Laboratori Nazionali del Gran Sasso
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Quinto Incontro Nazionale
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PRODUZIONE E TRASPORTO DI QUARK PESANTI NEL QGP

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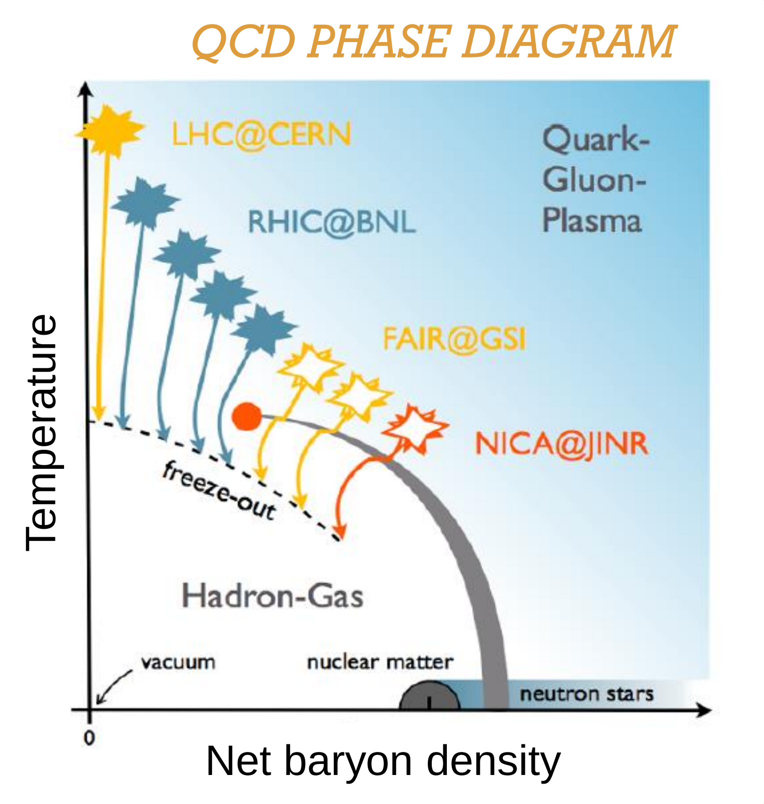
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

DIPARTIMENTO DI FISICA E ASTRONOMIA "ETTORE MAJORANA"

RELATIVISTIC HEAVY-ION COLLISIONS



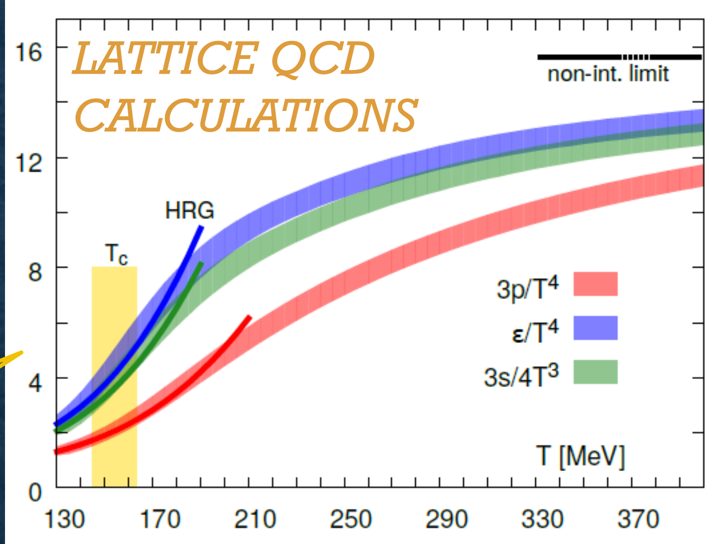
Heavy-Ion Collisions (HICs) at high energy

- allow to experimentally investigate the QCD phase diagram
- recreate the extreme condition of temperature and density required for the formation of the **Quark-Gluon Plasma (QGP)**

at $\mu = 0$

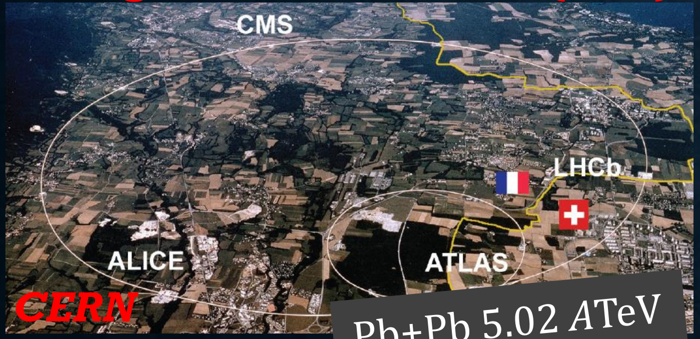
CROSSOVER

$T_c \approx 155$ MeV



HotQCD Coll., Phys. Rev. D 90 (2014) 094503

Large Hadron Collider (LHC)



Pb+Pb 5.02 ATeV

Relativistic Heavy Ion Collider (RHIC)

Au+Au 200 AGeV

Facility for Antiproton and Ion Research (FAIR)

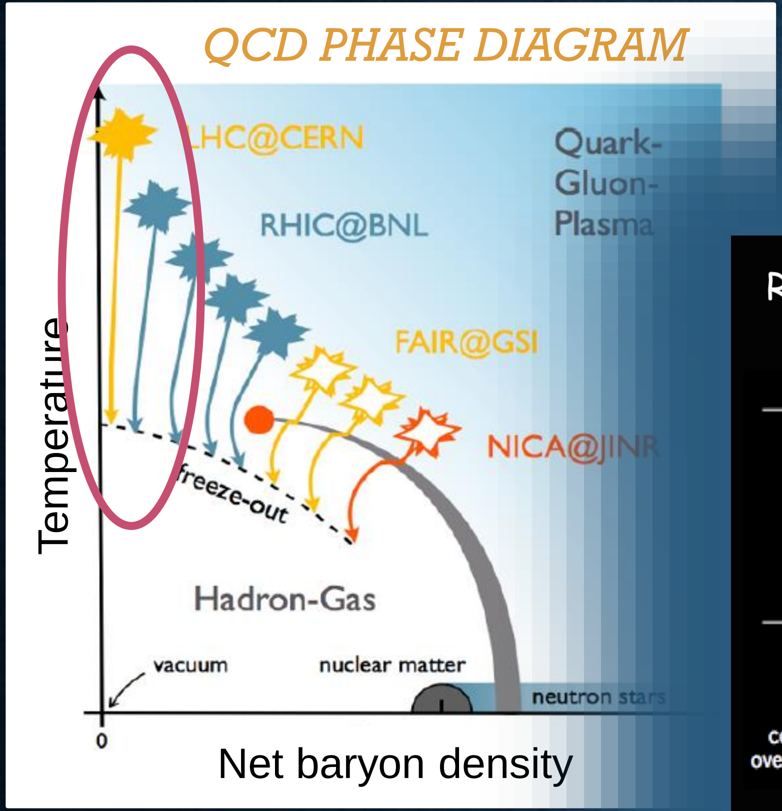
UNDER CONSTRUCTION

Au+Au 30 AGeV

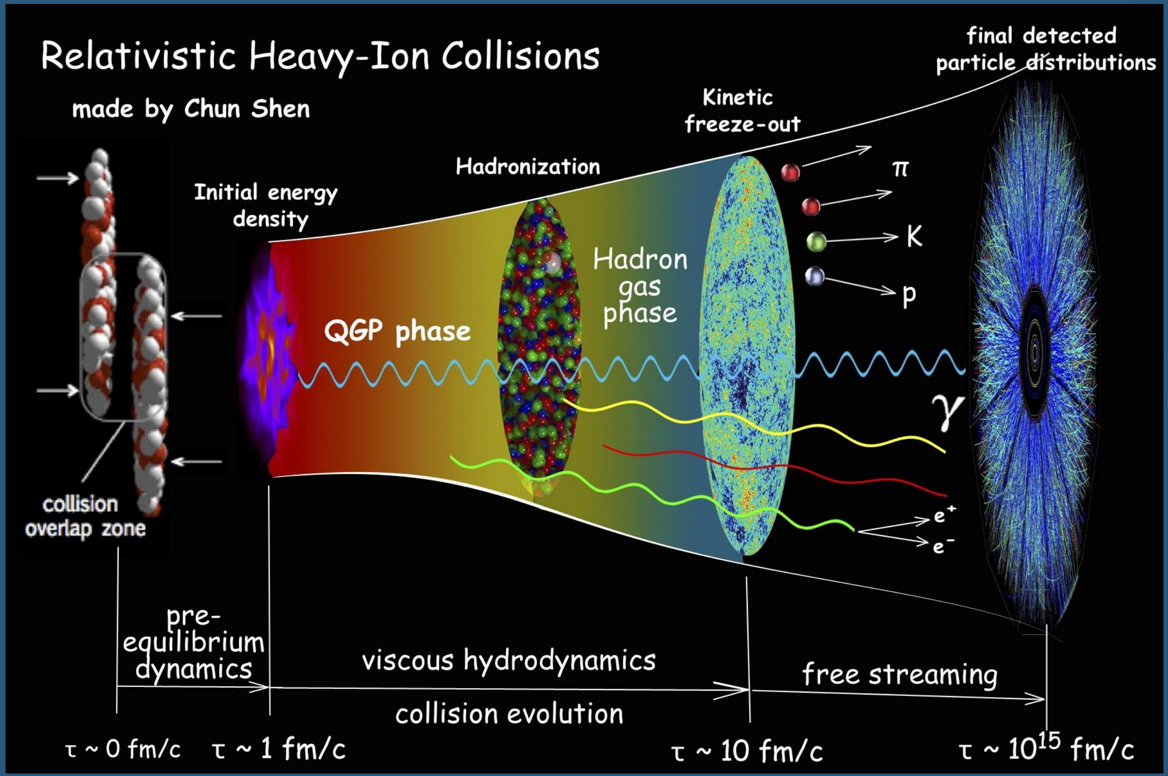
Nuclotron-based Ion Collider fAcility (NICA)

Au+Au 11 AGeV

RELATIVISTIC HEAVY-ION COLLISIONS



EVOLUTION OF A ULTRA-RELATIVISTIC HEAVY-ION COLLISION



Picture credit: Chun Shen (McGill University, Montreal QC, Canada)

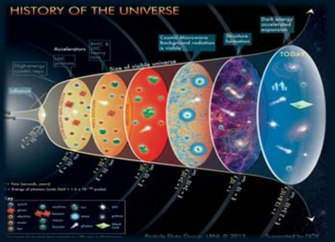
RELATIVISTIC HEAVY-ION COLLISIONS

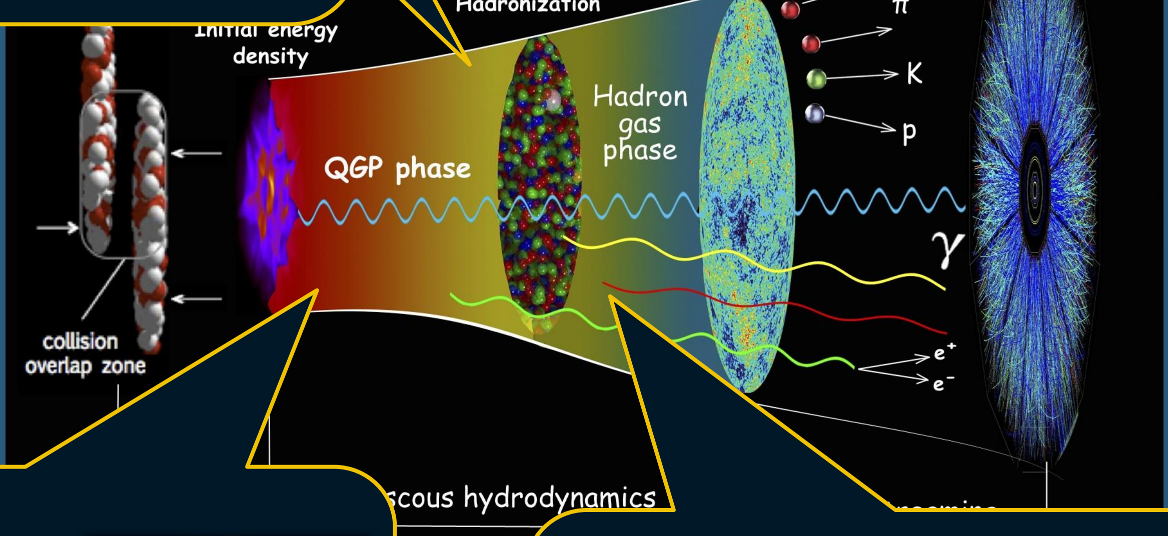
EXPANDING
QUARK-GLUON PLASMA
FIREBALL

TRANSIENT

$t \sim 10\ \mathrm{fm}/c \sim 10^{-23}$–$10^{-22}$ s

10^{18} times shorter than the QGP lifetime in the early Universe

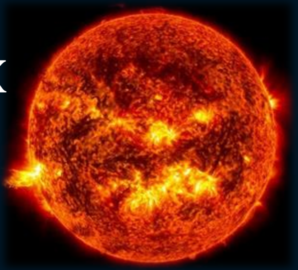




HOT

T ~ 300–600 MeV ~ 10^{12} K

10^{5} times hotter than the center of the sun



TINY

x ~ 10 fm ~ 10^{-14} m

10^{11} times smaller than a typical water droplet

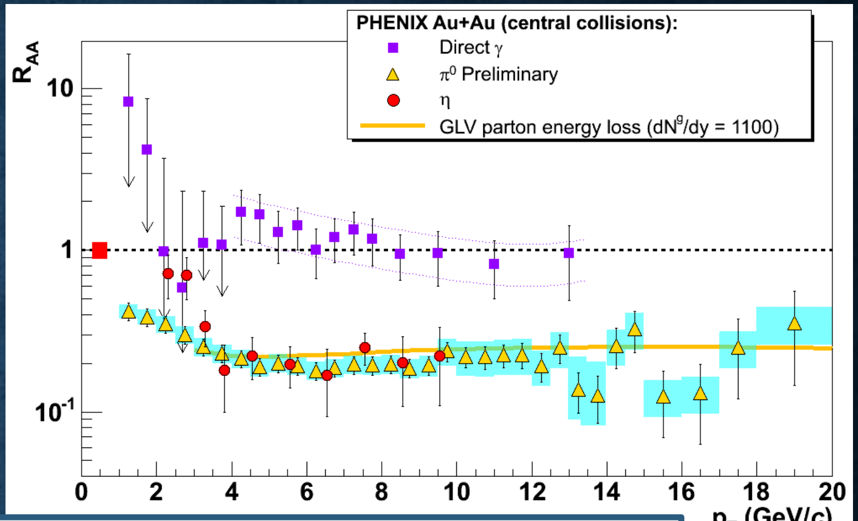
Picture credit: Chun Shen (McGill University, Montreal QC, Canada)

TWO MAIN OBSERVABLES IN HICS

- NUCLEAR MODIFICATION FACTOR R_{AA}

Modification of particle
p_T spectra in AA collisions
w.r.t. to pp collisions

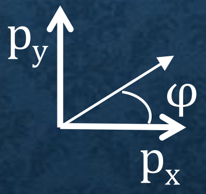
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{N_{coll} d^2N^{pp}/dp_T d\eta}$$

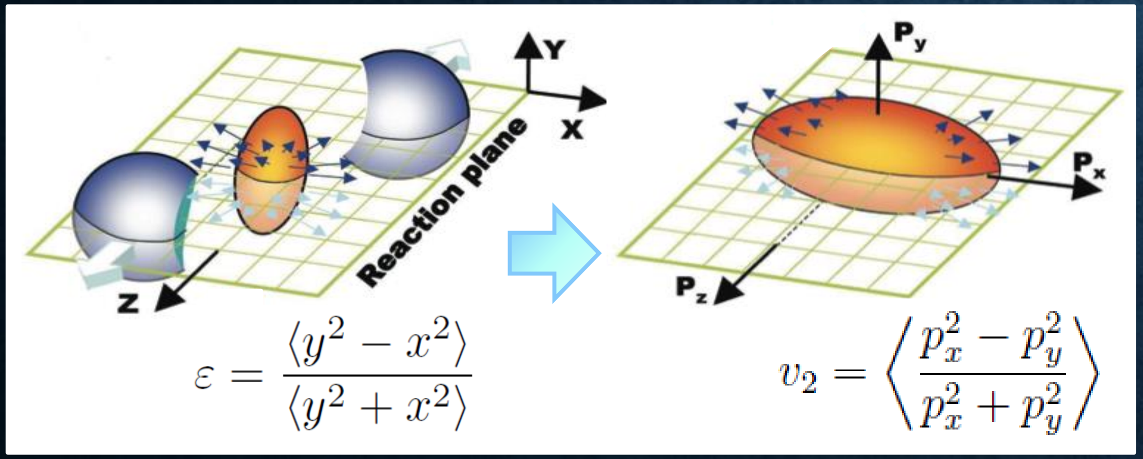


- ELLIPTIC FLOW v_2

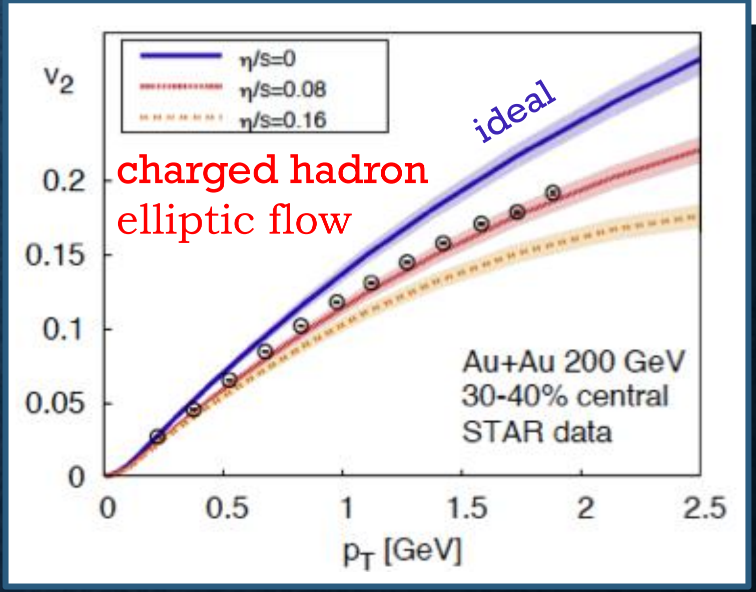
Anisotropic radial flow described by the Fourier coefficients of the azimuthal particle distributions

$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2\, v_n \cos[n\varphi]$$





$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

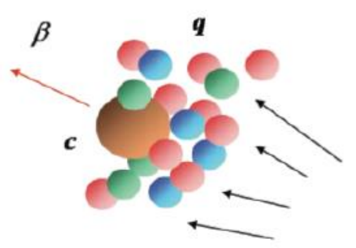


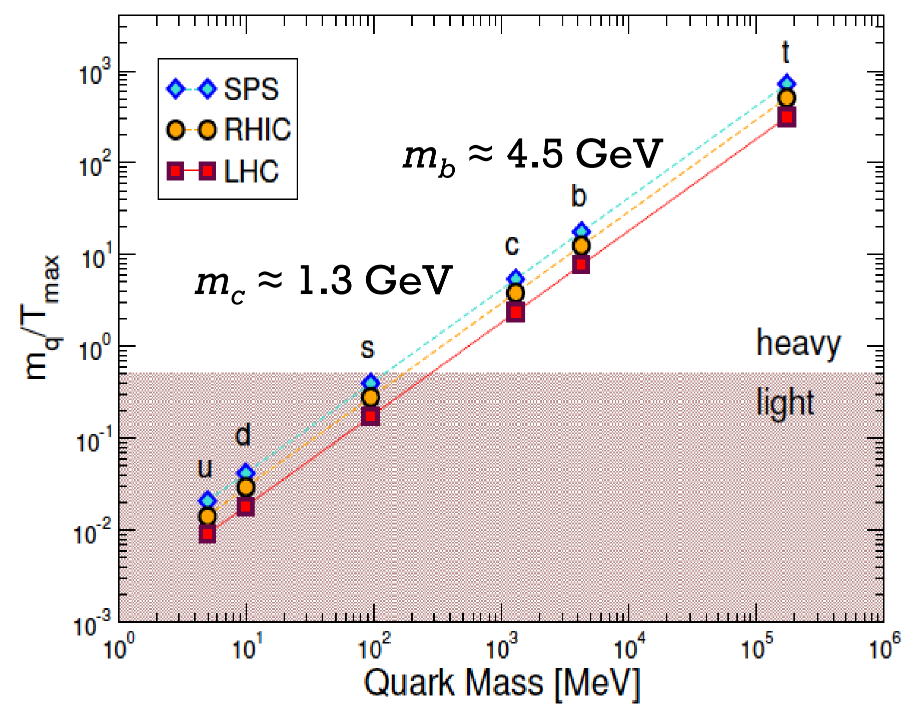
No interaction means $R_{AA}=1$ and $v_2=0$
More interaction decreases R_{AA} and increases v_2

QGP flows like an almost "perfect fluid"
$4\pi\eta/s \approx 1-2$ at $T \sim T_c$

HEAVY QUARKS IN QGP: BASIC SCALES

few heavy charm and bottom quarks
produced in relativistic heavy-ion collisions





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

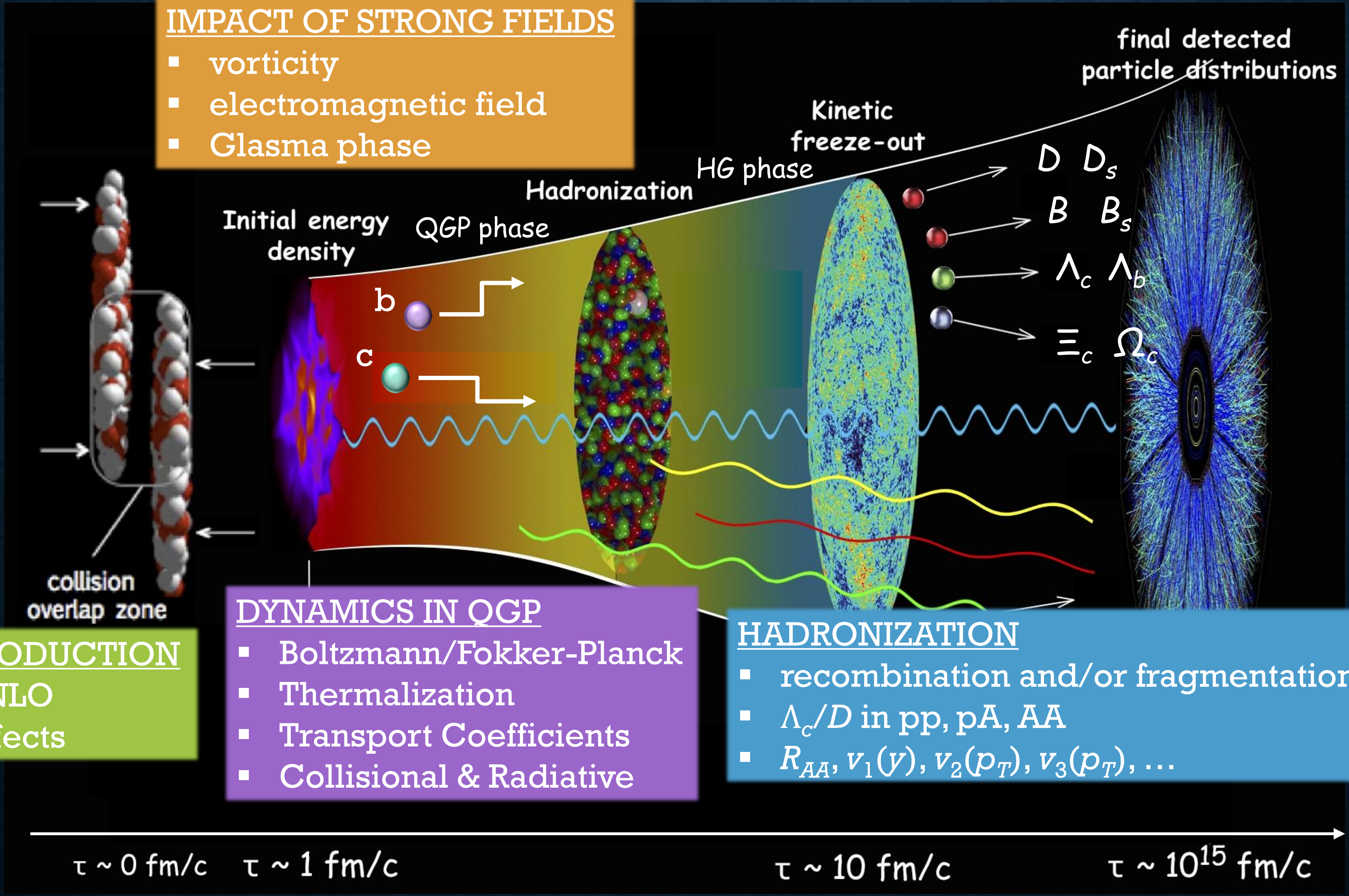
HQ production points symmetric in the forward-backward hemispheres

- $\tau_0^{HQ} < 0.08$ **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

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

HEAVY FLAVORS IN RELATIVISTIC HICS



IMPACT OF STRONG FIELDS

- vorticity
- electromagnetic field
- Glasma phase

INITIAL PRODUCTION

- pQCD-NLO
- CNM effects

DYNAMICS IN QGP

- Boltzmann/Fokker-Planck
- Thermalization
- Transport Coefficients
- Collisional & Radiative

HADRONIZATION

- recombination and/or fragmentation
- Λ_c/D in pp, pA, AA
- $R_{AA}, v_1(y), v_2(p_T), v_3(p_T), \ldots$

HEAVY QUARKS IN QGP: TRANSPORT APPROACHES

BOLTZMANN (BM) EQ.

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

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

soft-scattering approximation

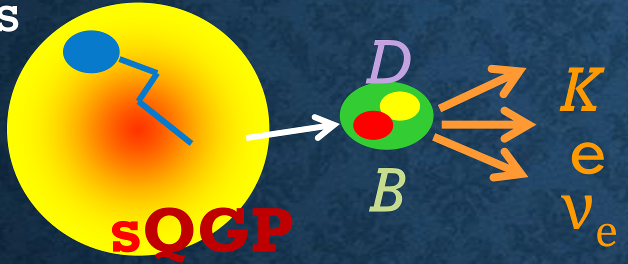
FOKKER-PLANCK (FP) EQ.

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

DRAG and **DIFFUSION** coefficients

c,*b* quarks

BROWNIAN MOTION



$$\langle p \rangle = p_0 e^{-\gamma t}$$

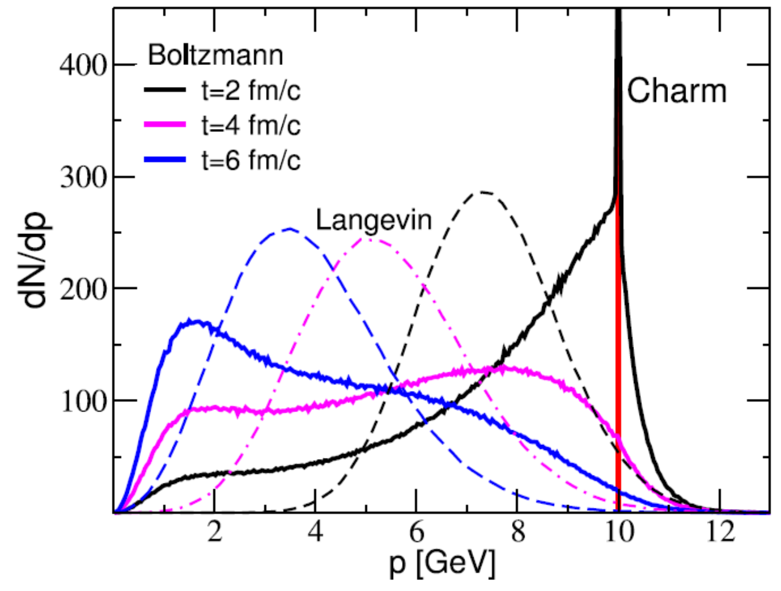
$$\langle \Delta p^2 \rangle = 3D_p / \gamma (1 - e^{-2\gamma t})$$

$D_p = MT\gamma$

Fluctuation-Dissipation Theorem

FP eq. solved through a LANGEVIN (LV) EQ.

[TAMU, Torino (POWLANG), Duke, Nantes, Catania, …]



BM eq. gives a non gaussian energy loss

Das et al., Phys. Rev. C 90, 044901 (2014)

$$\gamma = \int d^3k |M(k,p)|^2 p$$

$$D = \frac{1}{2}\int d^3k |M(k,p)|^2 p^2$$

$|M|^2$ scatt. matrix from some theory (HTL, pQCD coll., rad., T-matrix)

$$D_s = \frac{T}{M\gamma} = \frac{T^2}{D_p}$$

SPATIAL DIFFUSION coefficient D_s from lattice QCD

Dong and Greco, Prog. Part. Nucl. Phys. 104 (2019)

RELATIVISTIC BOLTZMANN EQUATION AT FINITE η/s

CATANIA APPROACH

Bulk evolution

$$p^\mu \partial_\mu f_q(x,p) + m(x)\partial^x_\mu m(x)\partial^\mu_p f_q(x,p) = C[f_q, f_g]$$
$$p^\mu \partial_\mu f_g(x,p) + m(x)\partial^x_\mu m(x)\partial^\mu_p f_g(x,p) = C[f_q, f_g]$$

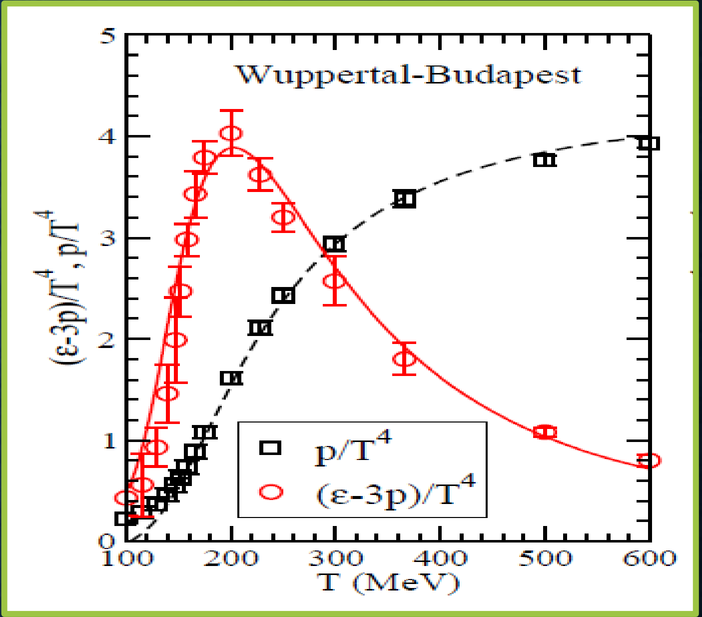
Free-streaming

Field interaction
$\varepsilon - 3p \neq 0$

Collision kernel
gauged to some η/s≠ 0

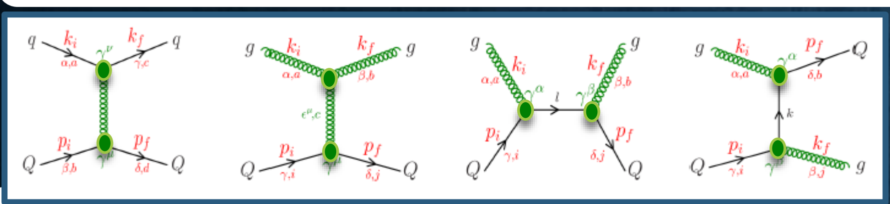
Boltzmann transport equivalent to viscous hydro at η/s ≈ 0.1

Scardina et al., Phys. Rev. C 97 (2017)



HQ evolution

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



$$\begin{aligned}\mathcal{C}[f_Q] \;=\; & \frac{1}{2E_1}\int\frac{d^3p_2}{2E_2(2\pi)^3}\int\frac{d^3p'_1}{2E_{1'}(2\pi)^3} \\ & \times[f_Q(p'_1)f_{q,g}(p'_2) - f_Q(p_1)f_{q,g}(p_2)] \\ & \times|\mathcal{M}_{(q,g)+Q}(p_1p_2 \to p'_1p'_2)|^2 \\ & \times(2\pi)^4\delta^4(p_1+p_2-p'_1-p'_2)\end{aligned}$$

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

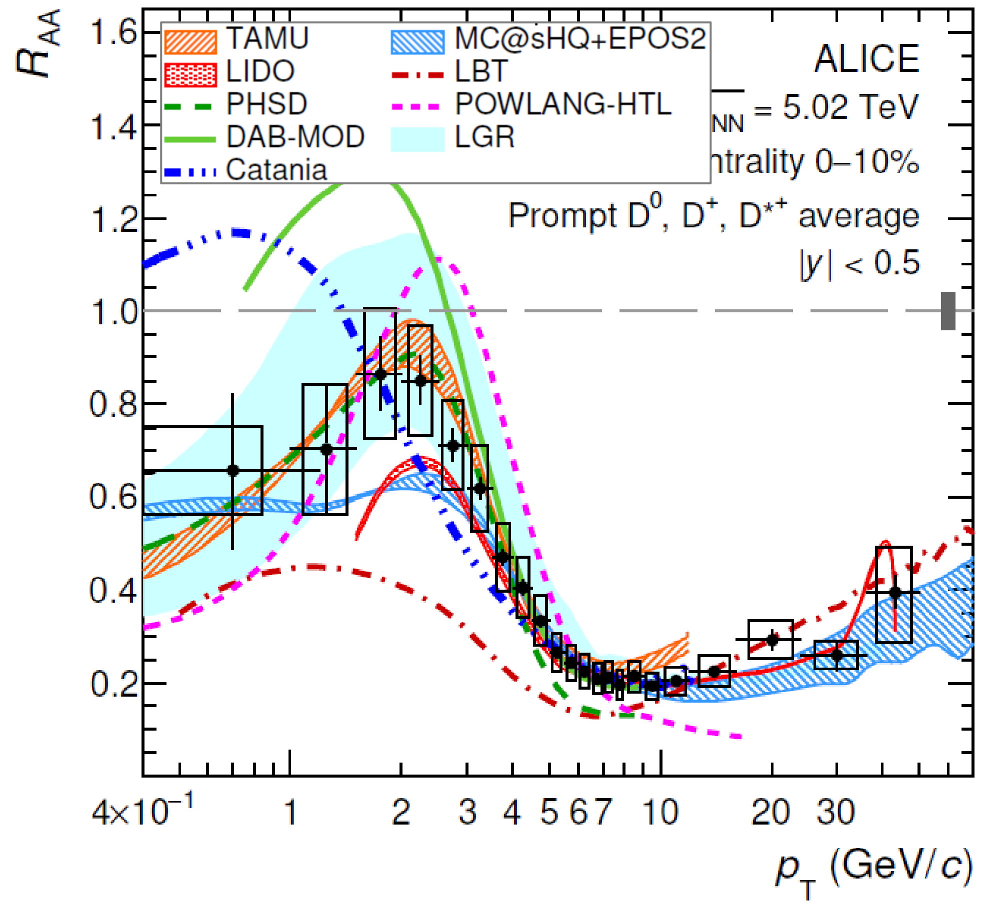
$$m_g^2(T) = \frac{2N_c}{N_c^2-1}g^2(T)T^2 \qquad g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$
$$m_q^2(T) = \frac{1}{N_c}g^2(T)T^2$$

Impact of off-shell dynamics: Sambataro et al., Eur. Phys. J. C 80, 1140 (2020)

TWO MAIN OBSERVABLES FOR HEAVY QUARKS

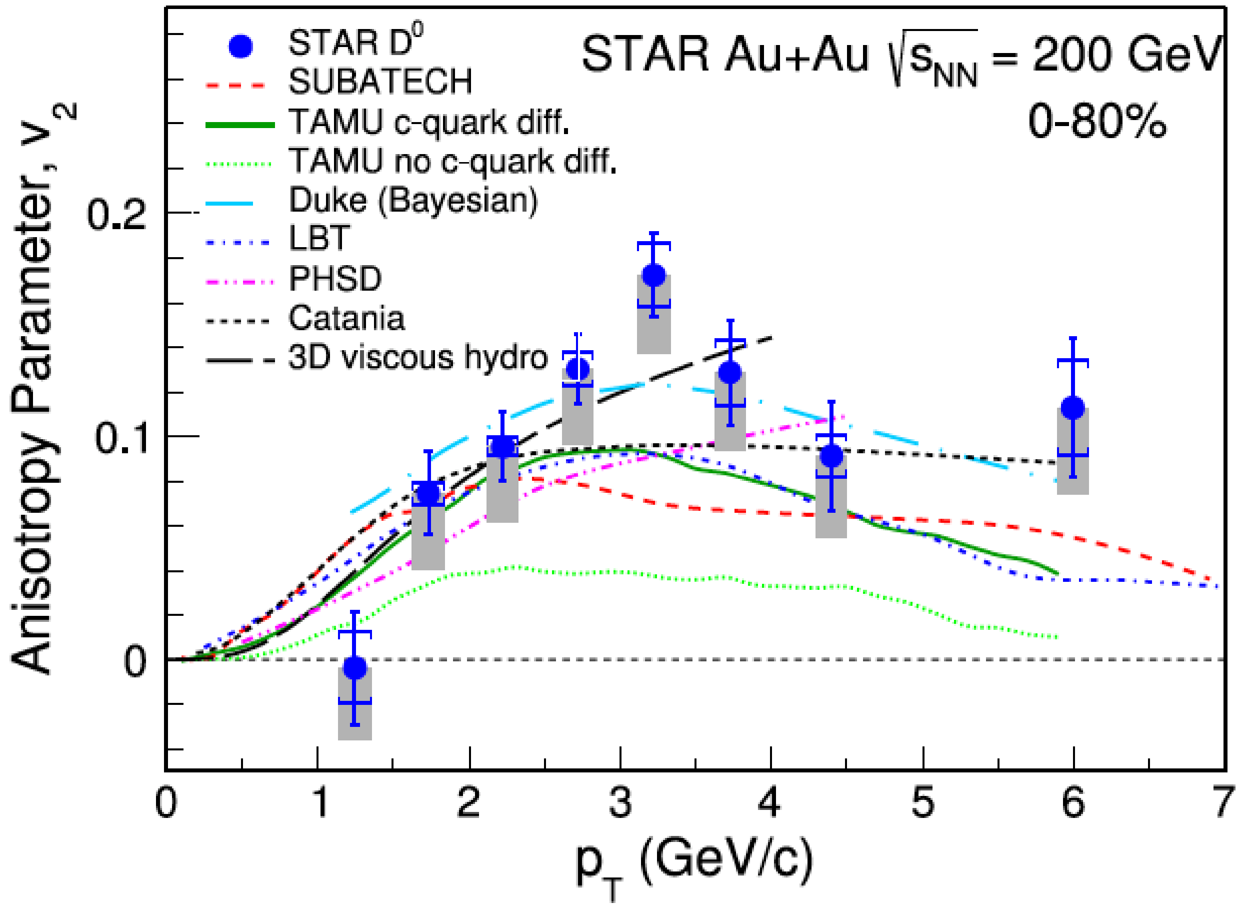
Predictions for $R_{AA}(p_T)$ and $v_2(p_T)$ of D mesons at top RHIC and LHC energies

NUCLEAR MODIFICATION FACTOR



ALICE Collaboration, JHEP 01, 174 (2022)

ELLIPTIC FLOW

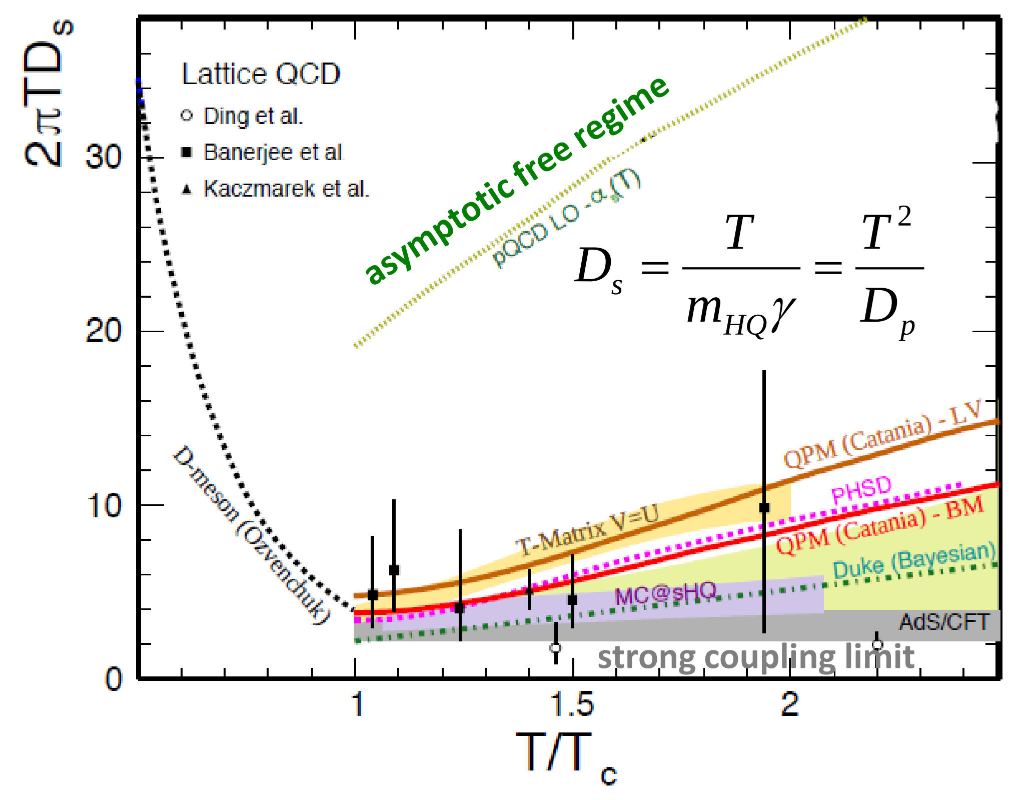


Dong and Greco, Prog. Part. Nucl. Phys. 104 (2019)

CHARM SPATIAL DIFFUSION COEFFICIENT

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

Greco, PoS HardProbes2020, 018 (2020)



CHARM-QUARK SPATIAL DIFFUSION COEFFICIENT

QGP diffuses charm quarks like an almost "perfect fluid"

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

HQ interaction in QGP largely
NON-PERTURBATIVE

Not a model fit to lQCD data!
Extracted independently by phenomenological models

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

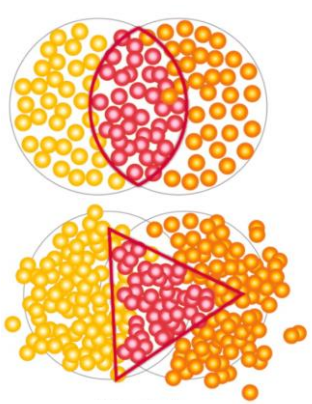
- access to low p_T and precision data
- more exclusive observables
- better insight into hadronization
- predictions and measurements for B mesons

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

reviews

HIGHER ORDER FLOW COEFFICIENTS

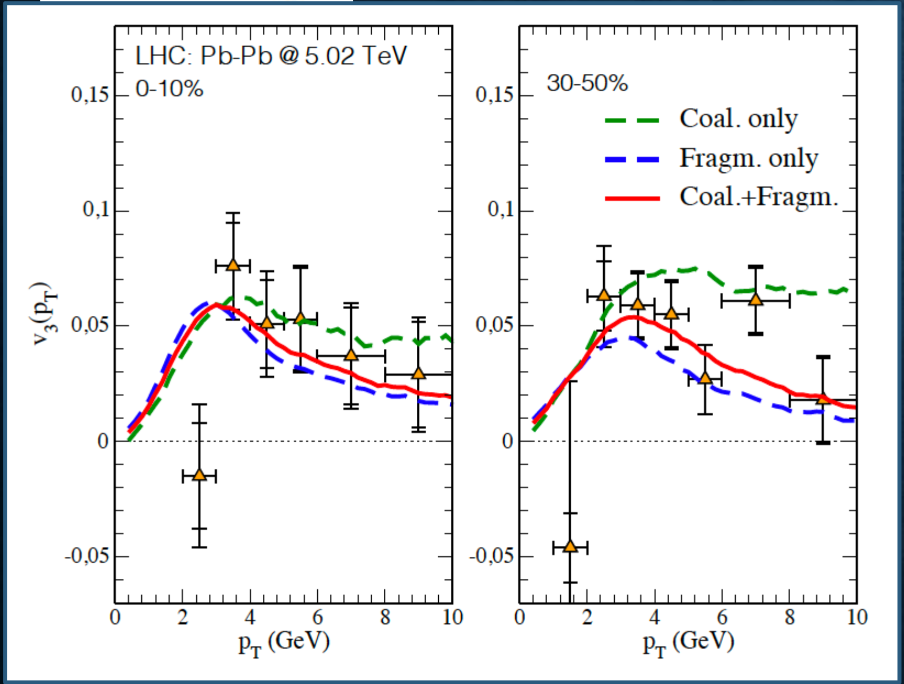
Event-by-event fluctuations in the initial nucleon positions give rise to odd flow harmonics



elliptic flow

$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$
$$v_3 = \langle \cos[3(\varphi - \Psi_3)] \rangle$$

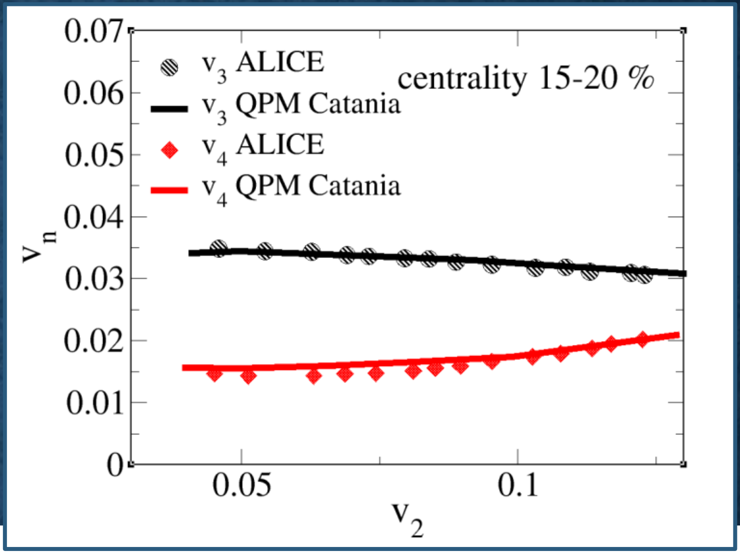
triangular flow



D MESON TRIANGULAR FLOW

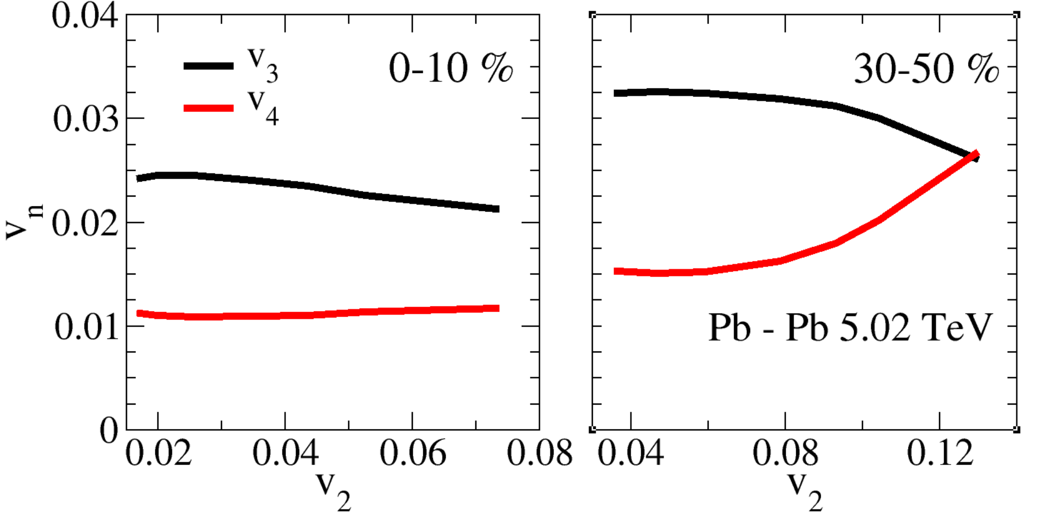
Plumari et al., Phys. Lett. B 805, 135460 (2020)

Sambataro et al., in preparation



CHARGED PARTICLES

v_n-v_m CORRELATIONS



D MESONS

Same approach and $D_s(T)$ describing $R_{AA}(p_T)$ & $v_2(p_T)$

EVENT-SHAPE ENGINEERING (ESE)

Selection of events with **same centrality** but **different initial geometry** on the basis of the magnitude of the 2°-order harmonic reduced flow vector q_2

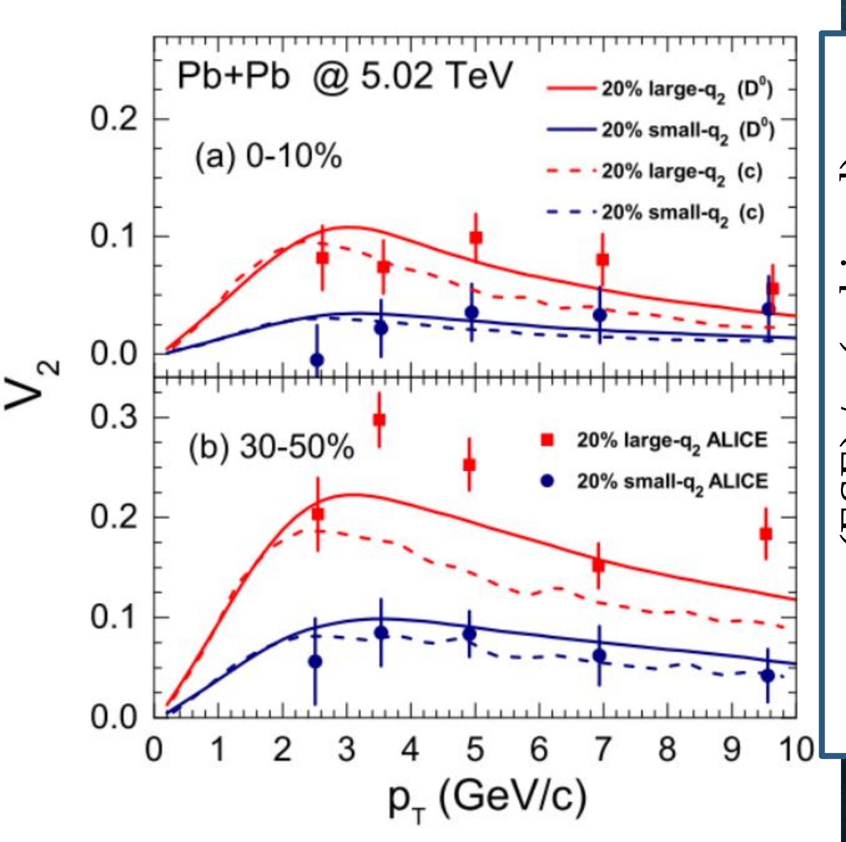
$$q_2 = |\overrightarrow{Q}_2| / \sqrt{M}$$

$$\overrightarrow{Q}_2 = \sum_{j=1}^{M} e^{i2\varphi_j}$$

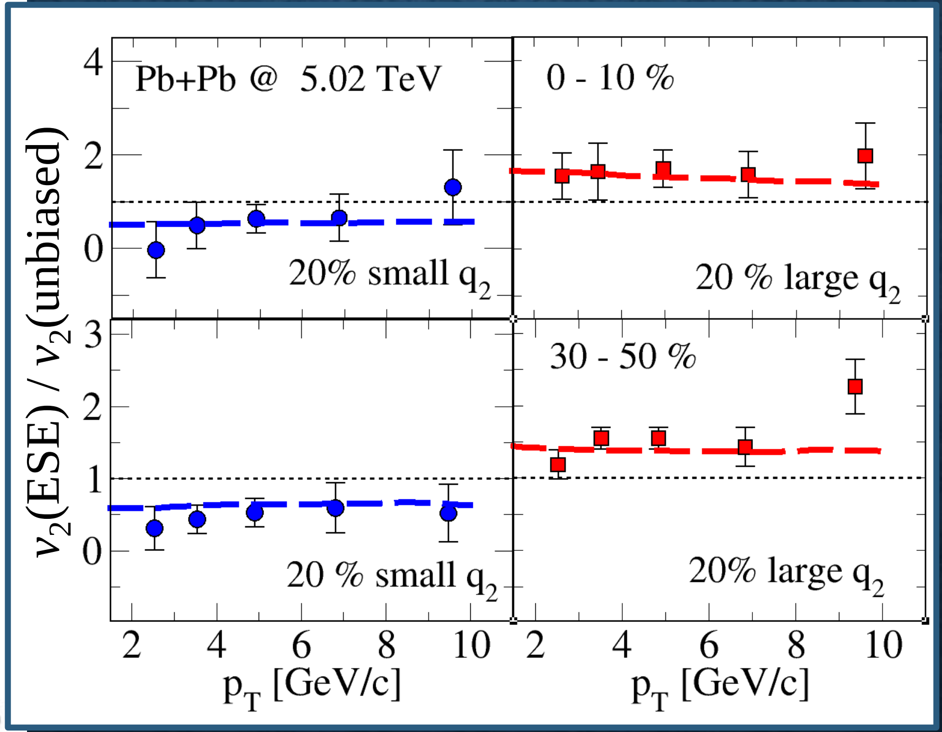
20% small q_2 20% large q_2

large q_2 → large ε_2

q_2-SELECTED D-MESON $v_2(p_T)$



D-MESON $v_2(p_T)$ RATIO



Sambataro et al., in preparation

v_2 (small q_2) < v_2 (unbiased)
v_2 (large q_2) > v_2 (unbiased)

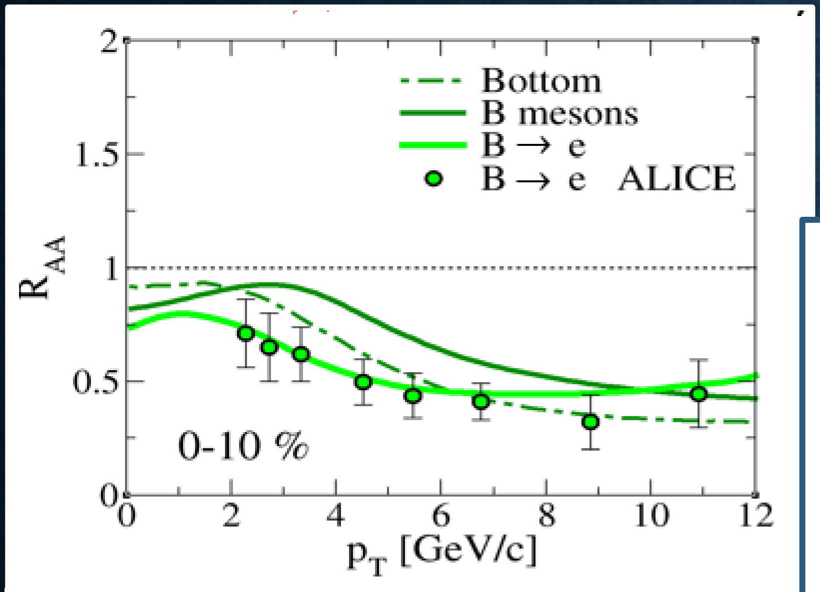
more pronounced difference for more peripheral collisions

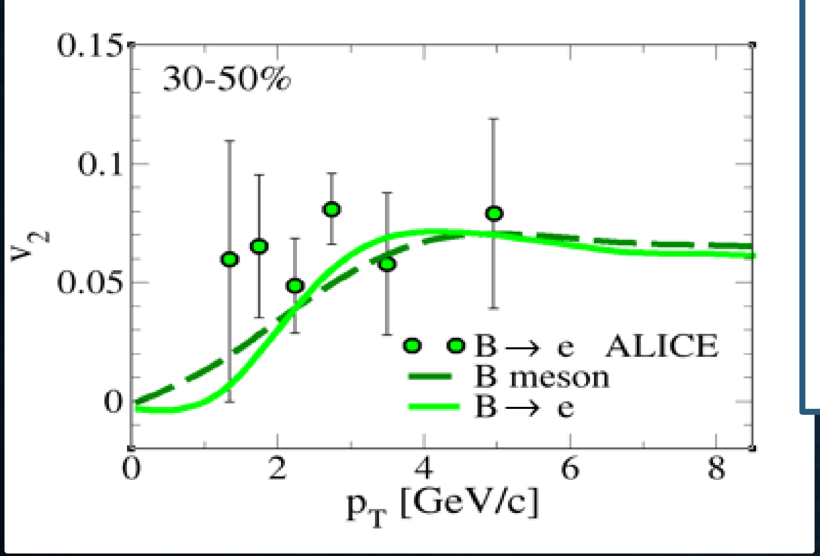
Same approach and $D_s(T)$ describing $R_{AA}(p_T)$ & $v_2(p_T)$

EXTENSION TO BOTTOM DYNAMICS

B MESONS (electrons from its semileptonic decay)

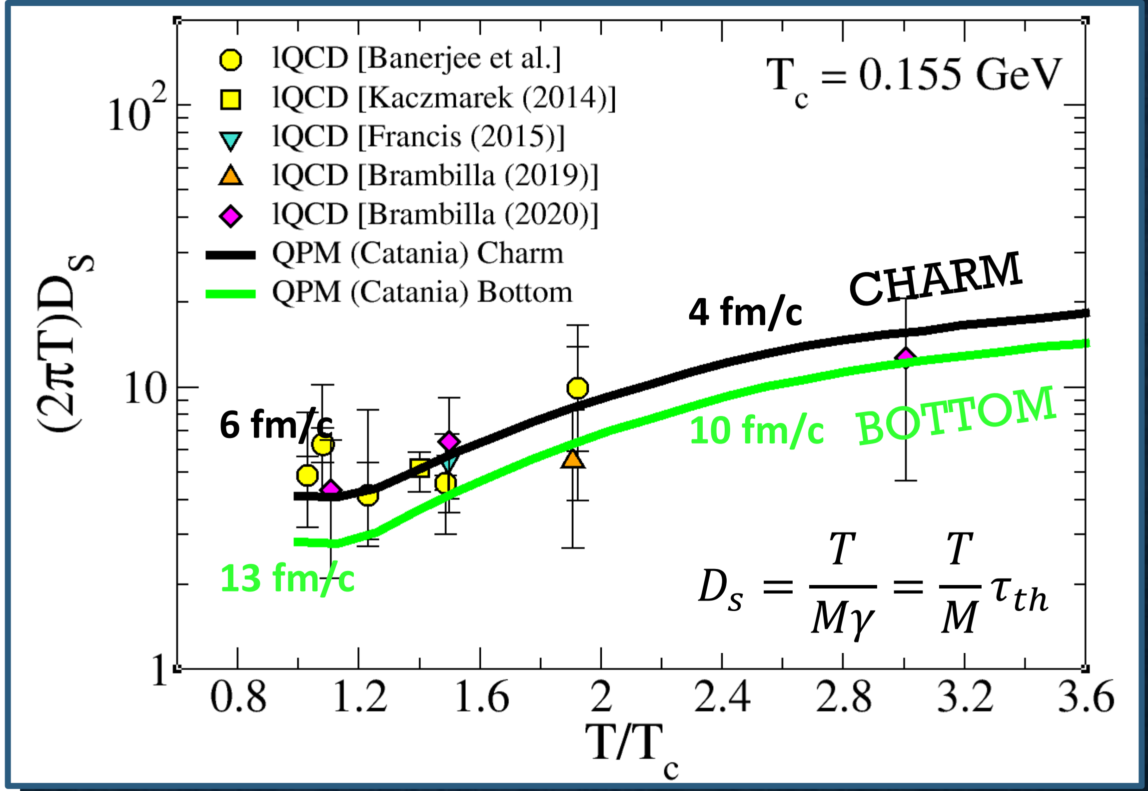
NUCLEAR MODIFICATION FACTOR





ELLIPTIC FLOW

- D_s is ideally M independent (M → ∞) since from kinetic theory: $\tau^b_{th}/\tau^c_{th} \approx \gamma_c/\,\gamma_b \approx M_b/M_c$
- $\tau_{th} \simeq 1.3\, M\, \dfrac{2\pi T D_s}{(T/T_c)^2}$ fm/c a measure of thermalization time



CHARM vs BOTTOM SPATIAL DIFFUSION COEFFICIENT

- ➢ In QPM approach D_s(c) is 30-40% larger than D_s(b)
- ➢ Bottom quarks expected to be fully thermalized @ FCC

M.L. Sambataro, V. Minissale et al., in preparation

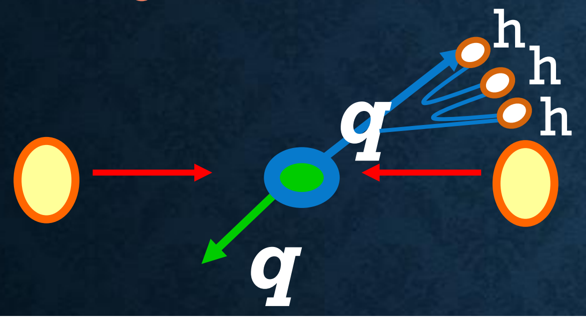
HADRONIZATION: HEAVY SECTOR

FRAGMENTATION

$$\frac{dN_h}{d^2p_h} = \Sigma_f \int dz \, \frac{dN_f}{d^2p_f} D_{f \to h}(z)$$

Peterson fragmentation function

Picture credit: Vincenzo Greco



COALESCENCE

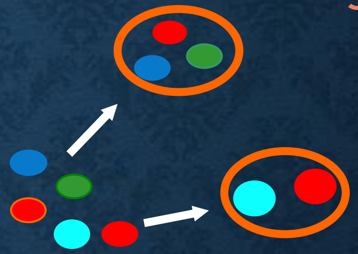
$$\frac{dN_{Hadron}}{d^2p_T} = g_H \int \prod_{i=1}^{n} p_i \cdot d\sigma_i \, \frac{d^3p_i}{(2\pi)^3} \, f_q(x_i, p_i) \, f_W(x_1, \dots, x_n; p_1, \dots, p_n) \, \delta\left(p_T - \sum_i p_{iT}\right)$$

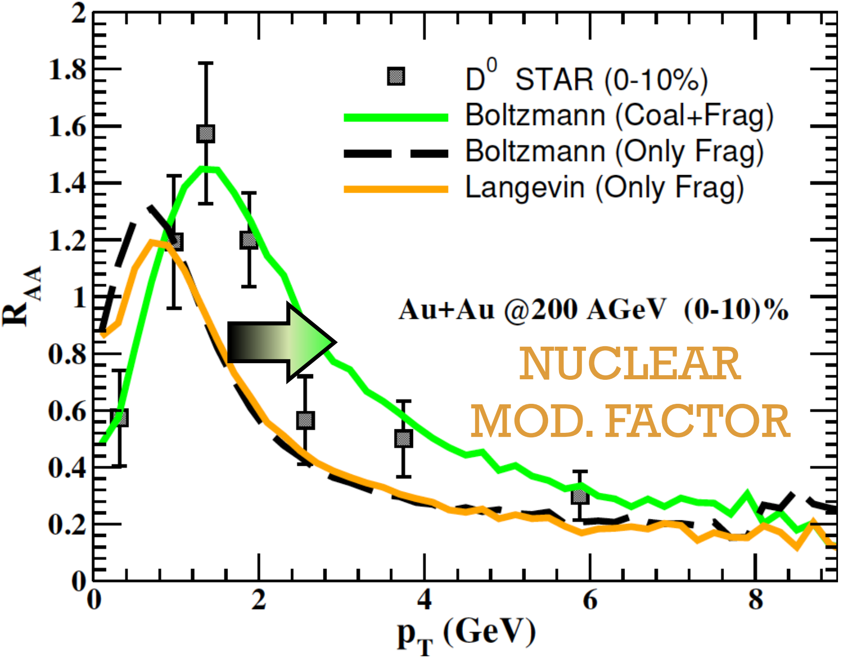
S. Plumari, V. Minissale et al.,
Eur. Phys. J. C 78, 348 (2018)

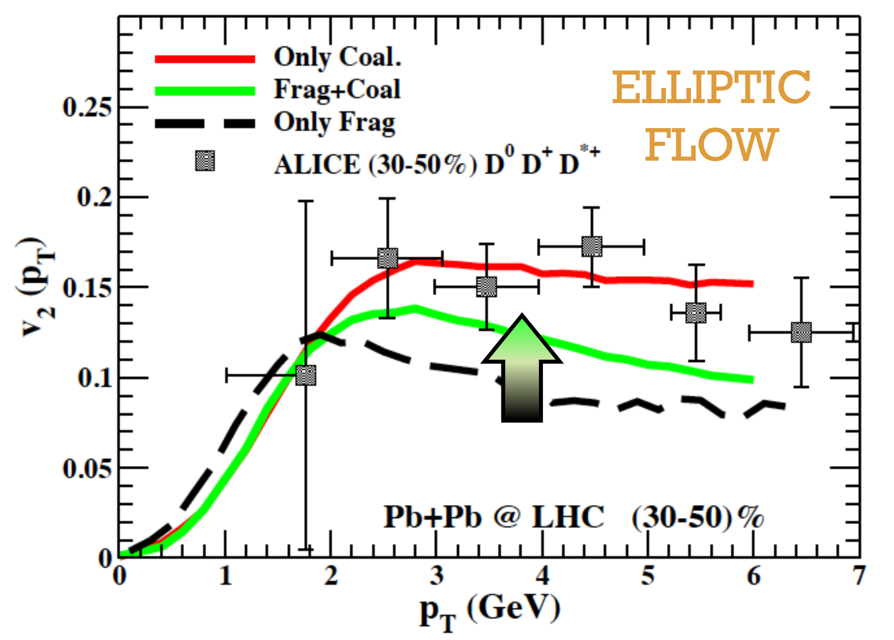
Wigner function

$P_{coal} = 1$ for $p = 0$

SEE MORE ON TALK OF VINCENZO MINISSALE





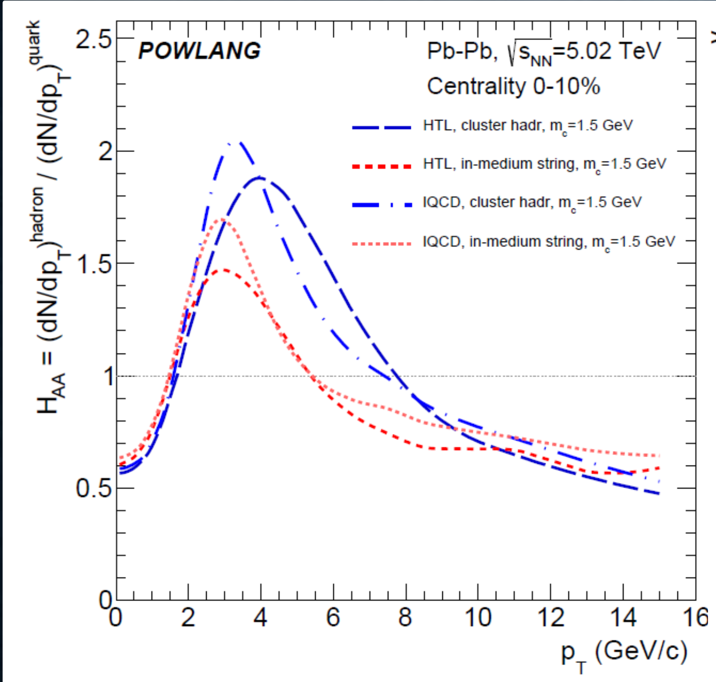


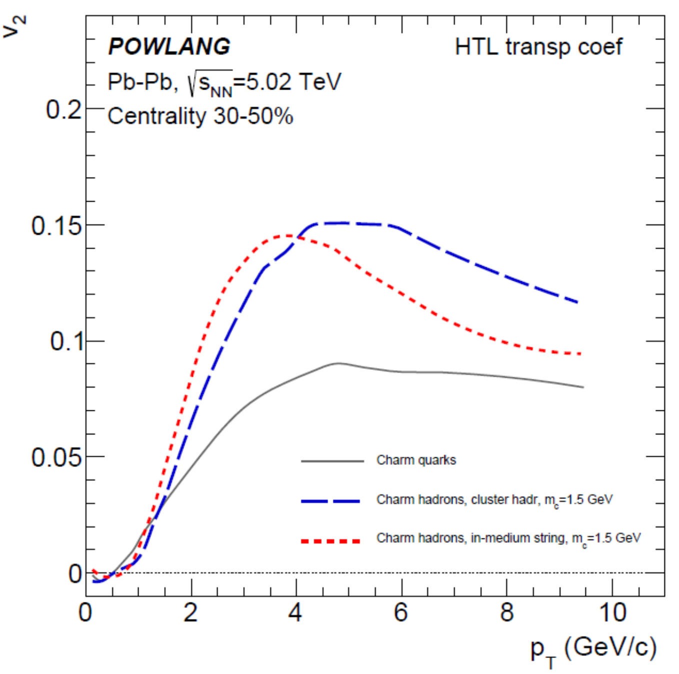
Coalescence for D mesons brings up R_{AA} and v_2 toward data

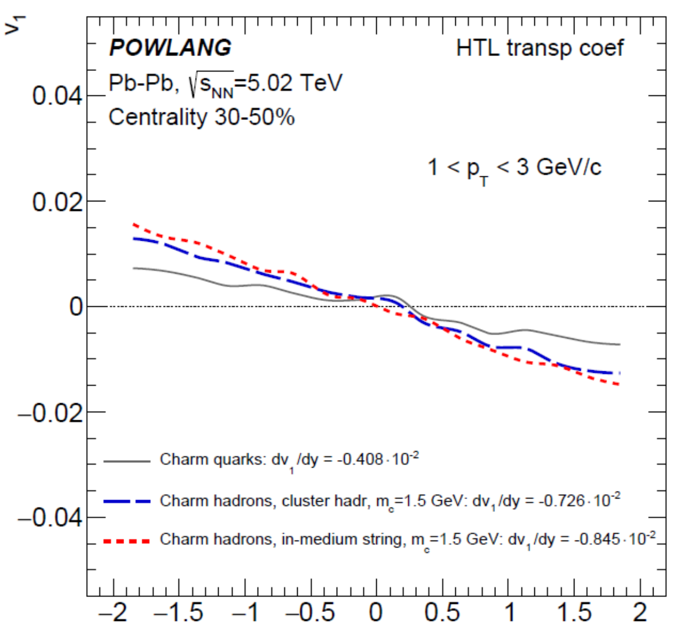
Scardina et al.,
Phys. Rev. C 96, 044905 (2017)

Coalescence predicts the large enhancement of baryon charm production measured by ALICE in pp collisions

HADRONIZATION: HEAVY SECTOR







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

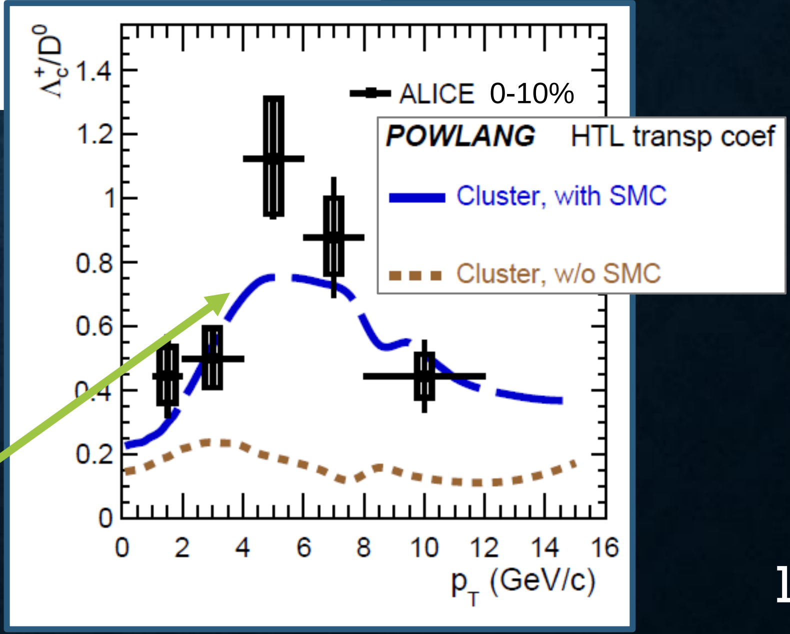
DIRECTED FLOW

$$y = \tanh^{-1}\frac{v_z}{c}$$

RAPIDITY
relativistic analog
of velocity
(v_z: longitudinal
particle velocity)

POWLANG APPROACH

- Hadronization via **in-medium recombination with string-breaking** enhances the $v_2(p_T)$ and for $1<p_T<3$ GeV the $v_1(y)$ of *D* mesons
  Beraudo, De Pace, Monteno, Nardi and Prino, JHEP 05, 279 (2021)
- **Cluster-hadronization** scheme enhances the radial flow of charmed hadrons w.r.t. string fragmentation; peak of v_2 is moved to higher p_T; enhancement of Λ_c^+/D^0 due to space-momentum correlations (SMC)
  Beraudo, De Pace, Monteno, Nardi and Prino, 2202.08732



INTENSE FIELDS AND HEAVY FLAVOR TRANSPORT

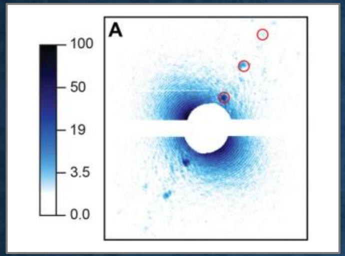
✓ HUGE ANGULAR MOMENTUM GENERATING A STRONG **VORTICITY**

tornado cores

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

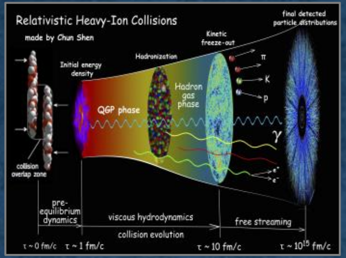
Jupiter's spot

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



He nanodroplets

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



urHICs

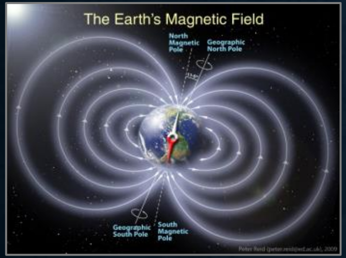
~ 10^{22}–$10^{23}\ s^{-1}$

vorticity ω

since 2017

impact on HQ transport coefficients and *D* meson directed flow

✓ INTENSE **ELECTROMAGNETIC FIELDS**



Earth's field

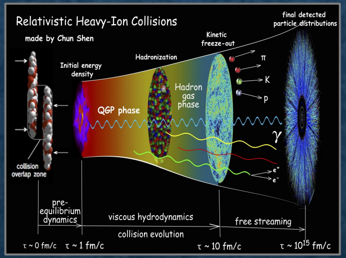
~ 1 G

laboratory

~ 10^{6} G

magnetars

~ 10^{14}–10^{15} G



urHICs

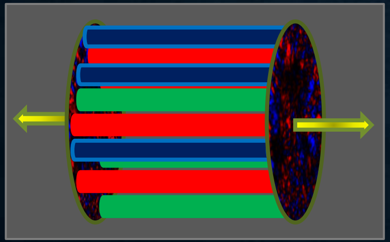
~ 10^{18}–10^{19} G

magnetic field *B*

since 2016

impact on *D* meson directed flow

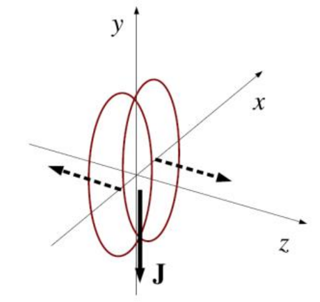
✓ INTENSE **COLOR FIELDS** IN THE EARLY STAGE OF URHICS



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 nuclear system

- in ultra-relatvistic HICs **$J \approx 10^5$ - 10^6 ħ**
- dominated by the y component perpendicular to the reaction plane
- partly transferred to the plasma

asymmetry in local participant density from forward and backward going nuclei

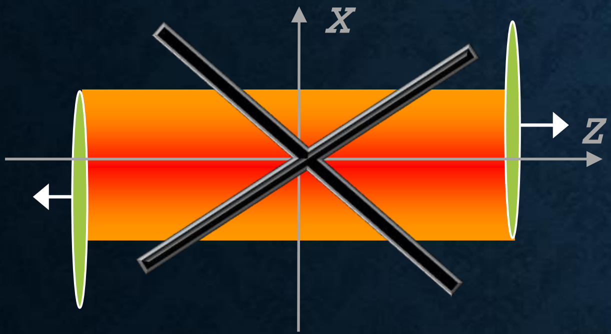
Bozek and Wyskiel, Phys. Rev. C 81, 054902 (2010)

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

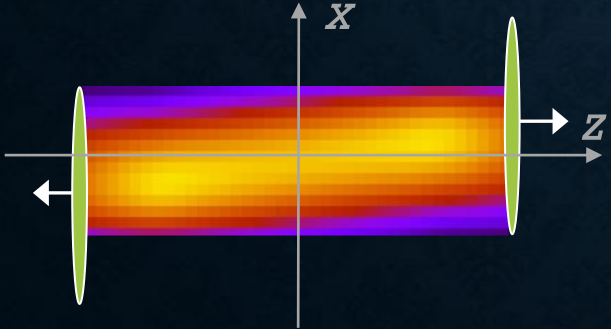
$$W(x_\perp,\eta_s) = 2\left(N_A(x_\perp)f_-(\eta_s) + N_B(x_\perp)f_+(\eta_s)\right)$$

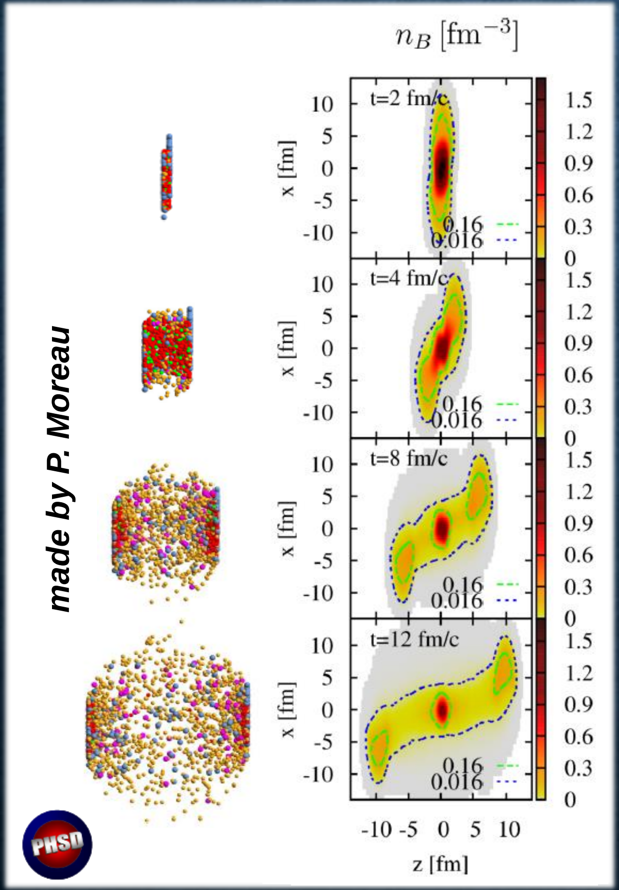
$$f_+(\eta_s) = f_-(-\eta_s) = \begin{cases} 0 & \eta_s < -\eta_m \\ \frac{\eta_s \boxed{+\eta_m}}{2\eta_m} & -\eta_m \le \eta_s \le \eta_m \\ 1 & \eta_s > \eta_m \end{cases}$$

Not a symmetric energy distribution…



…but a TILTED FIREBALL on the reaction plane





tilted initial conditions for the hydrodynamic or transport evolution of QGP

SPACETIME RAPIDITY

$\eta_s = \tanh^{-1}\frac{z}{t}$

PROPER TIME

$\tau = \sqrt{t^2 - z^2}$

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

THE VORTICAL QUARK-GLUON PLASMA

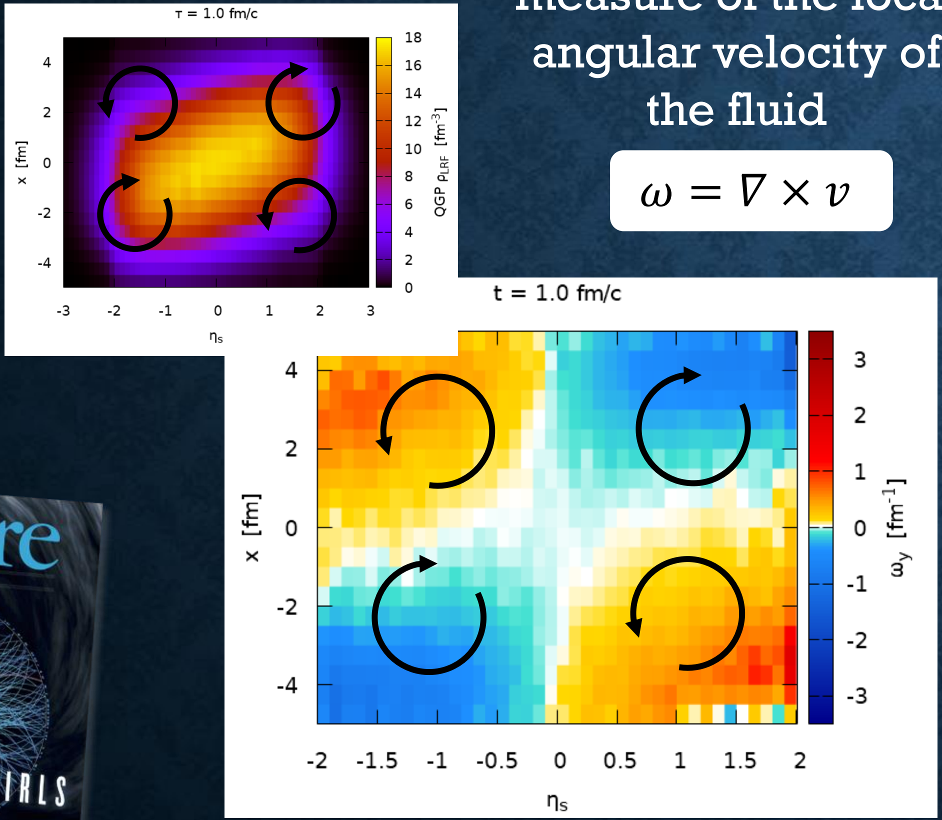
Oliva, Plumari and Greco, JHEP 05, 034 (2021)

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

an intense VORTICITY

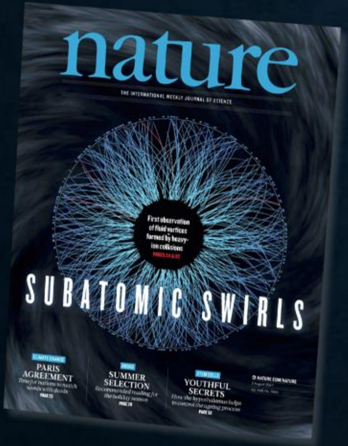
measure of the local angular velocity of the fluid

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



NONRELATIVISTIC VORTICITY

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

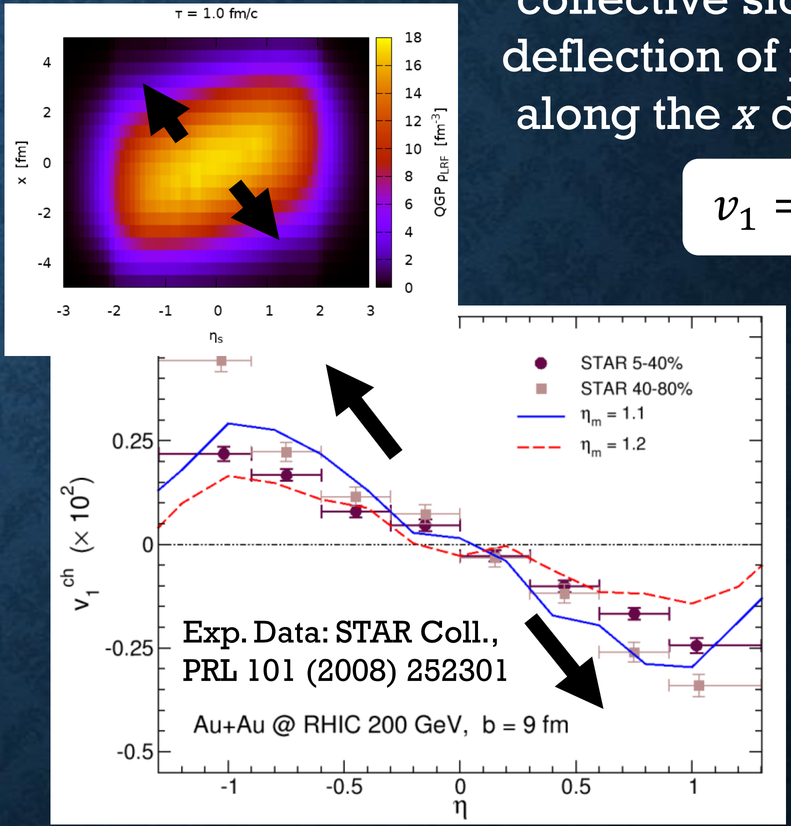


STAR Collaboration, Nature 548, 62 (2017)

a DIRECTED FLOW

collective sidewards deflection of particles along the *x* direction

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



$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

PSEUDORAPIDITY

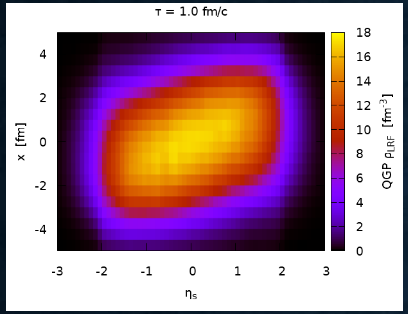
(θ: polar angle of particle momentum)

CHARGED PARTICLES DIRECTED FLOW

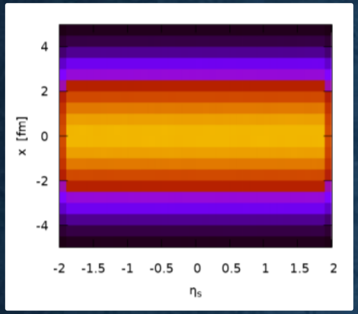
Negative slope in the η dependence of the v_1 of bulk particles due to the "tilt" ($v_1 = 0$ if the fireball is not tilted)

DIRECTED FLOW OF NEUTRAL D MESONS

tilted fireball



HQs production points



Excellent qualitative prediction with LV approach
$dv_1^D/dy \approx$ 0.02-0.04 (≈ 10-15 times larger than light charged)
Chatterjee and Bozek, Phys. Rev. Lett. 120, 192301 (2018)

LHC ENERGY:

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

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

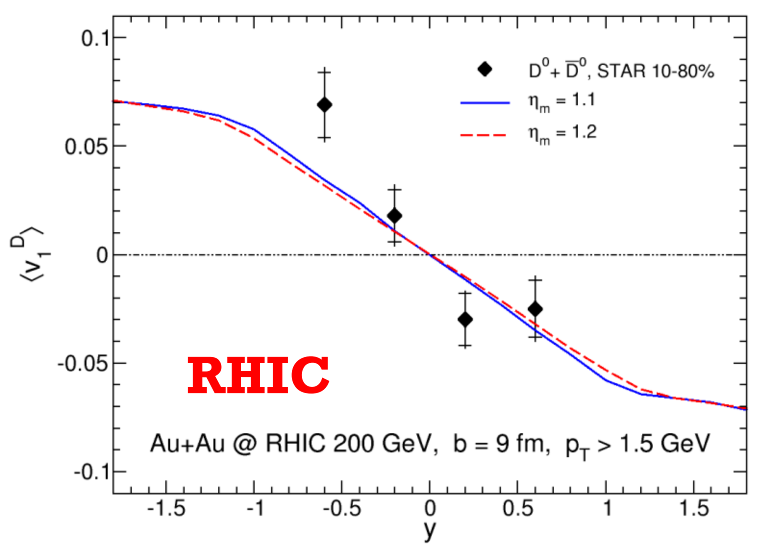
RHIC ENERGY

EXP: $dv_1^D/dy = -0.080 \pm 0.017(\mathrm{stat}) \pm 0.016(\mathrm{syst})$

about 30 times larger than that of kaons

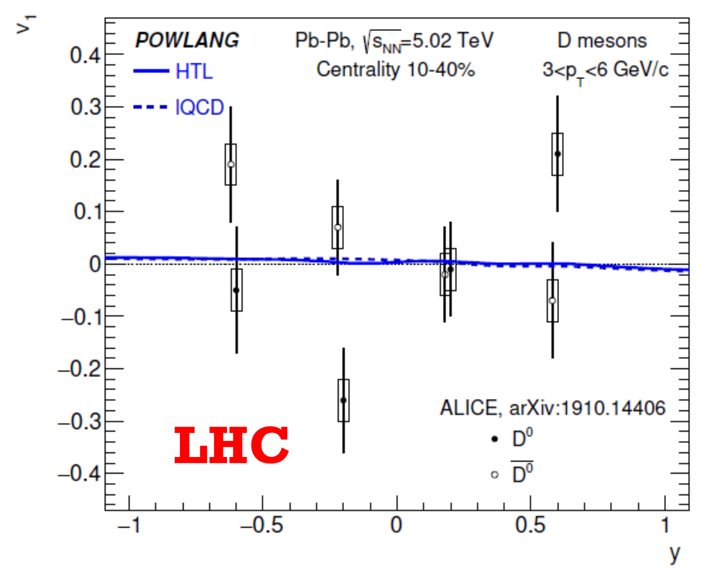
TH: $dv_1^D/dy = -0.065$ (25-30 times larger than ch.)

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



Exp. data: STAR Coll.,
Phys. Rev. Lett.. 123 (2019) 162301

Hadronization via in-medium recombination with string-breaking can enhance the D-meson $v_1(y)$ (for $1<p_T<3$ GeV)



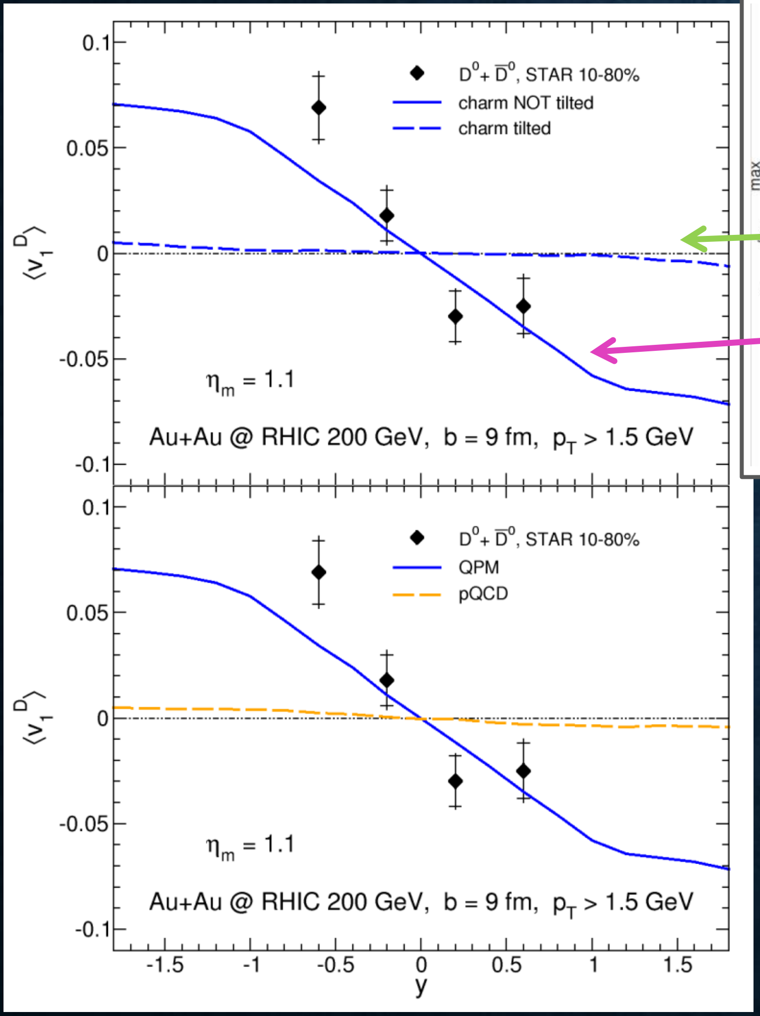
Exp. data: ALICE Collaboration,
Phys. Rev. Lett. 125, 022301 (2020)

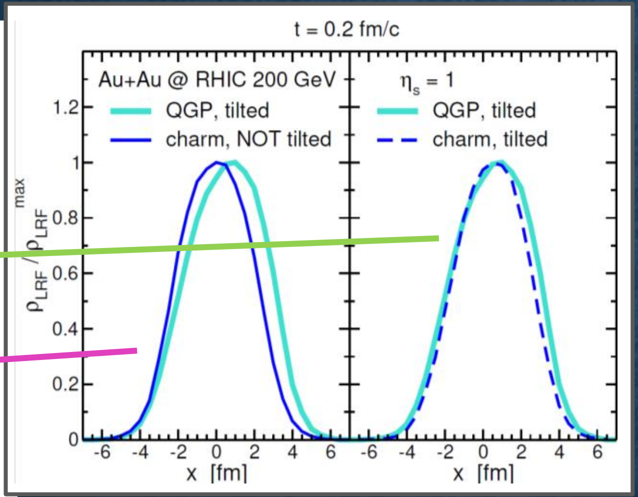
ORIGIN OF D MESON DIRECTED FLOW

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

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

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

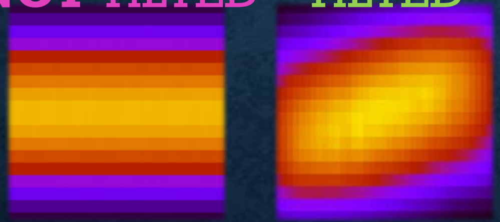




longitudinal asymmetry leads to pressure push of the bulk on the HQs

CHARM **NOT** TILTED

CHARM TILTED



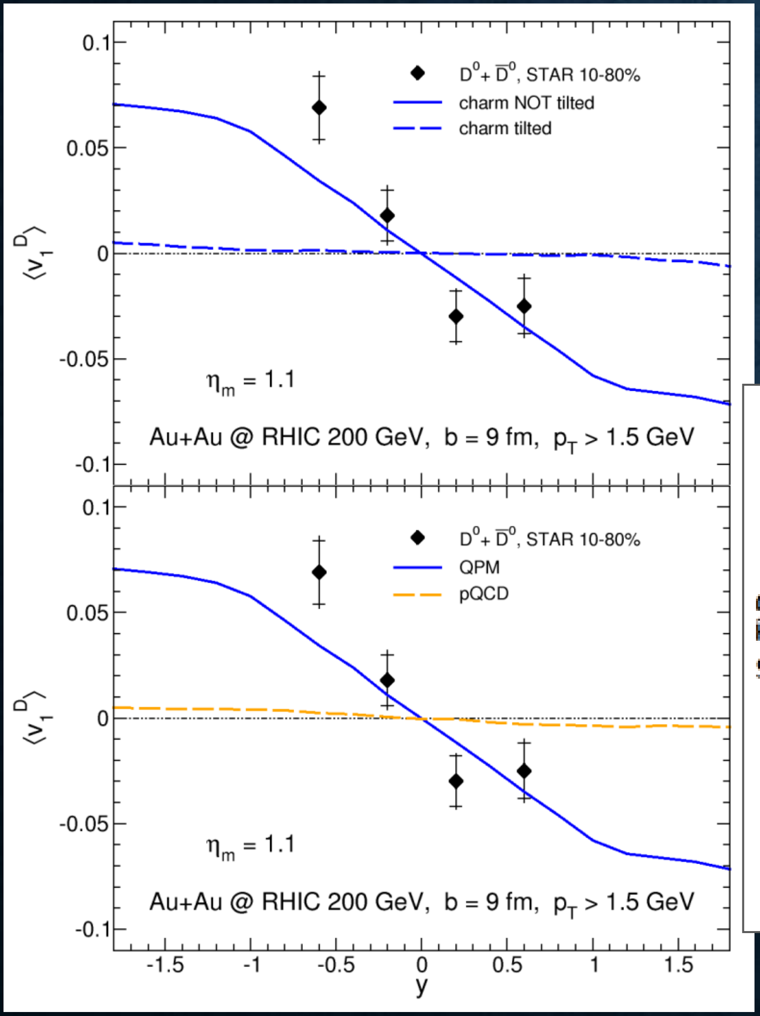
QGP tilted in both cases

ORIGIN OF D MESON DIRECTED FLOW

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

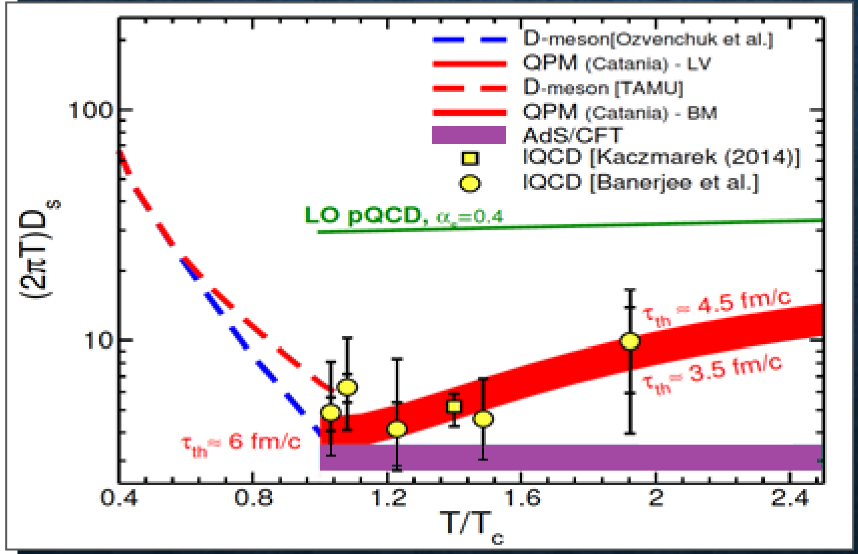
origin of the large directed flow of HQs different from the one of light particles

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



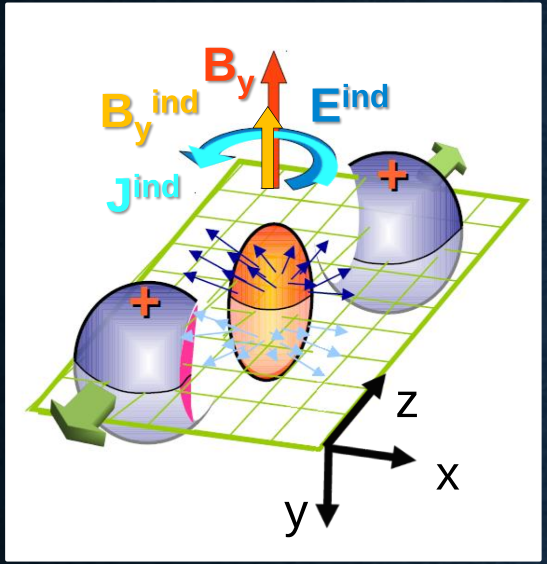
Greco, NPA 967, 200 (2017)

Similar conclusions with POWLANG approach

Beraudo et al., 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**

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

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

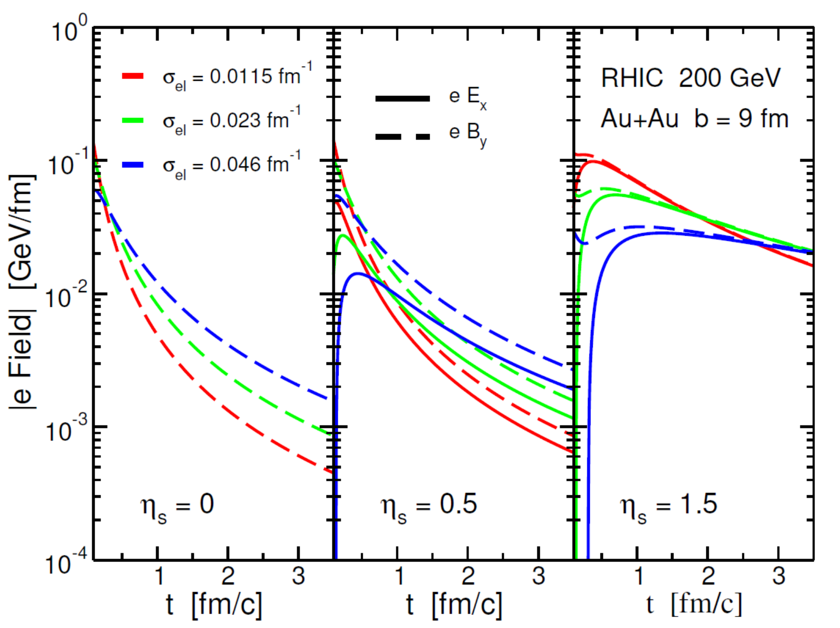
$$\rho = \rho_{ext} \qquad J = J_{ext} + J_{ind}$$
$$\rho_{ext} = e\delta(z-\beta t)\delta(x_\perp - x'_\perp)$$
$$J_{ext} = \hat{z}\beta e\delta(z-\beta t)\delta(x_\perp - x'_\perp)$$

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

induced current from Ohm's law

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)



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

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

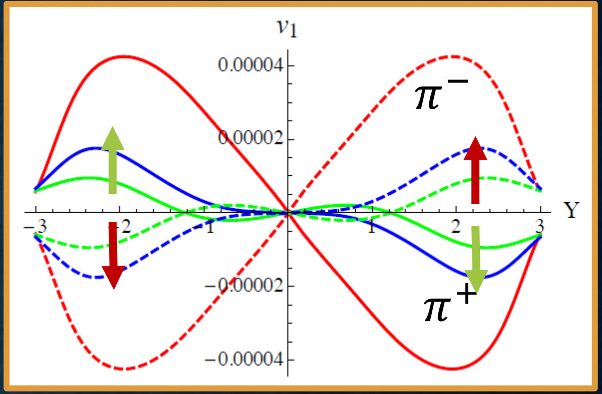
BM eq. with EM interaction term

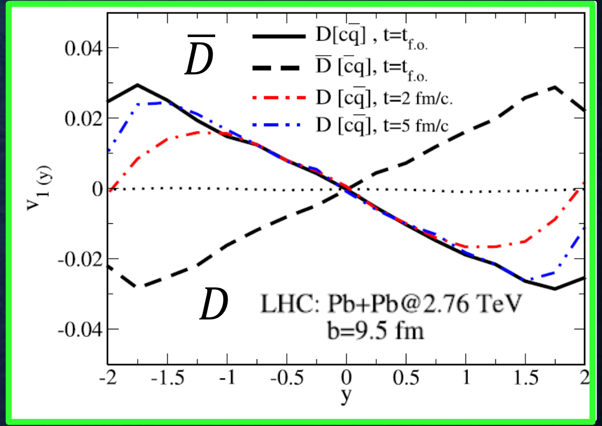
EMF AND DIRECTED FLOW

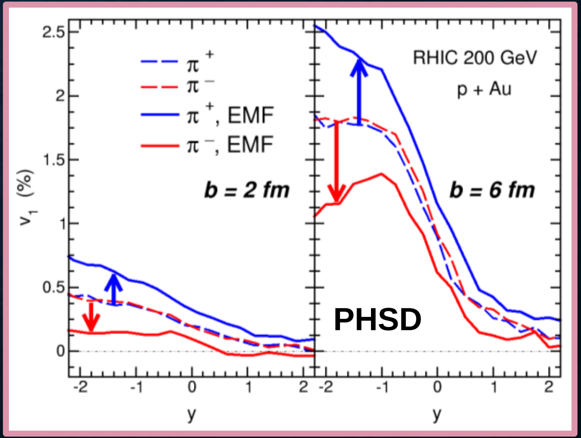
The huge EM fields induce a splitting in the DIRECTED FLOW of particles with the same mass and opposite charge

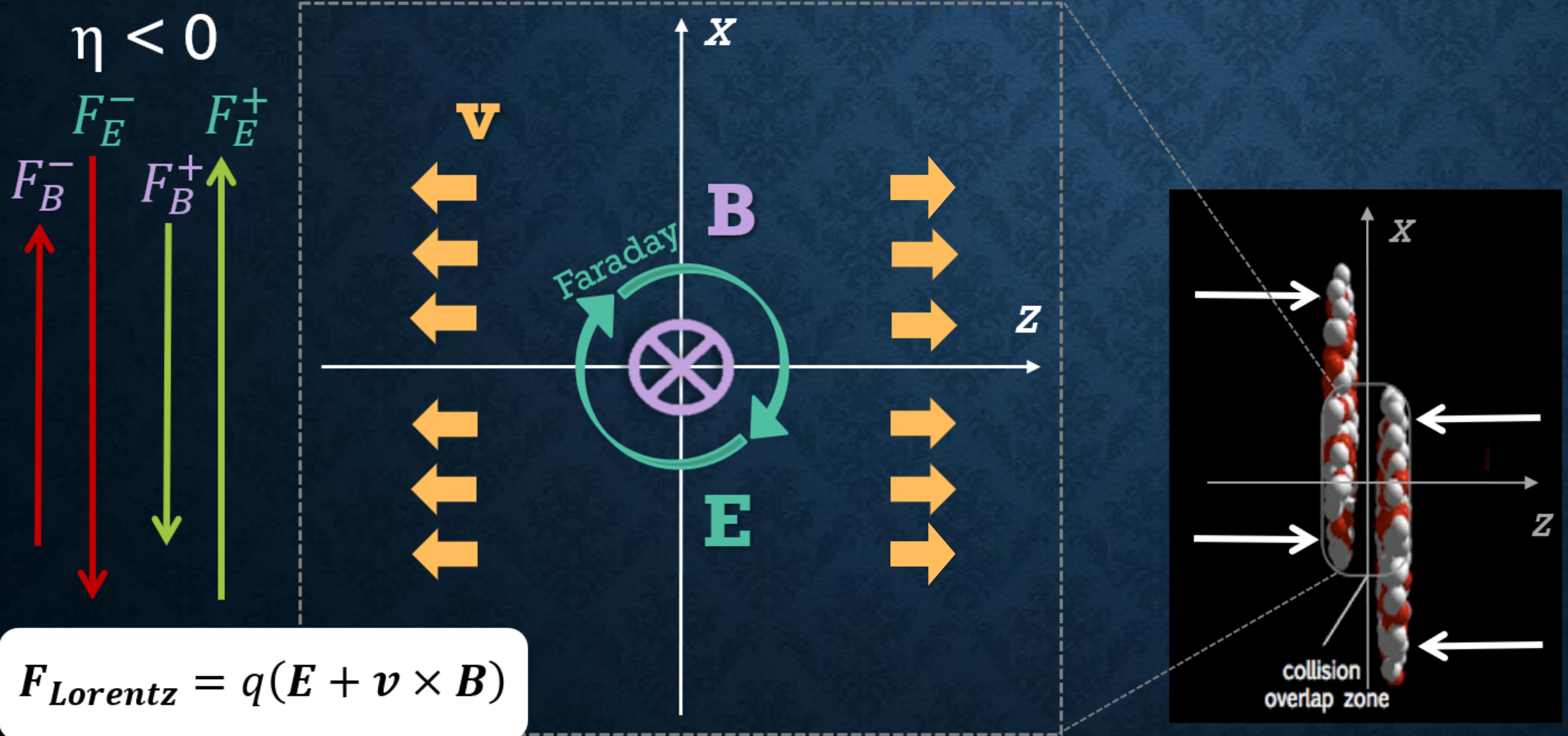
$$\Delta v_1 = v_1^+ - v_1^-$$

- ➢ Δv_1 of light hadrons in AA: $O(10^{-4}$–$10^{-3})$
  Gursoy et al., Phys. Rev. C 89, 054905 (2014)
- ➢ Δv_1 of heavy mesons in AA: $O(10^{-2})$
  Das et al., Phys. Lett. B 768, 260 (2017)
- ➢ Δv_1 of light mesons in pA: $O(10^{-2})$
  Oliva et al., Phys. Rev. C 101, 014917 (2020)









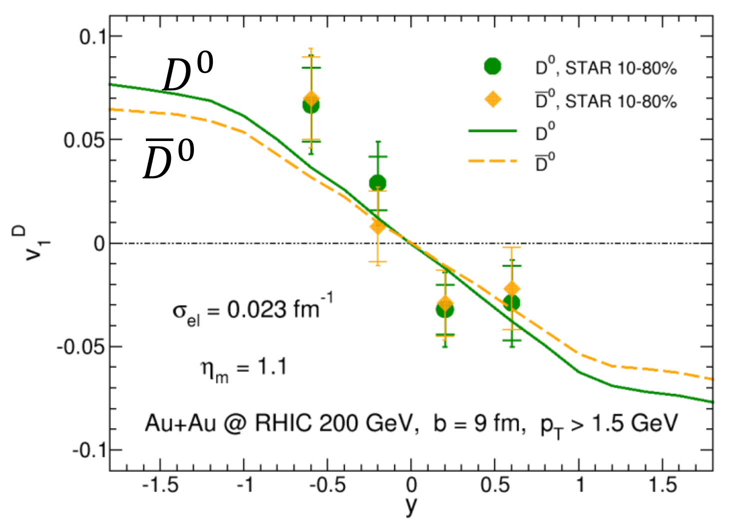
$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

reviews

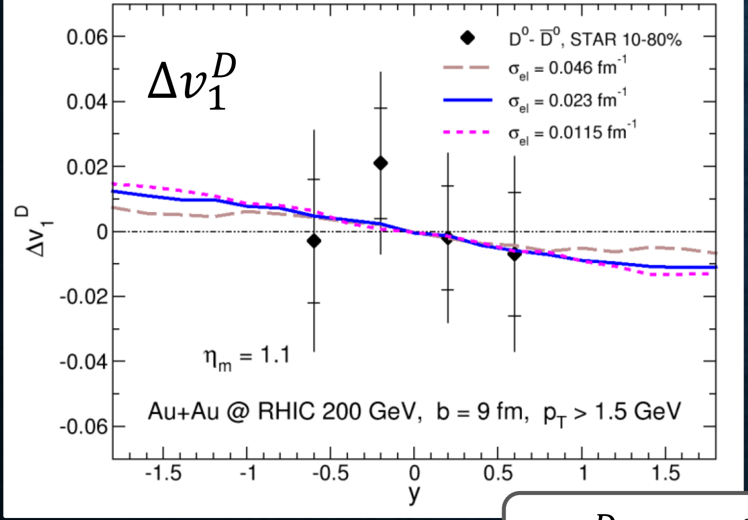
Oliva, Eur. Phys. J. A 56, 255 (2020)
Dubla, Gursoy and Snellings, Mod. Phys. Lett. A 35, 2050324 (2020)

DIRECTED FLOW IN A+A AT RHIC ENERGY

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



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



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

DIRECTED FLOW OF NEUTRAL D MESONS

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

RHIC ENERGY

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

$d(\Delta v_1)/dy|_{th} = -0.01$

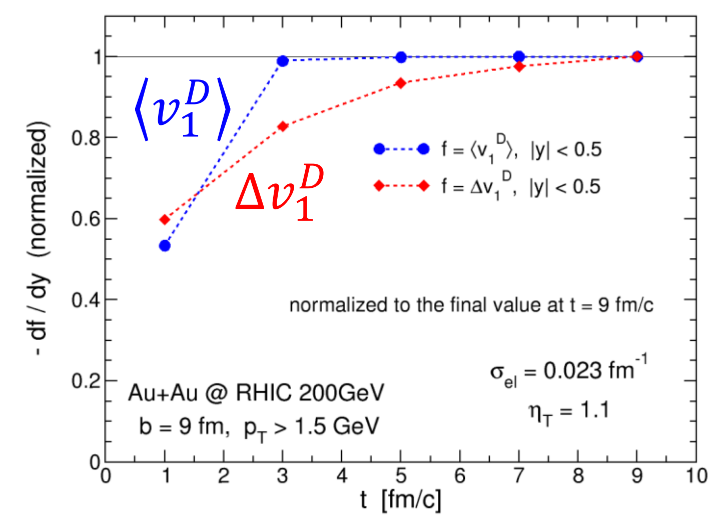
≈ 10 times larger than charged
in agreement with
Das et al., Phys. Lett. B 768, 260 (2017)

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

Δv_1 (HQ) ≫ Δv_1 (QGP)

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

SLOPE TIME EVOLUTION



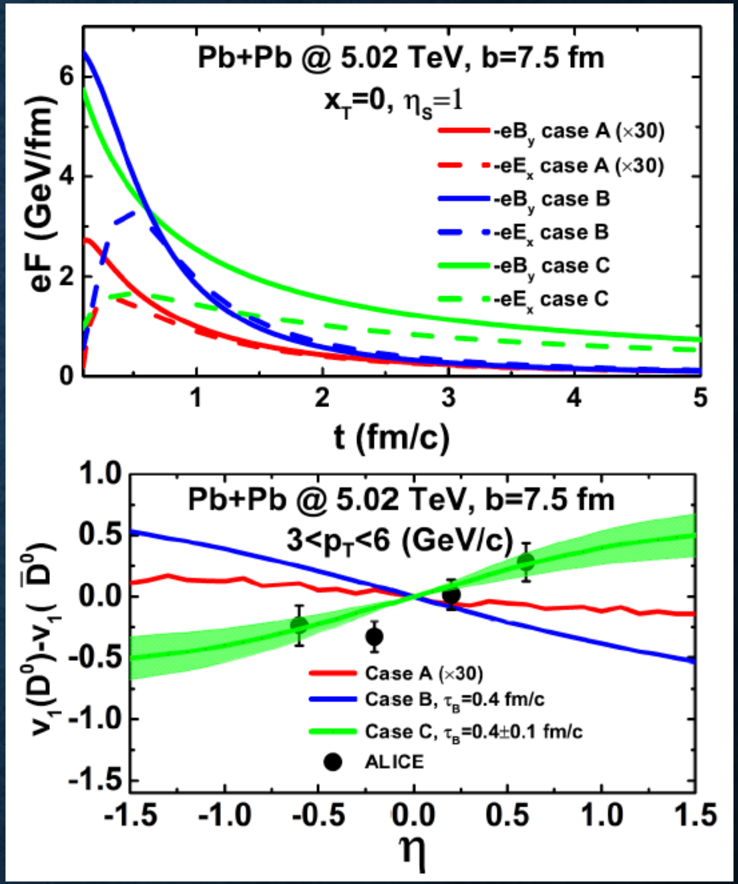
v_1^D more sensitive to the early QGP evolution when T is higher, while v_2^D probes more $T \sim T_c$
→ include v_1^D in Bayesian fits

DIRECTED FLOW IN A+A AT LHC ENERGY

LHC ENERGY   ALICE Coll., Phys. Rev. Lett. 125, 022301 (2020)
the $\Delta v_1{}^D$ has opposite sign and magnitude ~ 40 times larger than models
$(\Delta v_1^D(\text{LHC}) \approx \Delta v_1^D(\text{RHIC}))$

- Analytic solution of EM fields with constant σ_{el} case A
- B parametrization between in-vacuum and in-medium decay:
  $B(\tau) = B_0/[1+(\tau/\tau_B)^n]$ n=2 case B   n=1 case C
  E from Faraday law

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



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

DIRECTED FLOW IN A+A AT LHC ENERGY

LHC ENERGY ALICE Coll., Phys. Rev. Lett. 125, 022301 (2020)

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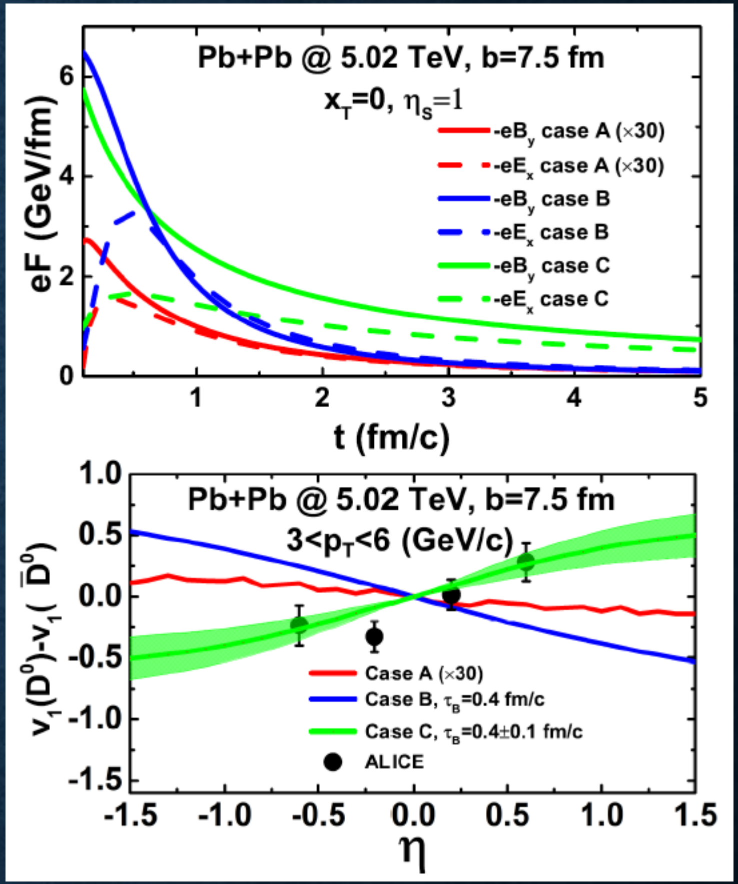
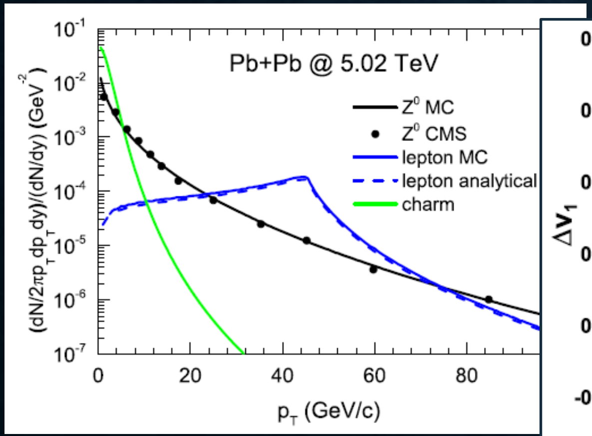
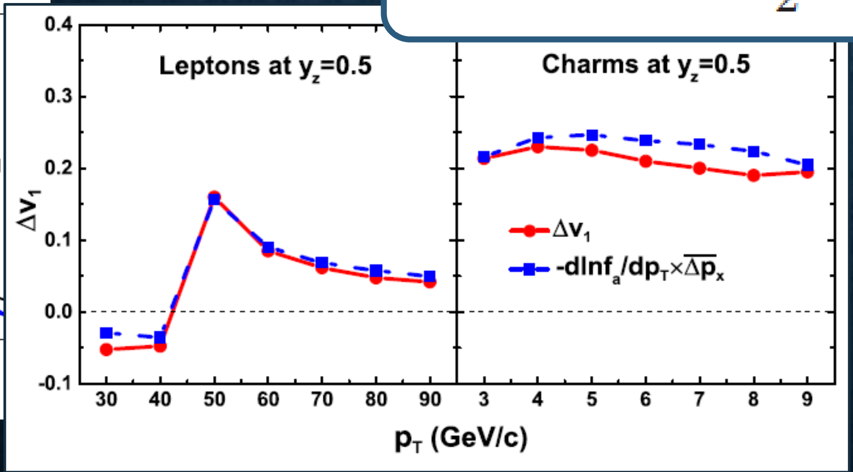


Probing the EMF with leptons from Z^0 decay:

- ▪ charged leptons only EM interaction
- ▪ $\tau_{decay}(Z^0) \approx \tau_{form}(c) \approx 0.08$ fm/c

$$v_1(p_T,y) \approx \frac{\overline{\Delta p_x}(p_T,y)}{2}\,\frac{-\partial \ln f_a}{\partial p_T}$$





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

Δv_1 of leptons from Z^0 decay can help to clarify the EM origin of Δv_1 of D^0 mesons

if Δv_1 of neutral D mesons has EM origin
it is a proof of QGP formation

HEAVY QUARKS IN THE GLASMA

What happens for 0<t<0.3 fm/c?
Imprints of early stage on HQ 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

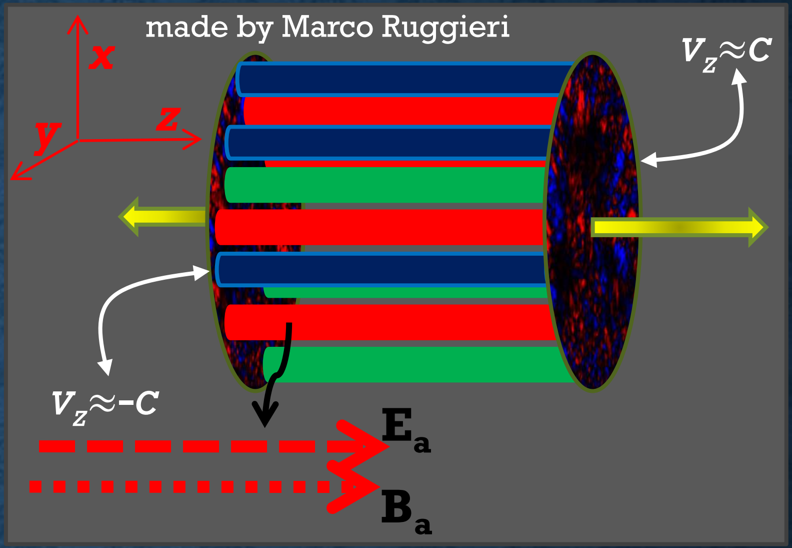
$$\begin{aligned} E^i &= \tau\partial_\tau A_i, & \partial_\tau E^i &= \frac{1}{\tau}D_\eta F_{\eta i} + \tau D_j F_{ji}, \\ E^\eta &= \frac{1}{\tau}\partial_\tau A_\eta, & \partial_\tau E^\eta &= \frac{1}{\tau}D_j F_{j\eta}. \end{aligned}$$

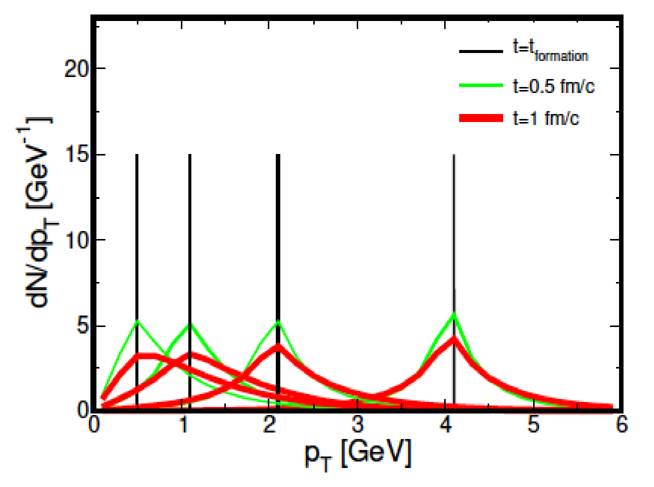
solved in SU(2)

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

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

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

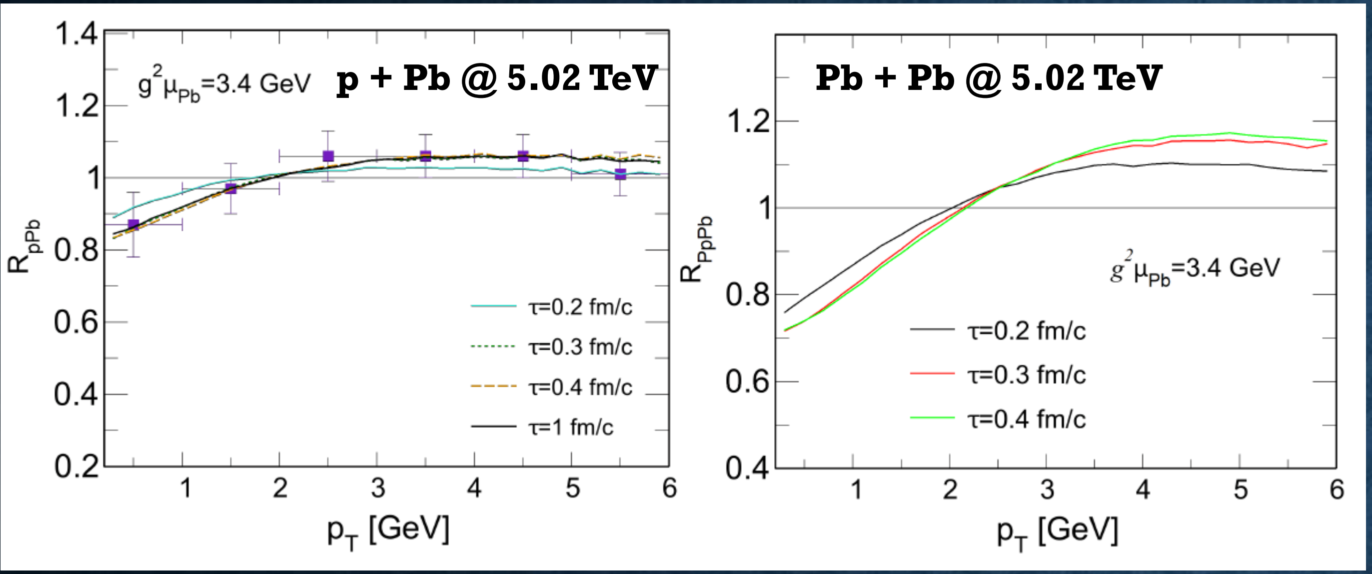

made by Marco Ruggieri



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)

HEAVY QUARKS IN THE GLASMA

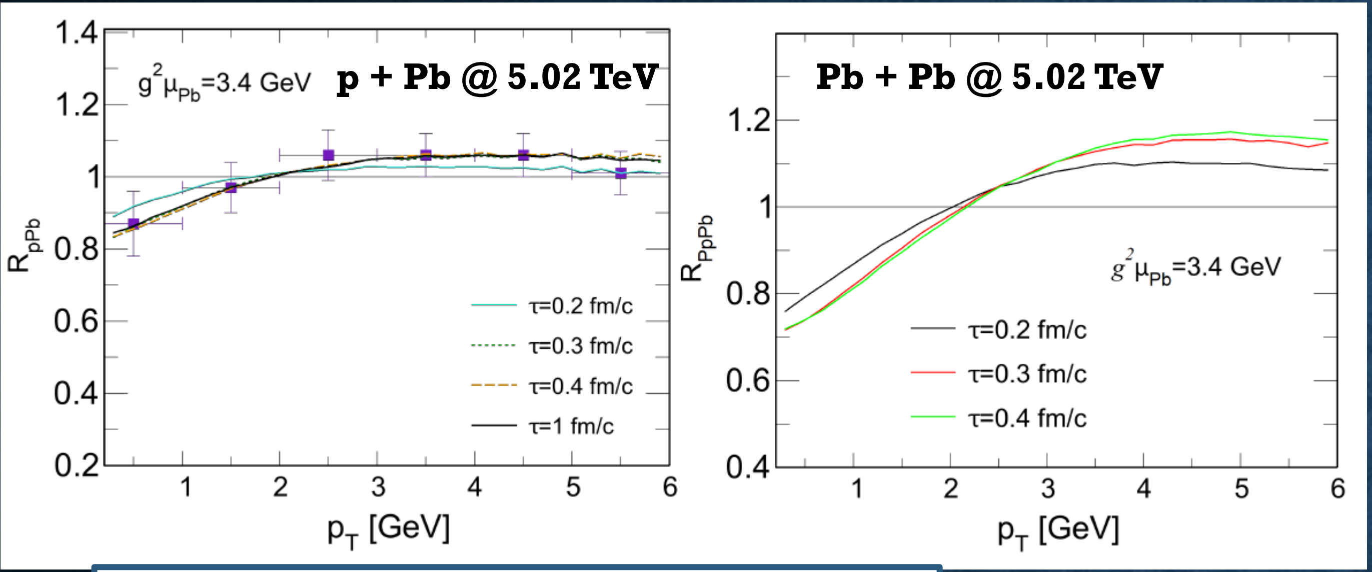


Strong and fast diffusion of HQs in the glasma

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

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

HEAVY QUARKS IN THE GLASMA



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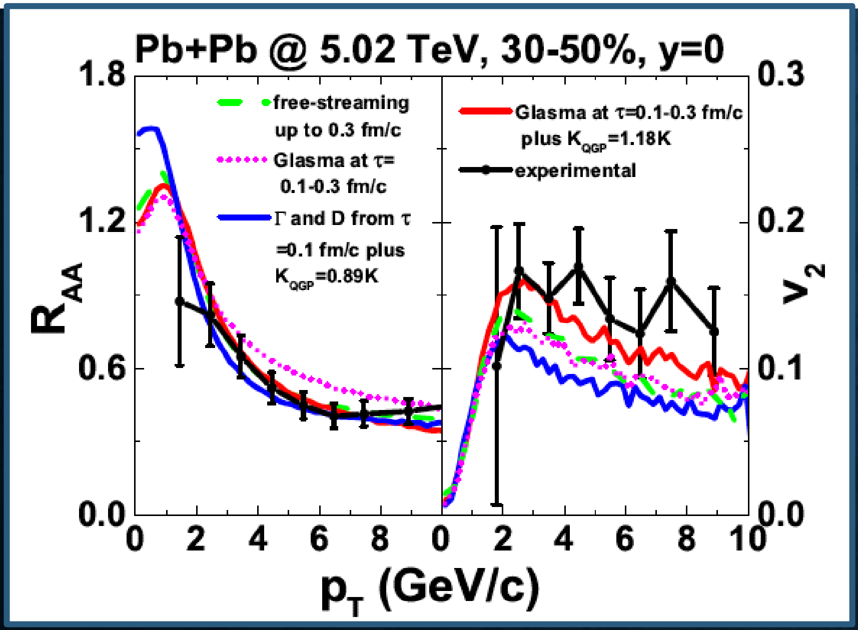
Liu, Plumari, Das, Greco and Ruggieri,
Phys. Rev. C 102, 044902 (2020)



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 AND FUTURE PERSPECTIVES

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 recombination/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 QGP.

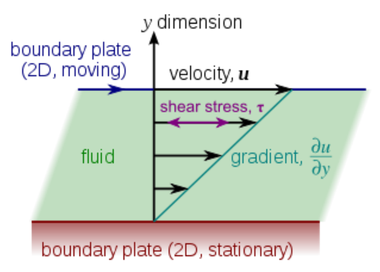
→ The Δv_1 of neutral D mesons is well described at RHIC energy but still a challenge at LHC. If confirmed to be of EM origin it is a proof of QGP formation and can constrain EM field evolution.

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

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!

QGP AS A NEARLY PERFECT FLUID

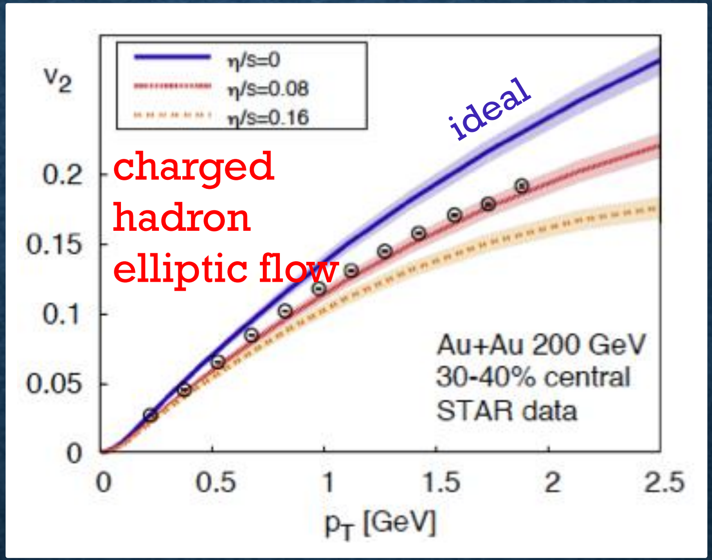


$$\frac{F_x}{A_{yz}} = -\eta \frac{\partial u_x}{\partial y}$$

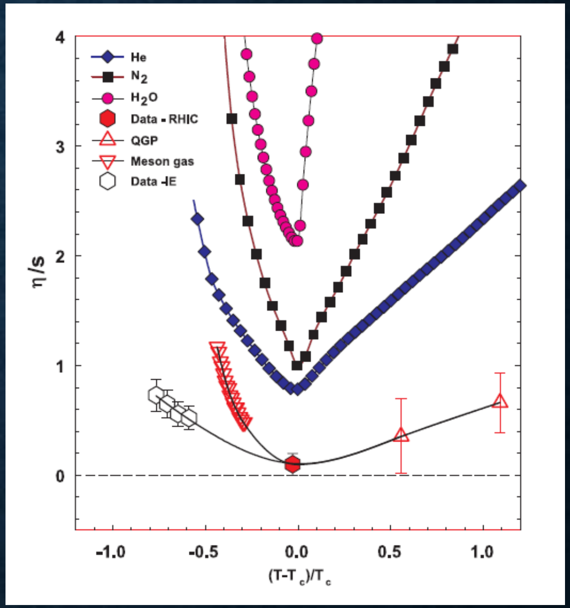
SHEAR VISCOSITY η
is a measure of how velocity of fluid changes with depth

SHEAR VISCOSITY OVER ENTROPY DENSITY RATIO η/s
is a measure of how much the system is strongly coupled

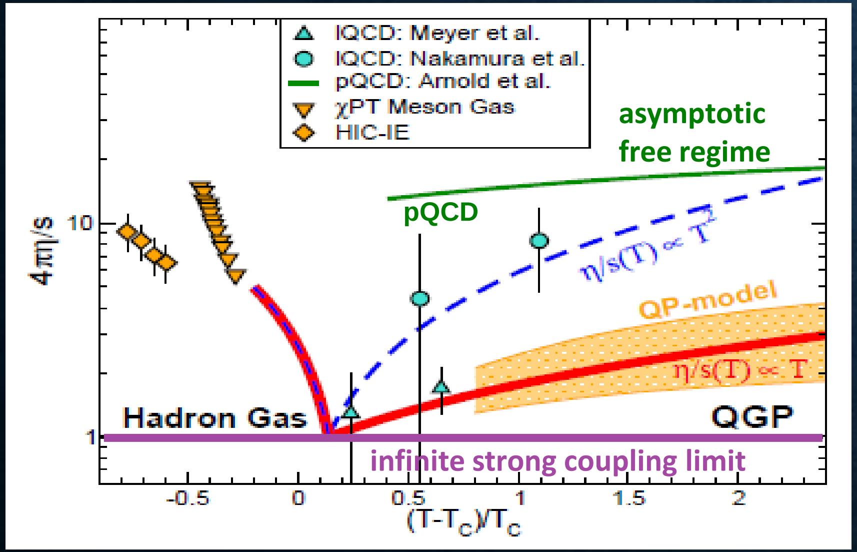
NON-PERTURBATIVE behaviour of QGP



Schenke, Jeon and Gale,
Phys. Rev. Lett. 106, 042301 (2011)



Lacey and Taranenko,
PoS CFRNC2006, 021 (2006)



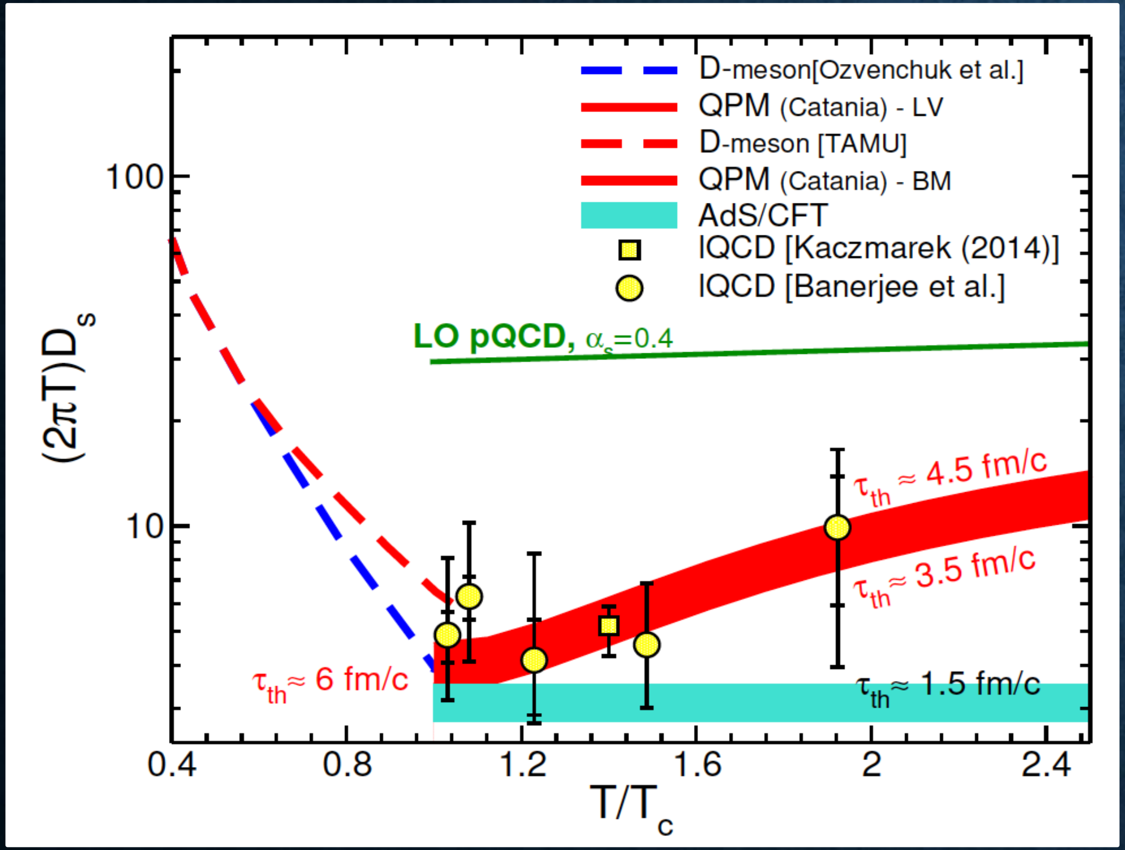
Plumari *et al.*, JPCS 420, 012029 (2013)

$$4\pi\eta/s \approx 1 - 2$$

QGP flows like an almost perfect fluid
with the smallest η/s ever observed in nature

CHARM SPATIAL DIFFUSION COEFFICIENT

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



CHARM-QUARK SPATIAL DIFFUSION COEFFICIENT

QGP diffuses charm quarks like an almost "perfect fluid"

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

	Matter State	D_s (cm^2/s)
Air in Water	liquid	2.0×10^{-5}
Hydrogen in Iron	solid	1.66×10^{-9}
HQ in QGP	Liquid?	$(100\text{-}500) \times 10^{-5}$

$$\tau_{th} \simeq 1.3\, M \frac{2\pi T D_s}{(T/T_c)^2}\ \mathrm{fm}/c$$

THERMALIZATION OF HEAVY QUARKS

The smaller D_s, the faster is the approach to thermalization

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

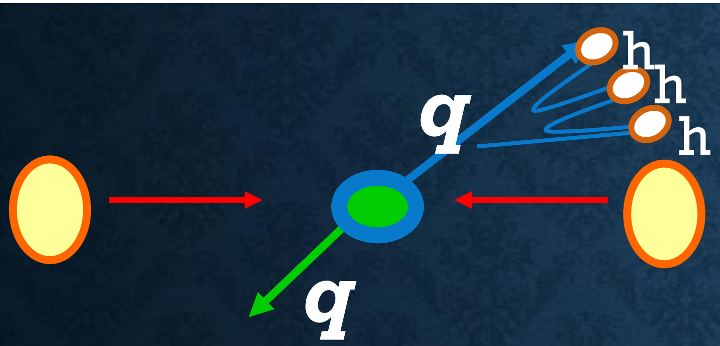
reviews

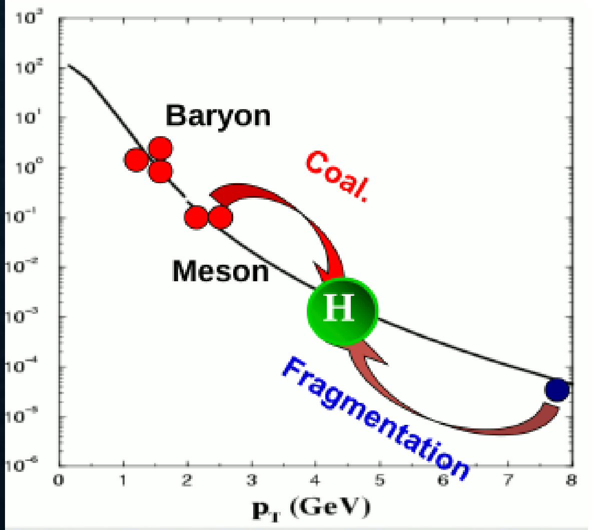
HADRONIZATION: LIGHT SECTOR

Fragmentation: e$^+$e$^-$, ep, pp

$$f_H(P_H = zp_T) = f_{q,g}(p_T) \otimes D_{q,g\to H}(z), \quad z < 1$$

Picture credit:
Vincenzo Greco

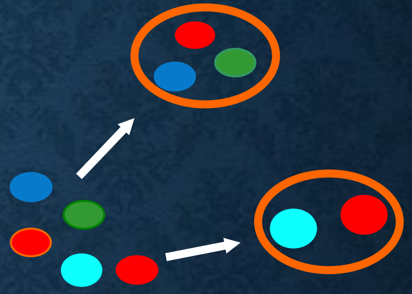


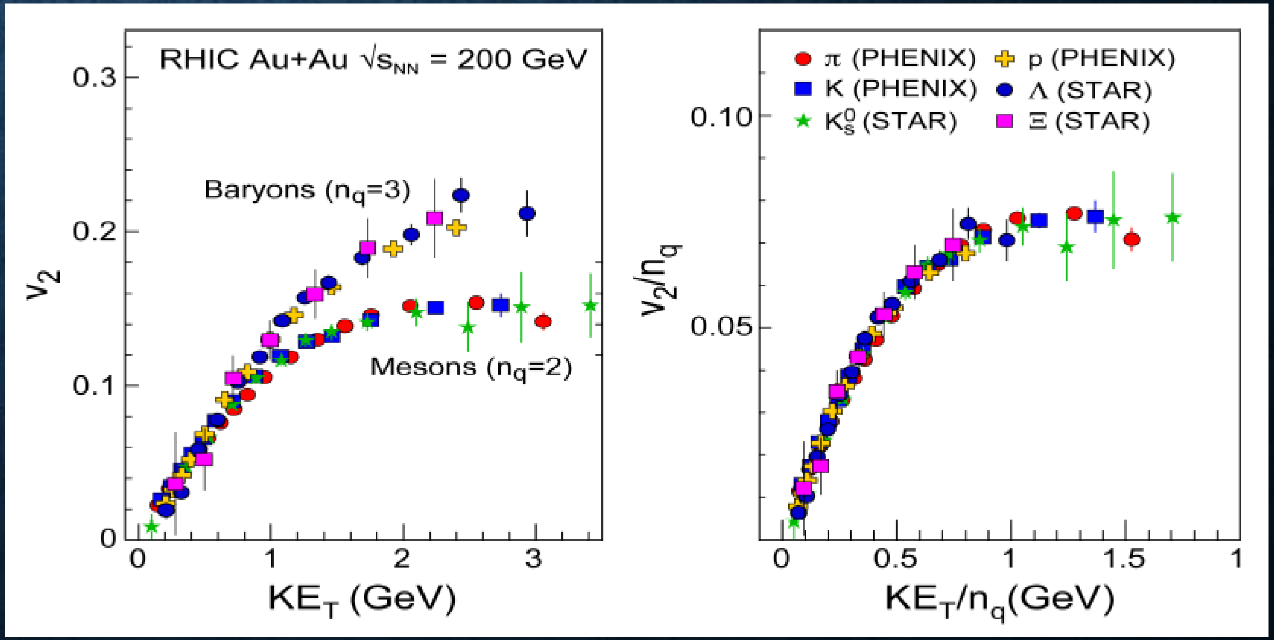


Greco, Ko and Levai, Phys. Rev. Lett. 90, 202302 (2003)
Fries, Muller, Nonaka and Bass, Phys. Rev. C 68, 044902 (2003)
Fries, Greco and Sorensen, Ann. Rev. Nucl. Part. Sci. 58, 177 (2008)

Quark recombination

$$f_H(P_H = 2p_T) \approx f_q(p_T) \otimes f_{\bar{q}}(p_T)$$





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)**

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

collision integral

$\eta/s \neq 0$

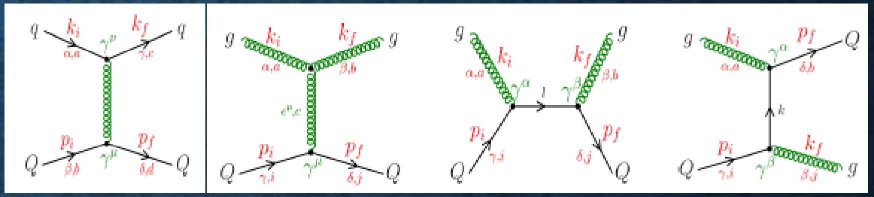
Instead of starting from cross sections we simulate a fluid at **fixed η/s**

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 **$\eta/s \approx 0.1$**



$$\begin{aligned}\mathcal{C}[f_Q] \;=\; & \frac{1}{2E_1}\int \frac{d^3p_2}{2E_2(2\pi)^3}\int \frac{d^3p_1'}{2E_{1'}(2\pi)^3} \\ & \times\left[f_Q(p_1')f_{q,g}(p_2') - f_Q(p_1)f_{q,g}(p_2)\right] \\ & \times\left|\mathcal{M}_{(q,g)+Q}(p_1p_2 \to p_1'p_2')\right|^2 \\ & \times(2\pi)^4\delta^4(p_1+p_2-p_1'-p_2')\ ,\end{aligned}$$

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

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

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

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)

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

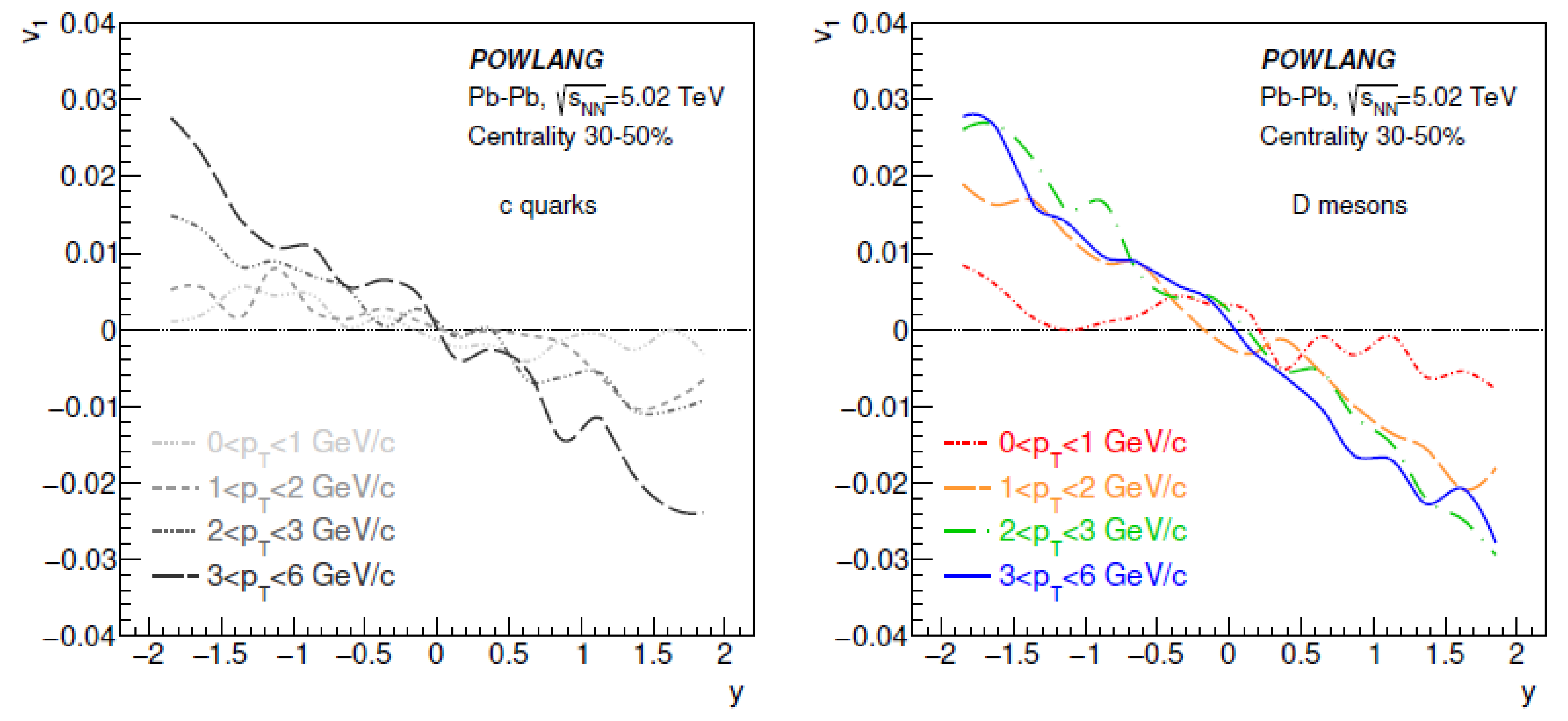
Field interaction

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)

IMPACT OF HADRONIZATION ON DIRECTED FLOW

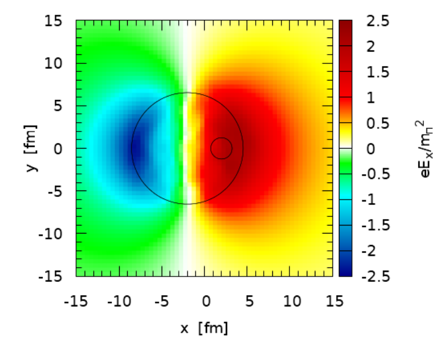
A. Beraudo, A. De Pace, M. Monteno, M. Nardi and F. Prino, JHEP 05, 279 (2021)

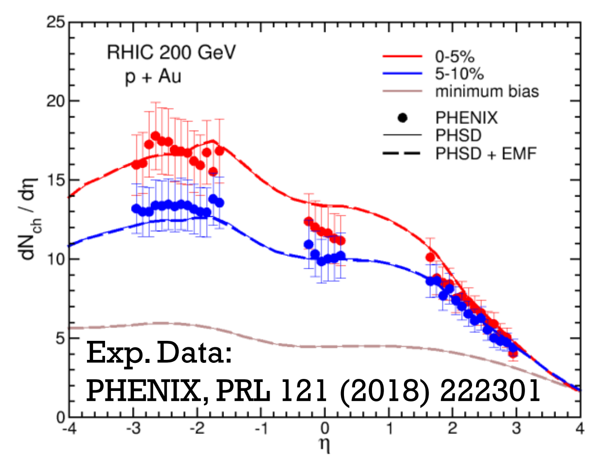


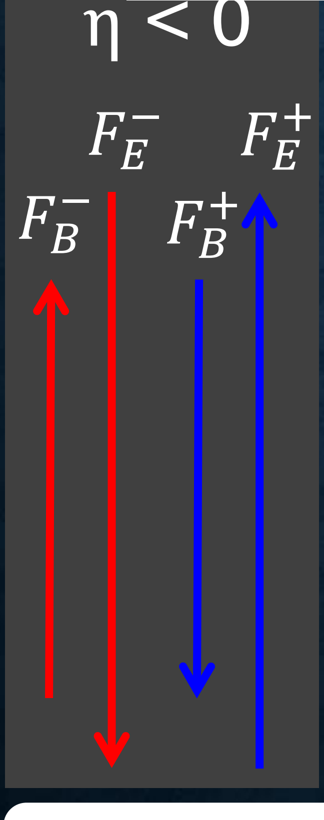
Hadronization via in-medium recombination with string-breaking
can enhance the D-meson $v_1(y)$ for $1<p_T<3$ GeV

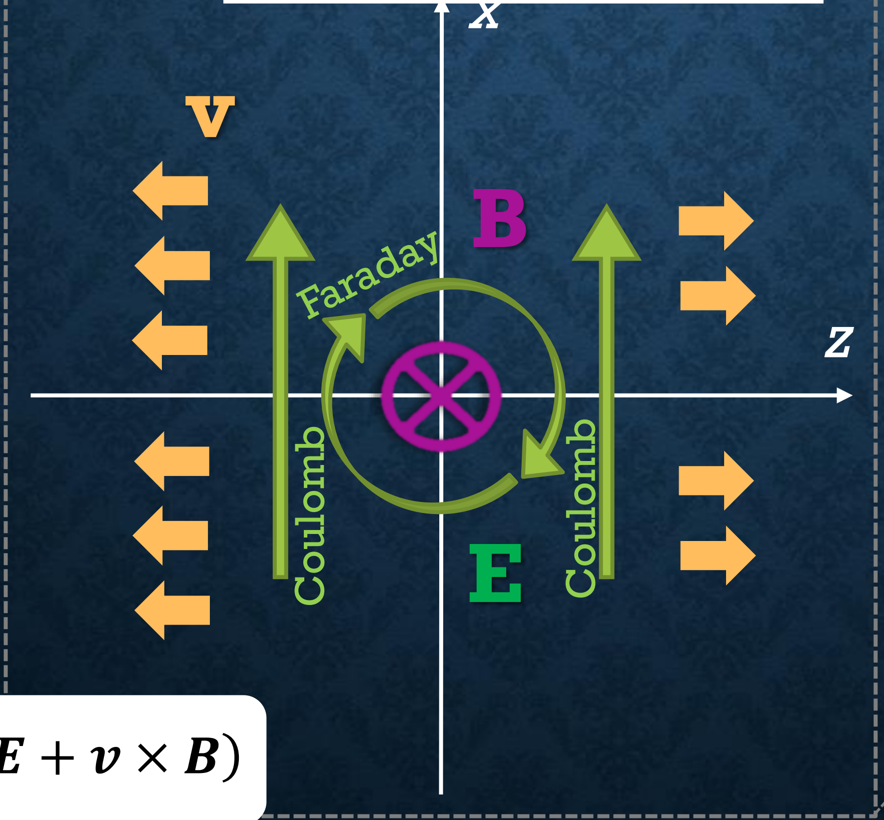
Even though the $v_1(y)$ of bulk medium is small, there is a strong correlation between the HQ momentum and position and four-velocity of its fluid cell at hadronization

EMF AND DIRECTED FLOW IN P+A









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

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)