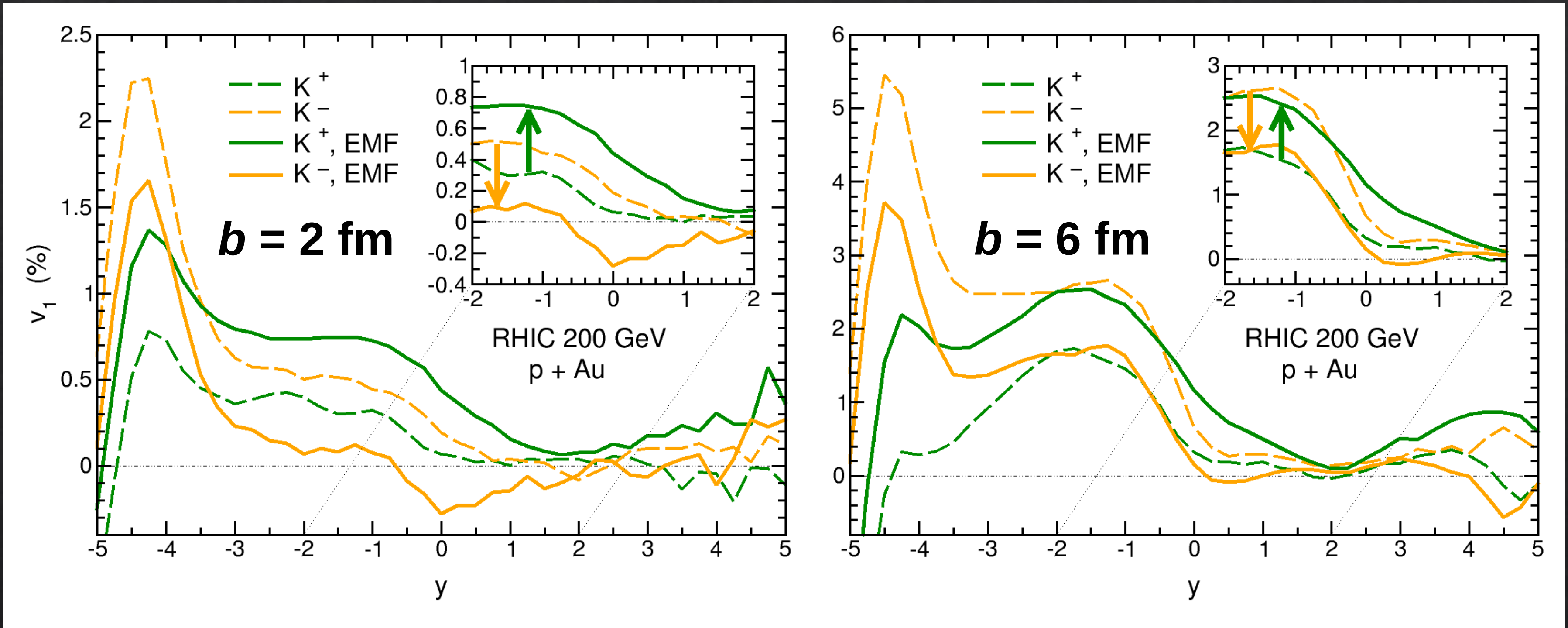
Oliva, Moreau, Voronyuk and Bratkovskaya,
Phys. Rev. C 101 (2020) 014917

Splitting of π^+ and π^- induced by the electromagnetic field

Directed flow in p+A

rapidity dependence of the
DIRECTED FLOW OF KAONS

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$



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different v_1 also in simulations without EMF

more contributions to K^+ $(\bar{s}u)$ with respect to K^- $(s\bar{u})$
from quarks of the initial colliding nuclei

STAR Coll., PRL 120 (2018) 062301

Splitting of K⁺ and K⁻ induced by the electromagnetic field