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ExHIC-p workshop on polarization phenomena in nuclear collisions
Institute of Physics, Academia Sinica
Taipei (Taiwan), 14-17 March 2024

OVERVIEW ON TRANSPORT SIMULATIONS OF VECTOR MESONS

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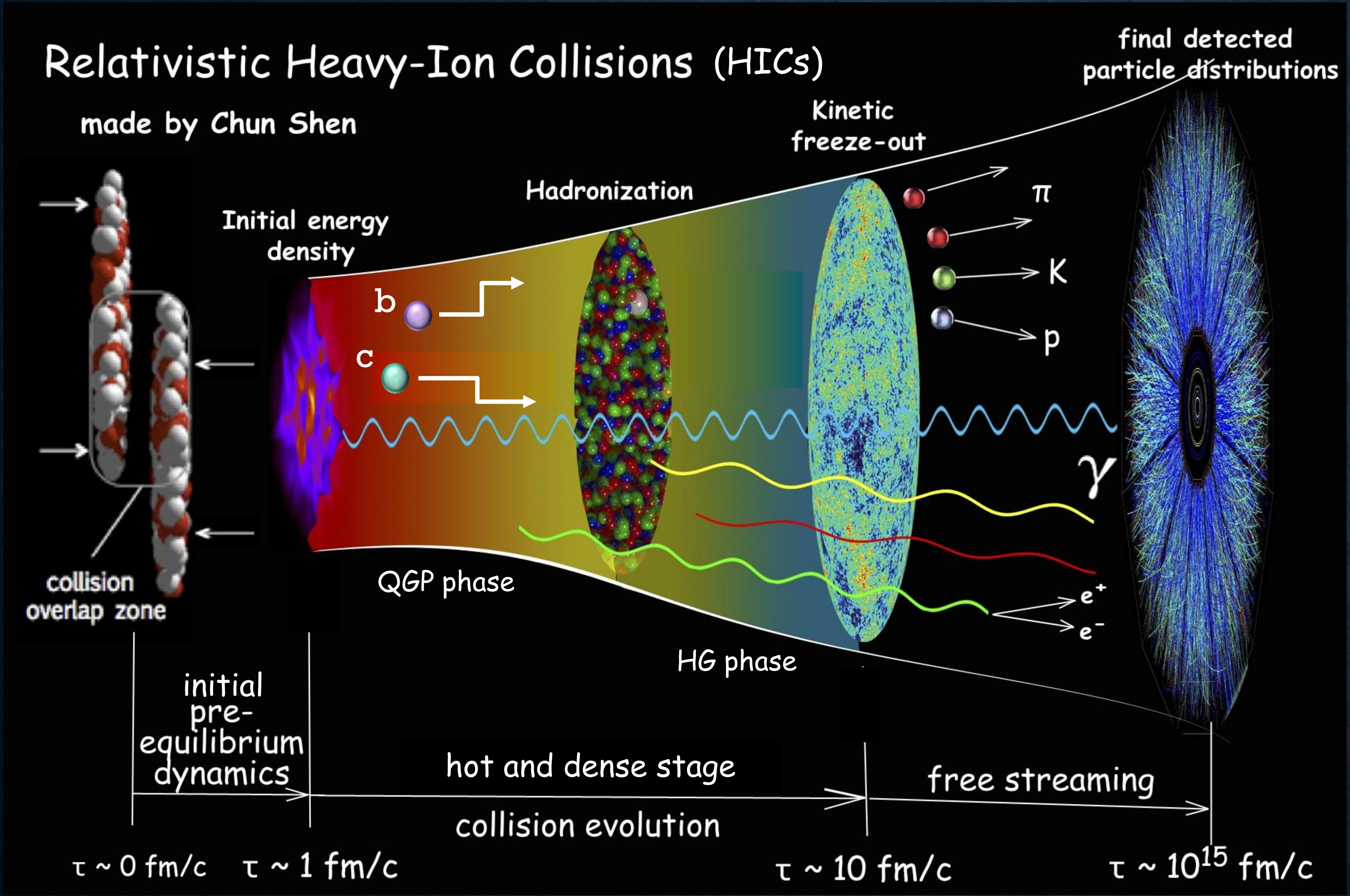
Sezione di Catania

DIPARTIMENTO DI FISICA E ASTRONOMIA "ETTORE MAJORANA"



Adapted from Chun Shen's picture

PRE-EQUILIBRIUM

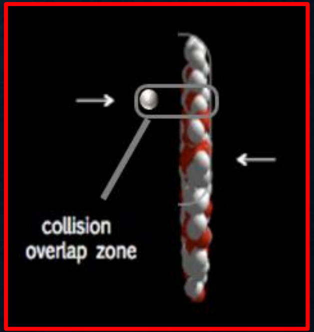
PARTONIC PHASE
- QGP dynamics
- heavy quark dynamics

HADRONIZATION

HADRONIC PHASE

INTENSE FIELDS
- vorticity
- electromagnetic field
- strong force fields

SMALL SYSTEMS



SIMULATING LARGE AND SMALL COLLIDING SYSTEMS

Two main approaches to simulate the
dynamics of hot and dense QCD medium

HYDRODYNAMIC MODELS

macroscopic description
evolution based on conservation laws
unreasonable effectiveness of hydrodynamics

energy-momentum tensor

$$\partial_\mu T^{\mu\nu} = 0$$

viscous corrections

$$T^{\mu\nu} = e u^\mu u^\nu - \Delta^{\mu\nu}(P + \Pi) + \pi^{\mu\nu}$$

fluid 4-velocity

TRANSPORT MODELS

microscopic description
evolution of particle distributions functions
inherent inclusion of nonequilibrium dynamics

collision integral

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

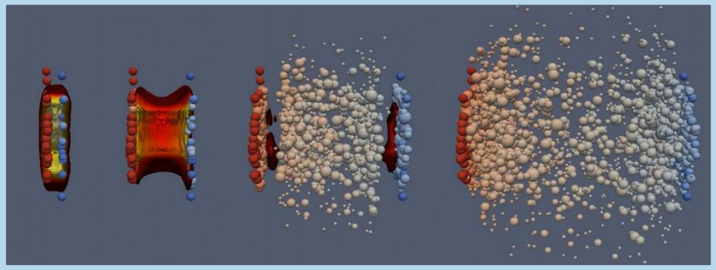
field interaction

one-particle distribution function

SIMULATING LARGE AND SMALL COLLIDING SYSTEMS

Two main approaches to simulate the
full dynamical collision evolution

initial conditions + **HYDRODYNAMIC MODELS** + hadronic afterburner
macroscopic description
evolution based on conservation laws
unreasonable effectiveness of hydrodynamics



Picture credit: MADAI Collaboration

TRANSPORT MODELS
microscopic description
evolution of particle distributions functions
inherent inclusion of nonequilibrium dynamics
suitable for the early pre-equilibrium stage
for partonic and hadronic phases

Picture credit: PHSD project

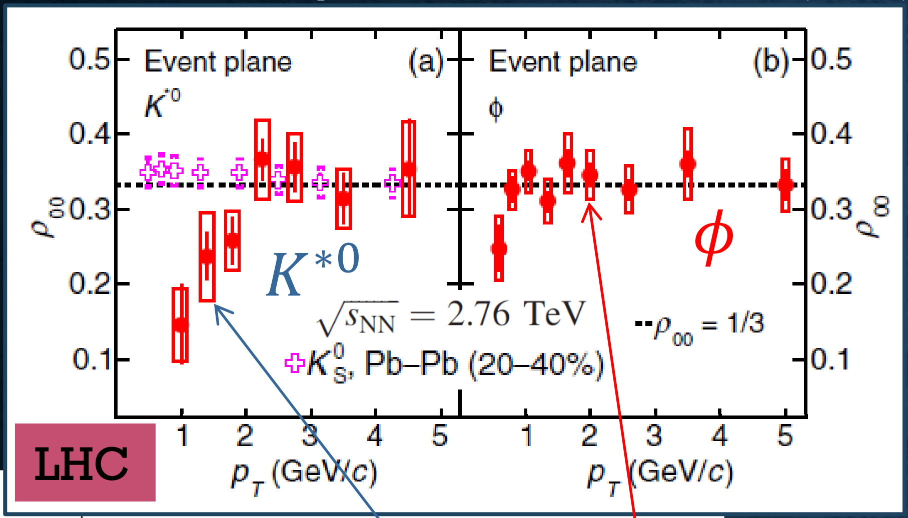
review M. Bleicher and E. Bratkovskaya, Prog. Part. Nucl. Phys. 122, 103920 (2022)

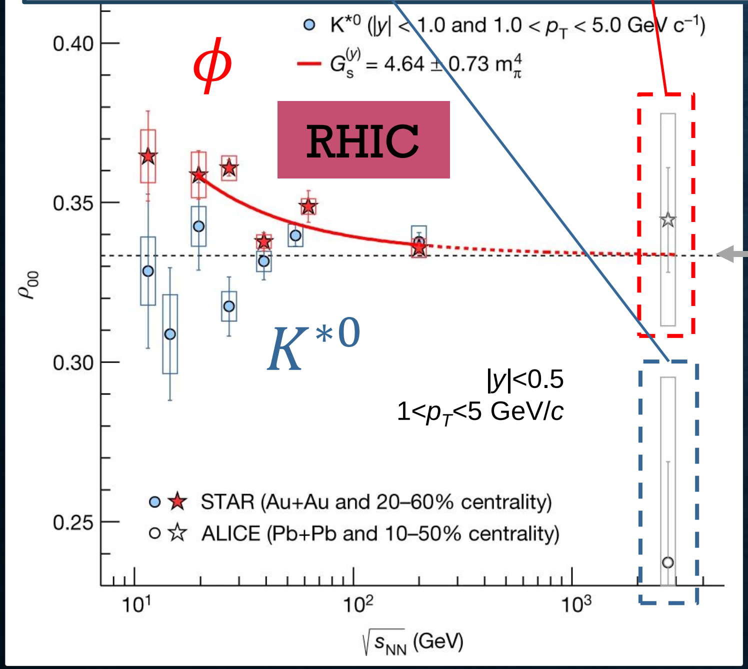
Both hybrid and transport approaches are successful in describing AA and pA collisions
→ applicability to small systems and lower collision energies
enlarged with core-corona approaches

☒ see talk of
Y. TACHIBANA
Fri 15/03

SPIN ALIGNMENT OF LIGHT VECTOR MESONS

ALICE Coll., Phys. Rev. Lett. 125, 012301 (2020)

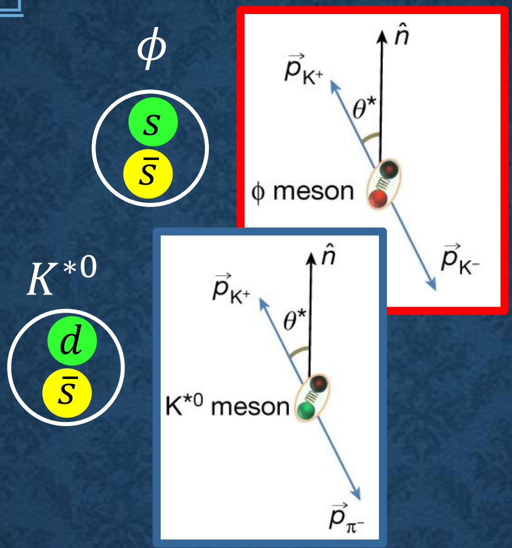




ρ_{00}^{y}

1/3
unpolarized case

STAR Collaboration, Nature 614, 244 (2023)



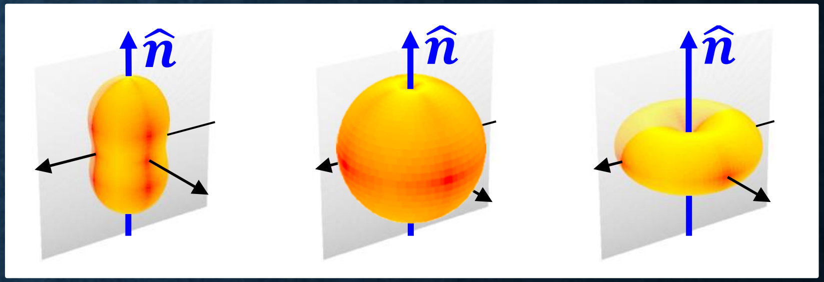
ϕ and K^{*0} mesons are spin-1 particles decaying through strong interaction

$\phi \rightarrow K^+ + K^-$ (BR ~49%)

$K^{*0} \rightarrow K^+ + \pi^-$ (BR ~67%)

$\Longrightarrow$ measure SPIN ALIGNMENT

$$\frac{dN}{d\cos\theta^*} = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$



$\rho_{00} > 1/3$ $|1,0\rangle$ $\rho_{00} = 1/3$ $\rho_{00} < 1/3$ $|1,\pm1\rangle$

- RHIC: ρ_{00}^{ϕ} significantly larger than 1/3 for $\sqrt{s_{NN}} \leq 62$ (7.4σ)
  $\rho_{00}^{K^{*0}}$ consistent with 1/3 within exp. uncertainties
- LHC: same pattern $\rho_{00}^{K^{*0}} < \rho_{00}^{\phi}$ than at RHIC but $\rho_{00}^{\phi} \lesssim 1/3$ (2σ)

SPIN POLARIZATION MECHANISMS

the vorticity contribution dominates. STAR measurements of the polarization of Λ and $\bar{\Lambda}$ (refs. [18,19]) indicate that the magnetic components of the vorticity and the electromagnetic field tensor in total give[2,12,25] a negative contribution to ρ_{00} at the level of 10^{-5}. Furthermore, the local vorticity loop in the transverse plane[26], when acting together with coalescence, gives a negative contribution to global ρ_{00}. From a hydrodynamic simulation of the vorticity field in heavy-ion collisions, it is known[2] that the electric component of the vorticity tensor gives a contribution on the order of 10^{-4}. Simulation of the electromagnetic field in heavy-ion collisions indicates[2] that the electric field gives a contribution on the order of 10^{-5}. Fragmentation of polarized quarks contributes on the order of 10^{-5} and the effect is mainly present in transverse momenta much larger than a few GeV c^{-1} (ref. [12]). Helicity polarization gives a negative contribution at all centralities[27]. Locally fluctuating axial charge currents induced by possible local charge violation gives rise to the expectation[29] of $\rho_{00}(K^{*0}) < \rho_{00}(\phi) < 1/3$. The aforementioned mostly conventional mechanisms make either positive or negative contributions to ϕ-meson ρ_{00}, but none of them can produce a ρ_{00} that is larger than 1/3 by more than a few times 10^{-4}. Recently, a theoretical model was proposed on the basis of the ϕ-meson vector field coupling to s and $\bar{s}$ quarks[2–6], analogous to the photon vector field coupled to electrically charged particles. In this mechanism, the observed global spin alignment is caused by the local fluctuation of the strong force field and can cause deviations of ρ_{00} from 1/3 larger than 10^{-4}.

The lifetime of K^{*0} is about ten times shorter than the ϕ lifetime, corresponding to a mean proper decay length $c\tau \approx 4.1$ fm, making it susceptible to in-medium effects. The difference between the global spin alignment for K^{*0} and ϕ may be attributed to different in-medium interactions resulting from this difference in lifetime, a polarization transfer during the late stage of hadronic interactions[38] and a different response to the vector meson field[2]. Similar to strange quarks

STAR Collaboration, Nature 614, 244 (2023)

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6. X.-L. Sheng, LO, Z.-T. Liang, Q. Wang & X.-N. Wang, *PRD* 109, 036004 (2024)
12. Z.-T. Liang & X.-N. Wang, *PLB* 629, 20 (2005)
25. Y.-G. Yang, R.-H. Fang, Q. Wang. & X.-N. Wang, *PRC* 97, 034917 (2018)
26. X.-L. Xia, H. Li, X.-G. Huang & H. Zhong Huang, *PLB* 817, 136325 (2021)
27. J.-H. Gao, *PRD* 104, 076016 (2021)
29. B. Müller & D.-L. Yang, *PRD* 105, L011901 (2022)
38. I. Karpenko & F. Becattini, *EPJC* 77, 213 (2017)

- **The local fluctuactions of strong force fields may be the key to solve the puzzle**
  Refs. 2-6

- Explore the in-medium effects on vector mesons

SPIN POLARIZATION OF QUARKS

spin polarization vector for massive fermion/antifermion

$$P^\mu_\pm(x,p) = \frac{1}{4m}\epsilon^{\mu\nu\varrho\sigma}\left(\omega^{\rm th}_{\varrho\sigma} \pm \frac{Q}{(u\cdot p)T}F^{\rm em}_{\varrho\sigma} \pm \frac{g_V}{(u\cdot p)T}F^{\rm V}_{\varrho\sigma}\right)p_\nu\left[1-f_{\rm FD}\left(E_p \mp \mu\right)\right]$$

thermal vorticity tensor

electromagnetic field strength tensor

vector meson field strength tensor

$$\omega^{\rm th}_{\varrho\sigma} = \frac{1}{2}\left(\partial_\varrho\beta_\sigma - \partial_\sigma\beta_\varrho\right)$$

"electric" $\boldsymbol{\varepsilon} = -\frac{1}{2}\left(\partial_t(\beta\mathbf{u}) + \nabla\left(\beta u^0\right)\right)$ "magnetic" $\boldsymbol{\omega} = \frac{1}{2}\nabla\times(\beta\mathbf{u})$

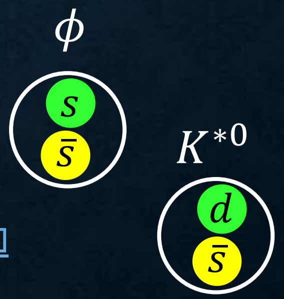
$$F^{\rm em,V}_{\varrho\sigma} = \partial_\varrho A^{\rm em,V}_\sigma - \partial_\sigma A^{\rm em,V}_\varrho$$

"electric" $\mathbf{E}^{\rm em,V}_i = \mathbf{E}^i_{\rm em,V} = F^{i0}_{\rm em,V}$ "magnetic" $\mathbf{B}^{\rm em,V}_i = \mathbf{B}^i_{\rm em,V} = -\frac{1}{2}\epsilon_{ijk}F^{jk}_{\rm em,V}$

spin polarization distribution for quarks/antiquarks along the y direction (~ parallel to $\boldsymbol{J}$ and $\boldsymbol{B}$)

$$P^y_{q/\bar q}(t,\mathbf{x},\mathbf{p}_{q/\bar q}) = \frac{1}{2}\omega_y \pm \frac{1}{2m_q}\left(\boldsymbol{\varepsilon}\times\mathbf{p}_{q/\bar q}\right)_y \pm \frac{Q_q}{2m_qT}B_y \pm \frac{Q_q}{2m_q^2T}\left(\mathbf{E}\times\mathbf{p}_{q/\bar q}\right)_y \pm \frac{g_V}{2m_qT}B^V_y \pm \frac{g_V}{2m_q^2T}\left(\mathbf{E}^V\times\mathbf{p}_{q/\bar q}\right)_y$$

Like the EM field, effective mesonic fields can polarize particles but with large magnitude due to the strong interaction



X.-L. Sheng, LO and Q. Wang, Phys. Rev. D 101, 096005 (2020) [Phys. Rev. D 105, 099903 (2022)]
X.-L. Sheng, Q. Wang and X.-N. Wang, Phys. Rev. D 102, 056013 (2020)

SPIN BOLTZMANN EQUATION FOR VECTOR MESONS

polarized quarks → COALESCENCE → polarized hadrons

V. Greco, C.M. Ko and P. Levai, Phys. Rev. Lett. 90, 202302 (2003)
R.J. Fries et al., Phys. Rev. Lett. 90, 202303 (2003)

spin Boltzmann equation for the
vector meson's matrix-valued spin-dependent distributions (MVSD)

QUANTUM RELATIVISTIC **TRANSPORT** THEORY FOR SPIN DYNAMICS

$$k\cdot\partial_x f^V_{\lambda_1\lambda_2}(x,\mathbf{k}) = \frac{1}{8}\left[\epsilon^*_\mu(\lambda_1,\mathbf{k})\epsilon_\nu(\lambda_2,\mathbf{k})\mathcal{C}^{\mu\nu}_{\mathrm{coal}}(x,\mathbf{k}) - \mathcal{C}_{\mathrm{diss}}(\mathbf{k}) f^V_{\lambda_1\lambda_2}(x,\mathbf{k})\right]$$

3×3 Hermitian matrix in spin space

COALESCENCE

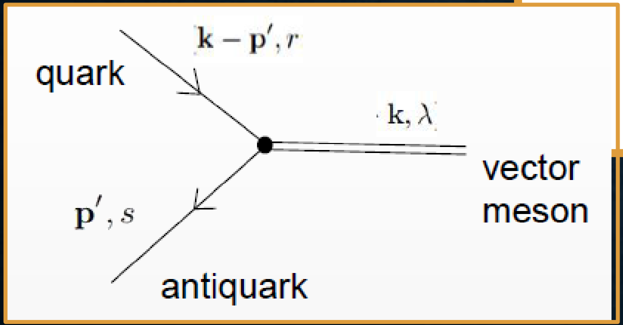
DISSOCIATION
independent from the quark/antiquark MVSDs

$$\mathcal{C}^{\mu\nu}_{\mathrm{coal}}(x,\mathbf{k}) = \int \frac{d^3\mathbf{p}'}{(2\pi\hbar)^2}\frac{1}{E^{\bar q}_{\mathbf{p}'}E^q_{\mathbf{k}-\mathbf{p}'}}\delta\left(E^V_{\mathbf{k}}-E^{\bar q}_{\mathbf{p}'}-E^q_{\mathbf{k}-\mathbf{p}'}\right)$$
$$\times \mathrm{Tr}\left\{\Gamma^\nu(p'\cdot\gamma - m_{\bar q})\left[1+\gamma_5\gamma\cdot P^{\bar q}(x,\mathbf{p}')\right]\right.$$
$$\left.\times\Gamma^\mu\left[(k-p')\cdot\gamma+m_q\right]\left[1+\gamma_5\gamma\cdot P^q(x,\mathbf{k}-\mathbf{p}')\right]\right\}$$
$$\times f_{\bar q}(x,\mathbf{p}')f_q(x,\mathbf{k}-\mathbf{p}')$$

$q\bar{q}V$ vertices

polarization distribution for quark/antiquark

unpolarized distribution for quark/antiquark



X.-L- Sheng, LO, Z.-T. Liang, Q. Wang and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023) ; Phys. Rev. D 109, 036004 (2024)

SPIN ALIGNMENT OF ϕ MESONS

ϕ

polarization distributions of strange/antistrange quarks appearing in ϕ mesons spin density matrix

$$P^{\mu}_{s/\bar{s}}(x,\mathbf{p}) = \frac{1}{4m_s}\epsilon^{\mu\nu\varrho\sigma}\left(\omega^{\text{th}}_{\varrho\sigma} \pm \frac{g_\phi}{(u\cdot p)T}F^{\phi}_{\varrho\sigma}\right)p_\nu$$

$$\rho^{\phi}_{00}(x,\mathbf{k}) \approx \frac{1}{3} + C_1\left[\frac{1}{3}\boldsymbol{\omega}'\cdot\boldsymbol{\omega}' - (\epsilon_0\cdot\boldsymbol{\omega}')^2\right] + C_2\left[\frac{1}{3}\boldsymbol{\varepsilon}'\cdot\boldsymbol{\varepsilon}' - (\epsilon_0\cdot\boldsymbol{\varepsilon}')^2\right]$$
$$-\frac{4g^2_\phi}{m^2_\phi T^2_{\text{h}}}C_1\left[\frac{1}{3}\mathbf{B}'_\phi\cdot\mathbf{B}'_\phi - (\epsilon_0\cdot\mathbf{B}'_\phi)^2\right] - \frac{4g^2_\phi}{m^2_\phi T^2_{\text{h}}}C_2\left[\frac{1}{3}\mathbf{E}'_\phi\cdot\mathbf{E}'_\phi - (\epsilon_0\cdot\mathbf{E}'_\phi)^2\right]$$

vorticity fields

ϕ-meson fields

neglecting EM fields

the 00 element of the spin density matrix for ϕ meson in its rest frame

$$C_1 = \frac{8m_s^4 + 16m_s^2 m_\phi^2 + 3m_\phi^4}{120m_s^2(m_\phi^2 + 2m_s^2)}$$

$$C_2 = \frac{8m_s^4 - 14m_s^2 m_\phi^2 + 3m_\phi^4}{120m_s^2(m_\phi^2 + 2m_s^2)}$$

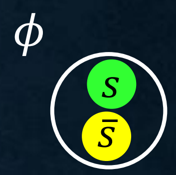
For quarkonium vector mesons like ϕ meson

- cancellation of all mixed terms of two different field components
- only short-distance correlations between same field components

ρ^{ϕ}_{00} measures local fluctuations of vortical and mesonic fields during hadronization

X.-L- Sheng, LO, Z.-T. Liang, Q. Wang and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023) ; Phys. Rev. D 109, 036004 (2024)

SPIN ALIGNMENT OF ϕ MESONS



in terms of lab-frame fields and taking the y-axis as spin quantization direction (**out-of-plane**)

$$\rho_{00}^{\phi}(x,\mathbf{k}) \approx \frac{1}{3} + \frac{1}{3}\sum_{i=1,2,3}\left\{I_{B_i}(\mathbf{k})\left[\omega_i^2 - \left(\frac{2}{m_\phi}\right)^2\left(\frac{g_\phi B_i^{\phi}(x)}{T_{\mathrm{h}}}\right)^2\right] + I_{E_i}(\mathbf{k})\left[\varepsilon_i^2 - \left(\frac{2}{m_\phi}\right)^2\left(\frac{g_\phi E_i^{\phi}(x)}{T_{\mathrm{h}}}\right)^2\right]\right\}$$

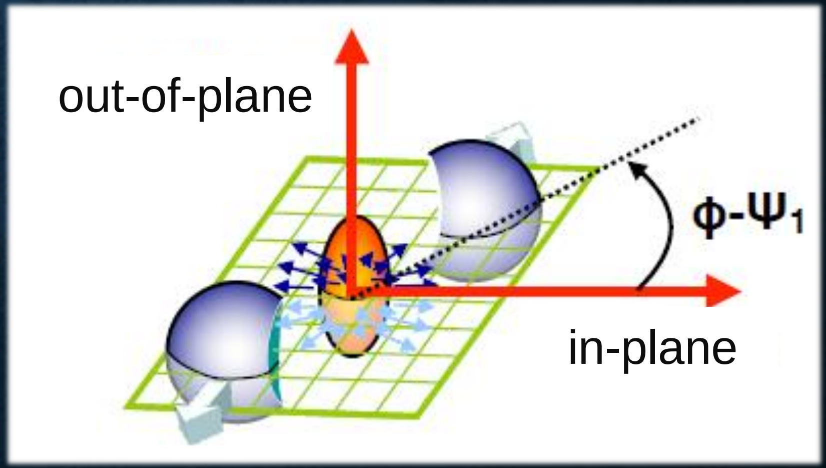
factorization of space-time and momentum dependence
in the field component squares and their coefficients

$$\rho_{00}^{\phi}(x,\mathbf{k}) \approx \frac{1}{3} - \frac{1}{3}\left(\frac{2}{m_\phi}\right)^2 \sum_{i=1,2,3}\left\{\left\langle I_{B_i}(\mathbf{k})\right\rangle_{\mathbf{k}}\left\langle\left(\frac{g_\phi B_i^{\phi}(x)}{T_{\mathrm{h}}}\right)^2\right\rangle_x + \left\langle I_{E_i}(\mathbf{k})\right\rangle_{\mathbf{k}}\left\langle\left(\frac{g_\phi E_i^{\phi}(x)}{T_{\mathrm{h}}}\right)^2\right\rangle_x\right\}$$

considering only
the ϕ-meson field

transverse fields
$$\left\langle\left(g_\phi B_{x,y}^{\phi}/T_{\mathrm{h}}\right)^2\right\rangle_x = \left\langle\left(g_\phi E_{x,y}^{\phi}/T_{\mathrm{h}}\right)^2\right\rangle_x \equiv F_T^2$$

longitudinal fields
$$\left\langle\left(g_\phi B_{z}^{\phi}/T_{\mathrm{h}}\right)^2\right\rangle_x = \left\langle\left(g_\phi E_{z}^{\phi}/T_{\mathrm{h}}\right)^2\right\rangle_x \equiv F_Z^2$$

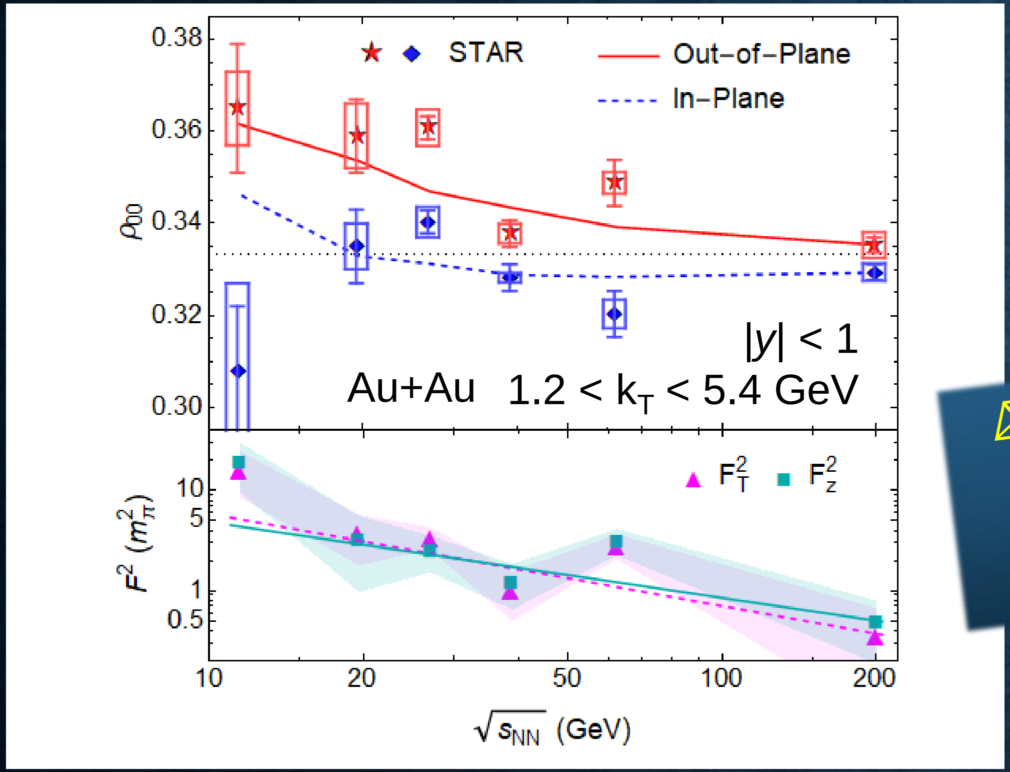


X.-L- Sheng, LO, Z.-T. Liang, Q. Wang and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023) ; Phys. Rev. D 109, 036004 (2024)

SPIN ALIGNMENT OF ϕ MESONS

Exp. data: STAR Coll., Nature 614, 244 (2023)

$\rho_{00}^{x,y}(\sqrt{s_{NN}})$



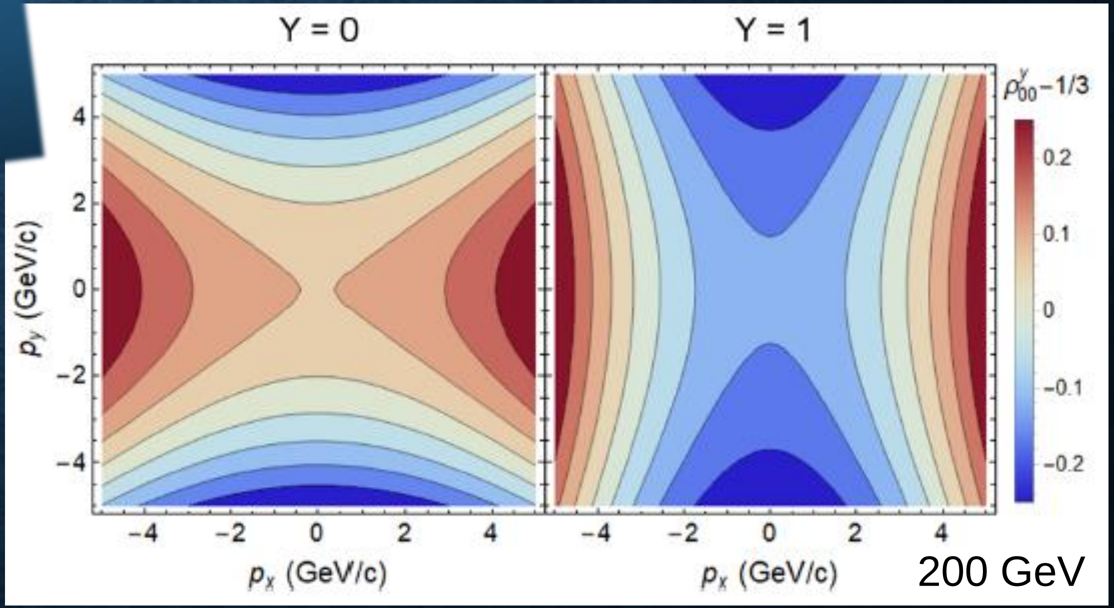
fit the exp. data for ρ_{00} vs collision energy

extract the field fluctuation parameters

determine ρ_{00} vs k_T, φ, Y

see talks of Q. WANG X.-L. SHENG Thu 14/03

$\rho_{00}^{y} - 1/3\,(k_x, k_y)$



- out-of-plane: $\rho_{00}^{y} > 1/3$ for all energies
  in-plane: $\rho_{00}^{x} \lesssim 1/3$ for $\sqrt{s_{NN}} \gtrsim 20$ GeV
- difference between ρ_{00}^{y} and ρ_{00}^{x} driven by the momentum anisotropy via the elliptic flow $v_2(k_T)$

X.-L- Sheng, LO, Z.-T. Liang, Q. Wang and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023)
X.-L. Sheng, S. Pu and Q. Wang, Phys. Rev. C 108, 054902 (2023)

SPIN POLARIZATION MECHANISMS

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- The local fluctuactions of strong force fields may be the key to solve the puzzle
  Refs. 2-6

- **Explore the in-medium effects on vector mesons**

hadronic resonance production and interaction in the confined phase

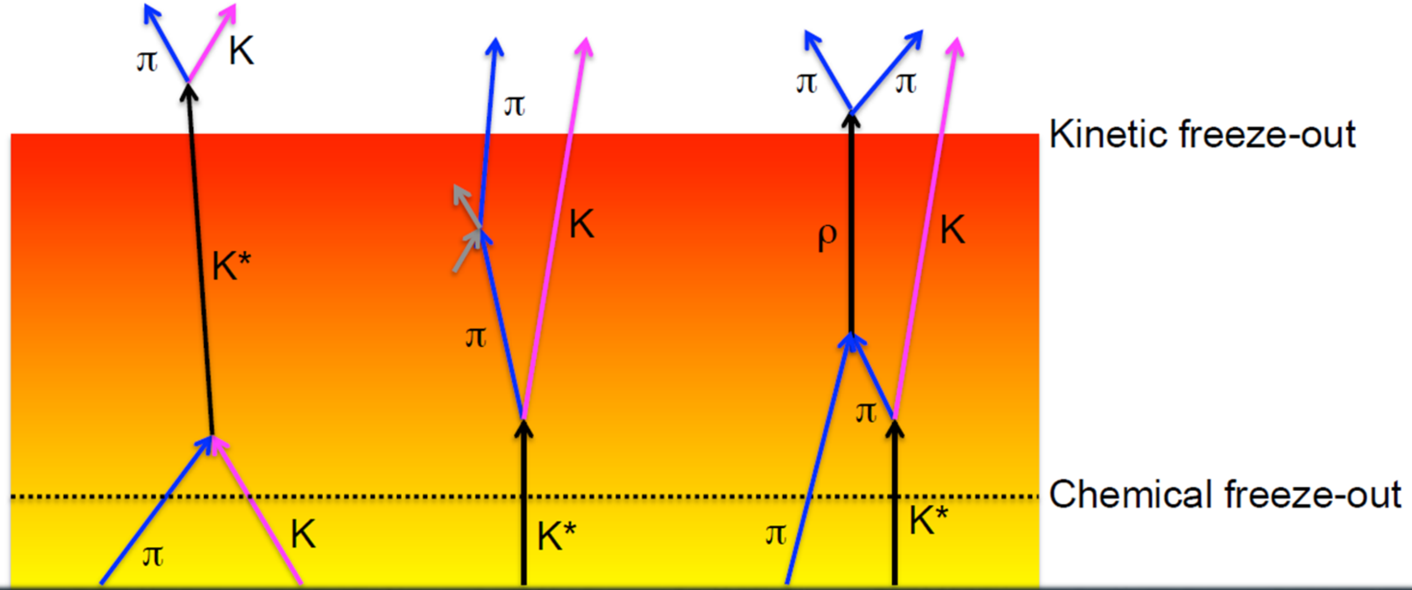
RESONANCE REGENERATOIN AND RESCATTERING

3

Hadronic Phase

Knospe

- Reconstructible resonance yields may be changed by hadronic scattering processes after chemical freeze-out:
  - **Regeneration:** pseudo-elastic scattering of decay products
    - e.g., $\pi K \rightarrow K^* \rightarrow \pi K$
  - **Re-scattering:**
    - Resonance decay products undergo elastic scattering
    - Or pseudo-elastic scattering through a different resonance (e.g. ρ)
    - Resonance not reconstructed through invariant mass



Slide of Anders Knospe showed at Strangeness in Quark Matter (SQM) 2016

RESONANCE REGENERATOIN AND RESCATTERING

3 Hadronic Phase Knospe

- Reconstructible resonance yields may be changed by hadronic scattering processes after chemical freeze-out:
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    - Resonance not reconstructed through invariant mass

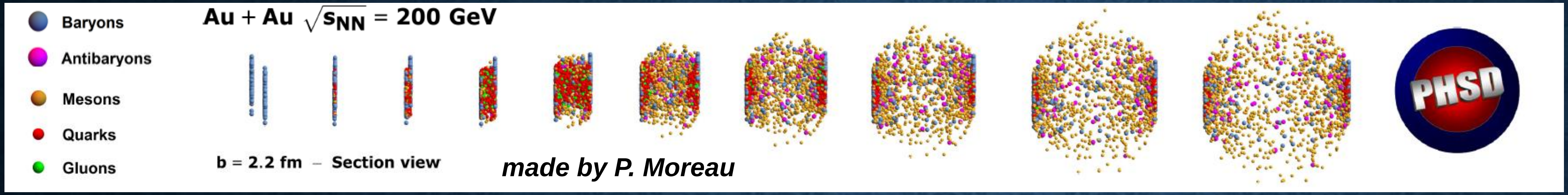
	$c\tau$ (fm)	quark content	Decay modes	BR [%]
$\rho(770)^0$	1.3	$(u\bar{u}+d\bar{d})/\sqrt{2}$	$\pi^+ + \pi^-$	100
$K^*(892)^0$	4.2	$d\bar{s}$	$K^+ + \pi^-$	66.6
$\Sigma(1385)^+$	5.5	uus	$\Lambda\pi^+ \to (p\pi^-)\pi^+$	87.0
$\Sigma(1385)^-$	5.0	dds	$\Lambda\pi^- \to (p\pi^-)\pi^-$	87.0
$\Xi(1820)^-$	8.1	dss	$\Lambda K \to (p\pi^-)K$	unknown
$\Lambda(1520)$	12.6	uds	$p + K^-$	22.5
$\Xi(1530)^0$	21.7	uss	$\Xi^-\pi^+ \to (\Lambda\pi^-)\pi^+ \to ((p\pi^-)\pi^-)\pi^+$	66.7
$\phi(1020)^0$	44	$s\bar{s}$	$K^+ + K^-$	48.9

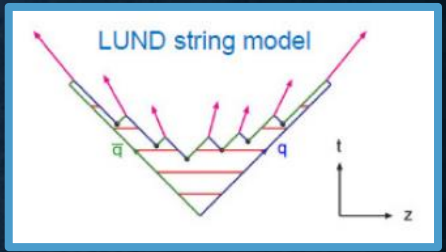
Slide of Anders Knospe showed at Strangeness in Quark Matter (SQM) 2016 [1]

PARTON-HADRON-STRING DYNAMICS – PHSD

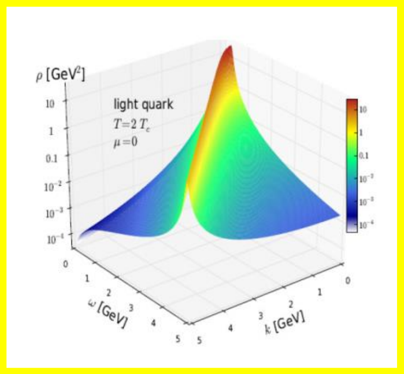
non-equilibrium off-shell transport approach

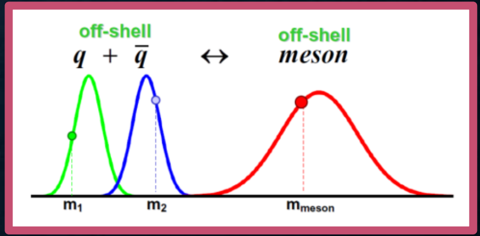
to study the phase transition from hadronic to partonic matter and QGP properties from a microscopic origin





- INITIAL NUCLEI COLLISION: 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, as in the Hadron-String Dynamics (HSD) model





W. Cassing and E. Bratkovskaya, Phys. Rev. C 78, 034919 (2008) ; Nucl. Phys. A 831, 215 (2009)
P. Moreau, O. Soloveva, LO, T. Song, W. Cassing and E. Bratkovskaya, Phys. Rev. C 100, 014911 (2019)
Giessen/Frankfurt groups: http://theory.gsi.de/~ebratkov/phsd-project/PHSD/index1.html

GENERALIZED TRANSPORT EQUATIONS (GTE)

After the first order gradient expansion of the Wigner transformed Kadanoff-Baym equations and separation into the real and imaginary parts one obtain GTE which describes the dynamics of broad strongly interacting quantum states

drift term — Vlasov term — backflow term — collision term = ‚gain‘ - ‚loss‘ term

$$\diamond \{ P^2 - M_0^2 - Re\Sigma^{ret}_{XP} \} \{ S^{<}_{XP} \} - \diamond \{ \Sigma^{<}_{XP} \} \{ Re S^{ret}_{XP} \} = \frac{i}{2} \left[\Sigma^{>}_{XP} S^{<}_{XP} - \Sigma^{<}_{XP} S^{>}_{XP} \right]$$

$$\diamond \{ F_1 \} \{ F_2 \} := \frac{1}{2} \left(\frac{\partial F_1}{\partial X_\mu} \frac{\partial F_2}{\partial P^\mu} - \frac{\partial F_1}{\partial P_\mu} \frac{\partial F_2}{\partial X^\mu} \right)$$

off-shell behavior

GTE govern the propagation of the Green functions

$i S^{<}_{XP} = A_{XP} N_{XP}$

N_{XP} → number of particles

A_{XP} → particle spectral function

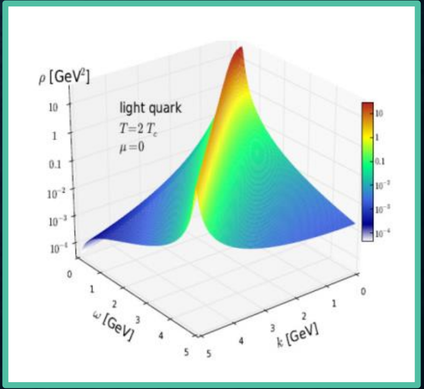
Dressed propagators (S_q, Δ_g)

$$S = \left(P^2 - \Sigma^2\right)^{-1}$$

with complex self-energies (Σ_q, Π_g):

$$\Sigma = m^2 - i2\gamma\omega$$

- the real part describes a dynamically generated mass (m_q, m_g)
- the imaginary part describes the interaction width (γ_q, γ_g)



W. Cassing and S. Juchem, Nucl. Phys. A 665, 377 (2000); 672, 417 (2000); 677, 445 (2000)

VECTOR MESONS IN OFF-SHELL TRANSPORT: *K**

$$\Pi_V = \Pi_{dec} + \Pi_{coll}$$

two sources of in-medium effects contributing to the self-energy of strange vector mesons

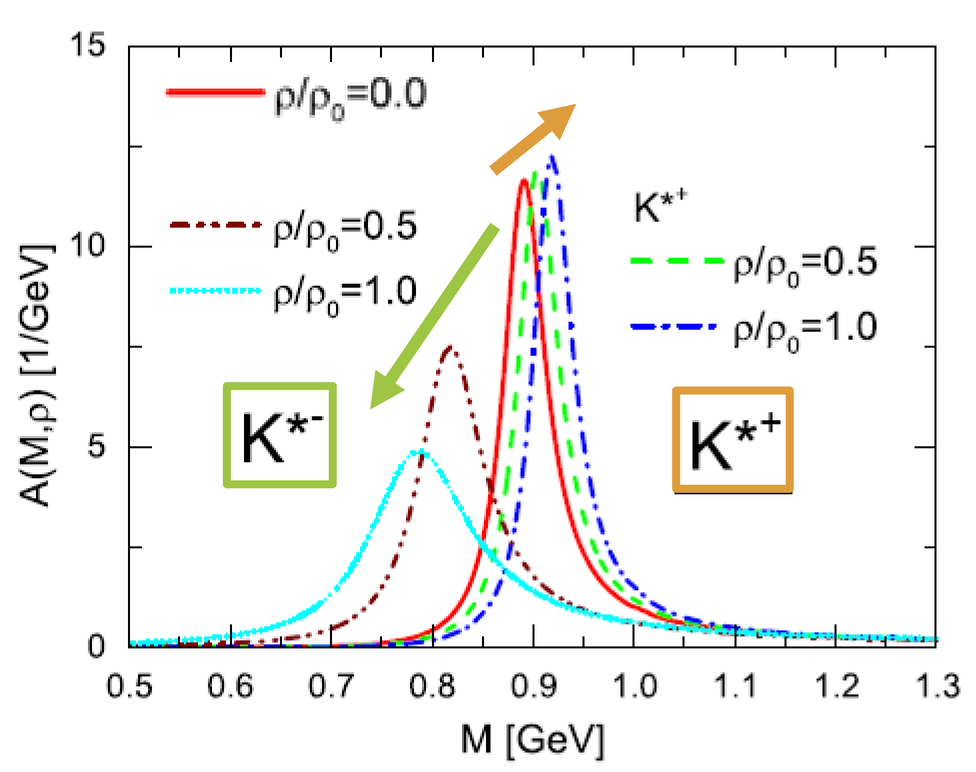
$$(M_V^*)^2 = M_V^2 + \mathrm{Re}\Pi_V(M_V^*, \rho),$$
$$\Gamma_V^*(M, \rho) = -\mathrm{Im}\Pi_V(M, \rho)/M,$$

in-medium mass and decay width

$$A_V(M, \rho) = C_1 \frac{2}{\pi} \frac{M^2 \Gamma_V^*(M, \rho)}{\left[M^2 - M_V^{*2}(\rho)\right]^2 + [M\Gamma_V^*(M, \rho)]^2}$$

relativistic Breit–Wigner spectral function

- net attractive interaction with the medium
- width largely enhanced
- diminished threshold energy for its creation



*K** spectral function

- net repulsive interaction with the medium
- width slightly lowered
- threshold energy for its creation shifted up

A. Ilner, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 95, 014903 (2017)
A. Ilner, J. Blair, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 99, 024914 (2019)

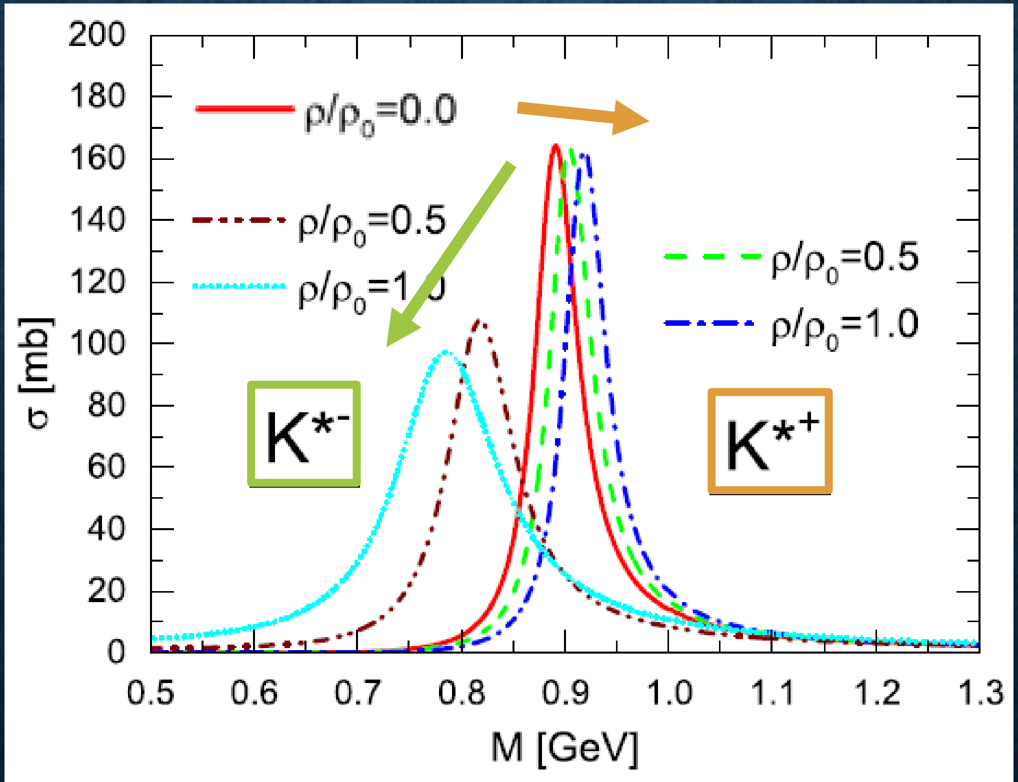
VECTOR MESONS IN OFF-SHELL TRANSPORT: *K**

$$\sigma_{K^*(\overline{K}^*)}(M,\rho) = \frac{6\pi^2 A_{K^*(\overline{K}^*)}(M,\rho)\,\Gamma^*_{K^*(\overline{K}^*)}(M,\rho)}{q(M,M_K,M_\pi)^2}$$

cross section for *K** production via annihilation

*K** cross section

- peak of the distribution shifted to lower invariant masses
- saturating fall of the cross section maximum value



- shift of the energy distribution to higher invariant masses
- cross section maximum slightly decreaseed

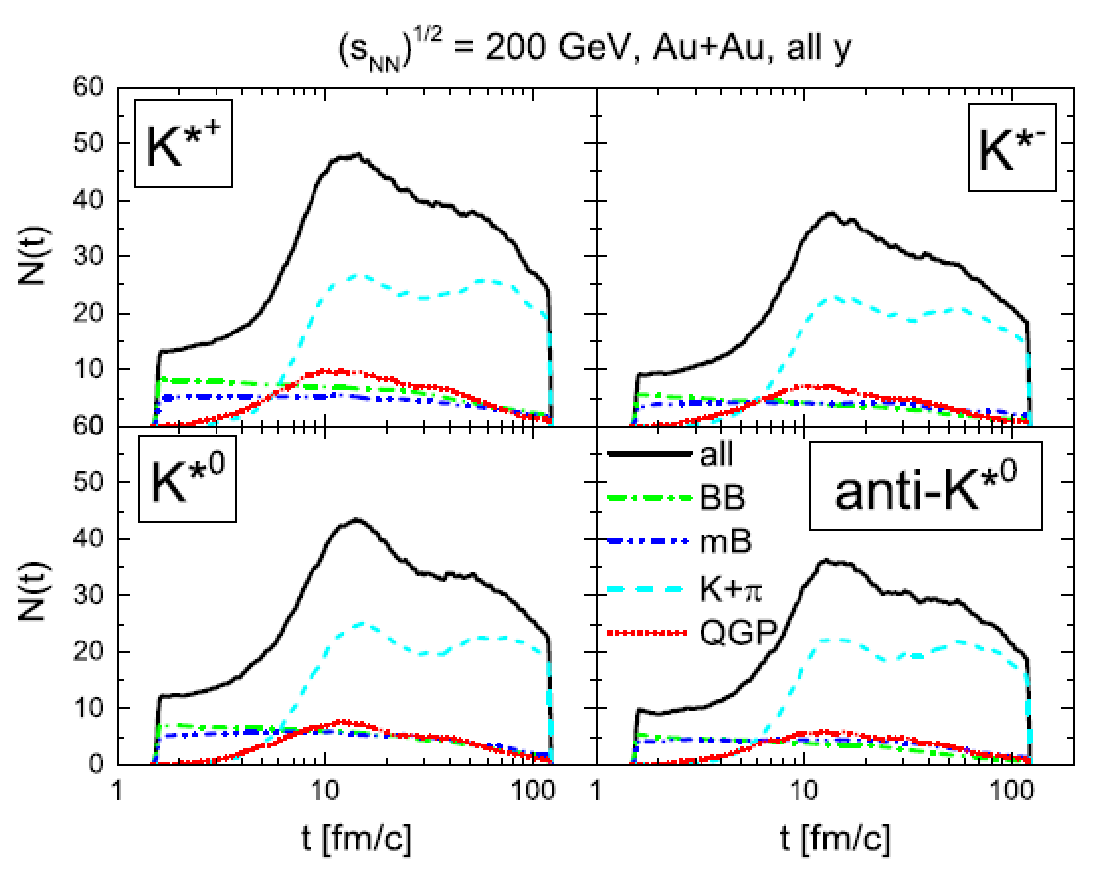
larger energies are needed as compared with the same reaction in vacuum

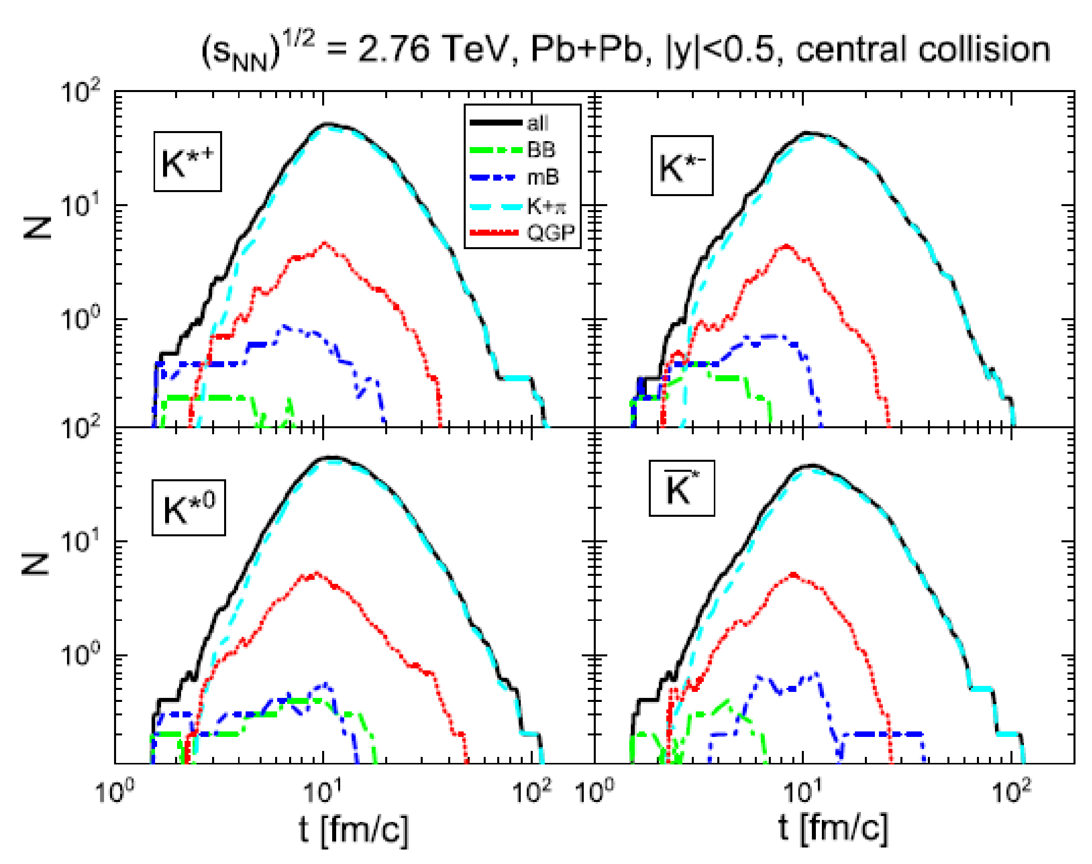
investigate "thermal" in-medium effects for LHC energies

A. Ilner, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 95, 014903 (2017)
A. Ilner, J. Blair, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 99, 024914 (2019)

VECTOR MESONS IN OFF-SHELL TRANSPORT: *K**

time evolution of the K production channels*



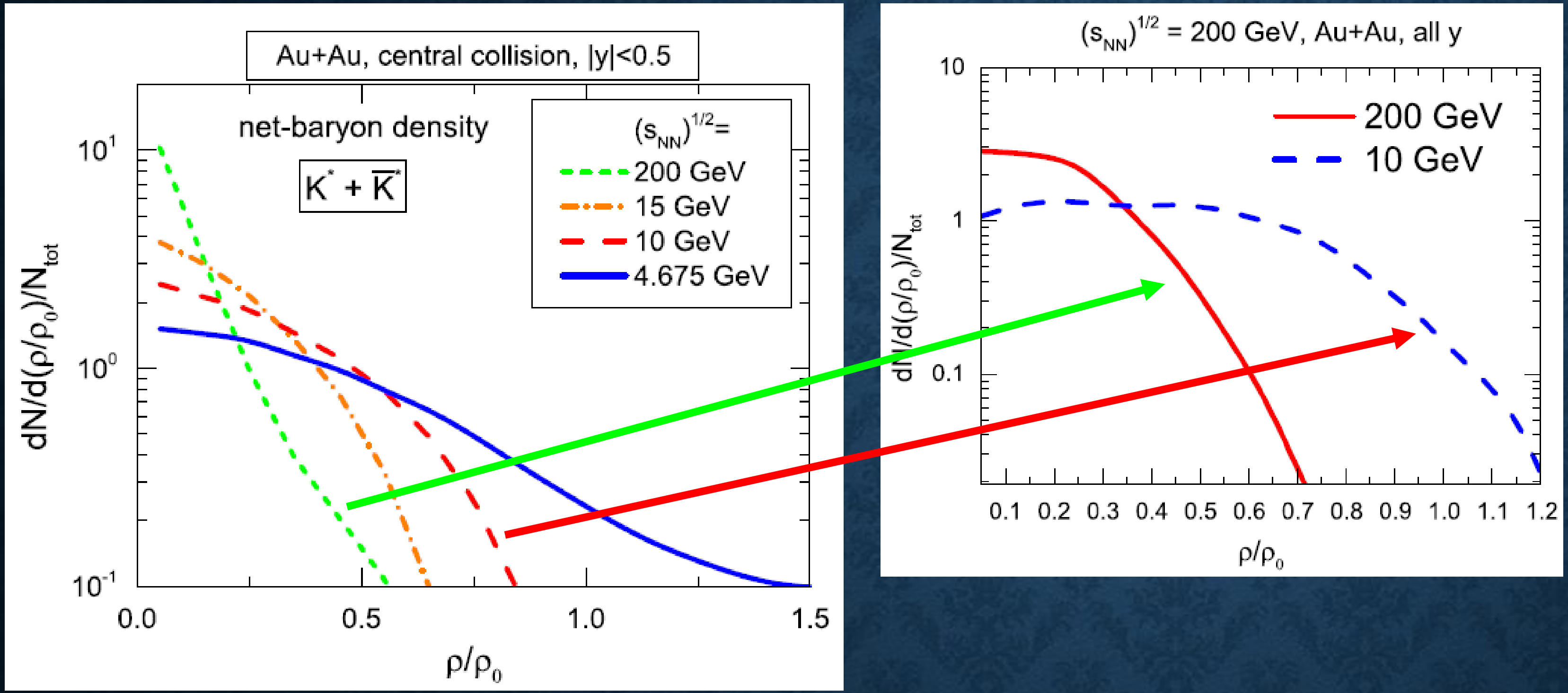


- production by BB and mB strings dominates early in the hadronic corona, then becomes negligible
- contribution from QGP is overall on the same level as string contribution but starts at hadronization
- the $K + \pi$ annihilation is the dominant channel and its relative fraction is larger at LHC than at RHIC

A. Ilner, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 95, 014903 (2017)
A. Ilner, J. Blair, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 99, 024914 (2019)

VECTOR MESONS IN OFF-SHELL TRANSPORT: *K**

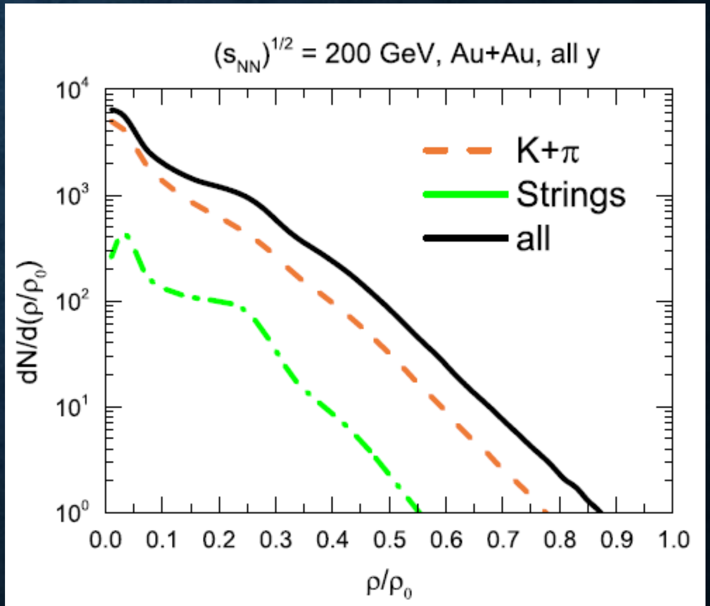
net-baryon density distribution of K* at production point



$$K^* = K^{*+} + K^{*0}$$
$$\overline{K^*} = K^{*-} + \overline{K}^{*0}$$

as expected, higher rapidities probes larger baryon densities

channel decomposition

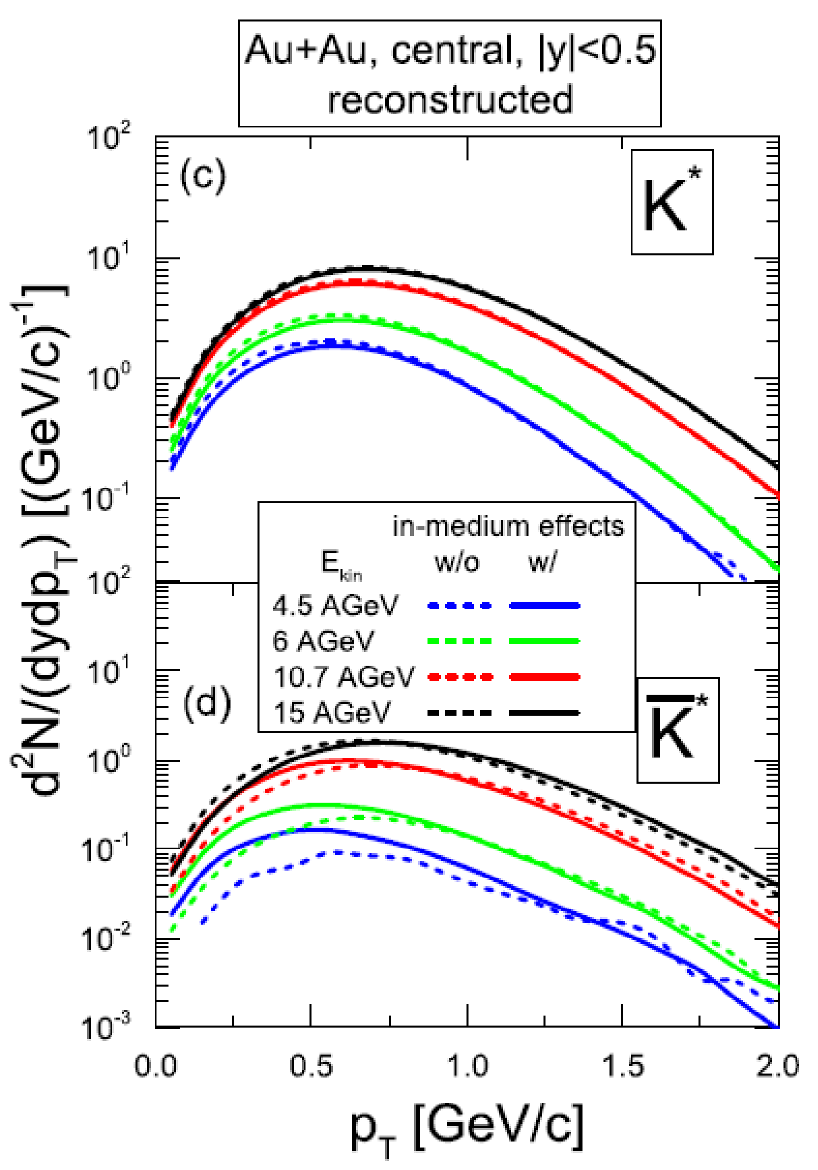


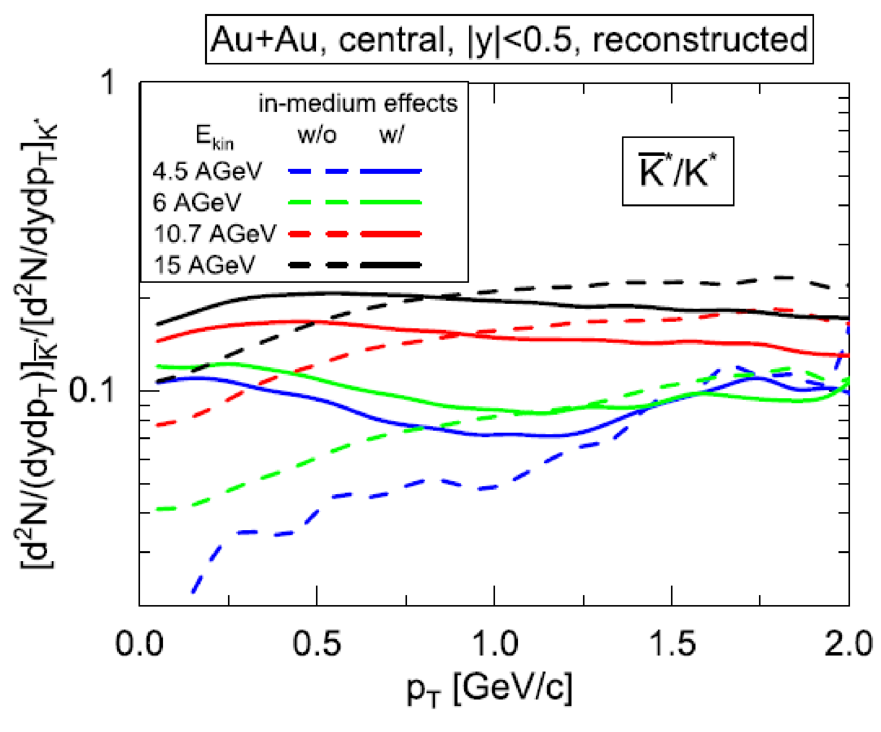
- at high collision energies *K** are produced at rather low net-baryon density
- when decreasing collision energy *K** production probes baryon densities even above normal nuclear matter density

K + *π* production channel dominates for all baryon densities at high energy

A. Ilner, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 95, 014903 (2017)
A. Ilner, J. Blair, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 99, 024914 (2019)

VECTOR MESONS IN OFF-SHELL TRANSPORT: *K**





$$K^* = K^{*+} + K^{*0}$$
$$\overline{K}^* = K^{*-} + \overline{K}^{*0}$$

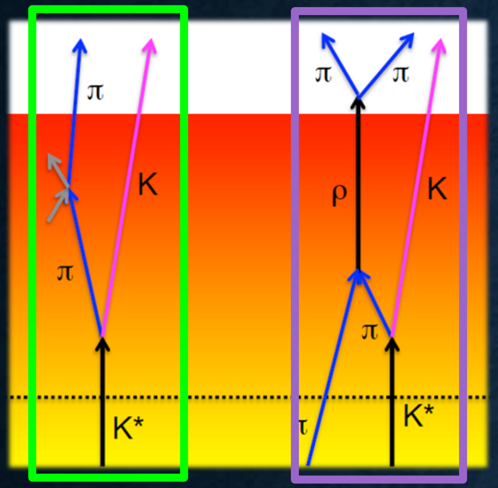
see talk of
K. AOKI
Sat 16/03

in-medium effects of K^* and $\overline{K}^*$ should be visible at FAIR/NICA and BES RHIC energies since the production occurs at large net-baryon densities

A. Ilner, J. Blair, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 99, 024914 (2019)

VECTOR MESONS IN OFF-SHELL TRANSPORT: *K**

Picture credit: Anders Knospe

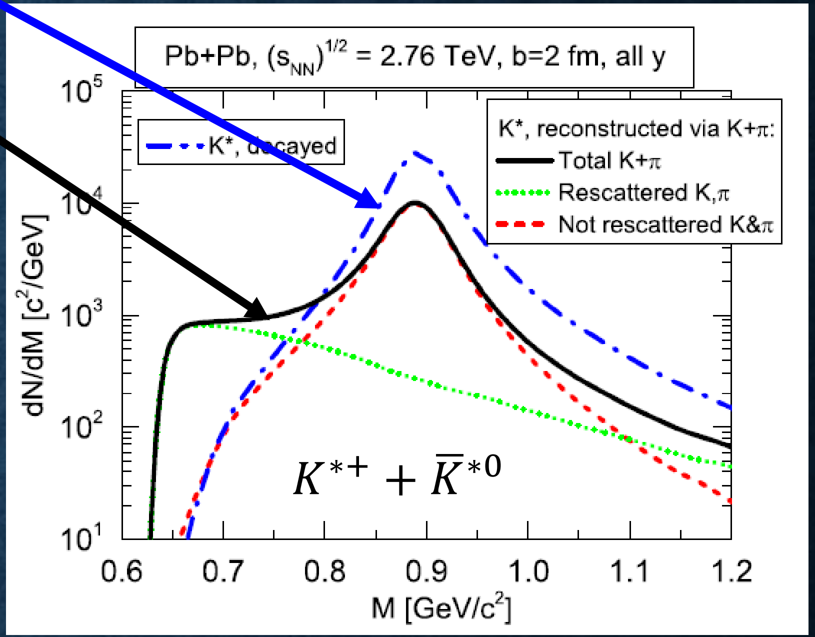


decayed K*
spectra obtained at K* decay point

reconstructed K*
spectra of K* whose decay products
scatter elastically or do not rescatter

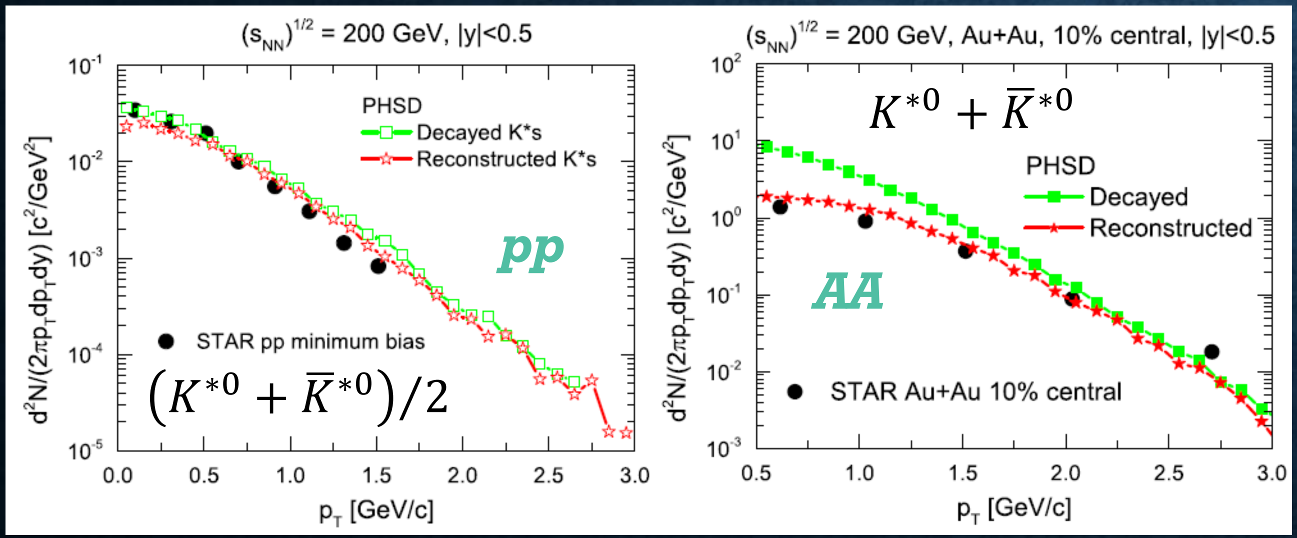
K* whose decay products suffer inelastic reactions are not reconstructible

K mass distribution*



clear distortion of the spectra due to final state interaction in hadronic phase

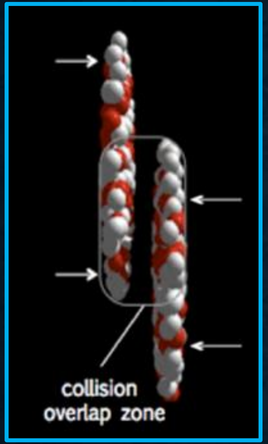
K transverse momentum spectra*



- ***pp***: same reconstructed and decay spectra due to negligible hadronic interaction
- ***AA***: strong reduction of the low p_T spectra due to signal "loss" from rescattering/absorbtion mechanisms and, especially, experimental cuts

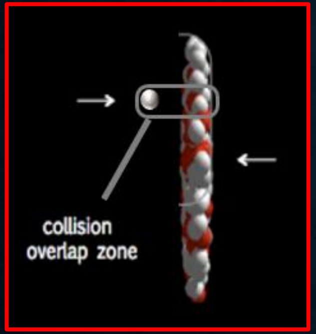
A. Ilner, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 95, 014903 (2017)
A. Ilner, J. Blair, D. Cabrera, C. Markert and E. Bratkovskaya, Phys. Rev. C 99, 024914 (2019)

VECTOR MESONS IN OFF-SHELL TRANSPORT: *K**

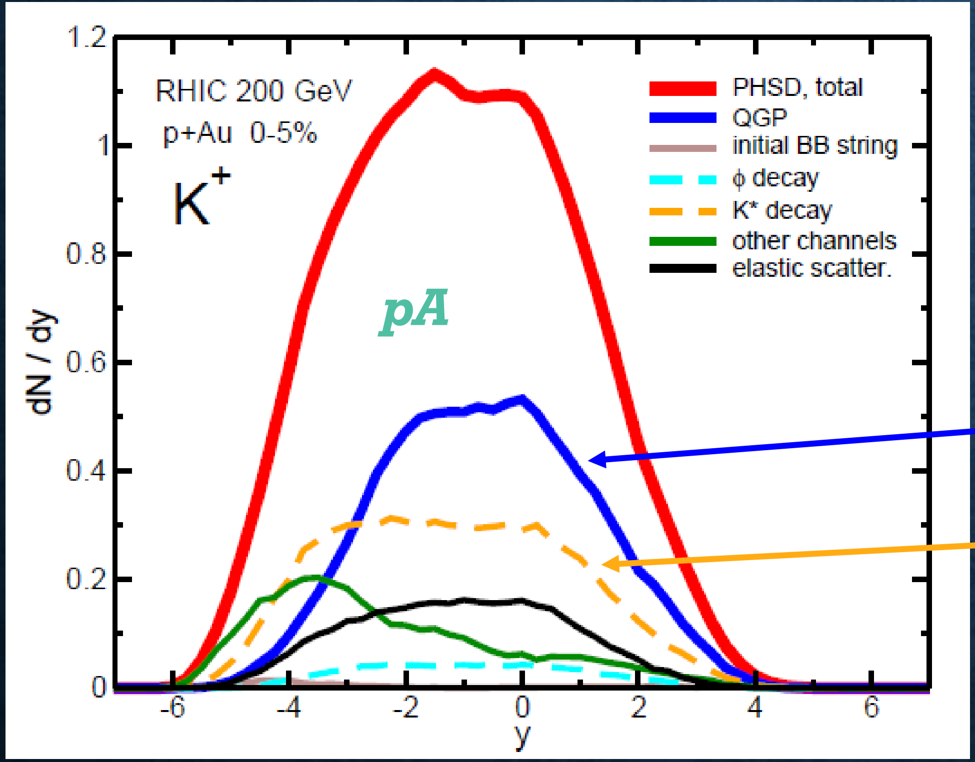


in ***AA*** kaons created by *K** decay are about twice those generated directly from QGP

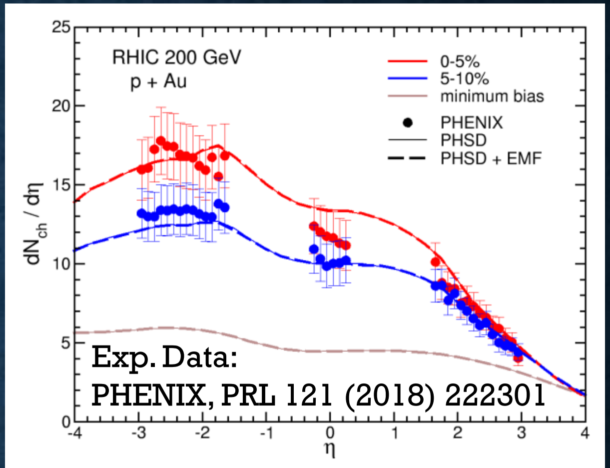
vs



channel decomposition of K⁺ production



LO, P. Moreau, V. Voroniuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)



in ***pA*** large amount of particles escapes from the medium just after production from QGP hadronization without further rescattering

directly from QGP hadronization

from K* decay

comparing vector meson spin alignment in small and large system may help to disentangle the impact of hadronic phase

Lucia Oliva (Catania University, INFN-Catania) - 16th March 2024 - Academia Sinica

VECTOR MESONS IN OFF-SHELL TRANSPORT: ϕ

relativistic Breit–Wigner spectral function

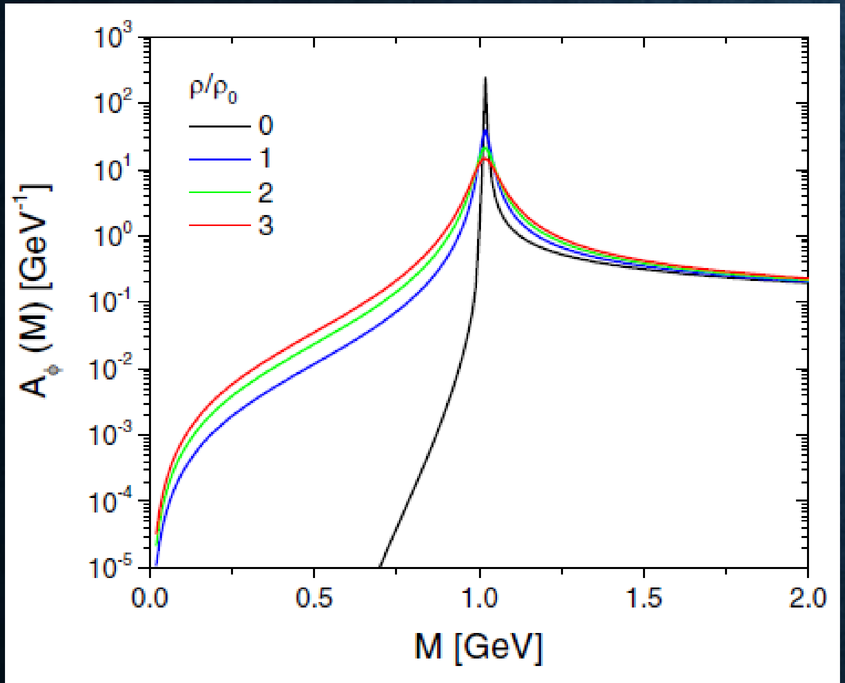
$$A_V(M,\rho) = C_1 \frac{2}{\pi} \frac{M^2 \Gamma_V^*(M,\rho)}{\left[M^2 - M_V^{*2}(\rho)\right]^2 + \left[M \Gamma_V^*(M,\rho)\right]^2}$$

collisional broadening

$$\Gamma_{\rm coll}(M, |\vec{p}|, \rho) = \gamma \rho < v\, \sigma_{VN}^{\rm tot} > \approx \alpha_{\rm coll} \frac{\rho}{\rho_0}$$

$\alpha_{\rm coll} = 25$ MeV

(small) mass shift in the medium neglected



***ϕ* spectral function**

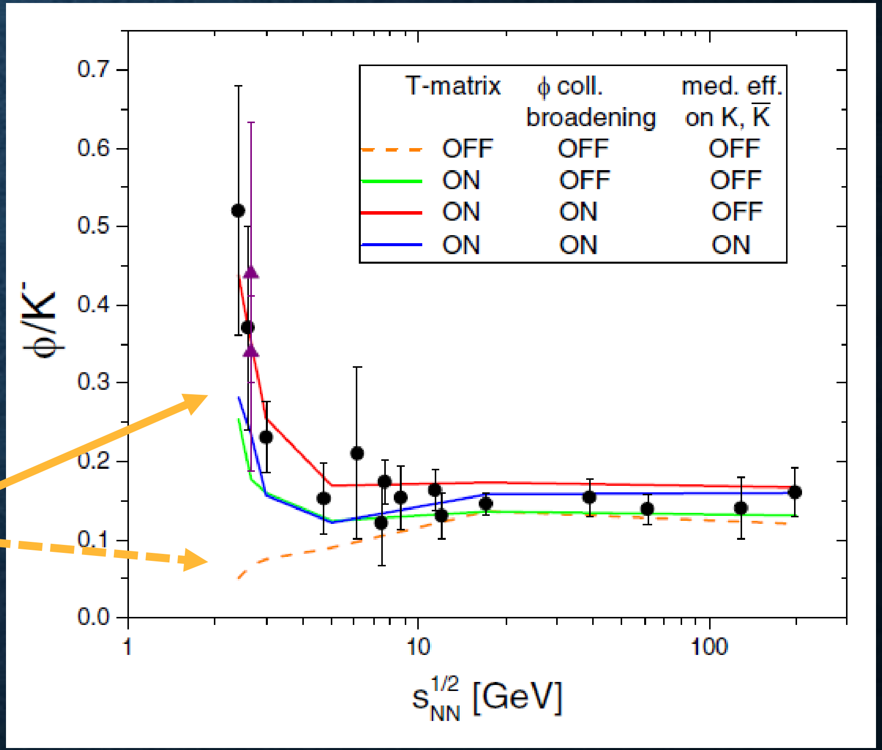
***ϕ/K⁻* ratio**

☒ see talk of P. GUBLER Sun 17/03

at low energy novel mB → ϕ production channels very relevant

ON

OFF

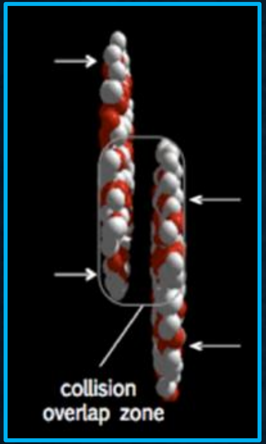


collisional broadening enhances ϕ-meson production especially at subthreshold energies

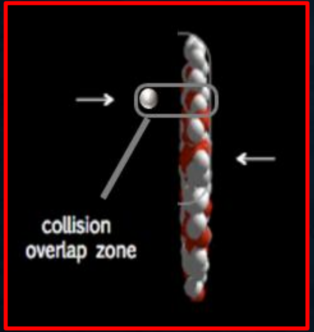
at high energies ϕ production dominated by string fragmentation and QGP hadronization

T. Song, J. Aichelin and E. Bratkovskaya, Phys. Rev. C 106, 024903 (2022)

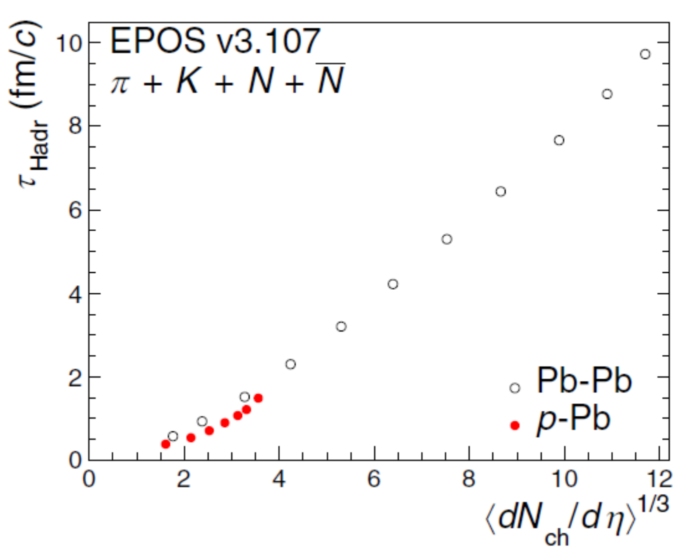
RESONANCE DYNAMICS IN SMALL SYSTEMS



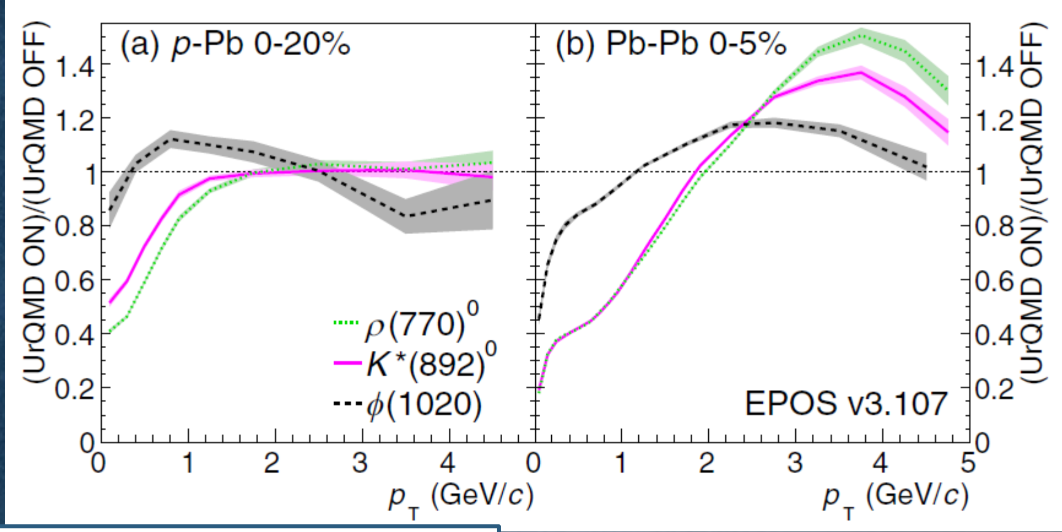
vs

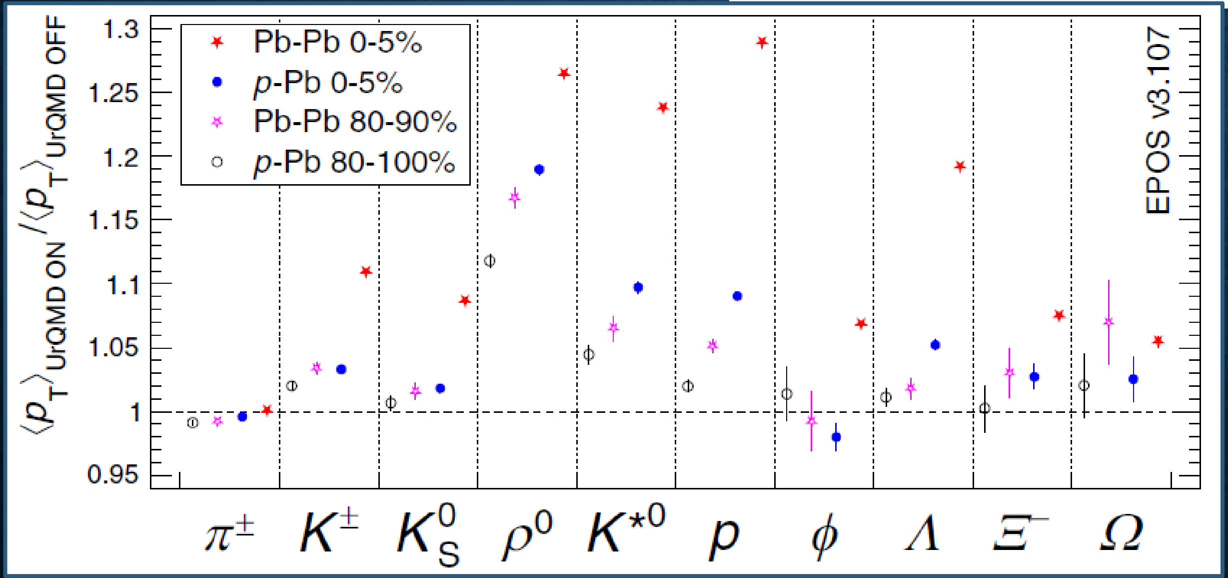


hadronic phase lifetime



ratios of p_T spectra w/ to w/o hadronic phase





ratios of mean p_T w/ to w/o hadronic phase

HYDRID MODEL

EPOS + UrQMD

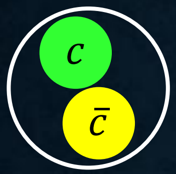
hadronic phase in central *pA* collisions

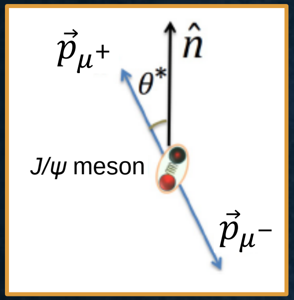
- estimated lifetime ≈1-2 fm/c
- important in determining final yields and p_T distributions of short-lived vector mesons

A. Knospe, C. Markert, K. Werner, J. Steinheimer and M. Bleicher, Phys. Rev. C 104, 054907 (2021)

J/ψ SPIN ALIGNMENT

J/ψ





J/ψ mesons are spin-1 particles decaying through electromagnetic interaction

$J/\psi \rightarrow \mu^+ + \mu^-$ (BR ~6%)

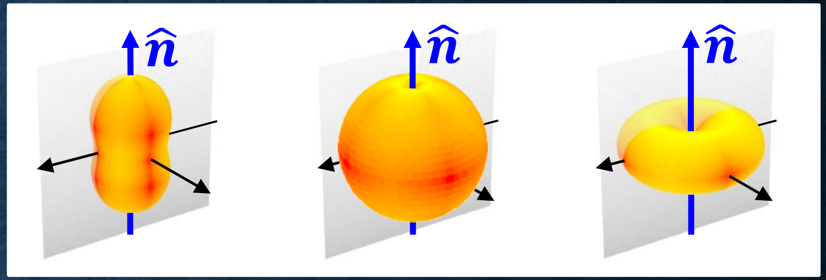
$\Longrightarrow$ measure **SPIN ALIGNMENT**

$$W(\theta^*) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta^*\right)$$

λ_θ: polarization parameter

$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$

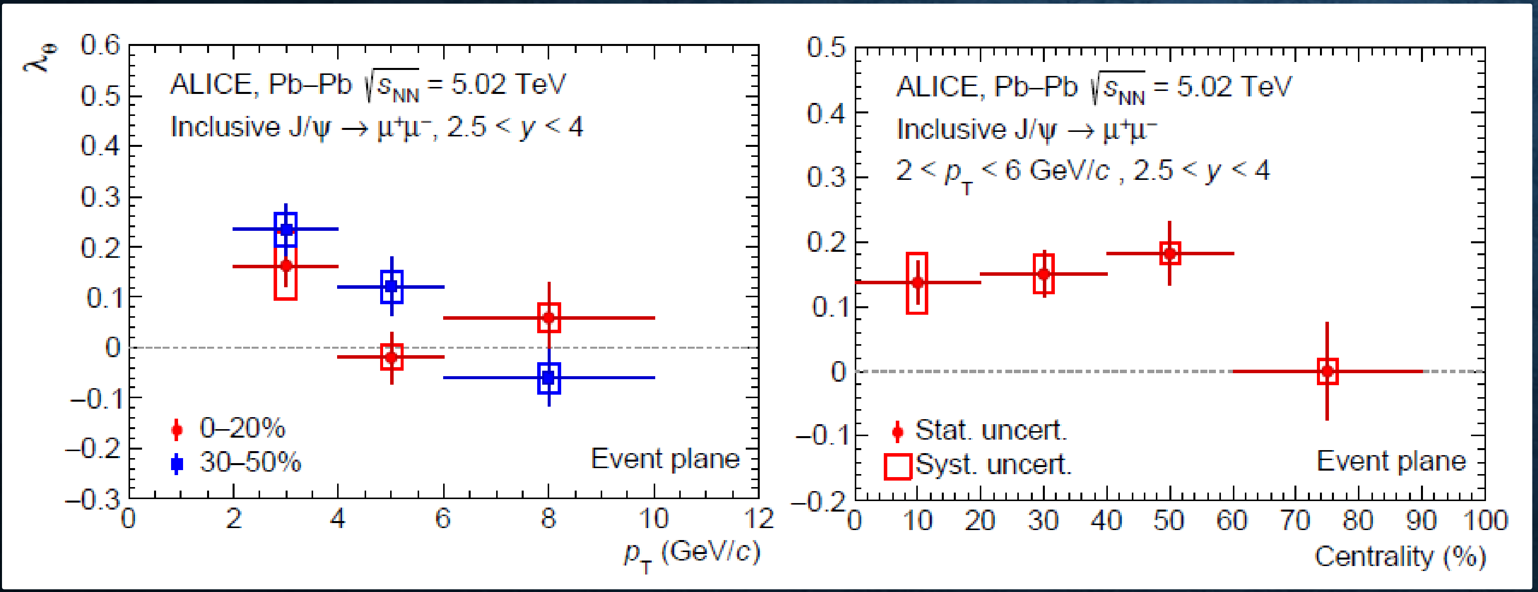
for vector meson decay into dileptons



$\lambda_\theta > 0$	$\lambda_\theta = 0$	$\lambda_\theta < 0$
$\rho_{00} < 1/3$	$\rho_{00} = 1/3$	$\rho_{00} > 1/3$
$\lvert 1, \pm 1\rangle$		$\lvert 1, 0\rangle$
"transverse" polarization		"longitudinal" polarization

P. Faccioli, C. Lourenço, J. Seixas and H. Wohri, Eur. Phys. J. C 69, 657 (2010)

ALICE Coll., Phys. Rev. Lett. 131, 042303 (2023)



small transverse polarization

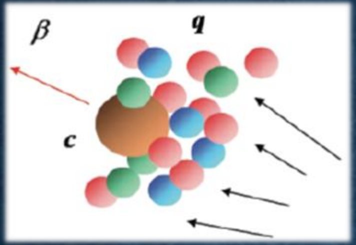
$\lambda_\theta \sim 0.2 > 0 \quad \Longrightarrow \quad \rho_{00} \sim 0.25 < 1/3$

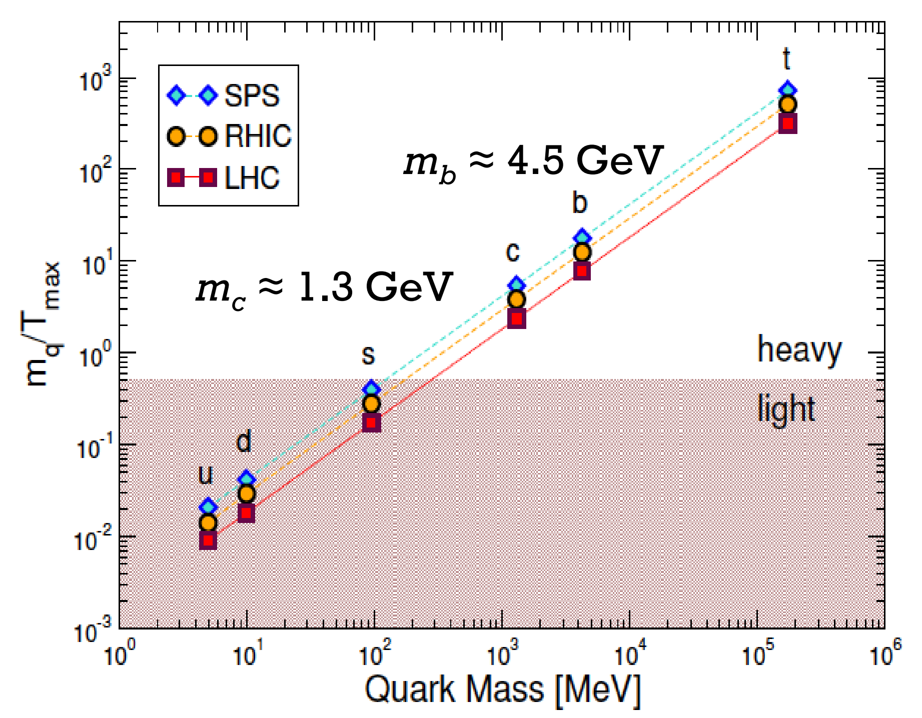
☒ see talk of S. LIM Thu 14/03

☒ see talks of X.-L. SHENG A. KUMAR Thu 14/03

HEAVY QUARKS IN QGP: BASIC SCALES

few Heavy Quarks (HQs), charm and bottom, produced in relativistic 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

- τ_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 Flavour (HF) hadrons are a very promising probe of the fascinating dinamycs of relativistic heavy-ion collisions

INTENSE FIELDS AND HEAVY FLAVOR TRANSPORT

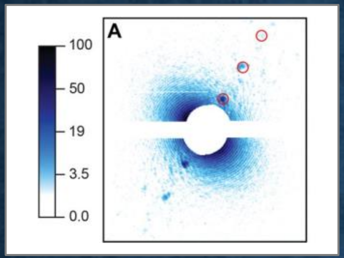
✓ HUGE ANGULAR MOMENTUM GENERATING A STRONG **VORTICITY**

tornado cores

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

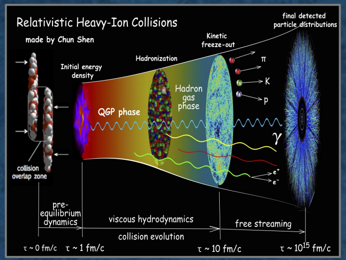
Jupiter's spot

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



He nanodroplets

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



urHICs

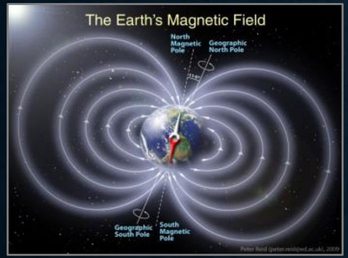
~ 10^{22}–10^{23} s^{-1}

vorticity ω

since 2017

- impact on HF directed flow and **spin polarization**
- connection to HQ transport coefficients

✓ INTENSE **ELECTROMAGNETIC FIELDS**



Earth's field

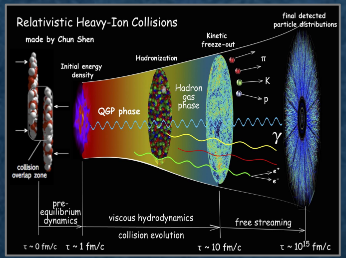
~ 1 G

laboratory

~ 10^{6} G

magnetars

~ 10^{14}–10^{15} G



urHICs

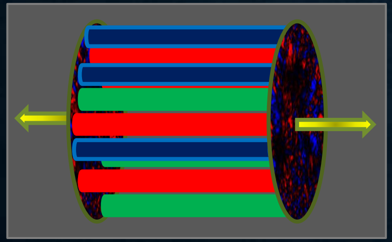
~ 10^{18}–10^{19} G

magnetic field B

since 2016

- impact on HF directed flow and **spin polarization**
- connection to QGP electric conductivity and formation time

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



since 2018

- impact on HF R_{AA}, v_2 and **spin polarization**
- connection to HQ transport coefficients

CATANIA TRANSPORT APPROACH

BULK EVOLUTION

$$p^\mu \partial_\mu f_g(x,p) = \mathcal{C}[f_g, f_q]$$
$$\left(p^\mu \partial_\mu + Q_q F^{\mu\nu}_{EM} p_\nu \partial^p_\mu\right) f_q(x,p) = \mathcal{C}[f_g, f_q]$$

free-streaming **field interaction** **collision kernel**

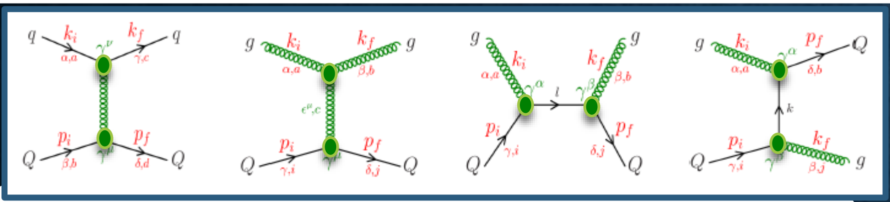
Boltzmann transport equivalent to viscous hydro at η/s ≈ 0.1

gauged to some $\eta/s \neq 0$

M. Ruggieri et al., Phys. Rev. C 89, 054914 (2014)

HQ EVOLUTION

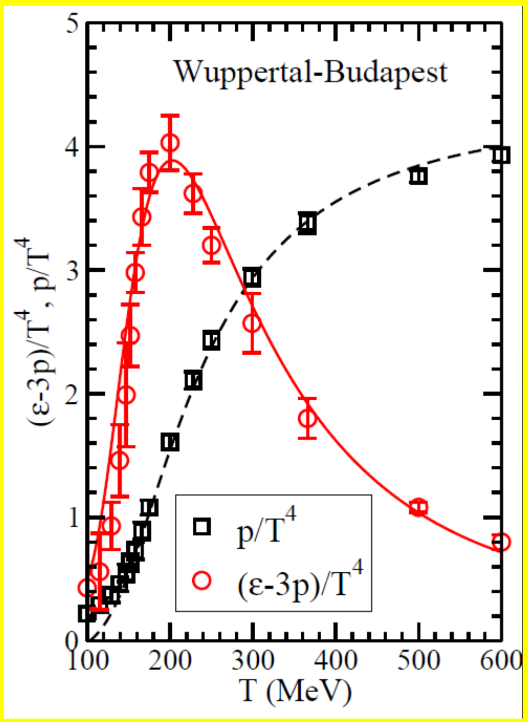
$$p^\mu \partial_\mu f_{HQ}(x,p) + Q_{HQ} F^{\mu\nu}_{EM} p_\nu \partial^p_\mu f_{HQ}(x,p) = \mathcal{C}[f_g, f_q, f_{HQ}]$$



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

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

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



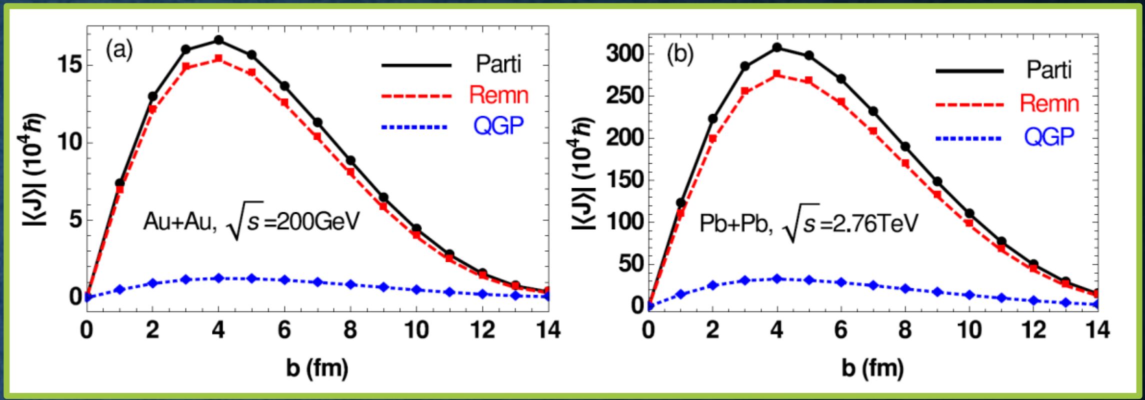
$$m_g^2(T) = \frac{2N_c}{N_c^2 - 1} g^2(T) T^2$$
$$m_q^2(T) = \frac{1}{N_c} g^2(T) T^2$$
$$g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f) \ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$

S. Plumari et al., Phys. Rev. D 84, 094004 (2011)

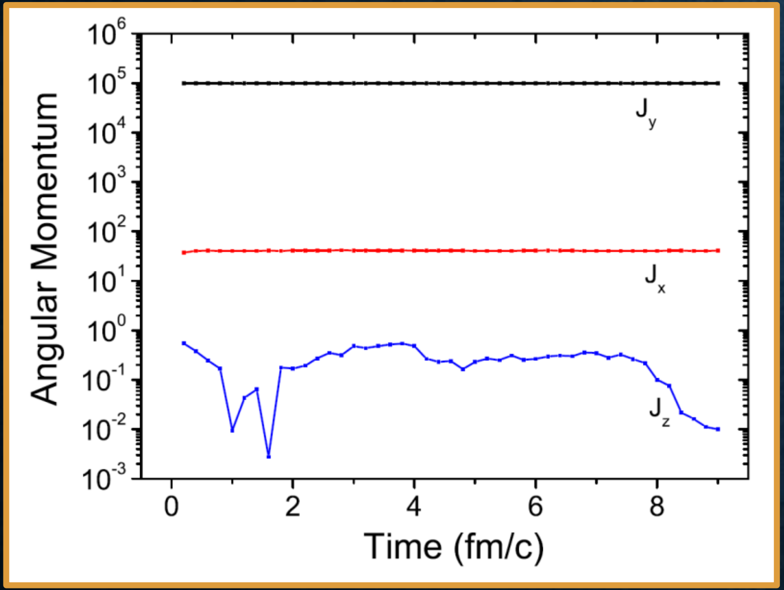
UPGRADING THE LONGITUDINAL VIEW

Huge **orbital angular momentum** in non-frontal nuclear collisions

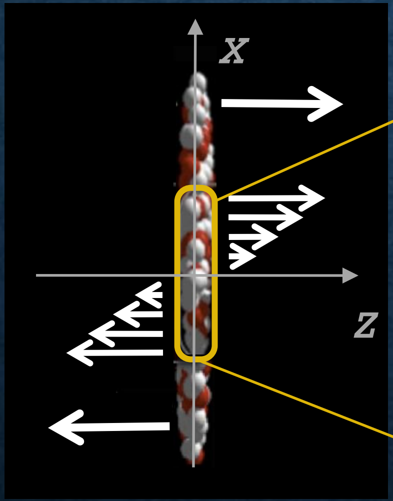
- in ultrarelatvistic HICs **$J \approx 10^5$ - 10^6 ħ**
- mainly perpendicular to the reaction plane
- **partly trasferred to the plasma**



W.-T. Deng and X.-G. Huang, Phys. Rev . C 93, 064907 (2016)

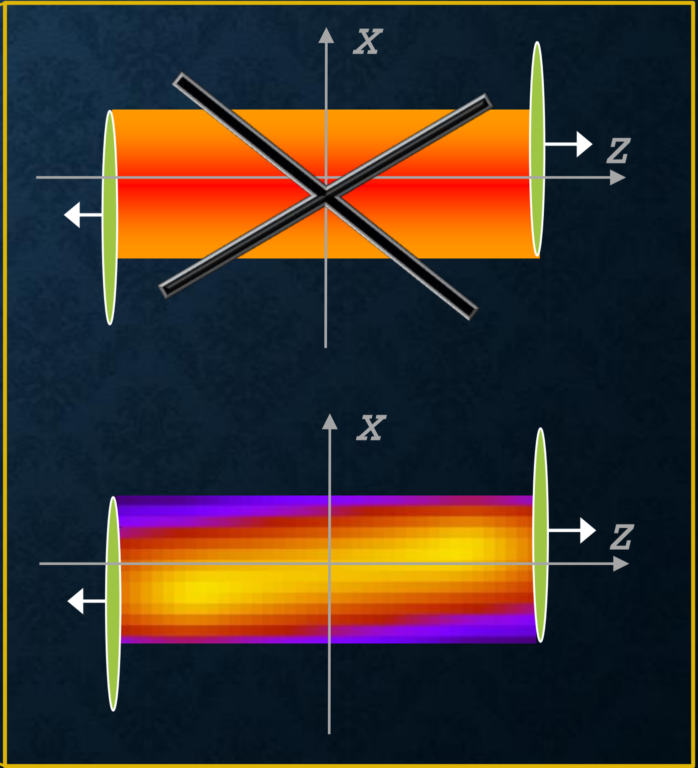


Y. Jiang, Z.-W. Lin and J. Liao, Phys. Rev. C 94, 044910 (2016)



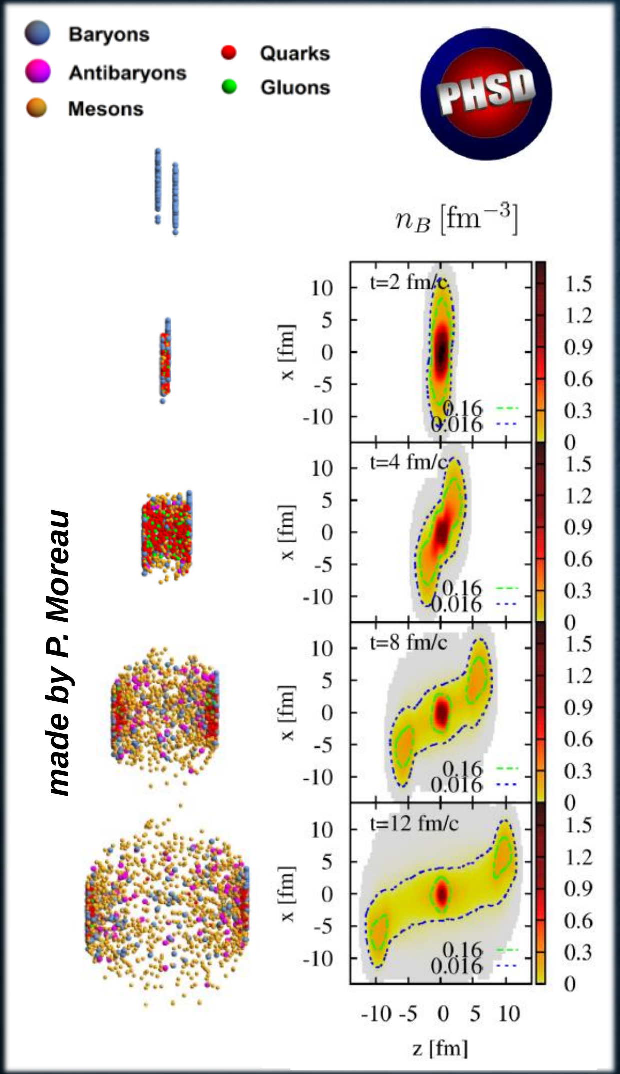
Not a symmetric energy distribution…

…but a TILTED FIREBALL on reaction plane



TWO APPROACHES: VORTICITY IN HICS

PHSD/AMPT APPROACH



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

CATANIA APPROACH

asymmetry in local participant density from forward and backward going nuclei

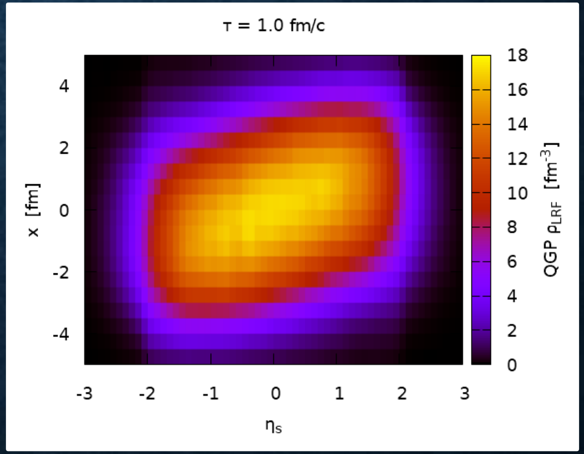
P. Bozek and I. Wyskiel, Phys. Rev. C 81, 054902 (2010)

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

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

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

tilted fireball on the reaction plane



QGP density

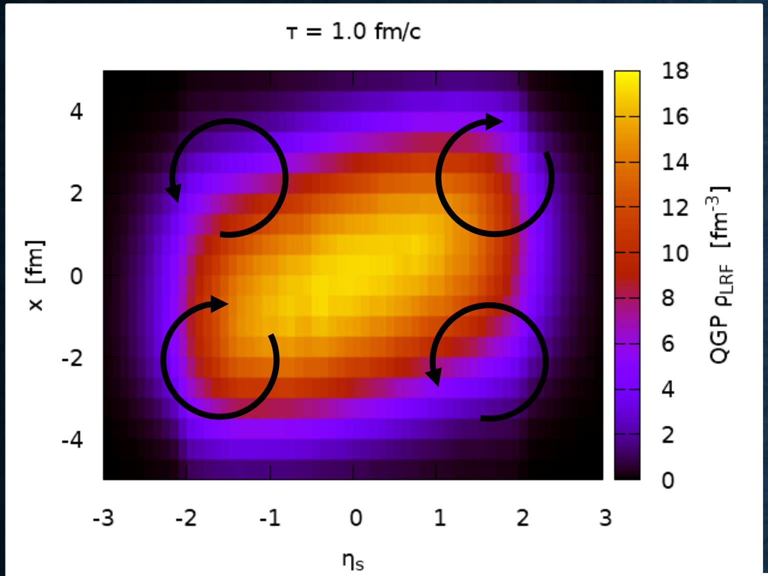
LO, S. Plumari and V. Greco, JHEP 05, 034 (2021)

THE VORTICAL QUARK-GLUON PLASMA

VORTICITY in the QGP

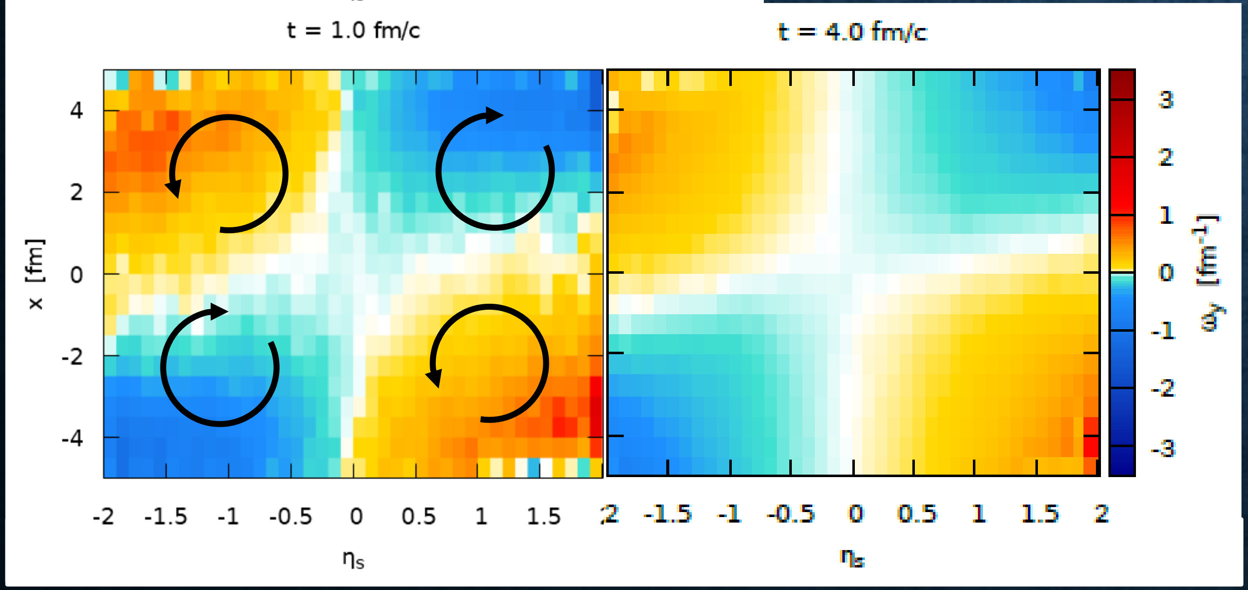
- nonuniform fireball expansion generates a quadrupole pattern
- tilted fireball leads to a net vorticity

L.P. Csernai, V.K. Magas and D.J. Wang, Phys. Rev. C 87, 034906 (2013)
W.-T. Deng and X.-G. Huang, Phys. Rev . C 93, 064907 (2016)
Y. Jiang, Z.-W. Lin and J. Liao, Phys. Rev. C 94, 044910 (2016)
X.-L. Xia, H. Li, Z. Tang and Q. Wang, Phys. Rev. C 98, 024905 (2018)

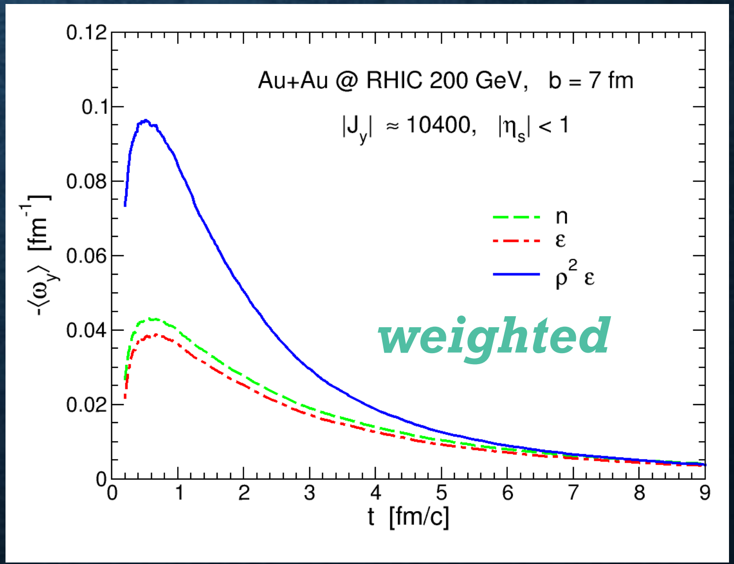


LO, S. Plumari and V. Greco, JHEP 05, 034 (2021)

many detailed studies of its spatial distribution, time evolution, dependence on collision energy and impact parameter



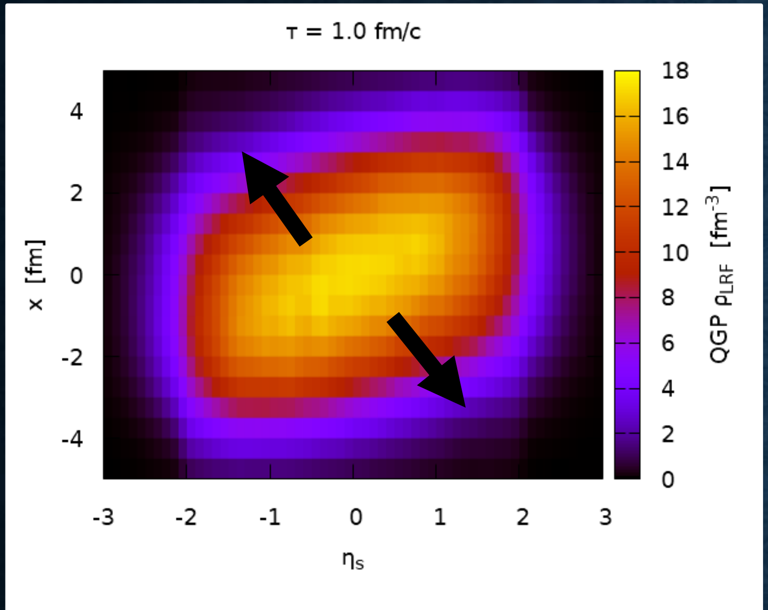
vorticity profile on reaction plane



time evolution of vorticity

$\omega \approx 3$ c/fm
QGP as the most vortical fluid

A PROBE OF VORTICITY: DIRECTED FLOW



Fireball tilt induce a negative slope in the η dependence of the particle DIRECTED FLOW

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

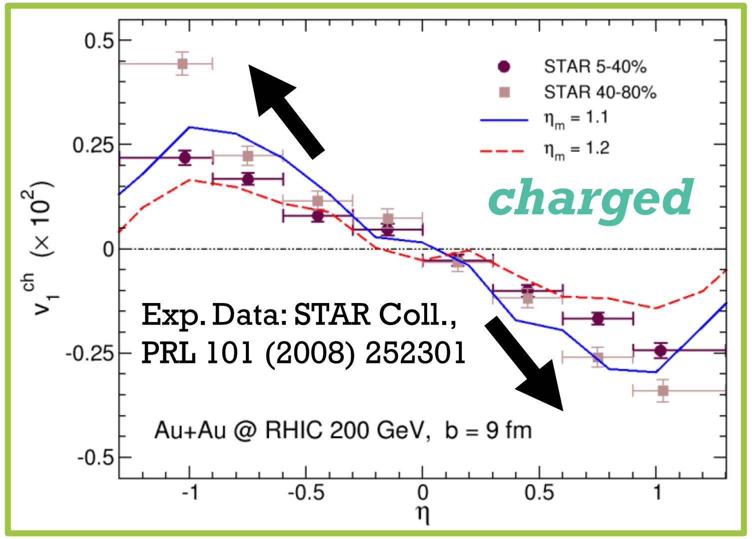
P. Bozek and I. Wyskiel, Phys. Rev. C 81, 054902 (2010)

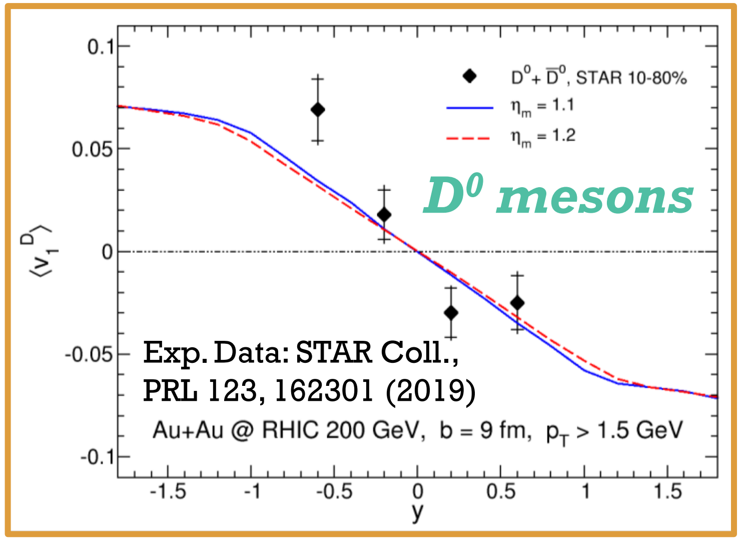
slope of v_1 of neutral D mesons is 20-30 times larger than that of light hadrons

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

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

LO, S. Plumari and V. Greco, JHEP 05, 034 (2021)





particles directed flow

RHIC ENERGY

EXP:

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

TH: $dv_1^D/dy = -\,0.065$

LHC ENERGY:

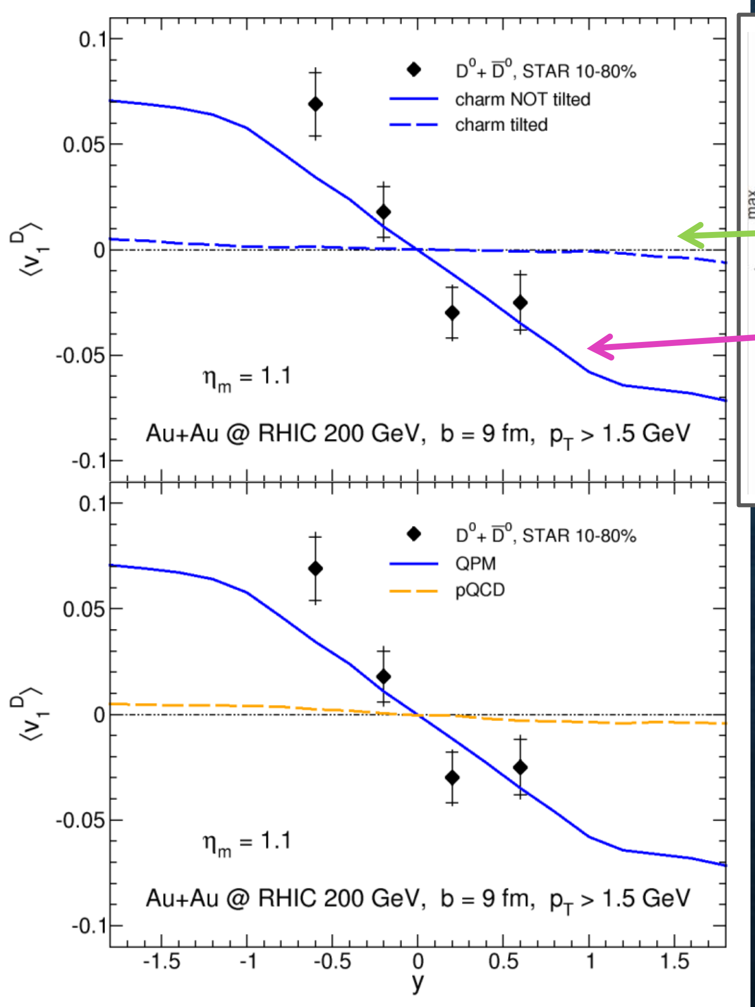
$\langle v_1^D \rangle$ slope ~ 50 times smaller than that at RHIC (in line with model predictions) and consistent with 0

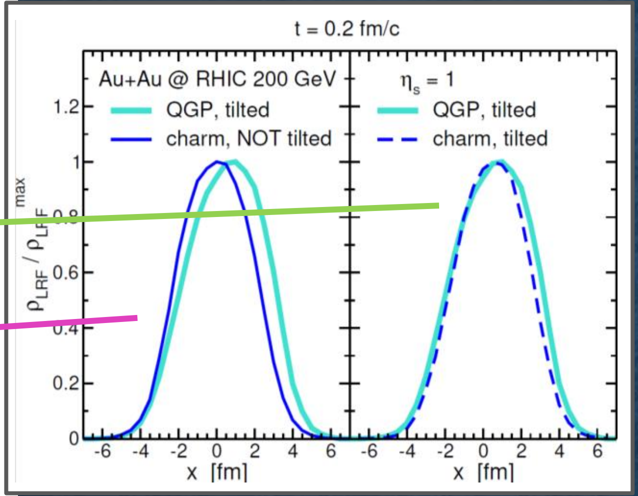
ALICE Collaboration, Phys. Rev. Lett. 125, 022301 (2020)

DIRECTED FLOW MAGNITUDE OF *D* MESONS

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

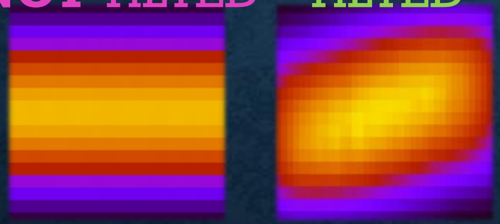
$\langle v_1^D \rangle (y)$





CHARM **NOT** TILTED

CHARM TILTED

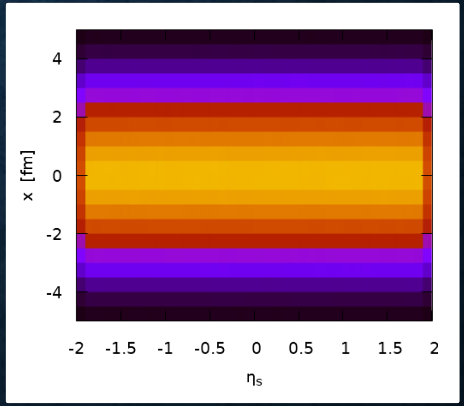


QGP tilted in both cases

v_1 (HQs) ≫ v_1 (QGP)

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

HQ production points symmetric in the forward-backward hemispheres

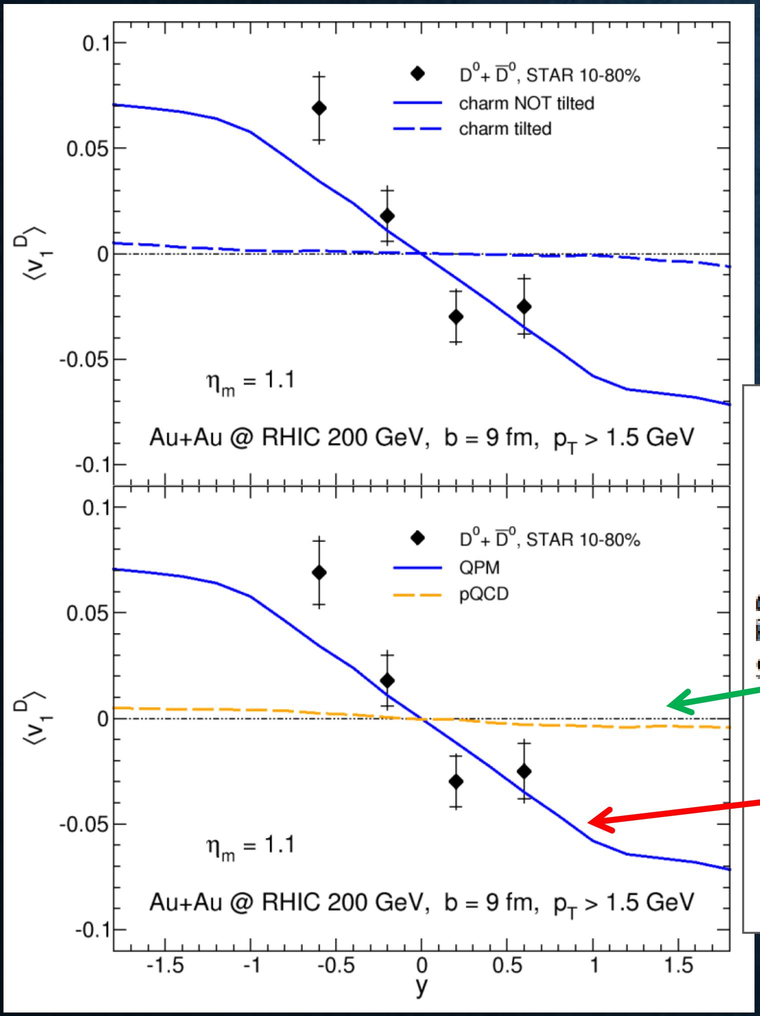


LO, S. Plumari and V. Greco, JHEP 05, 034 (2021)

DIRECTED FLOW MAGNITUDE OF *D* MESONS

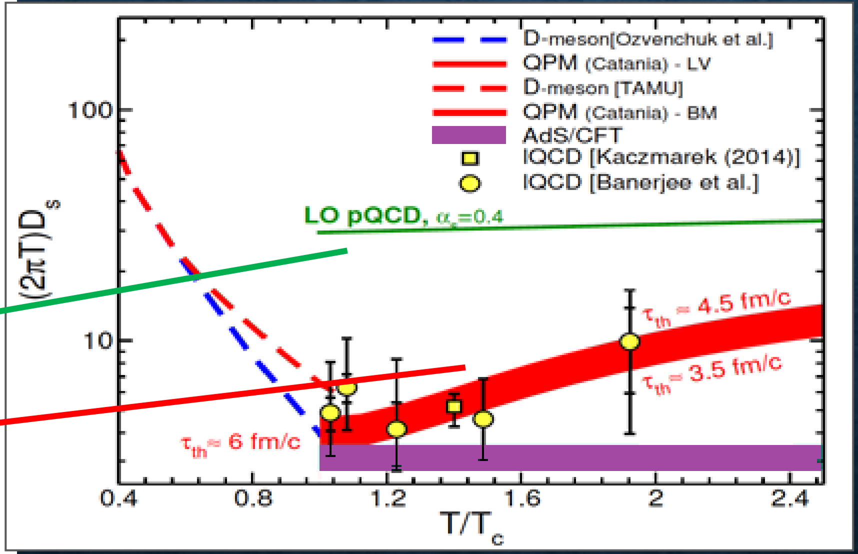
origin of the large directed flow of HQs different from the one of light particles

$\langle v_1^D \rangle(y)$



LO, S. Plumari and V. Greco, JHEP 05, 034 (2021)

charm-quark spatial diffusion coefficient



V. Greco, Nucl. Phys. A 967, 200 (2017)

v_1 (HQs) ≫ v_1 (QGP)

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

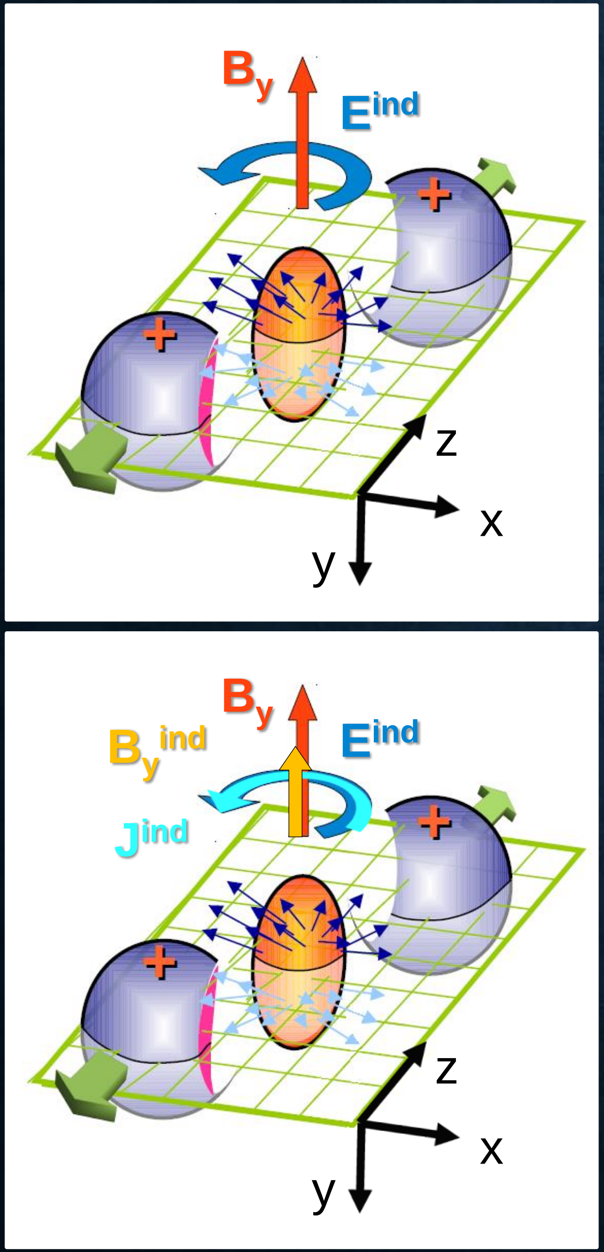
effective because the HQ interaction in QGP is largely non-perturbative

in agreement with
S. Chatterjee and P. Bozek, Phys. Rev. Lett. 120, 192301 (2018)
A. Beraudo et al., JHEP 05, 279 (2021)

a small spatial diffusion coefficient D_s characterizes a strong coupling

$2\pi T D_s \approx 3 - 6$
QGP diffuses charm quarks like an almost perfect fluid

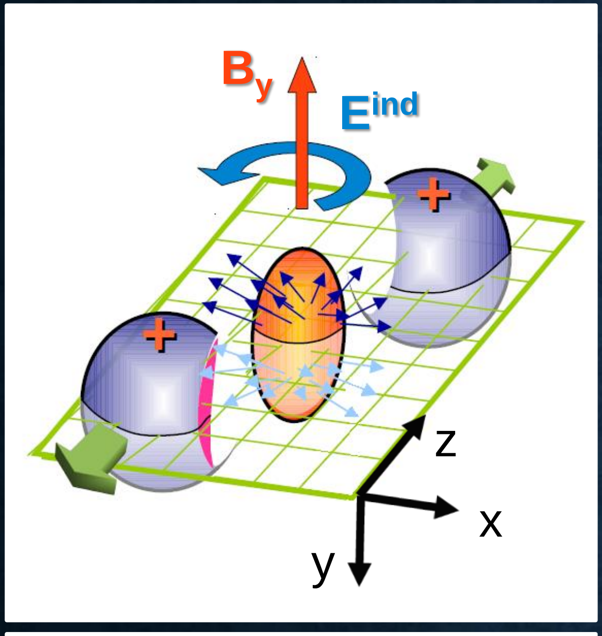
ELECTROMAGNETIC FIELDS IN HICS

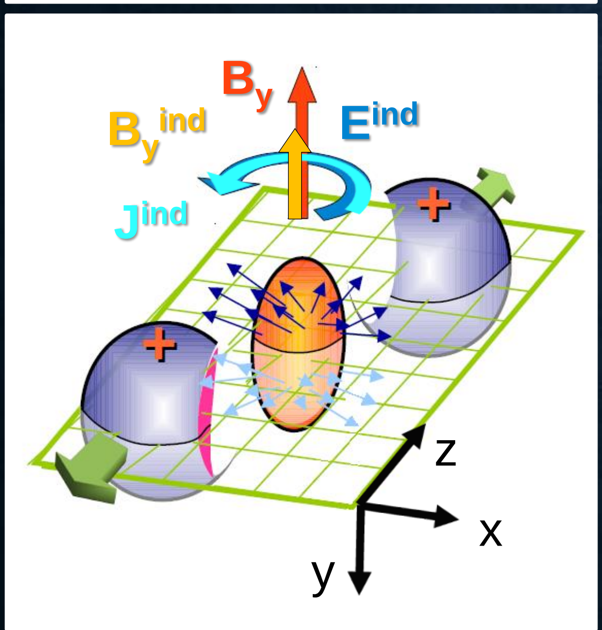


- Huge **magnetic field** in the overlapping area of the ultrarelatvistic HICs **$eB \approx 5\text{-}50\ m_\pi^2 \sim\ 10^{18}\text{-}10^{19}$ G**
- Intense electric field generated by Faraday induction

D.E. Kharzeev, L.D. McLerran and H.J. Warringa, Nucl. Phys. A 803, 227 (2008)
V. Skokov, A.Yu. Illarionov and V. Toneev, Int. J. Mod. Phys. A 24, 5925 (2009)
V. Voronyuk *et al.* (HSD), Phys. Rev. C 83, 054911 (2011)

ELECTROMAGNETIC FIELDS IN HICS





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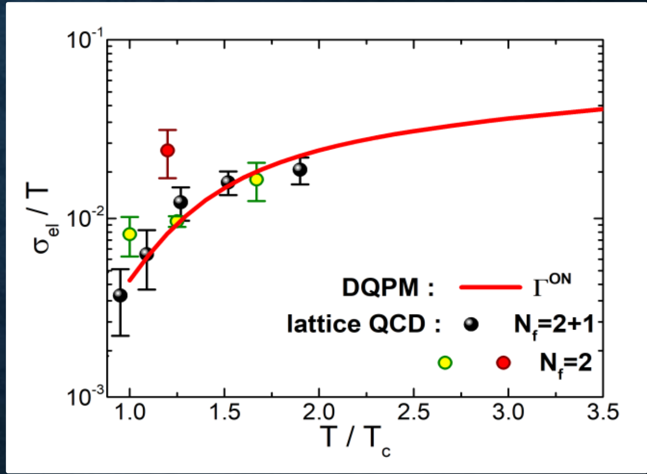
D.E. Kharzeev, L.D. McLerran and H.J. Warringa, Nucl. Phys. A 803, 227 (2008)
V. Skokov, A.Yu. Illarionov and V. Toneev, Int. J. Mod. Phys. A 24, 5925 (2009)
V. Voronyuk *et al.* (HSD), Phys. Rev. C 83, 054911 (2011)

Ohm's law

$$J = \sigma_{el} E$$

QGP electric conductivity

O. Soloveva, P. Moreau and E. Bratkovskaya, Phys. Rev. C 101, 045203 (2020)



generation of charged currents which lead to a slowdown of the magnetic field decay

reviews
X.-G. Huang, Rept. Prog. Phys. 79, 076302 (2016)
LO, Eur. Phys. J. A 56, 255 (2020)

EMF IN TRANPORT APPROACHES

In a kinetic framework the transport equations should be coupled to the Maxwell equations for describing the EMF produced in HICs and their effect on final observables

$$\left\{\frac{\partial}{\partial t} + \left(\frac{\mathbf{p}}{p_0} + \nabla_{\mathbf{p}} U\right)\nabla_{\mathbf{r}} + (-\nabla_{\mathbf{r}} U + e\mathbf{E} + e\mathbf{v}\times\mathbf{B})\nabla_{\mathbf{p}}\right\} f = \mathcal{C}[f]$$

TRANSPORT EQUATIONS

Lorentz force

$$\nabla\cdot\mathbf{B} = 0 \qquad \nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \qquad \nabla\cdot\mathbf{E} = 4\pi\rho \qquad \nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j}$$

MAXWELL EQUATIONS

charge distribution **electric current**

For a complete description

- nontrivial electromagnetic response of the QGP (electromagnetic conductivity, chiral conductivity, …)
- consistent solution of evolution equations for the many-particle system and the EMF

TWO APPROACHES: EMF IN NUCLEAR COLLISIONS

Through Liénard-Wiechert potentials one gets the retarded EM fields for a moving point-like charge

PHSD APPROACH

$$\mathbf{E}(\mathbf{r},t) = \frac{e}{4\pi}\left[\frac{\mathbf{n}-\boldsymbol{\beta}}{(1-\mathbf{n}\cdot\boldsymbol{\beta})^3\gamma^2 R^2} + \frac{\mathbf{n}\times\left((\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\right)}{(1-\mathbf{n}\cdot\boldsymbol{\beta})^3 c R}\right]_{\text{ret}}$$

Coulomb bremsstrahlung

$$\mathbf{B}(\mathbf{r},t) = [\mathbf{n}\times\mathbf{E}(\mathbf{r},t)]_{\text{ret}}$$

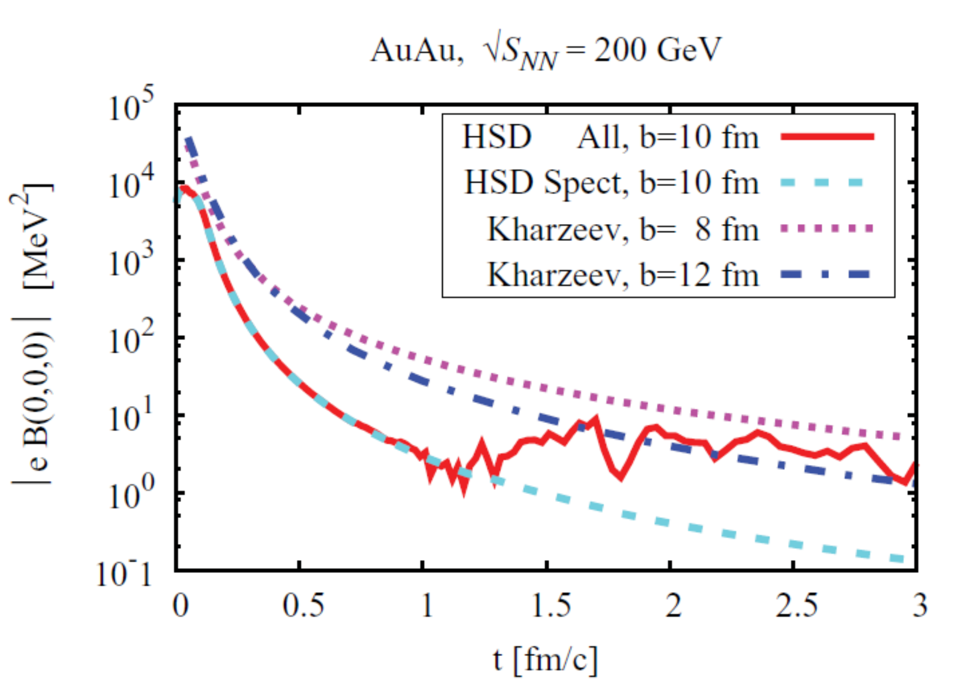
$$\mathbf{R} = \mathbf{r}-\mathbf{r}' \qquad \mathbf{n} = \frac{\mathbf{R}}{R} \qquad \boldsymbol{\beta} = \frac{\mathbf{v}}{c}$$

Neglecting the acceleration one obtains the EM field generted by a charge in uniform motion

$$eE(r,t) = \sum_i \frac{\mathrm{sgn}(q_i)\alpha_{em}\boldsymbol{R}_i(t)(1-\beta_i^2)}{\left\{[\boldsymbol{R}_i(t)\cdot\boldsymbol{\beta}_i]^2 + R_i(t)^2\,(1-\beta_i^2)\right\}^{3/2}}$$

$$eB(r,t) = \sum_i \frac{\mathrm{sgn}(q_i)\alpha_{em}\boldsymbol{\beta}_i\times\boldsymbol{R}_i(t)(1-\beta_i^2)}{\left\{[\boldsymbol{R}_i(t)\cdot\boldsymbol{\beta}_i]^2 + R_i(t)^2\,(1-\beta_i^2)\right\}^{3/2}}$$

The EM field are obtained summing over all charges in the collisions: spectators and participants protons, newly produced particles



V. Voronyuk *et al.* (HSD), Phys. Rev. C 83, 054911 (2011)
V.D. Toneev *et al.* (PHSD), Phys. Rev. C 86, 064907 (2012)

TWO APPROACHES: EMF IN NUCLEAR COLLISIONS

CATANIA APPROACH

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

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

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

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

induced current from

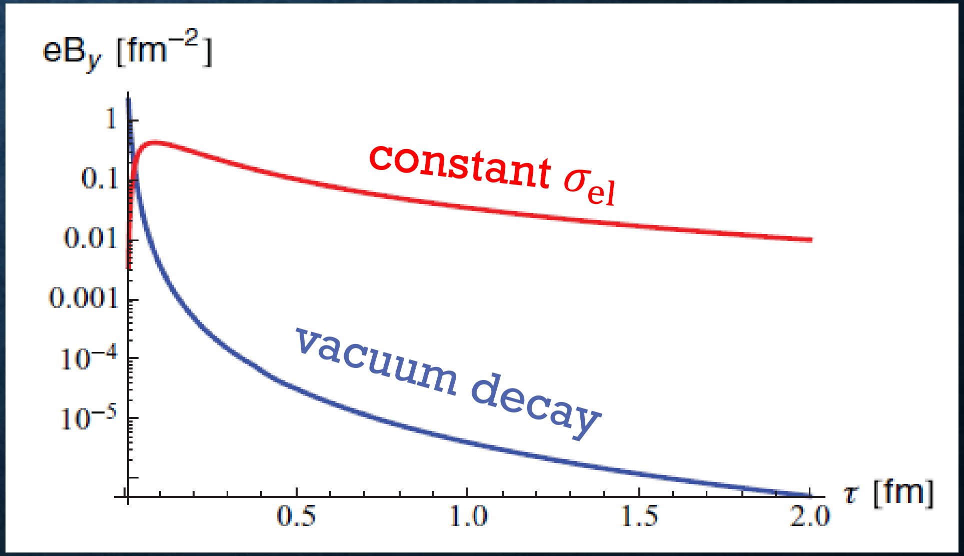
$$\boldsymbol{J}_{ind} = \sigma_{el}\boldsymbol{E}$$

From Maxwell equations one obtains wave equations for the EM fields that can be solved analytically considering a medium with **constant electric conductivity**

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

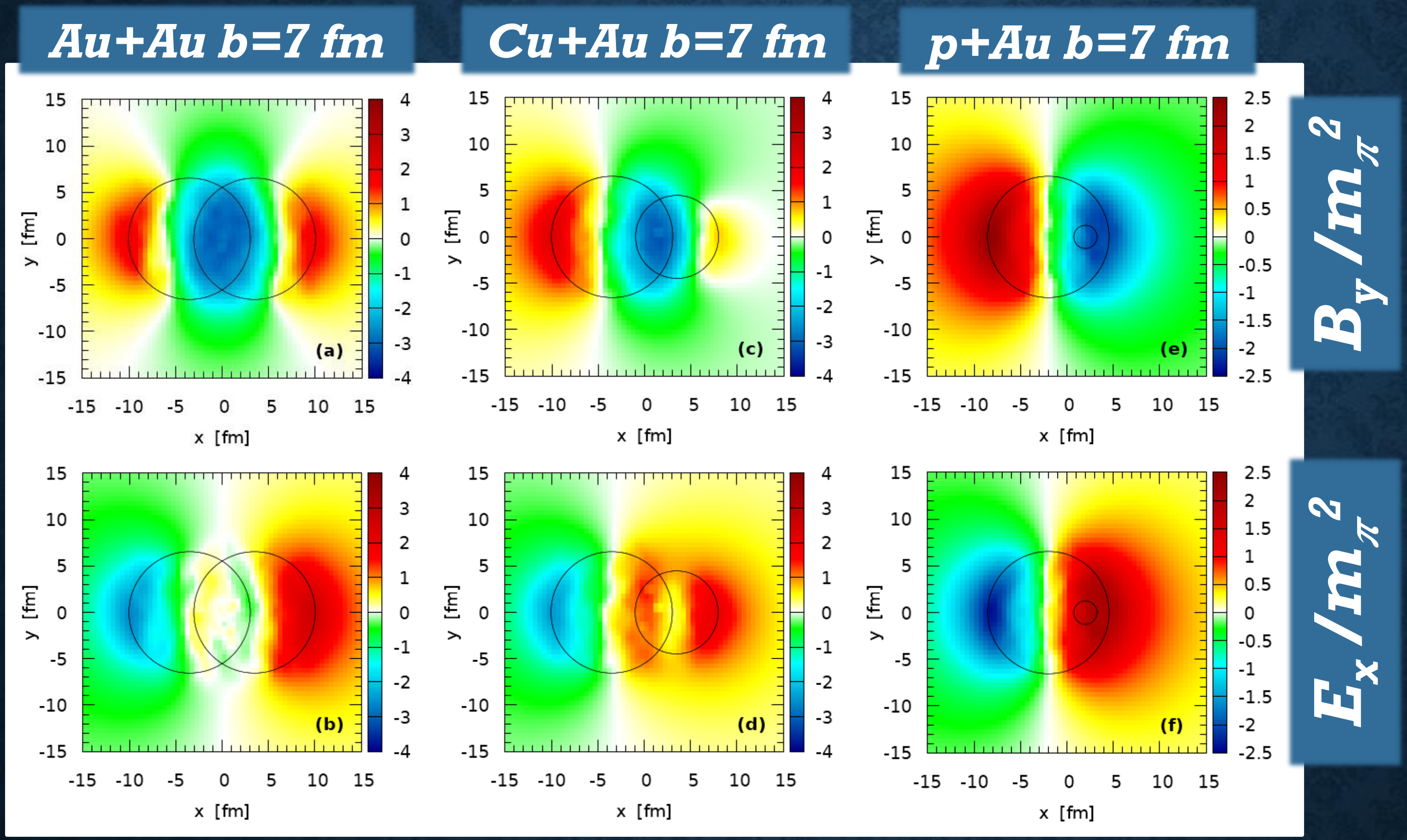
$$\left(\nabla^2 - \partial_t^2 - \sigma_{el}\,\partial_t\right)\boldsymbol{E} = -\nabla\rho_{ext} + \partial_t\boldsymbol{J}_{ext}$$

Fold the solution with the nuclear transverse density profile of the spectator nuclei and sum forward and backward contributions for obtaining the EM fields produced in HICs



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

EM FIELDS FROM LARGE TO SMALL SYSTEMS



initial transverse profiles at RHIC 200 GeV

intense electric fields directed from the heavy nuclei to light one in the overlap region of asymmetric colliding systems due to the different number of protons in the two nuclei

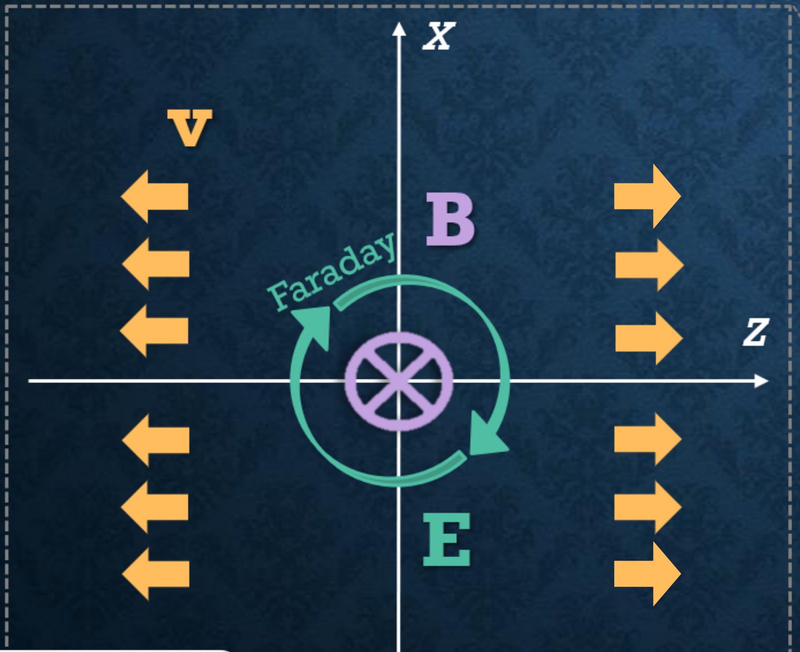
Voronyuk, Toneev, Voloshin and Cassing, Phys. Rev. C 90, 064903 (2014)
Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

A PROBE OF EM FIELDS: DIRECTED FLOW

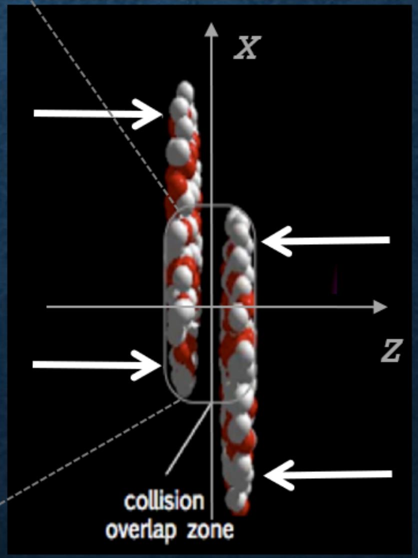
The huge EM fields induce a splitting in the DIRECTED FLOW of particles with the same mass and opposite charge

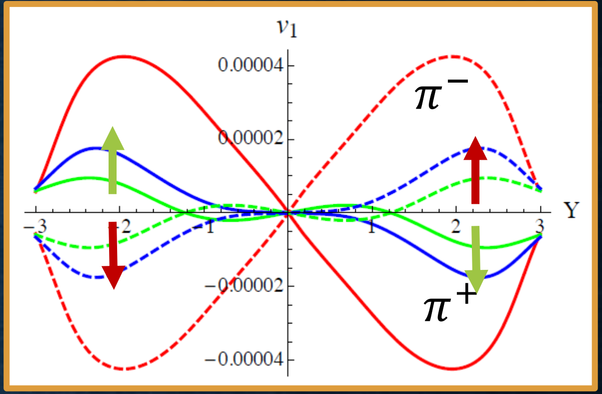
$$\Delta v_1 = v_1^+ - v_1^-$$

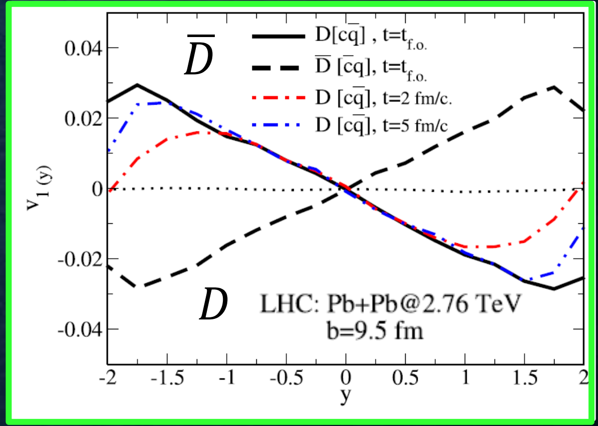
- Δv_1 of light hadrons in AA: $O(10^{-4}$–$10^{-3})$
  U. Gursoy et al., Phys. Rev. C 89, 054905 (2014)
- Δv_1 of heavy mesons in AA: $O(10^{-2})$
  S.K. Das et al., Phys. Lett. B 768, 260 (2017)
- Δv_1 of light mesons in pA: $O(10^{-2})$
  LO et al., Phys. Rev. C 101, 014917 (2020)

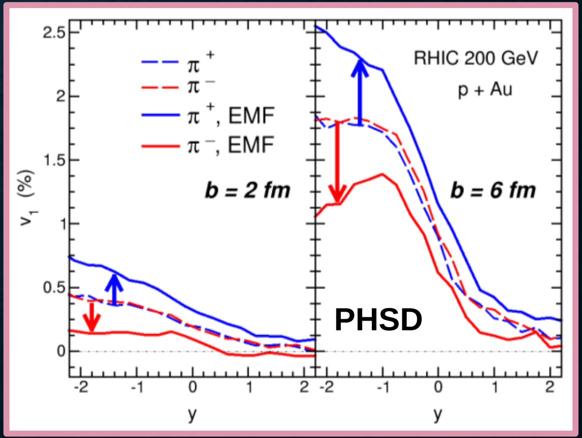


$$F_{Lorentz} = q(E + v \times B)$$



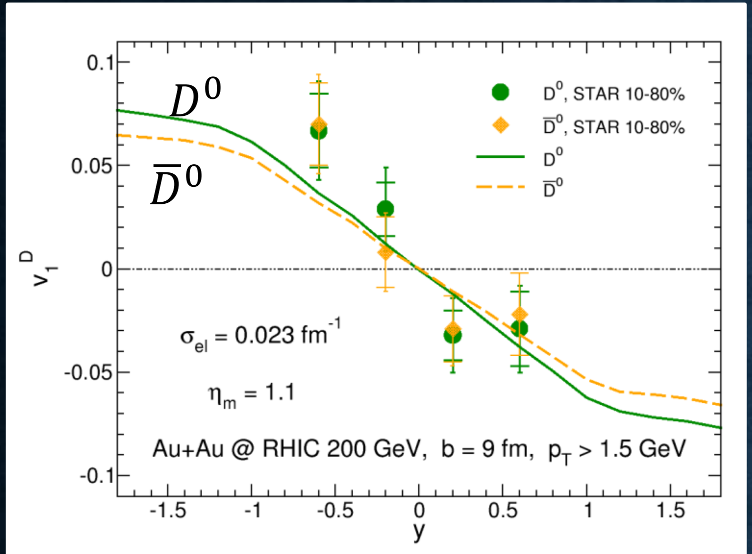




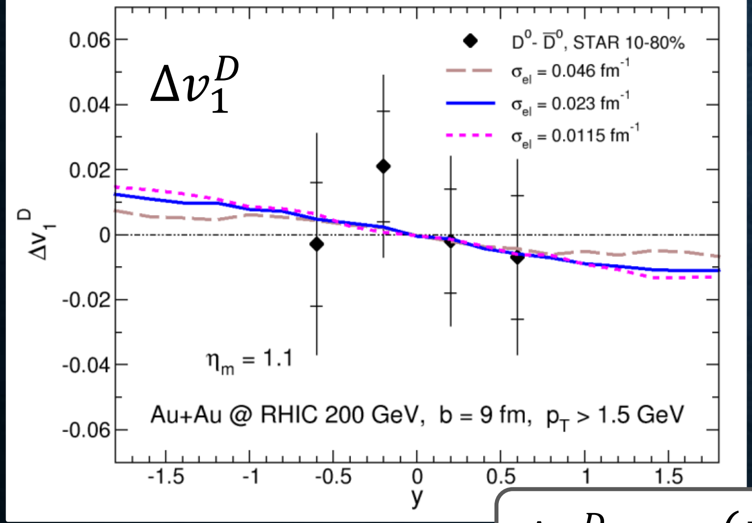


reviews
LO, Eur. Phys. J. A 56, 255 (2020)
A. Dubla, U. Gursoy and R. Snellings, Mod. Phys. Lett. A 35, 2050324 (2020)

DIRECTED FLOW IN A+A AT RHIC ENERGY



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



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

DIRECTED FLOW OF NEUTRAL D MESONS

The EM fields induce a large splitting in the HQ directed flow

Δv_1 (HQ) $\gg$ Δv_1 (QGP)

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

S.K. Das et al., Phys. Lett. B 768, 260 (2017)

RHIC ENERGY

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

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

v_1 of D mesons is ~10 times larger than that of light hadrons in agreement with STAR exp. data (still consistent with zero)

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

correction at most $O(10^{-3})$ from transported quarks

LHC ENERGY

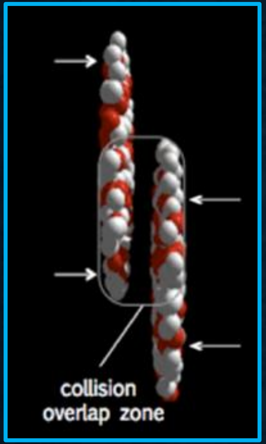
Δv_1^D has opposite sign and magnitude ~ 40 times larger than models

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

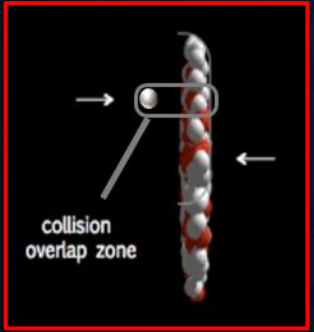
if the v_1 splitting of neutral D mesons is of EM origin it is a proof of QGP formation

LO, S. Plumari and V. Greco, JHEP 05, 034 (2021)

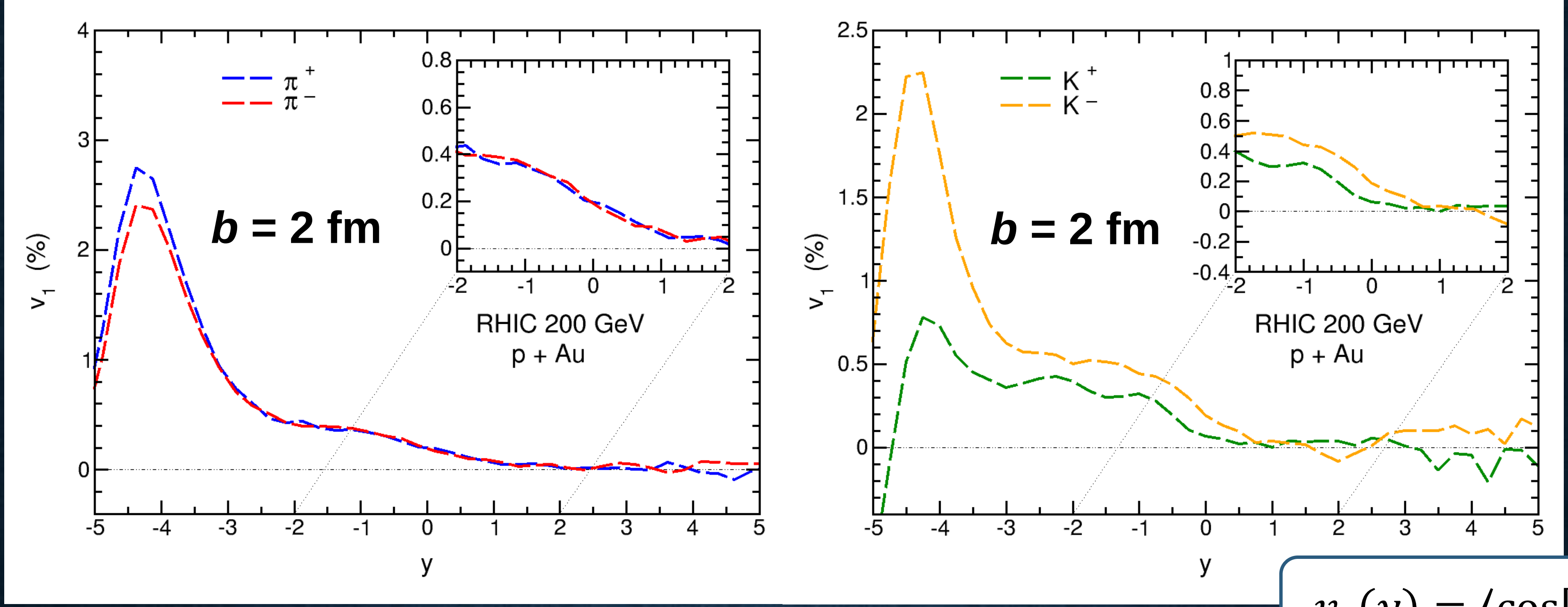
EM FIELDS AND DIRECTED FLOW IN SMALL SYSTEMS



vs



LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

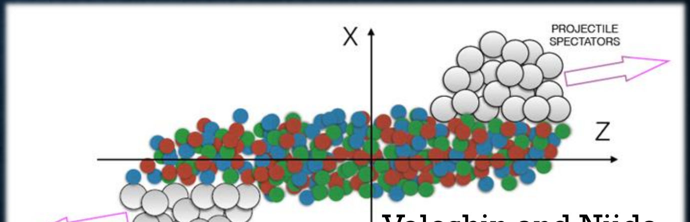


$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$

different v_1 for kaons also without EMF
due to baryon transport to midrapidity

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

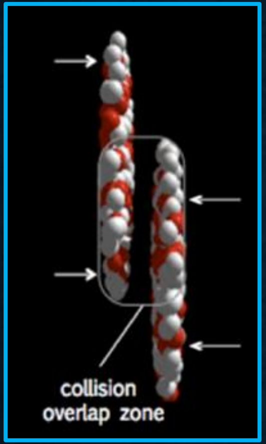
STAR Coll., PRL 120 (2018) 062301



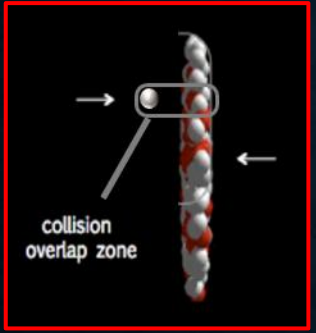
Voloshin and Niida,
PRC 94 (2016) 021901

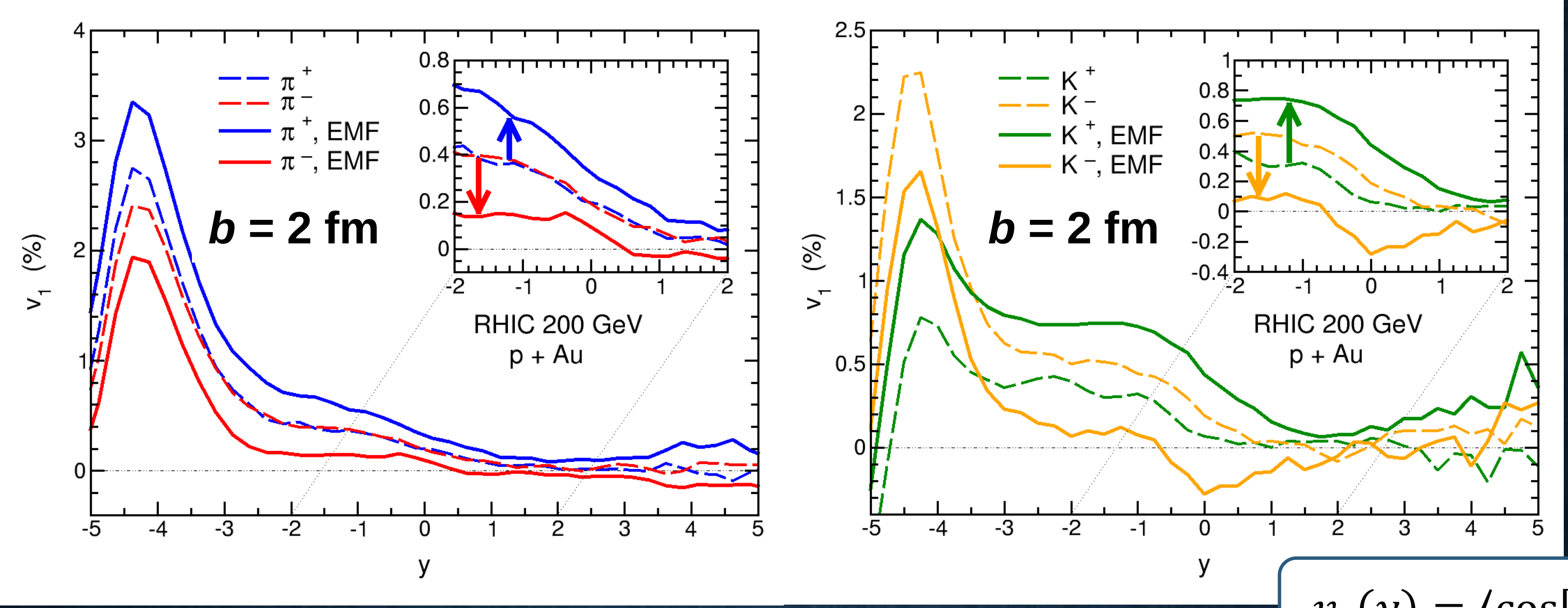
EM FIELDS AND DIRECTED FLOW IN SMALL SYSTEMS

LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)



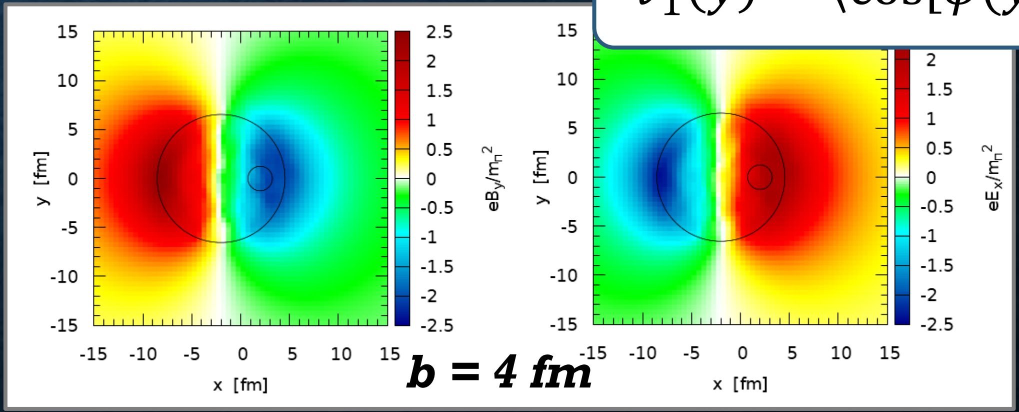
vs





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

Splitting of charged pions and kaons induced by the electromagnetic field



HQ DIFFUSION 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)

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

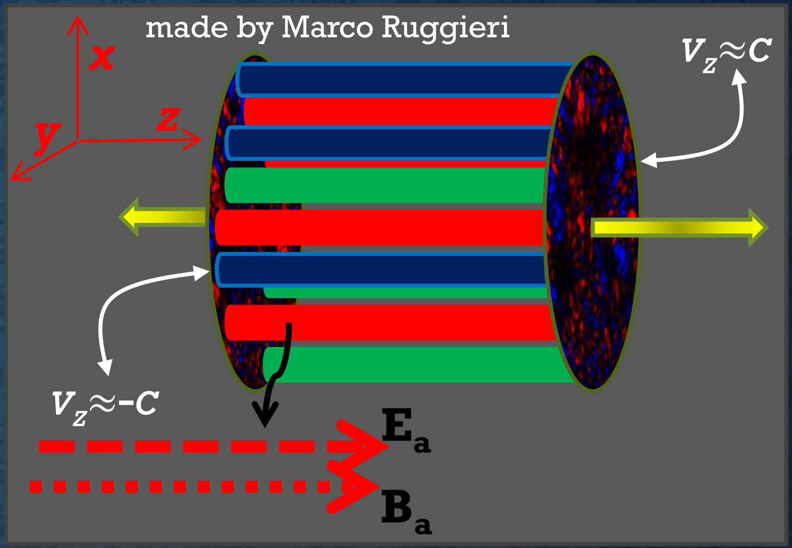
Classical Yang-Mills (CYM) equations for the dynamical evolution of glasma

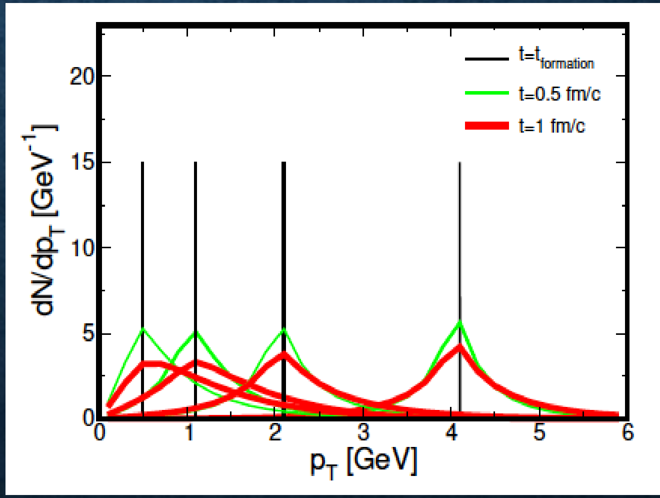
$$\begin{aligned} E^i &= \tau\partial_\tau A_i, & \partial_\tau E^i &= \frac{1}{\tau}D_\eta F_{\eta i} + \tau D_j F_{ji}, \\ E^\eta &= \frac{1}{\tau}\partial_\tau A_\eta, & \partial_\tau E^\eta &= \frac{1}{\tau}D_j F_{j\eta}. \end{aligned}$$

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

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

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

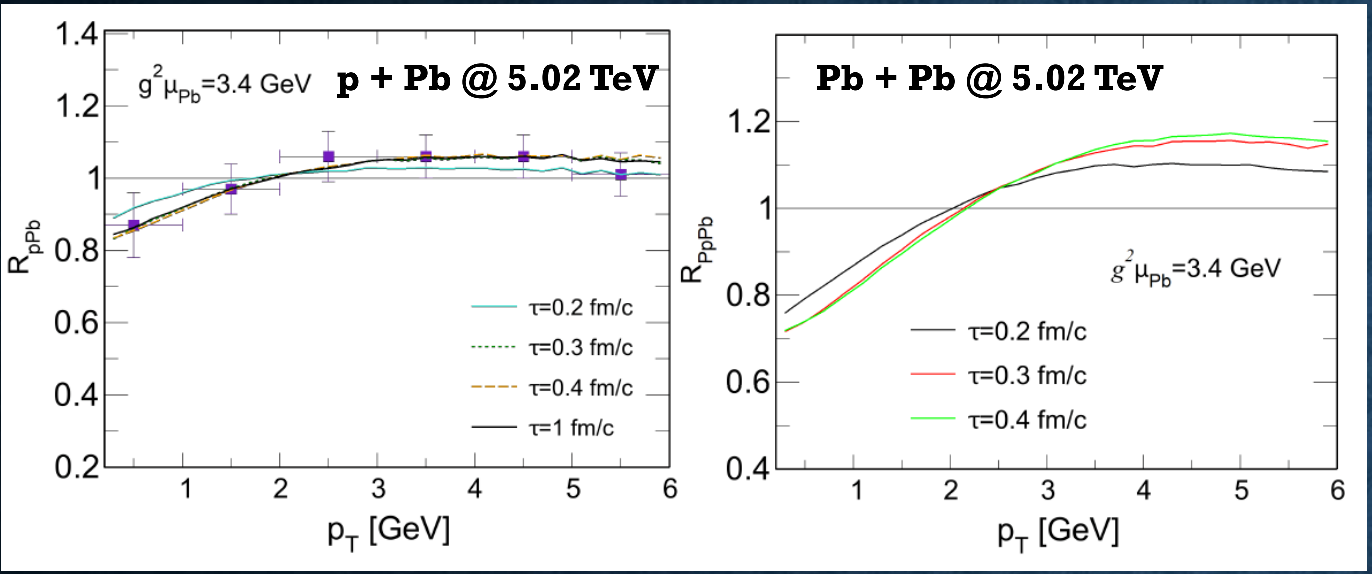




interaction with the initial glasma induce strong diffusion of charm quarks

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

IMPACT OF GLASMA ON HQ OBSERVABLES



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**

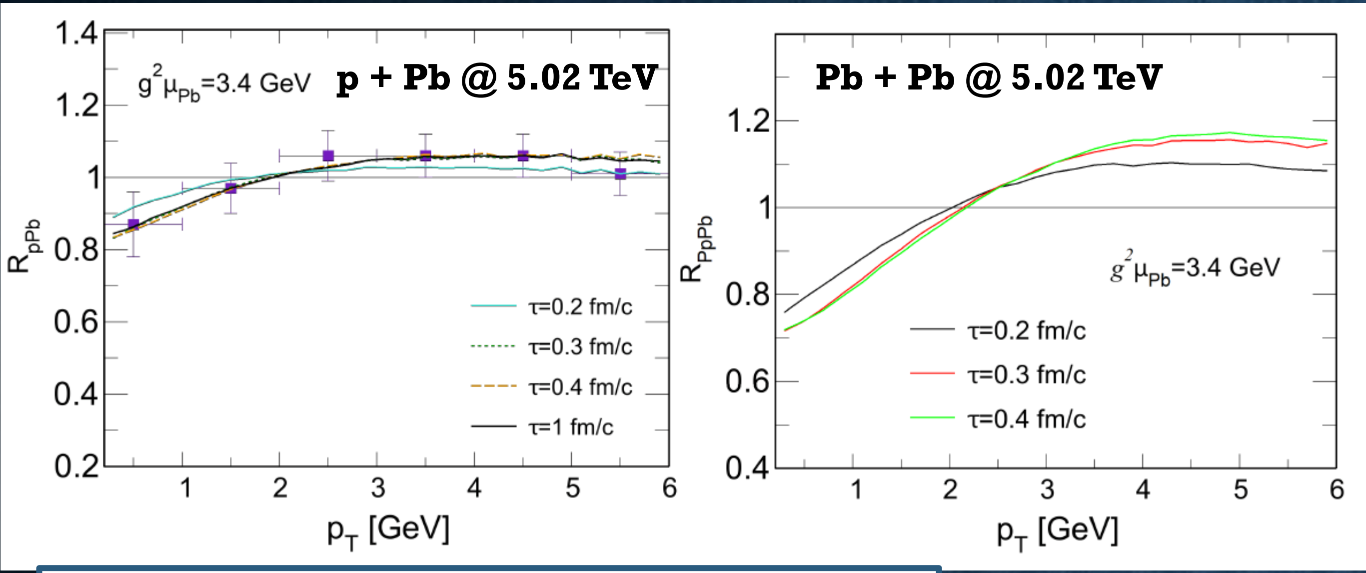
J.H. Liu, S. Plumari, S.K. Das, V. Greco and M. Ruggieri, Phys. Rev. C 102, 044902 (2020)

NUCLEAR MODIFICATION FACTOR

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

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

IMPACT OF GLASMA ON HQ OBSERVABLES



Strong and fast diffusion of HQs in the glasma

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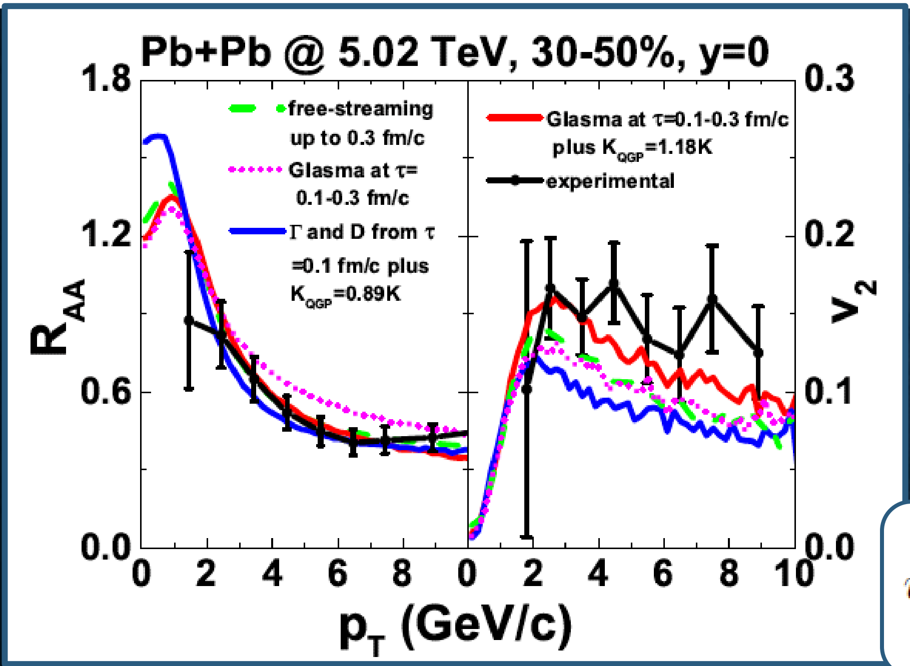
J.H. Liu, S. Plumari, S.K. Das, V. Greco and M. Ruggieri, Phys. Rev. C 102, 044902 (2020)



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 $R_{AA}(p_T)$

Y. Sun, G. Coci, S.K. Das, S. Plumari, M. Ruggieri and V. Greco, Phys. Lett. B 798, 134933 (2019)

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

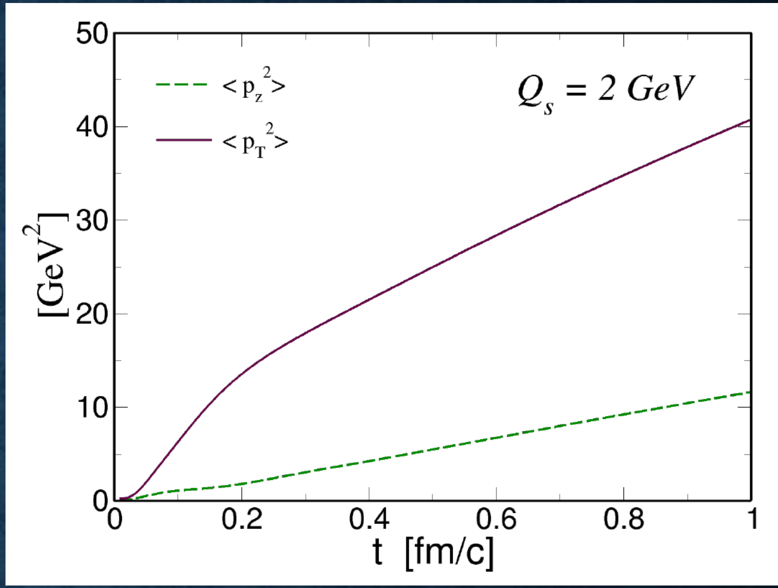
HQ ANGULAR MOMENTUM IN THE GLASMA

Diffusion of prompt HQs in anisotropic fields generates an anisotropic distribution of the HQ momentum

A. Ipp, D.I. Müller and D. Schuh, Phys. Lett. B 810, 135810 (2020)
D. Avramescu *et al.*, Phys. Rev. D 107, 114021 (2023)

- Distribution of HQs at the QGP formation time potentially affected by early stage evolution
- Anisotropic fluctuactions of HQ momentum leads to anisotropies in the HQ angular momentum

Pooja, S.K. Das, V. Greco and M. Ruggieri, Eur. Phys. J. Plus 138, 313 (2023)



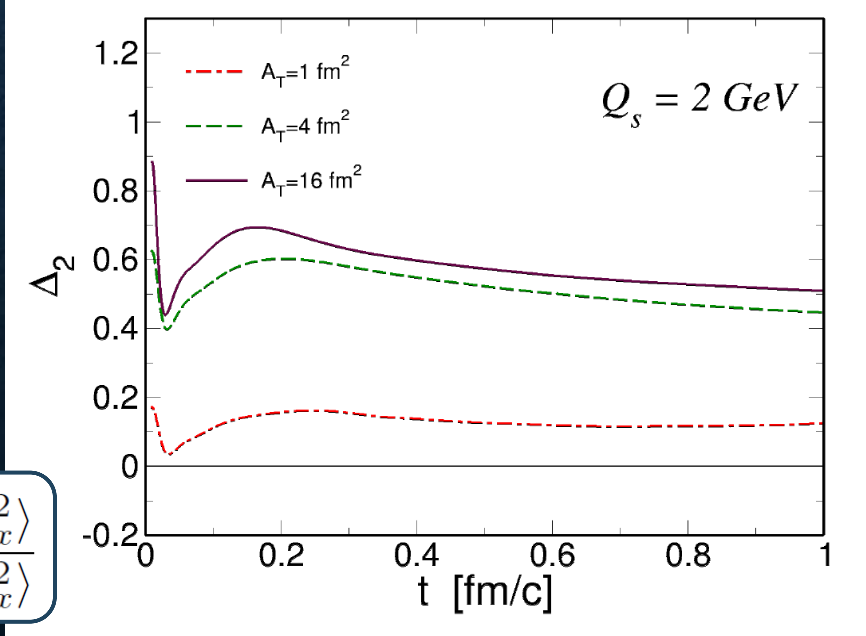
$$\frac{dx^i}{dt} = \frac{P^i}{m},$$

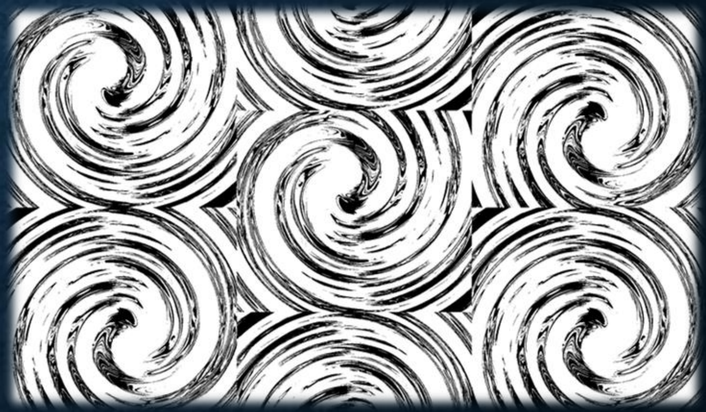
$$\frac{dP^i}{dt} = -\frac{g}{m} Q_a \left(m F_a^{i0} - P^j F_a^{ij} \right) - \frac{g}{m} Q_a S^j (\mathcal{D}^i B_a^j),$$

$$\frac{dQ_a}{dt} = \frac{g}{m} f_{abc} Q_c \left(P^i A_b^i + S^i B_b^i \right),$$

$$\frac{dS^i}{dt} = -\frac{g}{m} Q_a F_a^{ij} S^j,$$

$$\Delta_2 \equiv \frac{\langle L_z^2 - L_x^2 \rangle}{\langle L_z^2 + L_x^2 \rangle}$$





glasma induces vortex-like motion of HQs around color filaments

CONCLUSIONS

Relativistic transport theory allows to describe the whole evolution of heavy-ion reactions and small colliding systems at relativistic energy

glasma fields may affect HF observables and total angular momentum

HQ directed flow is a promising probe of EM fields and the realistic 3D view of the collision

ϕ spin alignment measures local fluctuations of mesonic fields at hadronization

identifying hadron production mechanisms, interactions and in-medium effects is needed to clarify the impact of the preceding collision stages

interesting phenomena generated in heavy-ion collisions from conventional to hitherto unknown mechanisms

unexpected laboratory for studying the fascinating dynamics emerged in heavy-ion collisions

PRE-EQUILIBRIUM

PARTONIC PHASE
- QGP dynamics
- heavy quark dynamics

HADRONIZATION

HADRONIC PHASE

INTENSE FIELDS
- vorticity
- electromagnetic field
- strong force fields

SMALL SYSTEMS

lucia.oliva@dfa.unict.it

Thank you for your attention!

And many thanks to my collaborators

Xin-Li Sheng, Qun Wang, Zuo-Tang Liang, Xin-Nian Wang

Vincenzo Greco, Salvatore Plumari, Marco Ruggieri

Elena Bratkovskaya, Pierre Moreau, Vadim Voronyuk

ϕ MESON SPIN ALIGNMENT

ϕ

polarized quarks → COALESCENCE → polarized hadrons

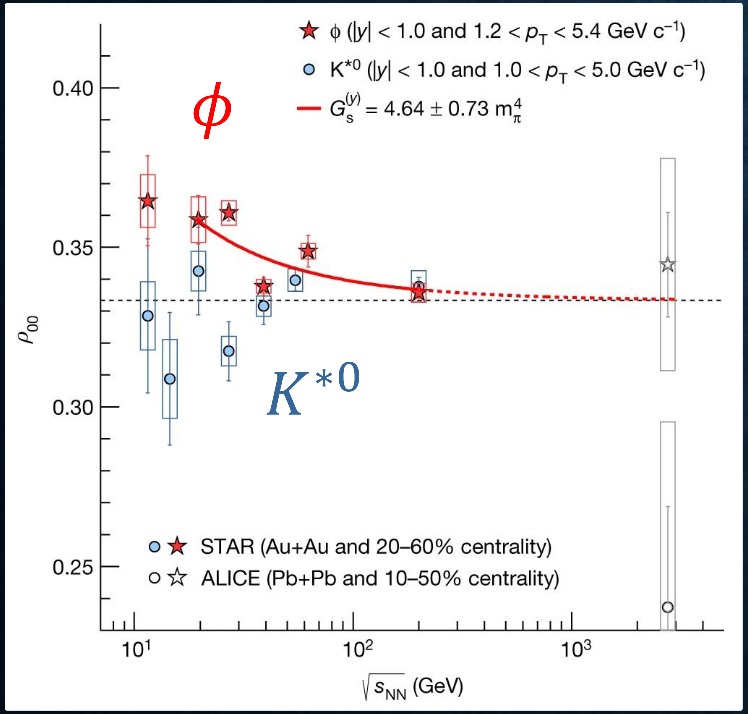
V. Greco, C.M. Ko and P. Levai, Phys. Rev. Lett. 90, 202302 (2003)
R.J. Fries, B. Muller, C. Nonaka and S.A. Bass, Phys. Rev. Lett. 90, 202303 (2003)

nonrelativistic quark coalescence model

$$\rho_{00}^{\phi}(t,\mathbf{x}) \approx \frac{1}{3} - \frac{4}{9}\int \frac{d^3\mathbf{p}}{(2\pi)^3} P_s^y(\mathbf{p}) P_{\bar{s}}^y(-\mathbf{p}) \left|\psi_\phi(\mathbf{p})\right|^2$$

Y.-G. Yang, R.-H. Fang, Q. Wang, and X.-N. Wang, Phys. Rev. C 97, 034917 (2018)

$\rho_{00}^{y}\left(\sqrt{s_{NN}}\right)$



STAR Coll., Nature 614, 244 (2023)

$$\rho_{00}^{\phi} \approx \frac{1}{3} + c_\Lambda + c_\varepsilon + c_E + c_\phi \qquad c_\Lambda \equiv -(4/9)\left\langle P_\Lambda^y P_{\bar{\Lambda}}^y \right\rangle = -\frac{1}{9}\left\langle \omega_y^2 \right\rangle + \frac{Q_s^2}{9m_s^2 T_{\text{eff}}^2}\left\langle B_y^2 \right\rangle$$

$$c_\varepsilon \equiv \frac{1}{27m_s^2}\left\langle \mathbf{p}^2 \right\rangle_\phi \left\langle \varepsilon_z^2 + \varepsilon_x^2 \right\rangle \qquad c_E \equiv -\frac{e^2}{243 m_s^4 T_{\text{eff}}^2}\left\langle \mathbf{p}^2 \right\rangle_\phi \left\langle E_z^2 + E_x^2 \right\rangle$$

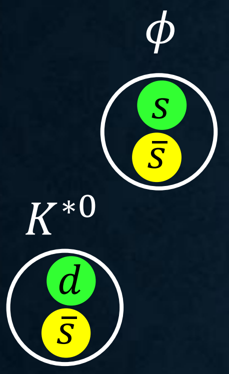
$$c_\phi \equiv \frac{g_\phi^2}{27 m_s^2 T_{\text{eff}}^2}\left[3\left\langle B_{\phi,y}^2 \right\rangle - \frac{\left\langle \mathbf{p}^2 \right\rangle_\phi}{m_s^2}\left\langle E_{\phi,z}^2 + E_{\phi,x}^2 \right\rangle\right]$$

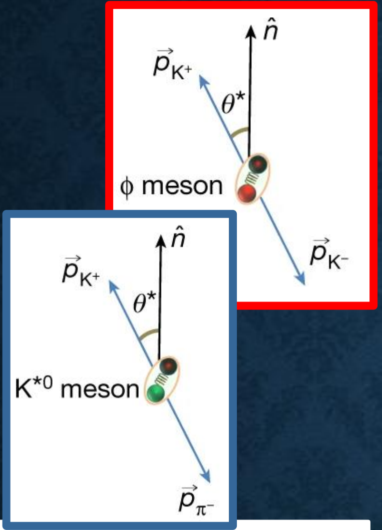
$c_\Lambda, c_\varepsilon, c_E \sim 10^{-3} - 10^{-5}$ are negligibly small compared to 1/3

the ϕ-meson effective field in c_ϕ may explain the large positive deviation of ρ_{00} from 1/3

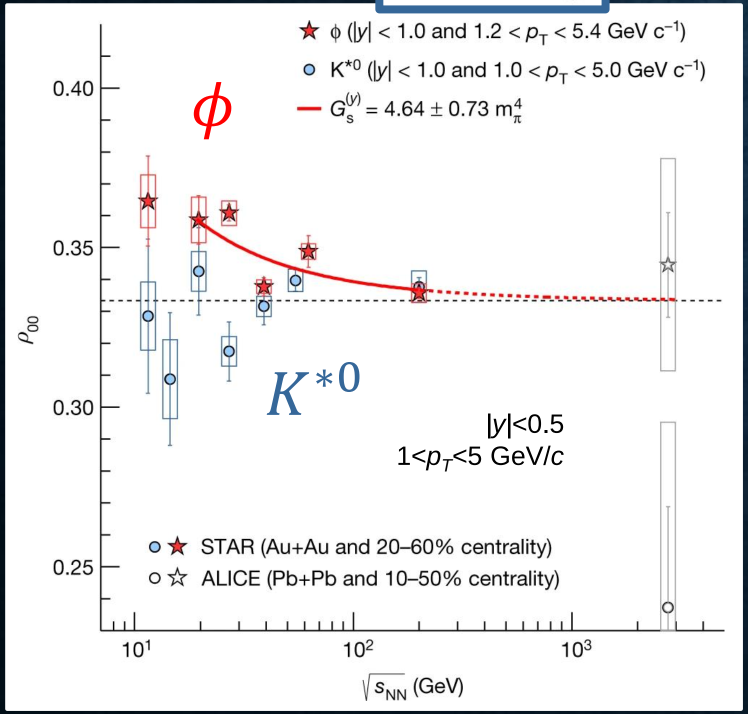
X.-L. Sheng, LO and Q. Wang, Phys. Rev. D 101, 096005 (2020) [Phys. Rev. D 105, 099903 (2022)]

WHY ONLY ϕ MESON?

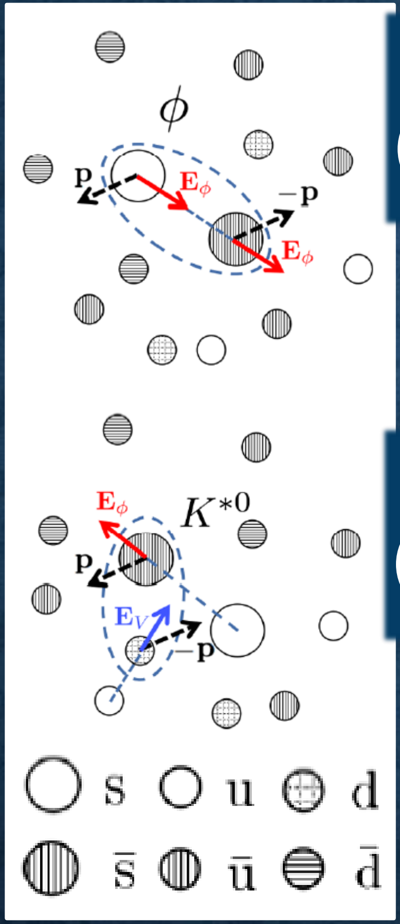




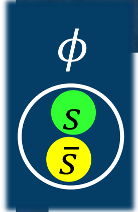
$\rho_{00}^{y}(\sqrt{s_{NN}})$



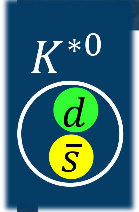
STAR Collaboration, Nature 614, 244 (2023)



neglecting EM fields



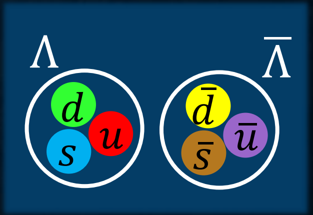
$$\rho_{00}^{\phi} \approx \frac{1}{3} - \frac{1}{9}\langle \omega_y^2 \rangle + \frac{\langle \boldsymbol{p}_b^2 \rangle_\phi}{27 m_s^2}\langle \varepsilon_z^2 + \varepsilon_x^2 \rangle + \frac{g_\phi^2}{27 m_s^2 T_{\text{eff}}^2}\left[3\left\langle \left(B_y^\phi\right)^2 \right\rangle - \frac{\langle \boldsymbol{p}_b^2 \rangle_\phi}{m_s^2}\left\langle \left(E_z^\phi\right)^2 + \left(E_x^\phi\right)^2 \right\rangle \right]$$



$$\rho_{00}^{K^{*0}} \approx \frac{1}{3} - \frac{1}{9}\langle \omega_y^2 \rangle + \frac{\langle \boldsymbol{p}_b^2 \rangle_{K^*}}{27 m_s m_d}\langle \varepsilon_z^2 + \varepsilon_x^2 \rangle + \frac{g_\phi g_V}{27 m_s m_d T_{\text{eff}}^2}\left[3\left\langle B_y^\phi B_y^V \right\rangle - \frac{\langle \boldsymbol{p}_b^2 \rangle_{K^*}}{m_s m_d}\left\langle E_z^\phi E_z^V + E_x^\phi E_x^V \right\rangle \right]$$

negligible assuming that different fields do not have large correlation in space

contribution on hyperon polarization proportional to the fluctuation of the ϕ-meson field that is on average negligible



X.-L. Sheng, LO and Q. Wang, PRD 101, 096005 (2020) [PRD 105, 099903 (2022)]

X.-L. Sheng, Q. Wang, and X.-N. Wang, Phys. Rev. D 102, 056013 (2020)

SPIN DENSITY MATRIX FOR VECTOR MESONS

Δt: vector meson formation time
$f^V_{\lambda_1\lambda_2}$ assumed = 0 at initial time

solution of the spin Boltzmann equation

$$f^V_{\lambda_1\lambda_2}(x,\mathbf{k}) \sim \frac{1}{\mathcal{C}_{\text{diss}}(\mathbf{k})}\left[1-e^{-\mathcal{C}_{\text{diss}}(\mathbf{k})\Delta t}\right]\epsilon^*_\mu(\lambda_1,\mathbf{k})\epsilon_\nu(\lambda_2,\mathbf{k})\mathcal{C}^{\mu\nu}_{\text{coal}}(x,\mathbf{k})$$

MVSD can be parameterized as
spin-independent distribution function
(unpolarized)
+
normalized spin density matrix
(polarization part)

$$\rho^V_{\lambda_1\lambda_2}(x,\mathbf{k}) = \frac{\epsilon^*_\mu(\lambda_1,\mathbf{k})\epsilon_\nu(\lambda_2,\mathbf{k})\mathcal{C}^{\mu\nu}_{\text{coal}}(x,\mathbf{k})}{\sum_{\lambda=0,\pm1}\epsilon^*_\mu(\lambda,\mathbf{k})\epsilon_\nu(\lambda,\mathbf{k})\mathcal{C}^{\mu\nu}_{\text{coal}}(x,\mathbf{k})}$$

spin density matrix for vector mesons

$\mathcal{C}^{\mu\nu}_{\text{coal}}$ include the polarization phase space distributions for quark/antiquark $P^\mu_{q/\bar{q}}(x,p)$

polarized quarks → COALESCENCE → polarized hadrons

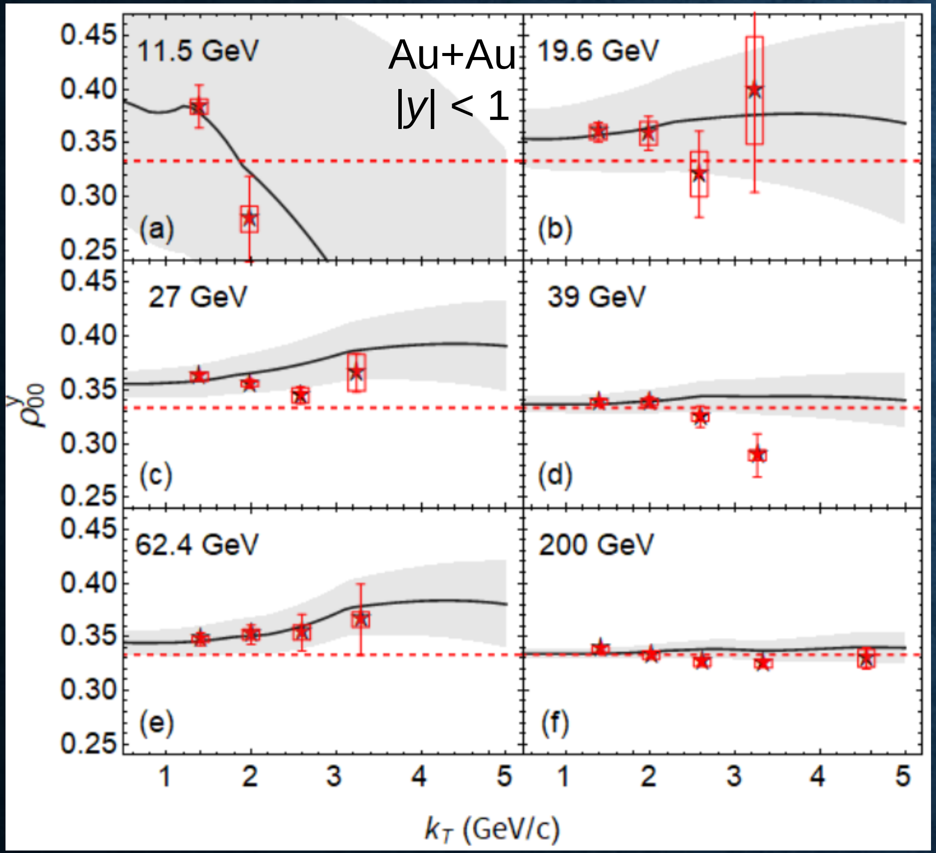
similar to the process in the nonrelativistic coalescence model

X.-L- Sheng, LO, Z.-T. Liang, Q. Wang and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023) ; Phys. Rev. D 109, 036004 (2024)

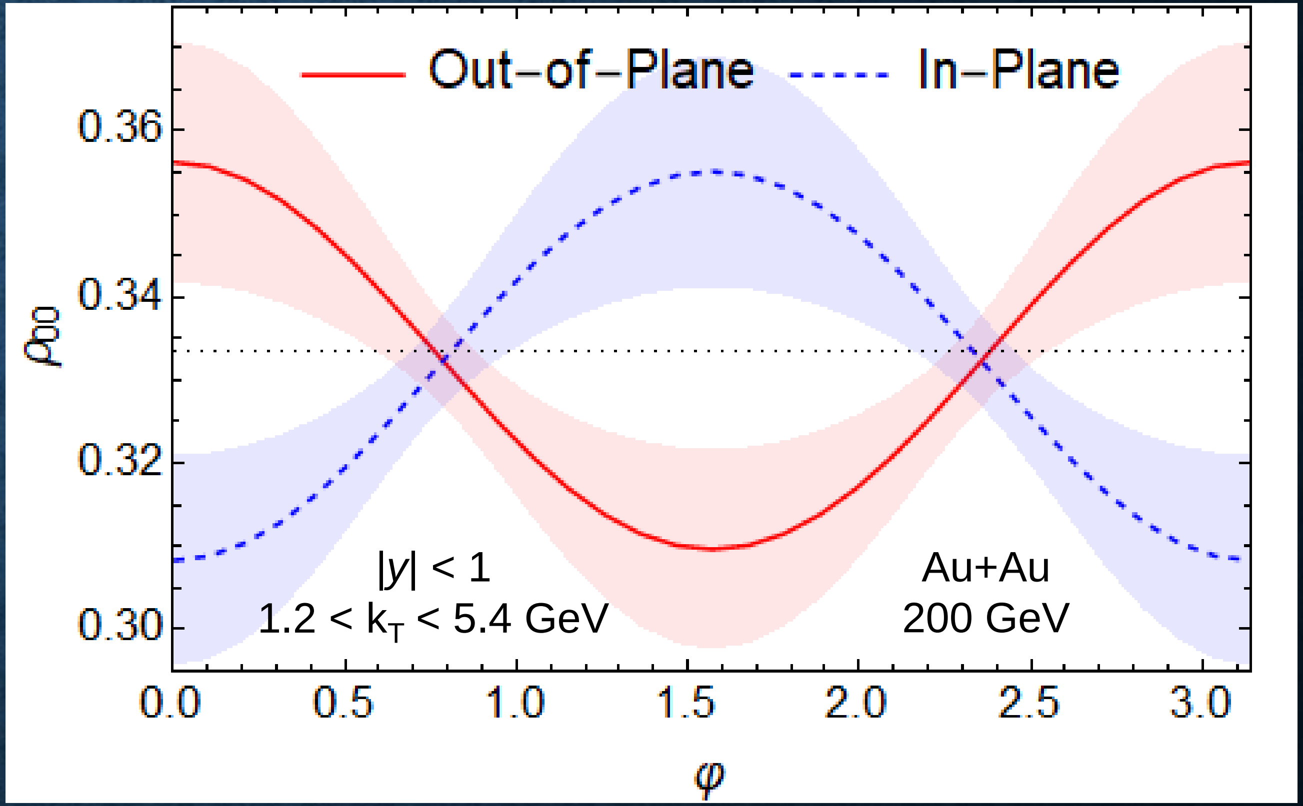
SPIN ALIGNMENT OF ϕ MESONS

Exp. data: STAR Coll., Nature 614, 244 (2023)

$\rho^{y}_{00}(k_T)$



$\rho^{x,y}_{00}(\varphi)$



- nearly constant at $k_T < 2$ GeV and then increases slightly
- at low k_T is significantly larger than 1/3 at lower energies

- modulation of $\rho^{x,y}_{00}$ with the azimuthal angle
- **can be tested in future experiments!**

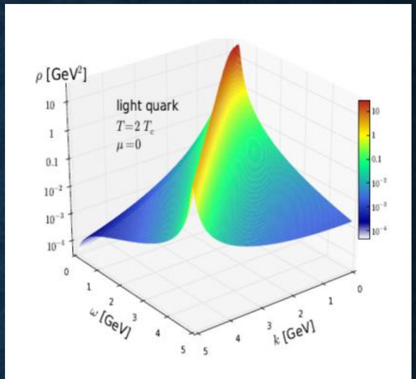
X.-L- Sheng, LO, Z.-T. Liang, Q. Wang and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023)

DYNAMICAL QUASIPARTICEL MODEL (DQPM)

The DQPM describes QGP in terms of interacting quasiparticle: massive quarks and gluons with Lorentzian spectral functions

$$A_j(\omega, \mathbf{p}) = \frac{\gamma_j}{\tilde{E}_j}\left(\frac{1}{(\omega - \tilde{E}_j)^2 + \gamma_j^2} - \frac{1}{(\omega + \tilde{E}_j)^2 + \gamma_j^2}\right)$$

$$\tilde{E}_j = p^2 + m^2 - \gamma^2$$



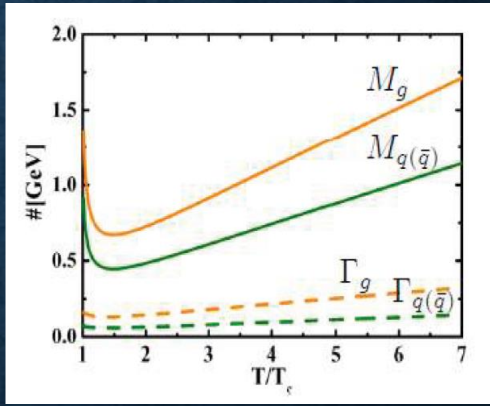
GLUONS QUARKS

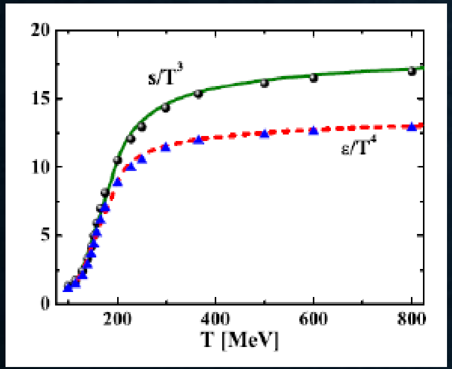
MASSES

$$m_g^2 = \frac{g^2}{6}\left(N_c + \frac{1}{2}N_f\right)T^2, \qquad m_q^2 = g^2\frac{N_c^2 - 1}{8N_c}T^2$$

WIDTHS

$$\gamma_g = \frac{1}{3}N_c\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right), \quad \gamma_q = \frac{1}{3}\frac{N_c^2 - 1}{2N_c}\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$$





$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f)\ln(\lambda^2(T/T_c - T_s/T_c)^2}$$

RUNNING COUPLING

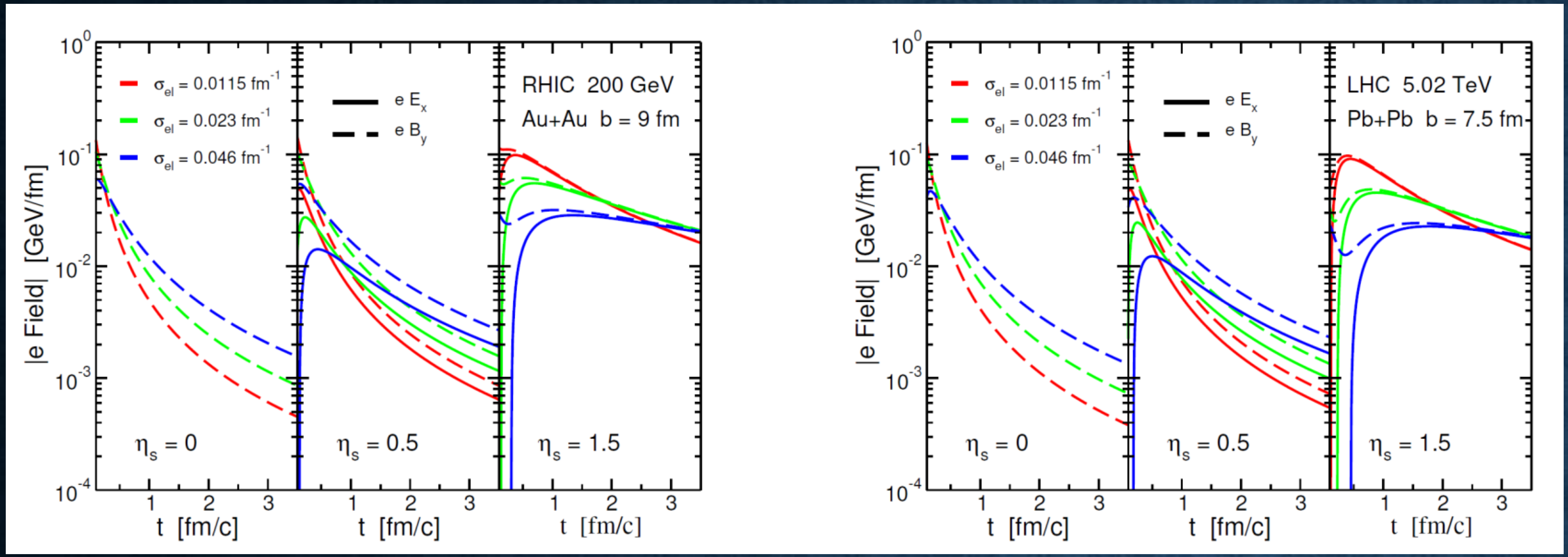
parameters from fit of lattice QCD thermodinamics

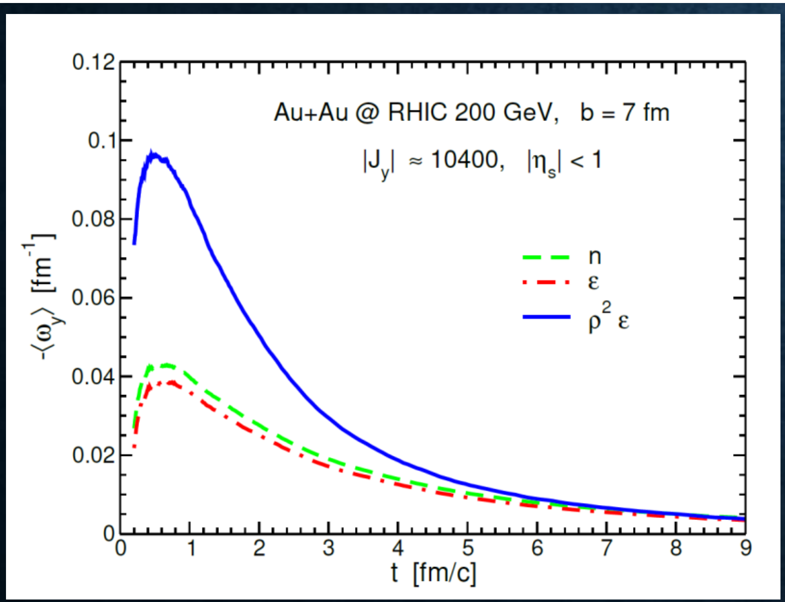
Peshier, Phys. Rev. D 70, 034016 (2004)
Peshier and Cassing, PRL 94 (2005) 172301
Cassing, NPA 791 (2007) 365; NPA 793 (2007)

PHSD extended to include chemical potential dependence of scattering cross sections

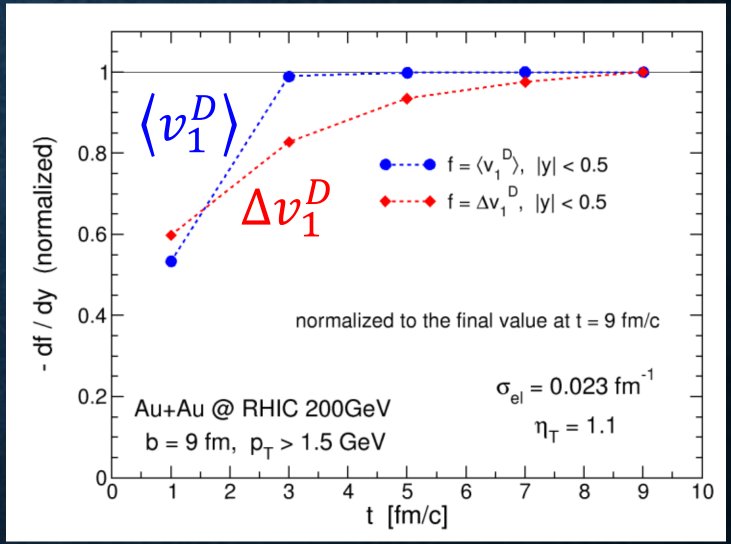
P. Moreau, O. Soloveva, LO, T. Song, W. Cassing and E. Bratkovskaya, Phys. Rev. C 100 (2019) 014911

DIRECTED FLOW IN A+A AT RHIC ENERGY





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

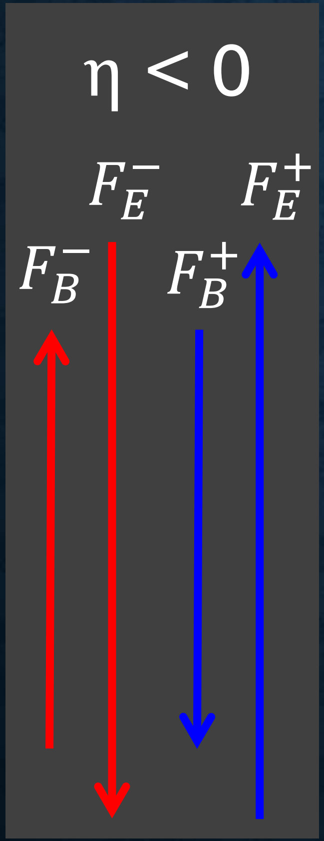
LO, S. Plumari and V. Greco, JHEP 05, 034 (2021)

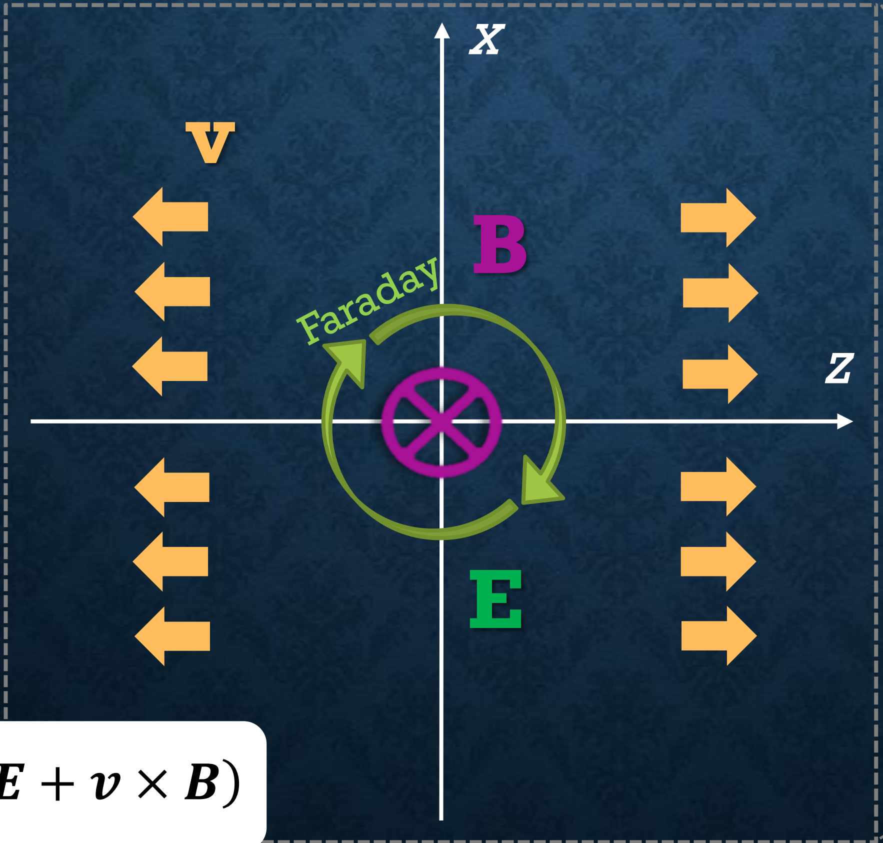
EM FIELDS AND DIRECTED FLOW IN AA

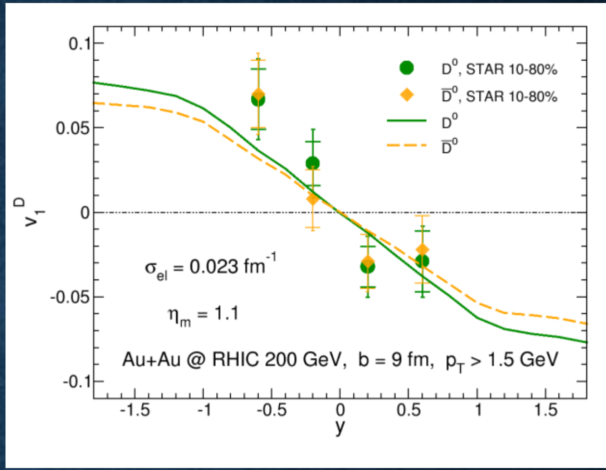
rapidity dependence of the DIRECTED FLOW

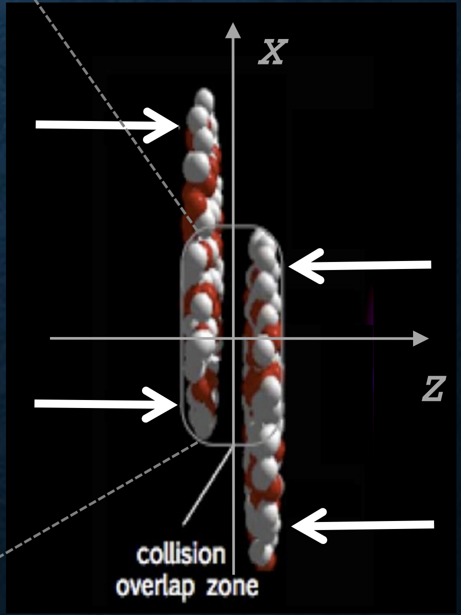
collective sidewards deflection of particles

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



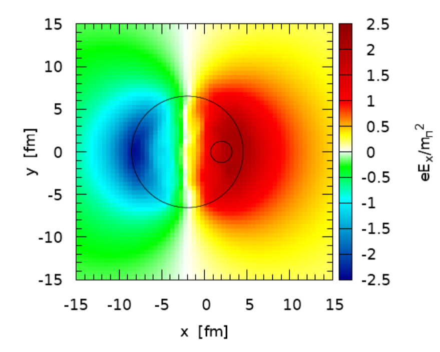


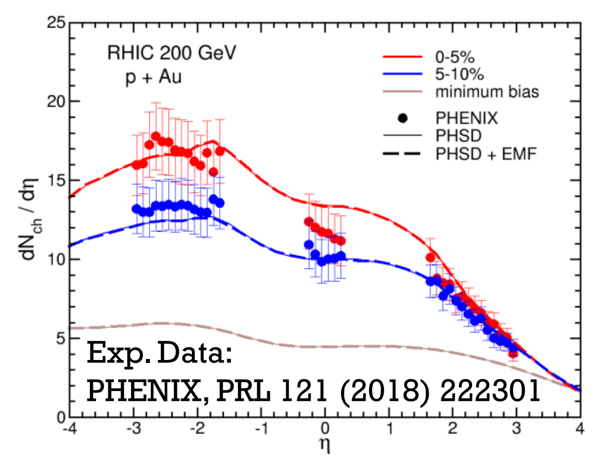




$$F_{Lorentz} = q(E + v \times B)$$

EM FIELDS AND DIRECTED FLOW IN pA

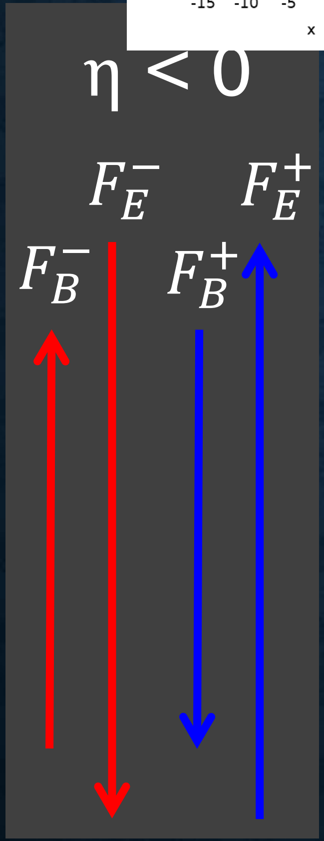




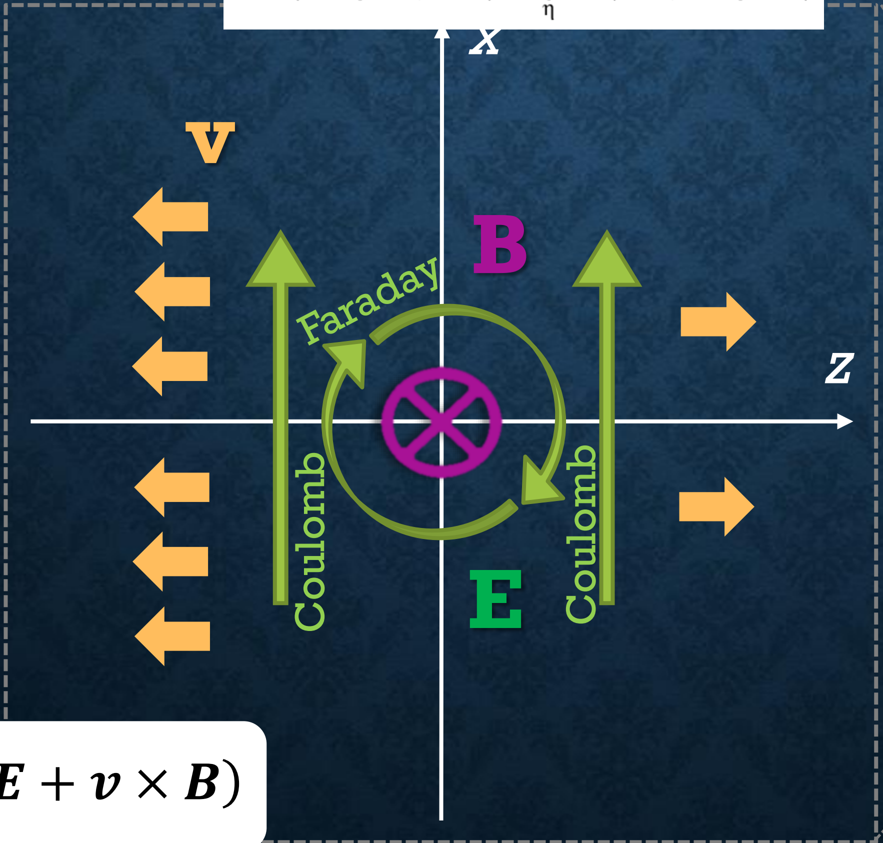
Asymmetry in charged particle and electric field profiles in p+Au

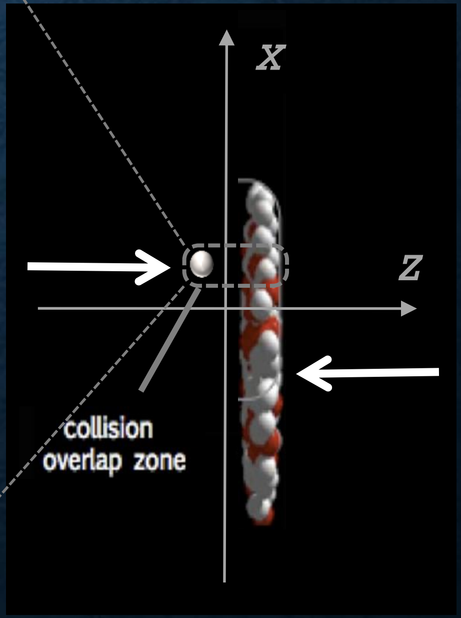
- enhanced particle production in the Au-going direction
- electric field directed from the heavy ion to the proton

LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)



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



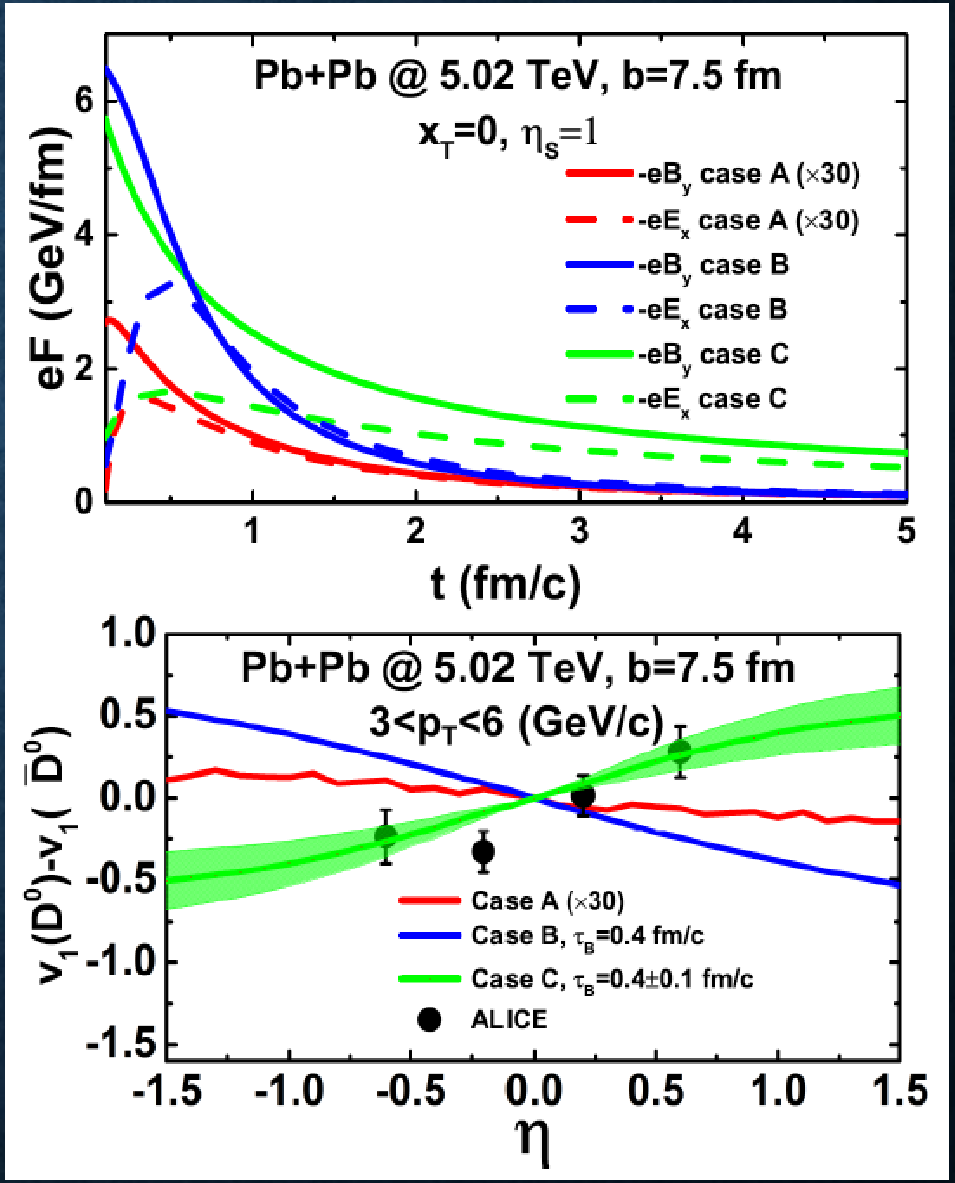


DIRECTED FLOW IN A+A AT LHC ENERGY

LHC ENERGY ALICE Coll., Phys. Rev. Lett. 125, 022301 (2020)
the Δv_1^D has opposite sign and magnitude
~ 40 times larger than models (Δv_1^D(LHC) ≈ Δv_1^D(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

a B decay $\propto (1 + \tau/\tau_B)^{-1}$ can 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)