Early time gluon fields in relativistic heavy ion collisions

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outline:

1. motivation
   glasma provides initial conditions for subsequent hydro phase
2. structure of the calculation
   ColourGlassCondensate effective field theory approach
3. results:
   3.1 isotropization
   3.2 azimuthal asymmetries
   3.3 angular momentum
   3.4 momentum broadening of hard probes
4. conclusions

motivation

goal: describe early time ($\tau \leq 1$ fm) dynamics of HIC
- evolution of system during this early stage not well understood
- importance: initial conditions for subsequent hydro evolution

more generally: want to understand transition between
early-time dynamics $\longrightarrow$ hydro phase

1. microscropic theory of non-abelian gauge fields
$=$ *far from equilibrium*

2. macroscopic effective theory
- based on universal conservation laws
- valid close to equilibrium

MEC, Czajka, Mrówczyński
arXiv:2012.03042; 2105.05327; 2112.0681; 2202.00357

Colour Glass Condensate (CGC) effective theory

method is based on a separation of scales between

1. valence partons with large nucleon momentum fraction (x)
2. gluon fields with small x and large occupation numbers

- gluons are in the saturation regime
- distributions are controlled by the saturation scale Q_s

dynamics of gluon fields determined from classical YM equation
$\rightarrow$ source provided by the valence partons

L. D. McLerran and R. Venugopalan, Phys. Rev. D **49**, 2233 (1994); **49**, 3352 (1994); **50**, 2225 (1994).
A. Kovner, L. D. McLerran and H. Weigert, Phys. Rev. D **52**, 6231 (1995).
J. Jalilian-Marian, A. Kovner, L. D. McLerran and H. Weigert, Phys. Rev. D **55**, 5414 (1997).

F. Gelis, E. Iancu, J. Jalilian-Marian and R. Venugopalan, Ann. Rev. Nucl. Part. Sci. **60**, 463 (2010).
T. Lappi, Int. J. Mod. Phys. E **20**, 1 (2011).

method - notation

light-cone coordinates $x^{\pm} = (t \pm z)/\sqrt{2}$
Milne coordinates $\tau = \sqrt{2x^+x^-} = \sqrt{t^2 - z^2}$ and $\eta = \ln(x^+/x^-)/2 = \ln((t+z)/(t-z))$.

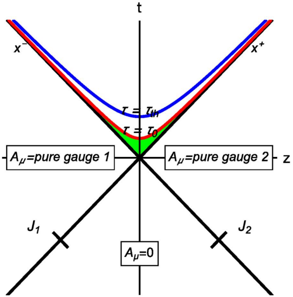
gauge: $A^{\mu}_{\rm milne} = \theta(\tau)\big(0, \alpha(\tau, \vec{x}_\perp), \vec{\alpha}_\perp(\tau, \vec{x}_\perp)\big)$

sources: $J^{\mu}(x) = J^{\mu}_1(x) + J^{\mu}_2(x)$

$J^{\mu}_1(x) = \delta^{\mu +} g\rho_1(x^-, \vec{x}_\perp)$ and $J^{\mu}_2(x) = \delta^{\mu -} g\rho_2(x^+, \vec{x}_\perp)$

ansatz:

$$A^+(x) = \Theta(x^+)\Theta(x^-)x^+\alpha(\tau, \vec{x}_\perp)$$
$$A^-(x) = -\Theta(x^+)\Theta(x^-)x^-\alpha(\tau, \vec{x}_\perp)$$
$$A^i(x) = \Theta(x^+)\Theta(x^-)\alpha^i_\perp(\tau, \vec{x}_\perp) + \Theta(-x^+)\Theta(x^-)\beta^i_1(x^-, \vec{x}_\perp) + \Theta(x^+)\Theta(-x^-)\beta^i_2(x^+, \vec{x}_\perp)$$



$\boxed{\text{step 1:}}$ solve YM equation in the pre-collision region

$$[D_\mu, F^{\mu\nu}] = J^\nu \quad \text{with} \quad F_{\mu\nu} = \frac{i}{g}[D_\mu, D_\nu] \quad \text{and} \quad D_\mu = \partial_\mu - igA_\mu$$

$\rho_1(x^+, \vec{x}_\perp) \to \beta_1^i(x^-, \vec{x}_\perp)$ and $\rho_2(x^+, \vec{x}_\perp) \to \beta_2^i(x^+, \vec{x}_\perp)$

1st ion:

$$\beta_1^i(x^-, \vec{x}_\perp) = \frac{i}{g} U_1^\dagger(x^-, \vec{x}_\perp)\partial^i U_1(x^-, \vec{x}_\perp)$$

$$U_1(x^-, \vec{x}_\perp) = \mathcal{P}\exp\Big[ig \int_{-\infty}^{x^-} dz^- \Lambda_1(z^-, \vec{x}_\perp)\Big]$$

$$\Lambda_1(x^-, \vec{x}_\perp) = \frac{1}{2\pi}\int d^2z_\perp\, K_0(m(\vec{x}_\perp - \vec{z}_\perp))\,\rho_1(x^-, \vec{z}_\perp)$$

K_0 is a modified Bessel function *similar expression for second ion*

physics:

1. $\rho_1(x^-, \vec{x}_\perp)$ is independent of the light-cone time x^+

- *the static approximation*

2. small width across light cone will be taken to 0

J. Jalilian-Marian, A. Kovner, L. D. McLerran and H. Weigert, Phys. Rev. D **55**, 5414 (1997).
Y. V. Kovchegov, Phys. Rev. D **60**, 034008 (1999).

$\boxed{\text{step 2:}}$ boundary conditions

$$\alpha^i_\perp(0,\vec{x}_\perp) = \alpha^{i(0)}_\perp(\vec{x}_\perp) = \lim_{w\to 0}\Big(\beta^i_1(x^-,\vec{x}_\perp) + \beta^i_2(x^+,\vec{x}_\perp)\Big)$$
$$\alpha(0,\vec{x}_\perp) = \alpha^{(0)}(\vec{x}_\perp) = -\frac{ig}{2}\lim_{w\to 0}\,[\beta^i_1(x^-,\vec{x}_\perp),\beta^i_2(x^+,\vec{x}_\perp)]$$

A. Kovner, L. D. McLerran and H. Weigert, Phys. Rev. D **52**, 6231 (1995).
MEC, Czajka, Mrówczyński, arXiv:2012.03042.

$\boxed{\text{step 3:}}$ glasma fields (at early times) with proper time expansion

$$\alpha(\tau,\vec{x}_\perp) \quad = \quad \alpha(0,\vec{x}_\perp) + \tau\alpha^{(1)}(\vec{x}_\perp) + \tau^2\alpha^{(2)}(\vec{x}_\perp) + \cdots$$

and similarly for $\alpha^i_\perp(\tau,\vec{x}_\perp)$ ... *(dimensionless small parameter is* $\tilde\tau = \tau Q_s$*)*

coefs of expansion: require vector potential satisfies sourceless YM eqn

$$[D_\mu, F^{\mu\nu}] = 0 \quad \text{with} \quad F_{\mu\nu} = \frac{i}{g}[D_\mu, D_\nu] \quad \text{and} \quad D_\mu = \partial_\mu - igA_\mu$$

$\rightarrow \alpha^{(n)}(\vec{x}_\perp)$ and $\vec\alpha^{(n)}_\perp(\vec{x}_\perp)$ in terms of $\alpha(0,\vec{x}_\perp)$ and $\vec\alpha_\perp(0,\vec{x}_\perp)$

R. J. Fries, J. I. Kapusta and Y. Li, Nucl. Phys. A **774***, 861 (2006).*
K. Fukushima, Phys. Rev. C **76***, 021902 (2007).*
H. Fujii, K. Fukushima and Y. Hidaka, Phys. Rev. C **79***, 024909 (2009).*
G. Chen, R. J. Fries, J. I. Kapusta and Y. Li, Phys. Rev. C **92***, 064912 (2015).*

summary of method:

$$\underbrace{\rho^n(x^\pm,\vec{x}_\perp)}_{\text{static valence parton sources}} \;\rightarrow\; \underbrace{\beta^n(x^\pm,\vec{x}_\perp)}_{\text{CGC pre-collision fields}} \;\rightarrow\; \underbrace{\alpha(0,\vec{x}_\perp)}_{\text{initial glasma fields (boost invariant)}} \;\rightarrow\; \underbrace{\alpha(\tau,\vec{x}_\perp)}_{\text{glasma fields}}$$

next: colour charge distributions are not known
- assume Gaussian distribution of colour charges in each nucleus
- a product of sources is replace by its average over this distro

an average over a Gaussian distribution of independent random variables
$\rightarrow$ sum over the averages of all possible pairs *(Wick's theorem)*
idea of CGC: local fluctuations $\propto$ surface colour charge density μ

$$\langle\rho_1(x^-,\vec{x}_\perp)\rho_1(y^-,\vec{y}_\perp)\rangle \propto g^2\,\mu_1(\vec{x}_\perp)\delta(x^- - y^-)\delta^2(\vec{x}_\perp - \vec{y}_\perp)$$

analogous expressions for the second ion

glasma graph approximation $\longrightarrow$

J. P. Blaizot, F. Gelis and R. Venugopalan, Nucl. Phys. A **743**, 57 (2004).
K. Fukushima and Y. Hidaka, JHEP **06**, 040 (2007).
F. Fillion-Gourdeau and S. Jeon, Phys. Rev. C **79**, 025204 (2009).
T. Lappi, B. Schenke, S. Schlichting and R. Venugopalan, JHEP **01**, 061 (2016).
J. L. Albacete, P. Guerrero-Rodríguez and C. Marquet, JHEP **01**, 073 (2019).

result for correlator of 2 potentials: $(\vec{R} = \frac{1}{2}(\vec{x}_\perp + \vec{y}_\perp),\ \vec{r} = \vec{x}_\perp - \vec{y}_\perp)$

$$\delta_{ab} B^{ij}(\vec{x}_\perp, \vec{y}_\perp) \equiv \lim_{\mathrm{w}\to 0} \langle \beta^i_a(x^-, \vec{x}_\perp) \beta^j_b(y^-, \vec{y}_\perp) \rangle$$

$$\lim_{r\to 0} B^{ij}(\vec{x}_\perp, \vec{y}_\perp) = \delta^{ij} g^2 \frac{\mu(\vec{R})}{8\pi} \left(\ln\left(\frac{Q_s^2}{m^2} + 1 \right) - \frac{Q_s^2}{Q_s^2 + m^2} \right) + \cdots$$

infra-red regulator $m \sim \Lambda_{\rm QCD} \sim 0.2$ GeV
ultra-violet regulator = saturation scale = $Q_s = 2$ GeV

dots indicate we have kept terms to 2nd order in grad expansion of $\mu(\vec{R})$

J. Jalilian-Marian, A. Kovner, L. McLerran, H. Weigert, Phys. Rev. D **55**, *5414 (1997).*
H. Fujii, K. Fukushima, Y. Hidaka, Phys. Rev. C **79**, *024909 (2009).*
G. Chen, R. Fries, J. Kapusta, Y. Li, Phys. Rev. C **92**, *064912 (2015).*

surface charge density μ

must specify the form of the surface colour charge density $\mu(\vec{x}_\perp)$
- 2-dimensional projection of a Woods-Saxon potential

$$\mu(\vec{x}_\perp) = \left(\frac{A}{207}\right)^{1/3} \frac{\bar{\mu}}{2a\log(1+e^{R_A/a})} \int_{-\infty}^{\infty} dz \frac{1}{1+\exp\left[(\sqrt{(\vec{x}_\perp)^2+z^2}-R_A)/a\right]}$$

R_A and $a =$ radius and skin thickness of nucleus mass number A
$r_0 = 1.25$ fm, $a = 0.5$ fm $\rightarrow$ when $A = 207$ gives
$R_A = r_0 A^{1/3} = 7.4$ fm

normalization: $\mu(\vec{0}) = \bar{\mu} = Q_s^2/g^4$ lead nucleus
$g^2\sqrt{\bar{\mu}} =$ McLerran-Venugopalan (MV) scale

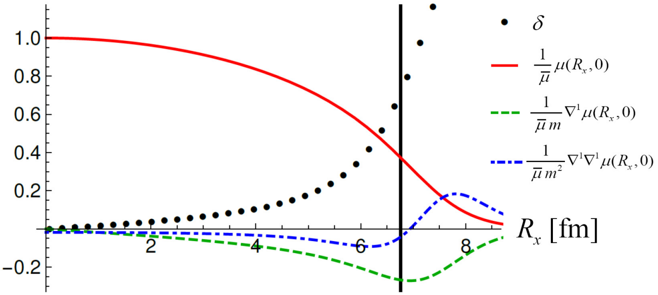
proportional to Q_s - exact relation not determined with CGC approach

E. Iancu and R. Venugopalan, in *Quark–Gluon Plasma 3*, eds. R.C. Hwa and X.-N. Wang (World-Scientific, Singapore, 2004), p. 249.
T. Lappi, Eur. Phys. J. C **55**, 285-292 (2008).

** numerical results for $\mathcal{E}$ ... are order of magnitude estimates
ratios of different elements of the energy momentum tensor
$\rightarrow$ will have much weaker dependence on the MV scale.

gradient expansion

the parameter that we assume small is $\delta = \frac{|\nabla^i \mu(\vec{R})|}{m\mu(\vec{R})}$



derivatives are appreciable only in a very small region at the edges

non-zero impact parameter (non-central collisions)
expand $\mu_{1/2}(\vec{z}_\perp)$ around ave coord $\vec{R} \mp \vec{b}/2$

summary of method:

YM eqn with average over gaussian distributed valence sources
$\rightarrow$ correlators of pre-collision fields
$\rightarrow$ glasma field correlators (b. conds, sourceless YM eqn, τ exp)
$\rightarrow$ correlators of glasma chromodynamic $\vec{E}$ and $\vec{B}$ fields
$\Rightarrow$ observables

we work to order τ^6 and study

1. isotropization of transverse/longitudinal pressures
2. azimuthal momentum distribution and spatial eccentricity
3. angular momentum
4. momentum broadening of hard probes

comment: many numerical approaches to study initial dynamics
our method is fully analytic
- allows control over different approximations and sources of errors
- can be systematically extended
- it has limitations (classical / no fluctuations of positions of nucleons)

isotropization

at $\tau = 0^+$ the energy-momentum tensor has the diagonal form

$$T(\tau = 0) = \begin{pmatrix} \mathcal{E}_0 & 0 & 0 & 0 \\ 0 & -\mathcal{E}_0 & 0 & 0 \\ 0 & 0 & \mathcal{E}_0 & 0 \\ 0 & 0 & 0 & \mathcal{E}_0 \end{pmatrix}$$

$\rightarrow$ the longitudinal pressure is large and negative
- system is far from equilibrium

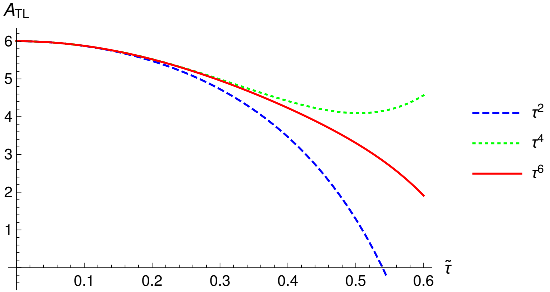
if the system approaches equilibrium as it evolves:
- the longitudinal pressure must grow
- transverse pressure must decrease ($T_{\mu\nu}$ is traceless)

to compare longitudinal and transverse pressures ($\tilde{\tau} \equiv \tau Q_s$)

$$A_{TL} \equiv \frac{3(p_T - p_L)}{2p_T + p_L}$$

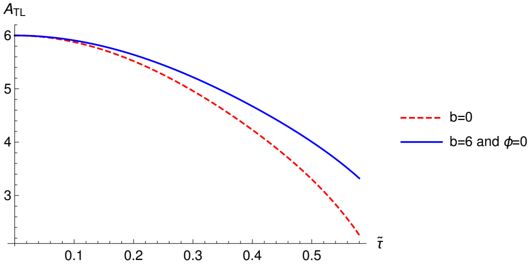
J. Jankowski, S. Kamata, M. Martinez and M. Spaliński, Phys. Rev. D **104**, 074012 (2021).

in equilibrium ($p_L = p_T = \mathcal{E}/3$) $\longrightarrow A_{TL} = 0$

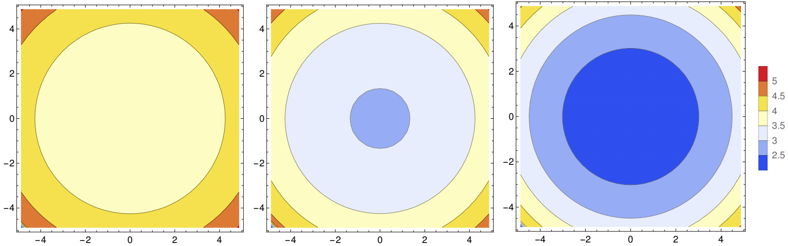


$R = 5$ fm, $\eta = 0$ and $b = 0$.

faster isotropization with smaller impact parameter
$\rightarrow$ increased region of overlap



reaction plane defined by collision axis and impact parameter
$\phi = 0$ is in reaction plane
$\phi = \pi/2$ is perpendicular to reaction plane



A_{TL} at order τ^6
$\tau = 0.04$ fm (left panel)
$\tau = 0.045$ fm (centre panel)
$\tau = 0.05$ fm (right panel)

the axes show R_x and R_y in fm

dependence on confinement and saturation scales

the correlator $\langle\beta^i_a(x^-,\vec{x}_\perp)\beta^j_b(y^-,\vec{y}_\perp)\rangle$

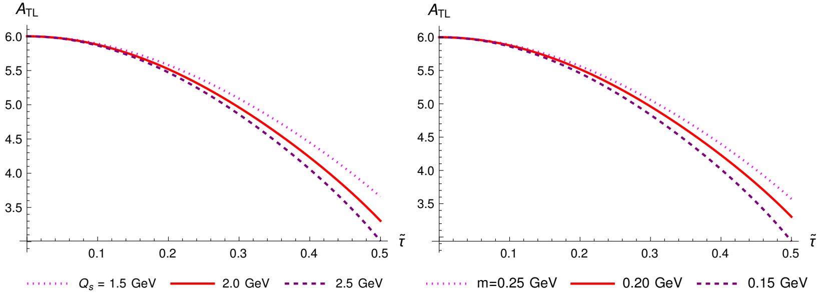
depends on two regulators: m (infra-red) and Q_s (ultra-violet)
- physically related to confinement / saturation scales
$\rightarrow$ constraints on how to choose them

we used: $m = 0.2$ GeV and $Q_s = 2.0$ Gev - standard choices

- want results $\approx$ independent of these numbers

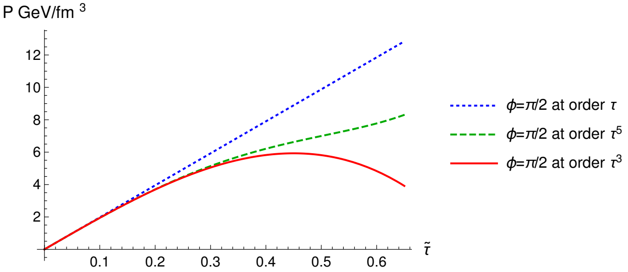
- especially since the two scales are pretty close together

A_{TL} at order τ^6 as a function of time
3 different values of Q_s with $m = 0.2$ GeV (left)
3 different values of m with $Q_s = 2.0$ GeV (right)
$R = 5$ fm, $b = 0$ and $\eta = 0$ at order τ^6
$\Rightarrow$ dependence on these scales is weak



Radial Flow

transverse momentum flow vector $= T_{i0}$ (trans. Poynting vector)
radial flow of the expanding glasma = radial projection $P \equiv \hat{R}_i T_{i0}$
$\phi = \pi/2$ is perpendicular to the reaction plane



- at lowest order P increases linearly with time
- including higher order contros $\to$ P slows as system expands
- order τ^5 shows flattening up to about $\tilde{\tau} = 0.5$

$\to$ indicates the limit of validity of the τ expansion

Azimuthal asymmetry

in a non-central collision - initial spatial asymmetry
relativistic collision $\rightarrow$ spatial asymmetries rapidly decrease
$\rightarrow$ anisotropic momentum flow can develop only in the first fm$/c$

- sensitive to system properties very early in its evolution
- provides direct information about the early stages of the system

$$\varphi(\vec{x}_\perp) = \tan^{-1}\left(\frac{T^{0y}(\vec{x}_\perp)}{T^{0x}(\vec{x}_\perp)}\right)$$

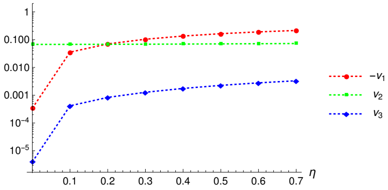
$$W(\vec{x}_\perp) \equiv \sqrt{\left(T^{0x}(\vec{x}_\perp)\right)^2 + \left(T^{0y}(\vec{x}_\perp)\right)^2}$$

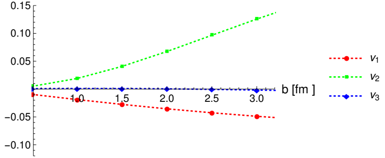
$$P(\phi) \equiv \frac{1}{\Omega}\int d^2\vec{x}_\perp\, \delta\big(\phi - \varphi(\vec{x}_\perp)\big)\, W(\vec{x}_\perp), \quad \Omega \equiv \int d^2\vec{x}_\perp\, W(\vec{x}_\perp)$$

$$P(\phi) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi)\right)$$

$$v_n = \int_0^{2\pi} d\phi\, \cos(n\phi)\, P(\phi)$$

first 3 fourier coefficients at $\tau = 0.04$ fm
left panel: $b = 2$ fm; right panel $\eta = 0.01$





v_2 and v_3 are $\sim$ experimental values
v_1 is bigger than expected

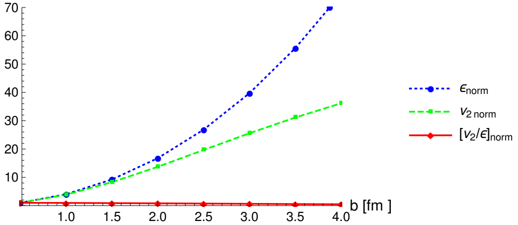
note: usually assumed anisotropy develops mostly during hydro evolution
$\rightarrow$ our results for all three Fourier coefficients are large

comment:
experimentally: impact parameter / reaction plane not precisely known
our calculation does not correspond exactly to what is measured

• spatial deviations from azimuthal symmetry

$$\varepsilon_n = -\frac{\int d^2\vec{R}|\vec{R}|\cos(n\phi)\mathcal{E}(\vec{R})}{\int d^2\vec{R}|\vec{R}|\mathcal{E}(\vec{R})} \quad \text{with} \quad \phi = \tan^{-1}(R_y/R_x)$$

where $\mathcal{E}(\vec{R})$ denotes the energy density



$\tau = 0.04$ fm and $\eta = 0$ [normalized to 1 at $b = 0.5$ fm]

$\rightarrow$ correlation btwn spatial asymmetry introduced by the initial geometry and anisotropy of azimuthal momentum distribution

these correlations $\sim$ characteristic of onset of hydrodynamic behaviour

angular momentum

define tensor $M^{\mu\nu\lambda} = T^{\mu\nu} R^{\lambda} - T^{\mu\lambda} R^{\nu}$ with $R^{\mu} = (\tau, \eta, \vec{R})$

$\nabla_{\mu} M^{\mu\nu\lambda} = 0 \rightarrow$ conserved charges $J^{\nu\lambda} = \int_{\Sigma} d^3y \sqrt{|\gamma|} n_{\mu} M^{\mu\nu\lambda}$
- n^{μ} is a unit vector perpendicular to the hypersurface Σ
- γ is the induced metric on this hypersurface
- d^3y is the corresponding volume element

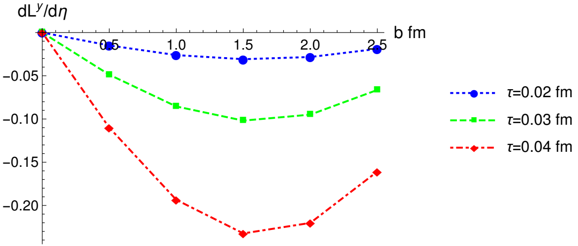
$n^{\mu} = (1, 0, 0, 0)$ in Milne coordinates
$\rightarrow$ $J^{\nu\lambda}$ defined on a hypersurface of constant τ

Pauli-Lubanski vector: $L_{\mu} = -\frac{1}{2} \epsilon_{\mu\alpha\beta\gamma} J^{\alpha\beta} u^{\gamma}$

result: angular momentum per unit rapidity (symmetric collision)

$$\frac{dL^y}{d\eta} = -\tau^2 \int d^2\vec{R}\, R^x T^{0z}$$

result:



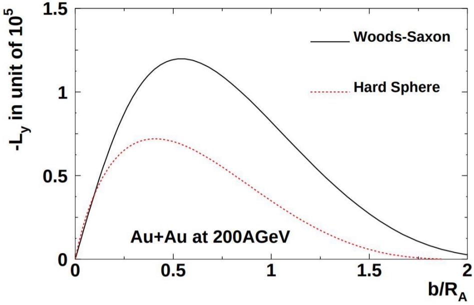
ions moving in $+/$-z dirns displaced in $+/$- x dirns $\rightarrow$ L_y is negative

warning: dominant contro to $\vec{L}$ from regions farthest from collision centre
$=$ regions gradient expansion is least trusted $\rightarrow$ error bars large

comparison:

$L_y \sim 10^5$ at RHIC energies for initial system of colliding ions

J. H. Gao, S. W. Chen, W. t. Deng, Z. T. Liang, Q. Wang and X. N. Wang



- even larger at LHC energies

F. Becattini, F. Piccinini and J. Rizzo, Phys. Rev. C **77**, *024906 (2008).*

idea: initial rapid rotation of glasma
$\rightarrow$ could be observed via polarization of final state hadrons
- large $\vec{L}$ & spin-orbit coupling $\rightarrow$ alignment of spins with $\vec{L}$

many experimental searches for this polarization
- effect of a few percent observed at RHIC
- at LHC result consistent with zero
- *difficult to measure ...*

F. Becattini, M.A. Lisa, Ann. Rev. Nucl. Part. Sci. 70, 395 (2020).

these results are consistent our calculation:
glasma carries only tiny imprint of the $\vec{L}$ of the intial state
$\rightarrow$ majority of the angular momentum is carried by valence quarks

hard probes - momentum broadening

idea:

hard probes produced via hard interactions at earliest phase of HIC

- propagate through the evolving medium
- suppression of high-p_T probes (jet quenching)

$\Rightarrow$ signal of formation of QGP

- deconfined state of matter = significant braking of hard partons

EL and MB of hard probes / equilibrium plasma studied extensvely

• contro from pre-equilibrium phases has been largely ignored

however, see for example:

Ruggieri, Das et al, Phys. Rev. D 98, 094024 (2018).

Boguslavski, Kurkela, Lappi, Peuron, JHEP 09, 077 (2020).

Ipp, Müller, Schuh, Phys. Lett. B 810, 135810 (2020).

D. Pablos, M. Singh, S. Jeon and C. Gale, arXiv:2202.03414.

Siggi Hauksson, talk presented at SEWM_2022, 21/06.

physics: frequent small $\vec{p}$ exchanges btwn probe and glasma fields
$\rightarrow$ transport equation in Fokker-Planck form

- describes interactions of hard probe interacting with glasma fields

see talk by Stanisław Mrówczński, 21/06 14:00

$$\Big(\mathcal{D} - \nabla_p^\alpha X^{\alpha\beta}(\vec{v})\nabla_p^\beta - \nabla_p^\alpha Y^\alpha(\vec{v})\Big)n(t,\vec{x},\vec{p}) = 0$$

notation: $\alpha \in (1,2,3)$

$n(t,\vec{x},\vec{p})$ = distribution function of heavy quarks
$\vec{v} = \vec{p}/E_{\vec{p}} = \vec{p}/\sqrt{p^2+m_Q^2}$ = velocity of heavy quark
$\mathcal{D} \equiv \frac{\partial}{\partial t} + \vec{v}\cdot\vec{\nabla}$ = material derivative (drift term)

Y^α related to collisional energy loss

$X^{\alpha\beta}$ related to momentum broadening

St. Mrówczyński, Eur. Phys. J. A **54***, 43 (2018).*

$$\hat{q} = \frac{1}{v}\Big(\delta^{\alpha\beta} - \frac{v^\alpha v^\beta}{v^2}\Big)\frac{\langle \Delta p^\alpha \Delta p^\beta\rangle}{\Delta t}$$

$$= \frac{2}{v}\Big(\delta^{\alpha\beta} - \frac{v^\alpha v^\beta}{v^2}\Big)X^{\alpha\beta}(\vec{v})$$

$$X^{\alpha\beta}(\vec{v}) \equiv \frac{1}{2N_c}\int_0^t dt' \,\mathrm{Tr}\Big[\Big\langle \mathcal{F}^\alpha(t,\vec{x})\mathcal{F}^\beta\big(t-t',\vec{x}-\vec{v}t'\big)\Big\rangle\Big]$$

colour Lorentz force: $\vec{\mathcal{F}}(t,\vec{x}) \equiv g\Big(\vec{E}(t,\vec{x}) + \vec{v}\times\vec{B}(t,\vec{x})\Big)$

$$X^{\alpha\beta}(\mathbf{v}) = \frac{g^2}{2N_c}\int_0^t dt'\Big[\big\langle E_a^\alpha(t,\vec{x})E_a^\beta(t-t',\vec{y})\big\rangle + \epsilon^{\beta\gamma\gamma'}v^\gamma\big\langle E_a^\alpha(t,\vec{x})B_a^{\gamma'}(t-t',\vec{y})\big\rangle$$
$$+\epsilon^{\alpha\gamma\gamma'}v^\gamma\big\langle B_a^{\gamma'}(t,\vec{x})E_a^\beta(t-t',\vec{y})\big\rangle + \epsilon^{\alpha\gamma\gamma'}\epsilon^{\beta\delta\delta'}v^\gamma v^\delta\big\langle B_a^{\gamma'}(t,\mathbf{x})B_a^{\delta'}(t-t',\vec{y})\big\rangle\Big]$$

where $\vec{y} = \vec{x} - \vec{v}t'$.

note: combination of two approaches

1. medium that the hard probe interacts with is a glasma
$\rightarrow$ described with CGC effective theory with proper time expansion
*** description is valid only at very early times*

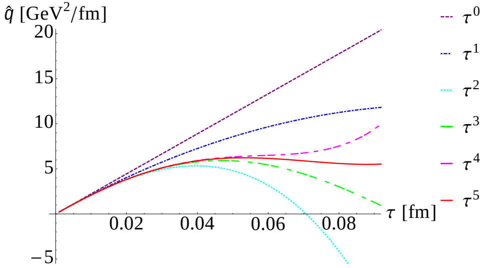
2. FP eqn describes interactions of hard probe with glasma fields
*** valid at times long enough that collision terms saturate*

$\Rightarrow$ conflict btwn assumptions that set these two time scales

also:
- FP description requires gradient expansion type approximations
- our CGC approach assumes boost invariance

** can all these conditions can be satisfied simultaneously?

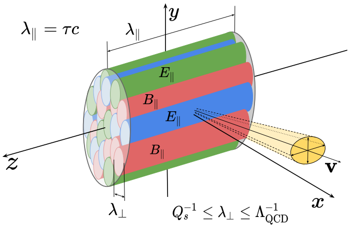
result: $\hat{q}$ as a function of τ at different orders in the expansion



key: saturation regime appears before τ expansion breaks down

caution:
figure above obtained for $v_\perp = v$
calculation works less well when $v_\parallel \neq 0$

reason: at very early times
glasma fields represented as longitudinal flux tubes

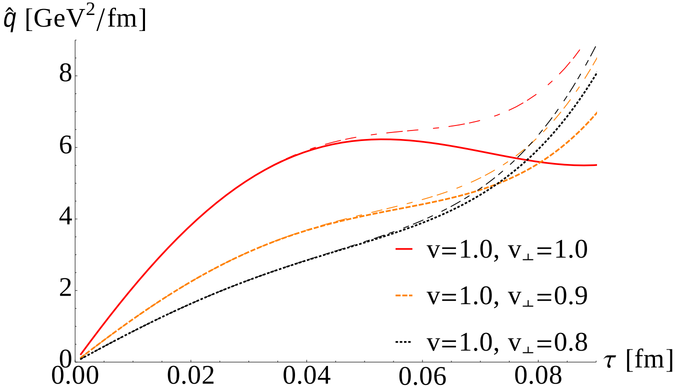


$\lambda_{\perp}$ can be inferred the 2-point correlator

$\hat{q}$ built up during time probe is in domain of correlated fields
at zeroth order this time is determined by
- transverse correlation length
- orientation and magnitude of the probe's velocity

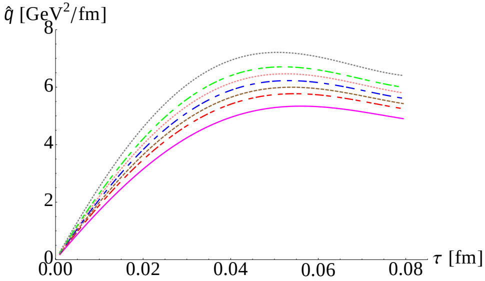
$\rightarrow$ saturation is faster if $v_{\|} = 0$

note: probe's velocity also enters through the Lorentz force



fifth and fourth order results for increasing $v_{||}$
- saturation is less pronounced as $v_{||}$ increases

scale dependence



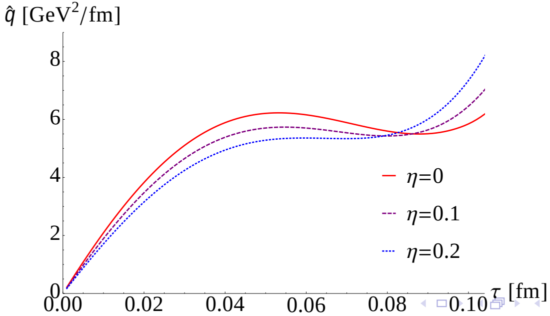
Q_s between 1.9 (bottom) and 2.1 (top) GeV with ratio Q_s/m fixed
- one sees that the dependence is fairly weak

boost and translation invariance

calculation of $\hat{q}$ is formulated in Minkowski space
- assumes at least approximate translation invariance

but used correlators of electric and magnetic fields obtained from an boost invariant ansatz for the vector potential

check of consistency:
previous result was $z = \eta = 0$ (red line)
$\hat{q}$ as a function of τ for three values of η



impact of the glasma on jet quenching

radiative Eloss/length of probe traversing medium of length L
$\propto$ total accumulated transverse momentum broadening

$$\Delta p_T^2 = \int_0^L dt \hat{q}(t)$$

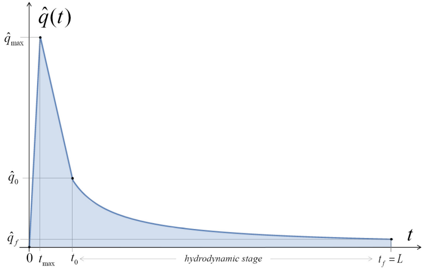
our calculation gives $\hat{q}_{\mathrm{max}} = 6 \ \mathrm{GeV}^2/\mathrm{fm}$

compare with equilibrium values:
hard quark of $p_T > 40$ GeV $\quad \longrightarrow \quad 2 < \hat{q}/T^3 < 4$
- inferred from experimental data *S. Cao et al. [JETSCAPE], Phys. Rev. C* **104**, *024905 (2021).*

$\hat{q} = 3T^3$ and $450 > T > 150$ MeV $\rightarrow (0.05 < \hat{q} < 1.0)$ GeV^2/fm
$\Rightarrow$ equilibrium value of $\hat{q}$ is much smaller

<u>but</u> τ_{life} of pre-equilibrium phase < 1 fm/c
$\rightarrow$ contro of pre-equilibrium phase to jet quenching usually ignored

schematic representation of the time dependence of $\hat{q}$



1. rapid growth to $\hat{q}_{\rm max} \approx 6~{\rm GeV}^2/{\rm fm}$ at $t_{\rm max} \approx 0.06$ fm
- this is a rough description of our result
- no saturation region because of time scales
2. decrease from $t_{\rm max} \to t_0$ - not captured by our calculation
- is reproduced by the simulations

A. Ipp, D. I. Müller and D. Schuh, Phys. Lett. B **810**, *135810 (2020)*

$$\to \quad \Delta p_T^2\Big|^{\rm non-eq} = \int_0^{t_0} dt\, \hat{q}(t) = \frac{1}{2}\hat{q}_{\rm max}\, t_0 + \frac{1}{2}\hat{q}_0(t_0 - t_{\rm max})$$

3. assume hydro evolution from t_0

- using 1d boost invariant hydrodynamics

$\hat{q} = 3T^3$ with $T = T_0\left(\frac{t_0}{t}\right)^{1/3}$ and

$$\Delta p_T^2\Big|^{\rm eq} = \int_{t_0}^{L} dt\, \hat{q}(t) = 3T_0^3\, t_0\, \ln\frac{L}{t_0}$$

values:

$t_0 = 0.6$ fm, T_0=0.45 GeV

C. Shen, U. Heinz, P. Huovinen and H. Song, Phys. Rev. C **84**, *044903 (2011)*

$L = 10$ fm

result: $\quad \dfrac{\Delta p_T^2[\text{non-equib}]}{\Delta p_T^2[\text{equib}]} \approx 0.93$

rough estimate that depends on values of parameters chosen
– but result is not very sensitive to values of shape of peak

$\Rightarrow$ glasma plays an important role in jet quenching

conclusions

1. developed an efficient method to calculate correlators of electric and magnetic fields using a CGC approach and a proper time expansion
2. 6th order τ expansion can be trusted to about $\tau = 0.05$ fm
3. correlation btwn elliptic flow coef v_2 / spatial eccentricity
   - spatial asymmetry introduced by initial geometry is effectively transmitted to azimuthal distribution of gluon momentum field

   $\rightsquigarrow$ indication of the onset of hydrodynamics.
4. most of the angular momentum of the intial system not transmitted to glasma
   - contradicts picture of a rapidly rotating initial glasma state
5. glasma plays an important role in jet quenching