The earliest phase of relativistic heavy-ion collisions

Stanisław Mrówczyński

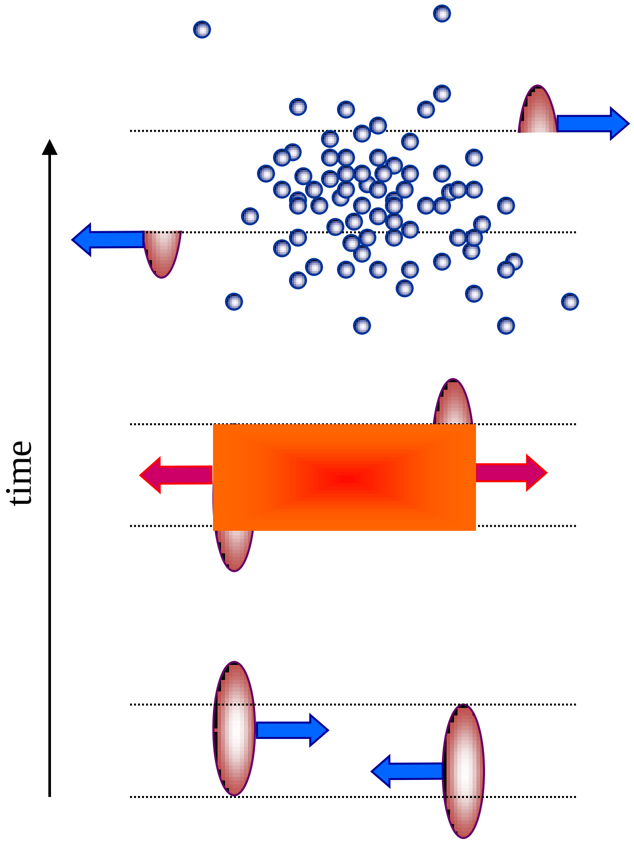
National Centre for Nuclear Research, Warsaw, Poland
and Jan Kochanowski University, Kielce, Poland

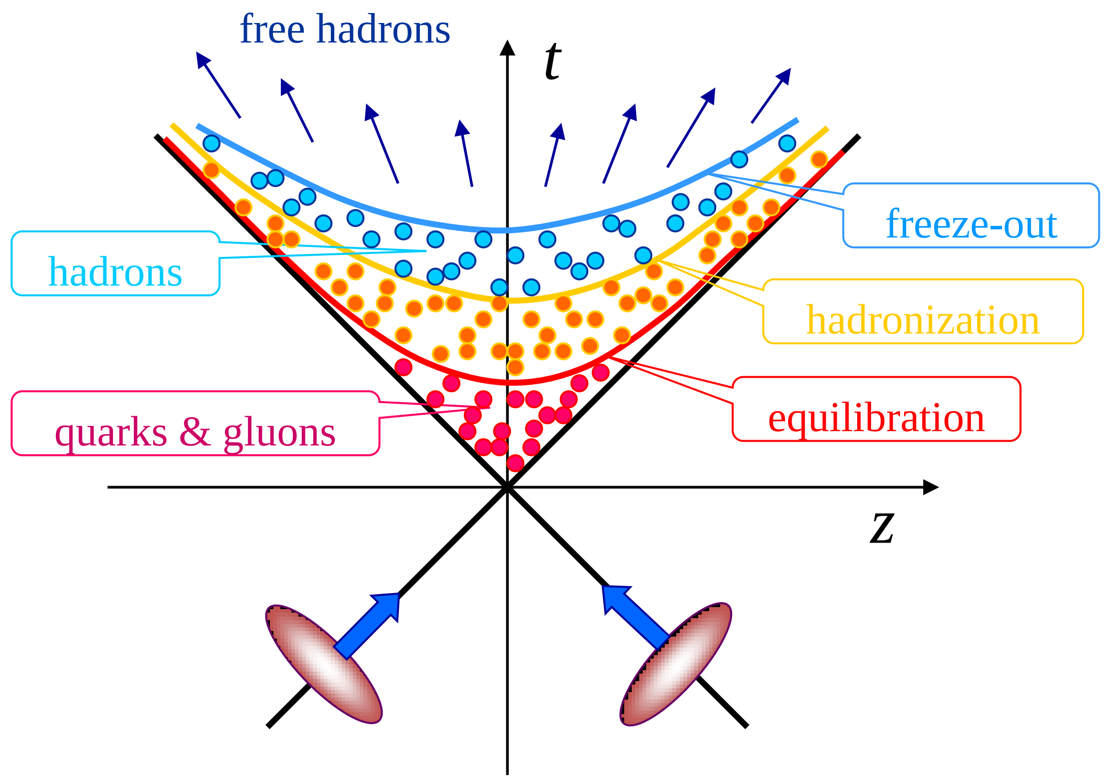
in collaboration with **Margaret Carrington & Alina Czajka**

Outline

- What it is about
- Introduction to Color Glass Condensate
- Proper time expansion
- Glasma characteristics from energy-momentum tensor
- Jet quenching in glasma

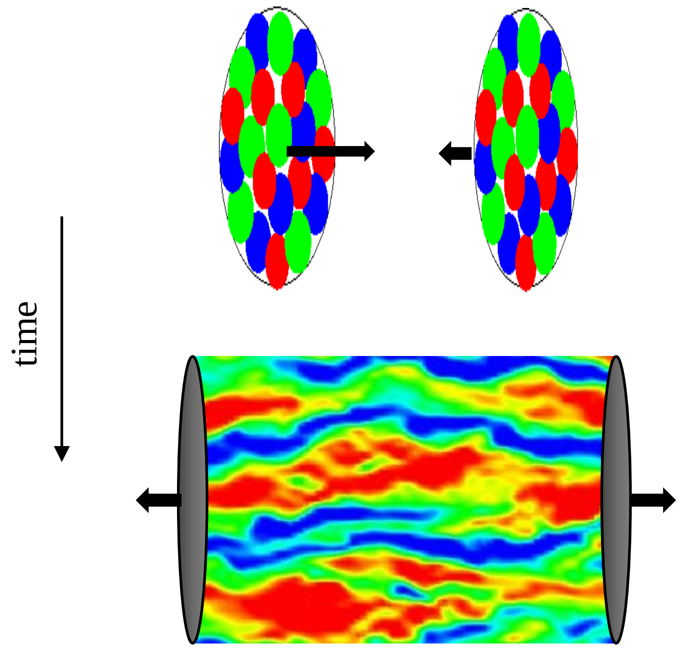
Relativistic heavy-ion collisions





Color Glass Condensate

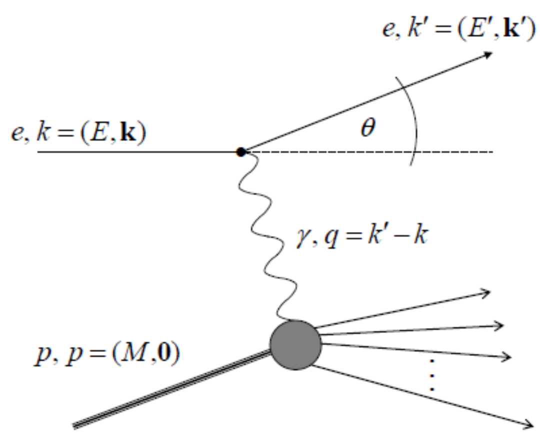
Color charges confined in the colliding nuclei generate **glasma** – the system of strong mostly classical chromodynamic fields which evolves towards equilibrium.



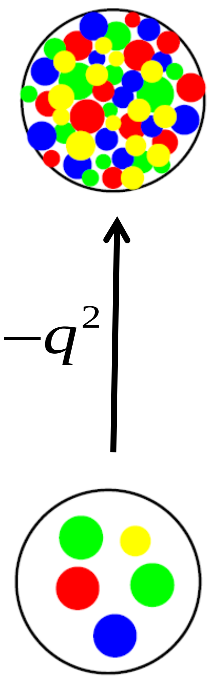
What are characteristics of the earliest (τ < 0.1 fm/c) stage of relativistic heavy-ion collisions?

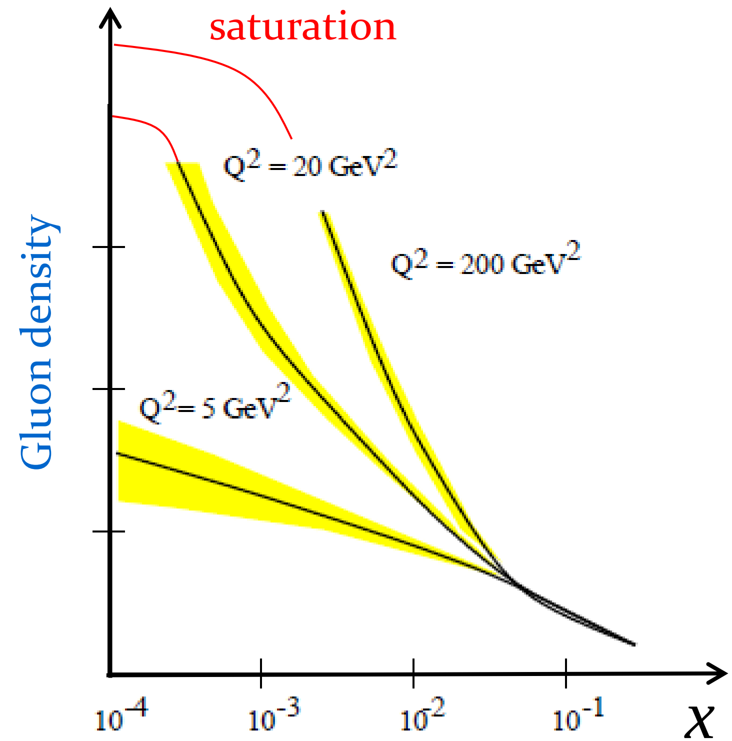
Saturation

Deep Inelastic Scattering



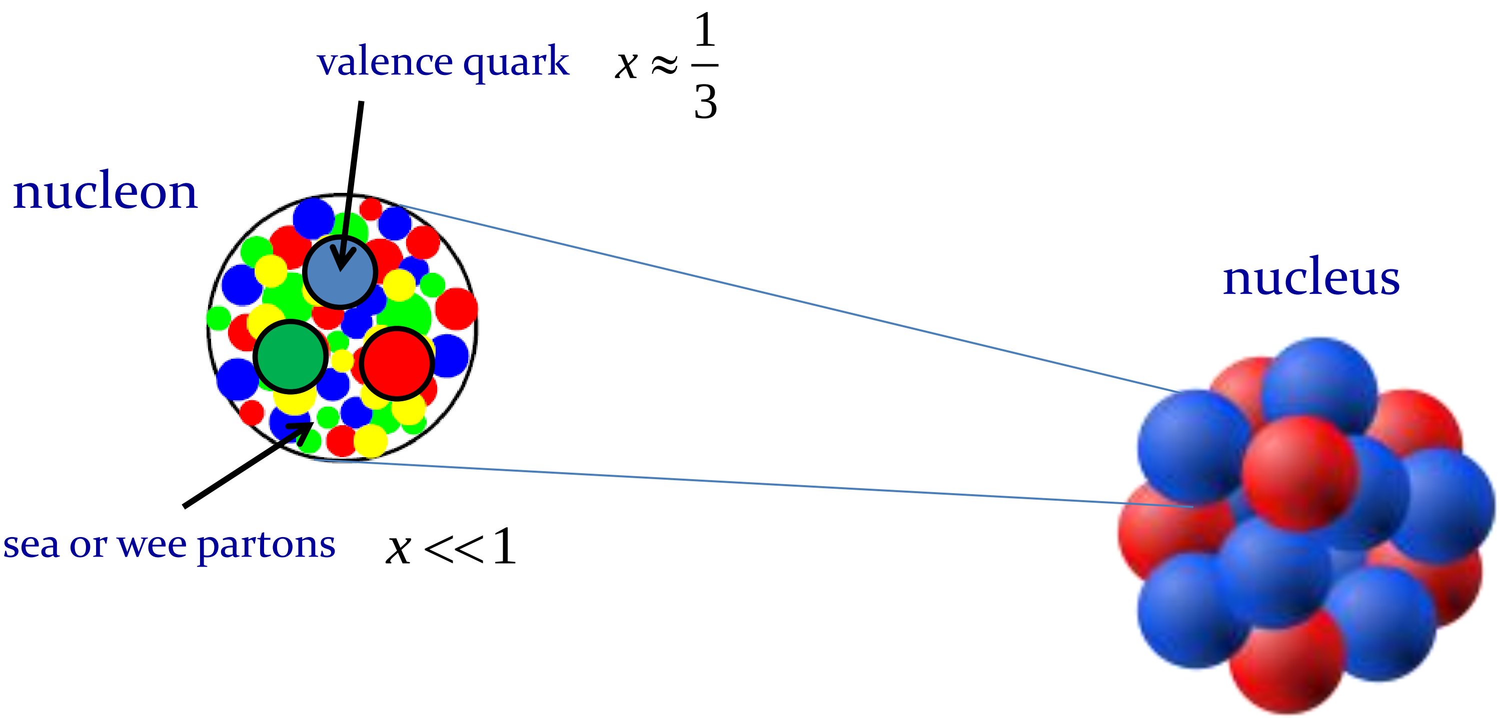
$$Q^2 = -q^2$$





Saturated gluon system can be described in terms of classical chromodynamic fields.

Wee partons & valence quarks

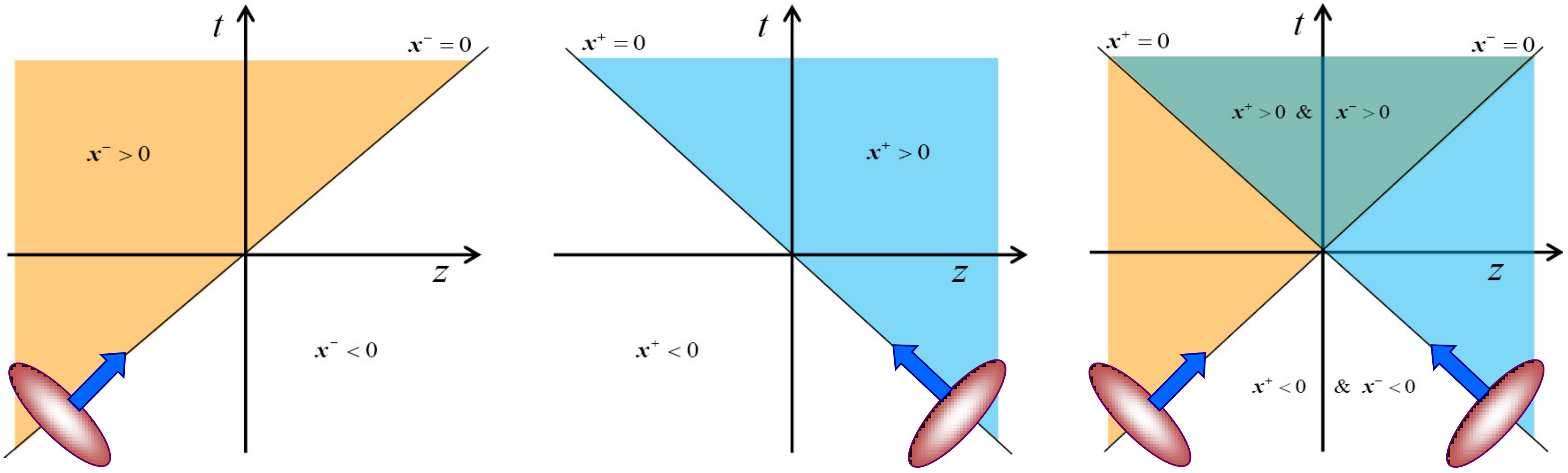


In relativistic heavy-ion collsions

- Saturated wee partons – classical chromodynamic fields
- Valence quarks – classical sources of chromodynamic fields
- Saturation scale for A-A at LHC: $Q_s \approx 2\,\mathrm{GeV} >> \Lambda_{\mathrm{QCD}} \approx 0.2\,\mathrm{GeV} \Rightarrow \alpha_s(Q_s) << 1$

Heavy-ion collisions in light-cone variables

$$x^{\pm} \equiv \frac{t \pm z}{\sqrt{2}}$$



$x^- = 0$

$x^+ = 0$

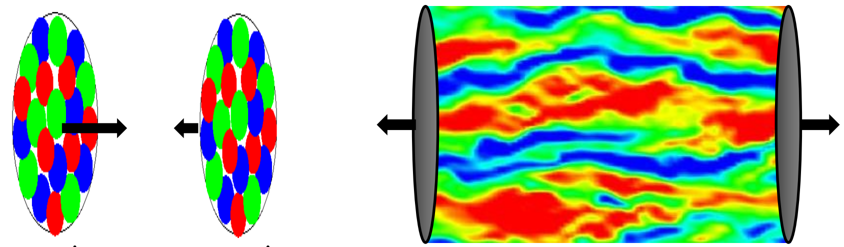
Color Glass Condensate

Classical Yang-Mills equation

$$\boxed{D_\mu F^{\mu\nu}(x) = j^\nu(x)}$$

$$j^\mu(x) = j_1^\mu(x) + j_2^\mu(x)$$

$$j_{1,2}^\mu(x) = \pm\delta^{\mu\mp}\delta(x^\pm)\rho_{1,2}(\mathbf{x}_\perp)$$



β_1^i β_2^i

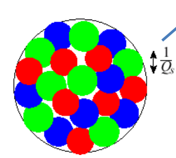
pre-collision potentials

$\alpha, \alpha_\perp^i$

post-collision potentials

Ansatz of gauge potentials

$$\begin{cases} A^+(x) = \Theta(x^+)\Theta(x^-)x^+\alpha(\tau,\mathbf{x}_\perp) \\ A^-(x) = -\Theta(x^+)\Theta(x^-)x^-\alpha(\tau,\mathbf{x}_\perp) \\ A^i(x) = \Theta(x^+)\Theta(x^-)\alpha_\perp^i(\tau,\mathbf{x}_\perp) \\ \qquad + \Theta(-x^+)\Theta(x^-)\beta_1^i(\mathbf{x}_\perp) + \Theta(x^+)\Theta(-x^-)\beta_2^i(\mathbf{x}_\perp) \end{cases}$$



Boundary condition

$$\begin{cases} \alpha(0,\mathbf{x}_\perp) = \beta_1^i(\mathbf{x}_\perp) + \beta_2^i(\mathbf{x}_\perp) \\ \alpha_\perp^i(0,\mathbf{x}_\perp) = -\frac{ig}{2}[\beta_1^i(\mathbf{x}_\perp), \beta_2^i(\mathbf{x}_\perp)] \end{cases}$$

Gauge condition

$$x^+A^- + x^-A^+ = 0$$

E. Iancu, R. Venugopalan, in *Quark-Gluon Plasma 3*,
ed. by R.C. Hwa, X.-N. Wang (World Scientific, Singapore, 2004

Proper time expansion

$$\alpha(\tau,\mathbf{x}_\perp)=\sum_{n=0}^{\infty}\tau^n\alpha_{(n)}(\mathbf{x}_\perp), \qquad \alpha_\perp^i(\tau,\mathbf{x}_\perp)=\sum_{n=0}^{\infty}\tau^n\alpha_{\perp(n)}^i(\mathbf{x}_\perp)$$

Proper time τ is treated as a small parameter $\tau << Q_s^{-1}$

Yang-Mills equations for the expanded potentials are solved recursively

$$\alpha_{(n)}=\alpha_{\perp(n)}^i=0 \quad \text{for} \quad n=1,3,5,\ldots$$

0th order - oboundary conditions

$$\begin{cases}\alpha_{(0)}=-\dfrac{ig}{2}[\beta_1^i,\beta_2^i] \\ \alpha_{\perp(0)}^i=\beta_1^i+\beta_2^i\end{cases}$$

Post-collision potentials are expressed through pre-collision potentials

2nd order

$$\begin{cases}\alpha_{(2)}=-\dfrac{ig}{16}[D^j,[D^j,[\beta_1^i,\beta_2^i]]] \\ \alpha_{\perp(2)}^i=\dfrac{ig}{4}\varepsilon^{zij}\varepsilon^{zkl}[D^j,[\beta_1^k,\beta_2^l]]\end{cases}$$

$$D^i\equiv\partial^i-ig(\beta_1^i+\beta_2^i)$$

Fully analytic approach!

R. J. Fries, J. I. Kapusta, and Y. Li, arXiv:nucl-th/0604054
G.Chen, R.J. Fries, J.I. Kapusta and Y. Li, Physical Review D **92**, 064912 (2015)

Proper time expansion cont.

Chromoelectric and chromomagnetic fields

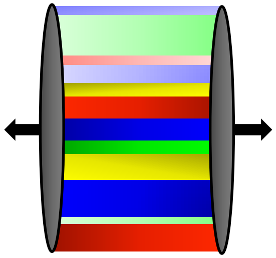
$$E^i = F^{i0}, \quad B^i = \frac{1}{2}\varepsilon^{ijk}F^{kj}$$

0th order

$$\mathbf{E}_{(0)} = (0,0,E), \qquad \mathbf{B}_{(0)} = (0,0,B)$$

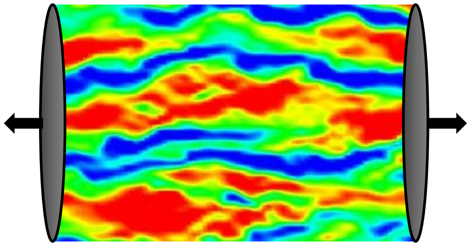
$$E^z_{(0)}(\mathbf{x}_\perp) = -ig[\beta^i_1(\mathbf{x}_\perp), \beta^i_2(\mathbf{x}_\perp)]$$

$$B^z_{(0)}(\mathbf{x}_\perp) = -ig\varepsilon^{zij}[\beta^i_1(\mathbf{x}_\perp), \beta^j_2(\mathbf{x}_\perp)]$$



E & *B* fields along the axis *z*

At higher orders transverse fields show up



R. J. Fries, J. I. Kapusta, and Y. Li, arXiv:nucl-th/0604054
G.Chen, R.J. Fries, J.I. Kapusta and Y. Li, Physical Review D **92**, 064912 (2015)

Energy-momentum tensor

$$T^{\mu\nu} = 2\mathrm{Tr}[F^{\mu\rho}F_{\rho}{}^{\nu} + \frac{1}{4}g^{\mu\nu}F^{\rho\sigma}F_{\rho\sigma}]$$

$$F^{\mu\nu} = \partial^{\mu}A^{\nu} - \partial^{\nu}A^{\mu} - ig[A^{\mu}, A^{\nu}]$$

The energy-momentum tensor is symmetric, gauge invariant and obeys

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

T^{00} - energy density

T^{0i} - energy flux, Poynting vector

T^{xx}, T^{yy}, T^{zz} - pressures

T^{ij} - momentum flux

Averaging over collisions

$$T^{\mu\nu} \sim \sum \partial^i \partial^j \beta^k \beta^l \dots \beta^m \quad \Rightarrow \quad \left\langle T^{\mu\nu} \right\rangle \sim \sum \partial^i \partial^j \left\langle \beta^k \beta^l \dots \beta^m \right\rangle$$

The pre-collision potentials in covariant gauge $\partial_\mu \beta^\mu = 0$ obey

$$-\nabla^2 \beta^+(\mathbf{x}_\perp) = \rho(\mathbf{x}_\perp) \quad \Rightarrow \quad \beta^+(\mathbf{x}_\perp) = \frac{1}{2\pi} \int d^2 x'_\perp K_0(m\,|\,\mathbf{x}_\perp - \mathbf{x}'_\perp\,|)\rho(\mathbf{x}'_\perp)$$

IR regulator $m = \Lambda_{\rm QCD}$

The potentials are transformed from the covariant to light-cone gauge $\beta_1^+ = \beta_2^- = 0$

Wick theorem

$$\boxed{\left\langle \rho_a^k(\mathbf{x}_\perp)\rho_b^l(\mathbf{y}_\perp)\dots\rho_c^m(\mathbf{z}_\perp)\right\rangle = \sum \prod \left\langle \rho_a^i(\mathbf{x}_\perp)\rho_b^j(\mathbf{y}_\perp)\right\rangle}$$

Glasma graph approximation

$$\left\langle \beta_a^k(\mathbf{x}_\perp)\beta_b^l(\mathbf{y}_\perp)\dots\beta_c^m(\mathbf{z}_\perp)\right\rangle = \sum \prod \left\langle \beta_a^i(\mathbf{x}_\perp)\beta_b^j(\mathbf{y}_\perp)\right\rangle = \sum \prod B_{ab}^{ij}(\mathbf{x}_\perp, \mathbf{y}_\perp)$$

Basic correlator in transversaly uniform system

$$B^{ij}_{ab}(\mathbf{x}_\perp - \mathbf{y}_\perp) \equiv \left\langle \beta^i_a(\mathbf{x}_\perp)\beta^j_b(\mathbf{y}_\perp)\right\rangle = \int d^2x'_\perp\, d^2y'_\perp \cdots\cdots \left\langle \rho^i_a(\mathbf{x}'_\perp)\rho^j_b(\mathbf{y}'_\perp)\right\rangle$$

$$\left\langle \rho^i_a(\mathbf{x}_\perp)\rho^j_b(\mathbf{y}_\perp)\right\rangle = g^2\mu\,\delta^{ab}\delta^{(2)}(\mathbf{x}_\perp - \mathbf{y}_\perp)$$

color charge surface density

$$\mu = g^{-4}Q_s^2$$

$$\boxed{B^{ij}_{ab}(\mathbf{x}_\perp - \mathbf{y}_\perp) \equiv \delta^{ab}\left(\delta^{ij}C_1(r) - \hat{r}^i\hat{r}^jC_2(r)\right)}$$

$$\mathbf{r} \equiv \mathbf{x}_\perp - \mathbf{y}_\perp, \quad r \equiv |\mathbf{r}|, \quad \hat{r}^i \equiv \frac{r^i}{r}$$

$$\begin{cases} C_1(r) \equiv \dfrac{m^2K_0(mr)}{g^2N_c\left(mrK_1(mr)-1\right)}\left\{\exp\left[\dfrac{g^4N_c\mu\left(mrK_1(mr)-1\right)}{4\pi m^2}\right]-1\right\} \\[2ex] C_2(r) \equiv \dfrac{m^3rK_1(mr)}{g^2N_c\left(mrK_1(mr)-1\right)}\left\{\exp\left[\dfrac{g^4N_c\mu\left(mrK_1(mr)-1\right)}{4\pi m^2}\right]-1\right\} \end{cases}$$

$$\underset{r<<m^{-1}}{\approx} \quad \#\log(mr)$$

UV regularization required

$$r > Q_s^{-1}$$

J. Jalilian-Marian, A. Kovner, L. D. McLerran and H. Weigert, Physical Review D **55**, 5414 (1997)

Basic correlator in transversaly non-uniform system

$$B^{ij}_{ab}(\mathbf{x}_\perp,\mathbf{y}_\perp) \equiv \left\langle \beta^i_a(\mathbf{x}_\perp)\beta^j_b(\mathbf{y}_\perp)\right\rangle = \int d^2x'_\perp\, d^2y'_\perp \cdots\cdots \left\langle \rho^i_a(\mathbf{x}'_\perp)\rho^j_b(\mathbf{y}'_\perp)\right\rangle$$

$$\left\langle \rho^i_a(\mathbf{x}_\perp)\rho^j_b(\mathbf{y}_\perp)\right\rangle = g^2\mu(\mathbf{x}_\perp)\delta^{ab}\delta^{(2)}(\mathbf{x}_\perp-\mathbf{y}_\perp)$$

color charge surface density

$$\mu = g^{-4}Q_s^2$$

Projected Woods-Saxon distribution

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

System uniform in the transverse plane

$$B^{ij}_{ab}(\mathbf{x}_\perp,\mathbf{y}_\perp) = \delta^{ab} f^{ij}(\mathbf{x}_\perp-\mathbf{y}_\perp) = \delta^{ab} f^{ij}(\mathbf{r})$$

$$\begin{cases}\mathbf{R} = \frac{1}{2}(\mathbf{x}_\perp+\mathbf{y}_\perp)\\ \mathbf{r} = \mathbf{x}_\perp-\mathbf{y}_\perp\end{cases}$$

System weakly nonuniform in the transverse plane

$$B^{ij}_{ab}(\mathbf{x}_\perp,\mathbf{y}_\perp) = \delta^{ab} f^{ij}(\mathbf{R},\mathbf{r}) \approx \text{``}\textit{gradient expansion in } \mathbf{R}\text{''}$$

G.Chen, R.J. Fries, J.I. Kapusta and Y. Li, Physical Review D **92**, 064912 (2015)

Numerical results

Pb-Pb collisions at LHC

$N_c = 3$

$g = 1$

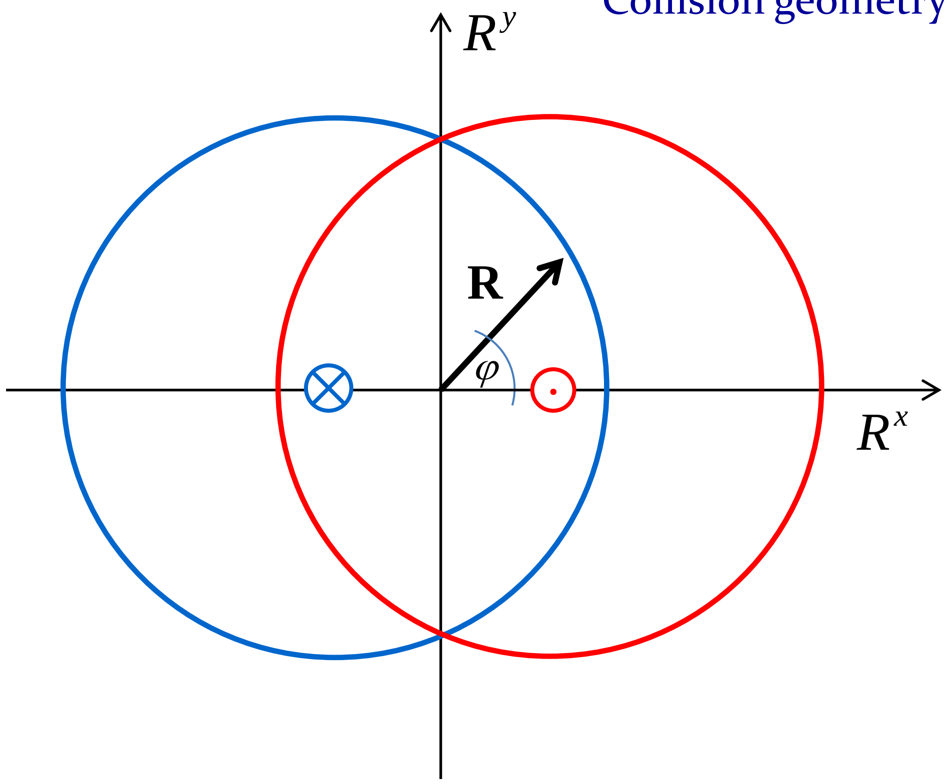
$Q_s = 2 \text{ GeV}$

$m = 0.2 \text{ GeV}$

$R_A = 7.4 \text{ fm}$

$a = 0.5 \text{ fm}$

Collision geometry



M. Carrington, A. Czajka & St. Mrówczyński, European Physical Journal A **58**, 5 (2022)

M. Carrington, A. Czajka & St. Mrówczyński, Physical Review C **106**, 034904 (2022)

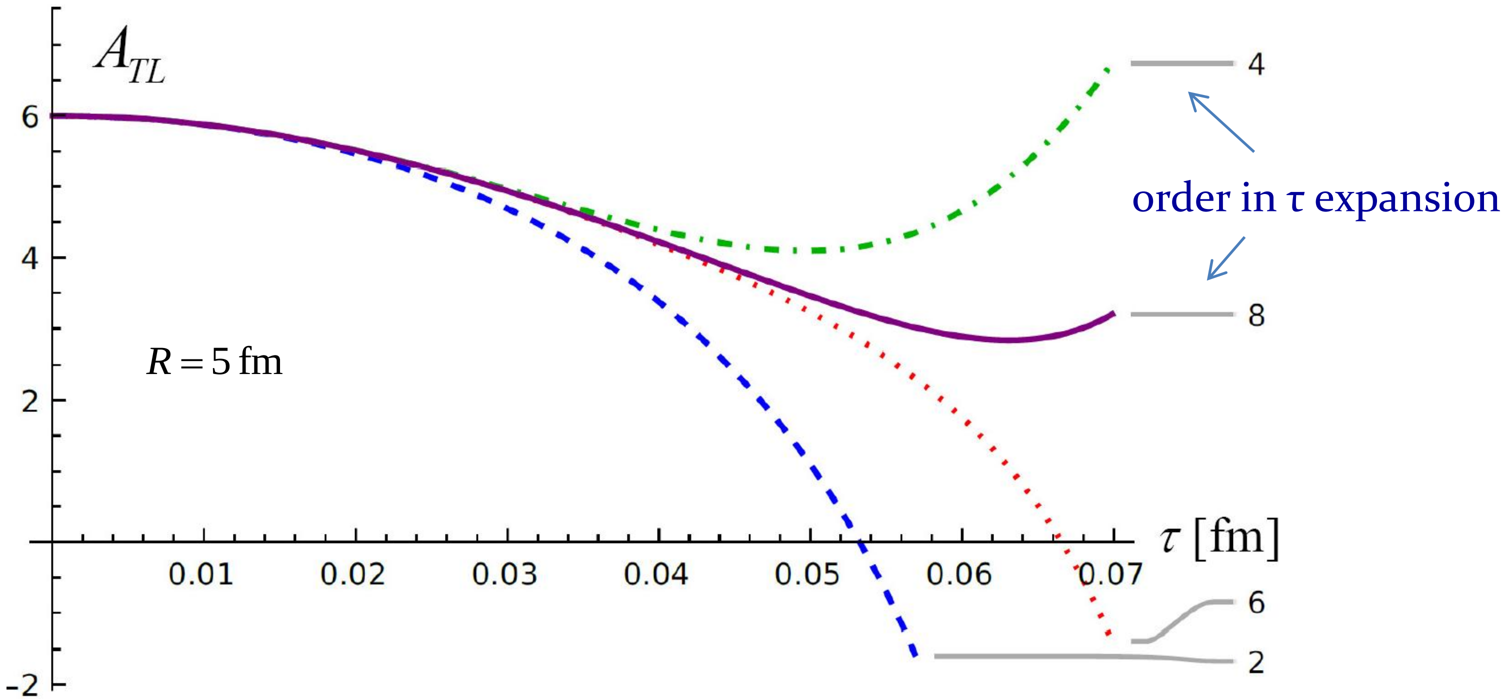
M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Anisotropy

Central Pb-Pb collsions

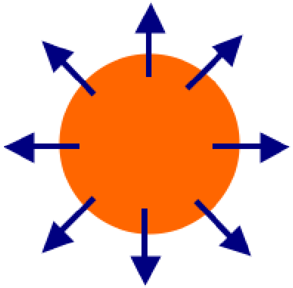
$$A_{TL} \equiv \frac{3(p_T - p_L)}{2p_T + p_L} \qquad p_T \equiv \langle T^{xx} \rangle, \quad p_L \equiv \langle T^{zz} \rangle$$

$$\tau = 0 \quad \Rightarrow \quad p_T = -p_L = \varepsilon \quad \Rightarrow \quad A_{TL} = 6$$



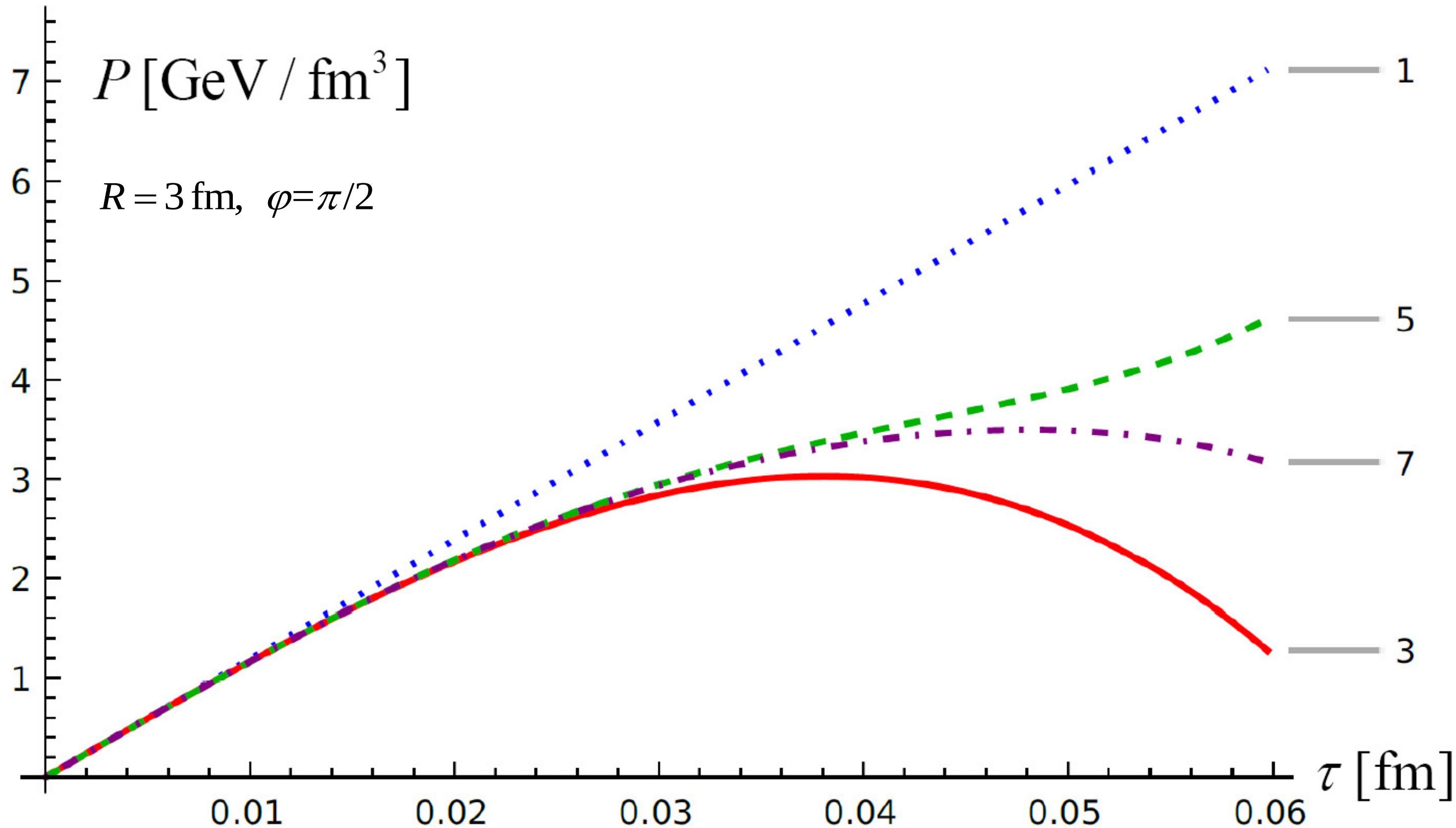
M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Radial flow



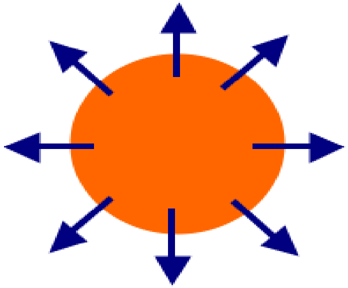
Pb-Pb collisions at b = 6 fm

$$P \equiv R^i T^{0i}$$



M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Radial flow cont.



Pb-Pb collisions at b = 6 fm

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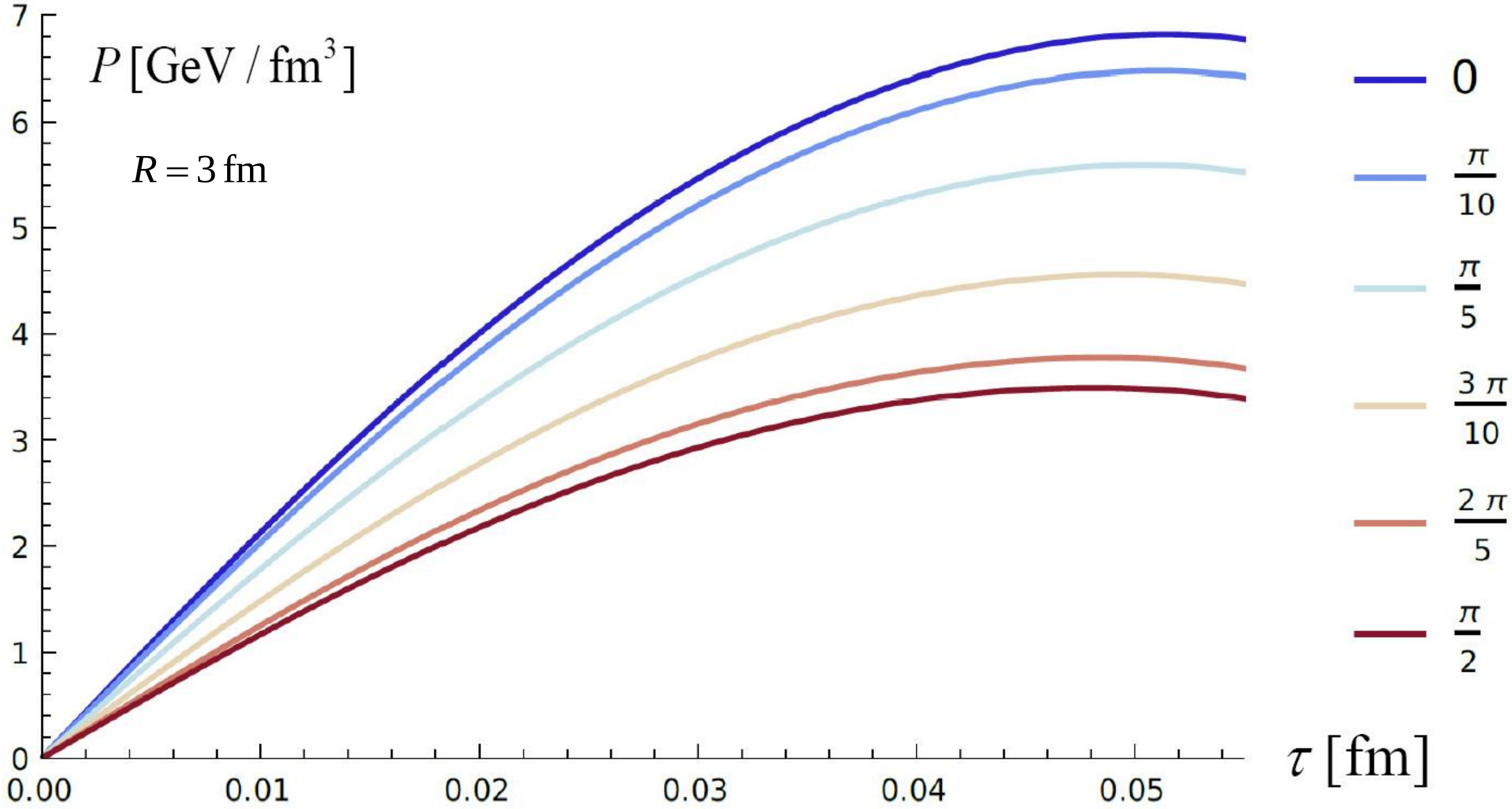
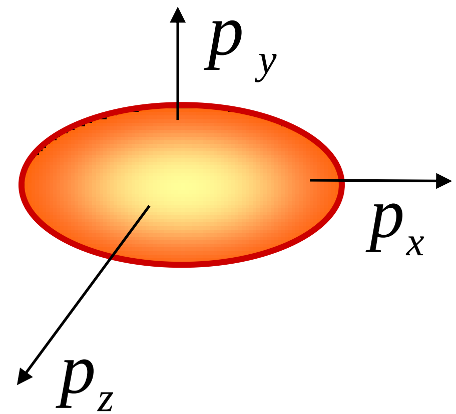


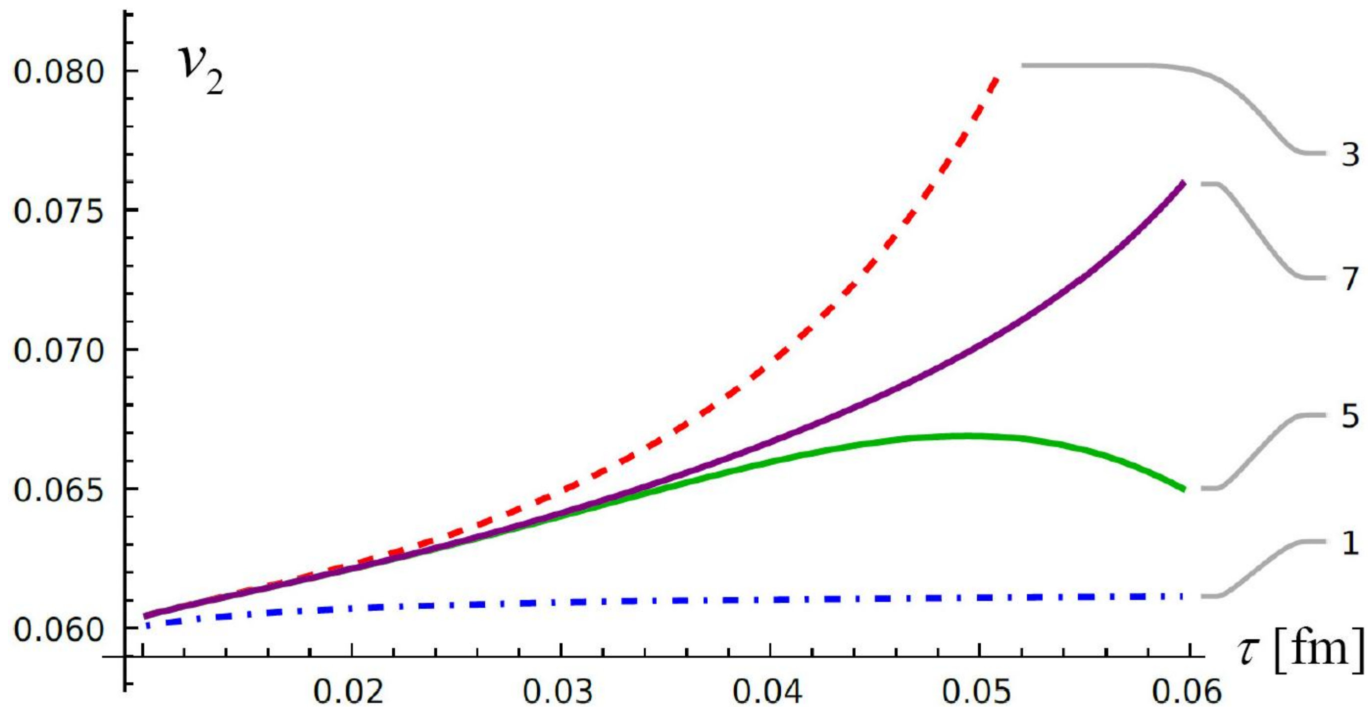
M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Elliptic flow

Pb-Pb collisions at b = 2 fm

$$v_2 = \frac{\int d^2R \, \frac{T_{0x}^2 - T_{0y}^2}{\sqrt{T_{0x}^2 + T_{0y}^2}}}{\int d^2R \sqrt{T_{0x}^2 + T_{0y}^2}}$$



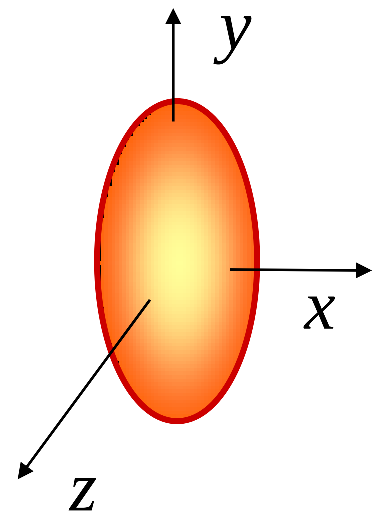


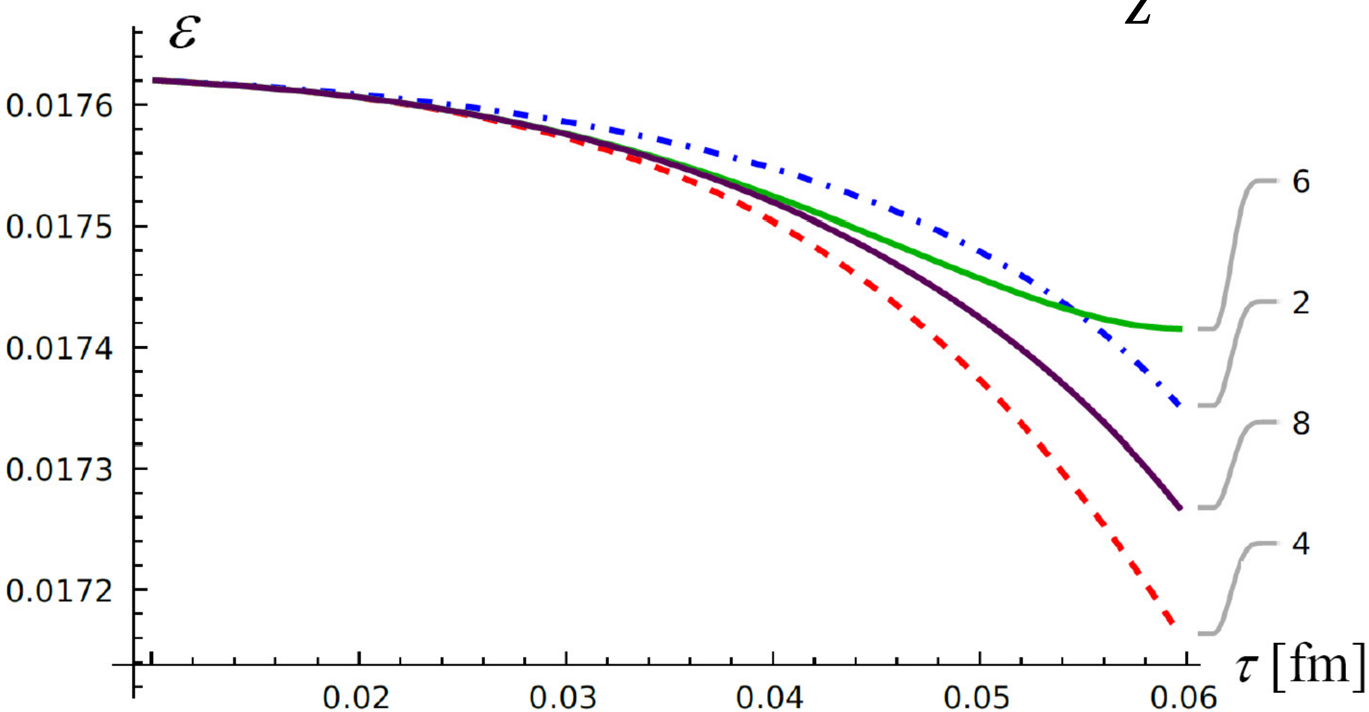
M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Eccentricity

Pb-Pb collisions at b = 2 fm

$$\varepsilon = \frac{\int d^2R \, \frac{R_x^2 - R_y^2}{\sqrt{R_x^2 + R_y^2}} T^{00}}{\int d^2R \sqrt{R_x^2 + R_y^2} \, T^{00}}$$

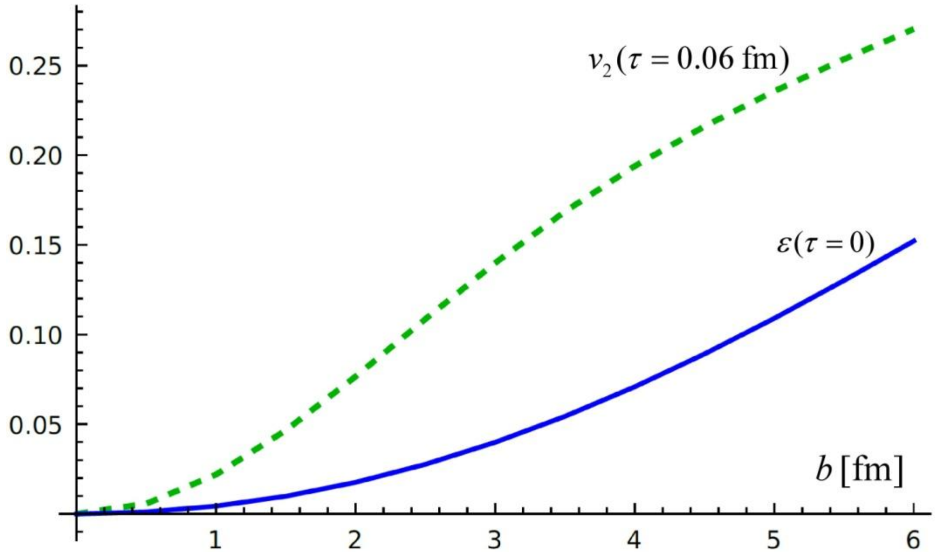


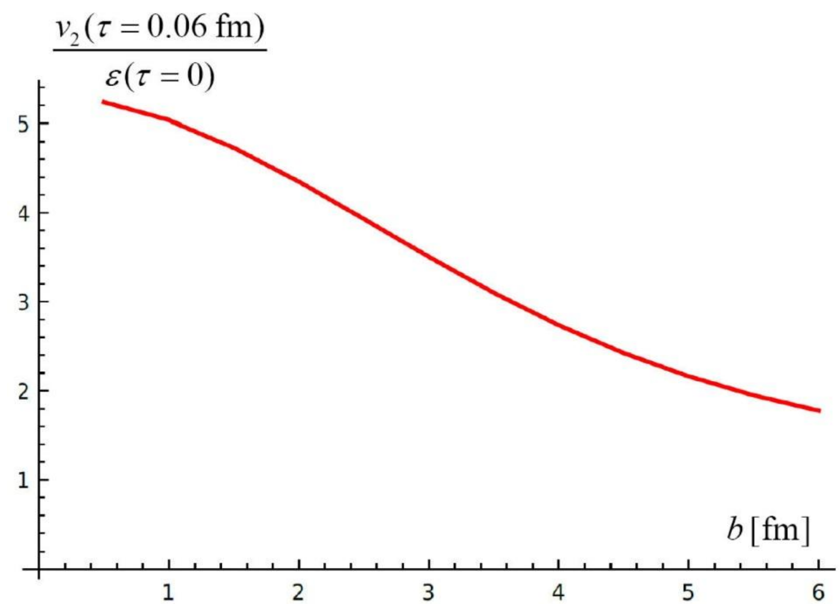


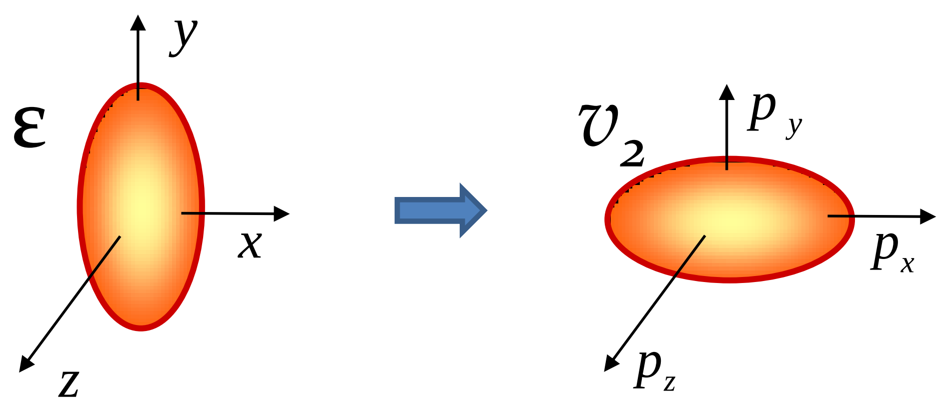
M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Hydrodynamic-like behavior

Pb-Pb collisions

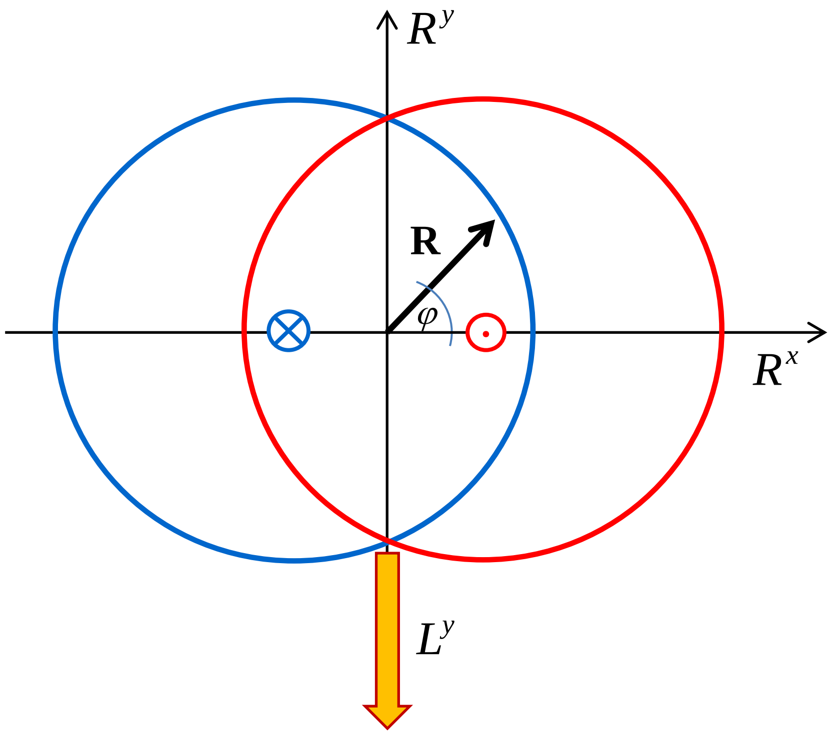


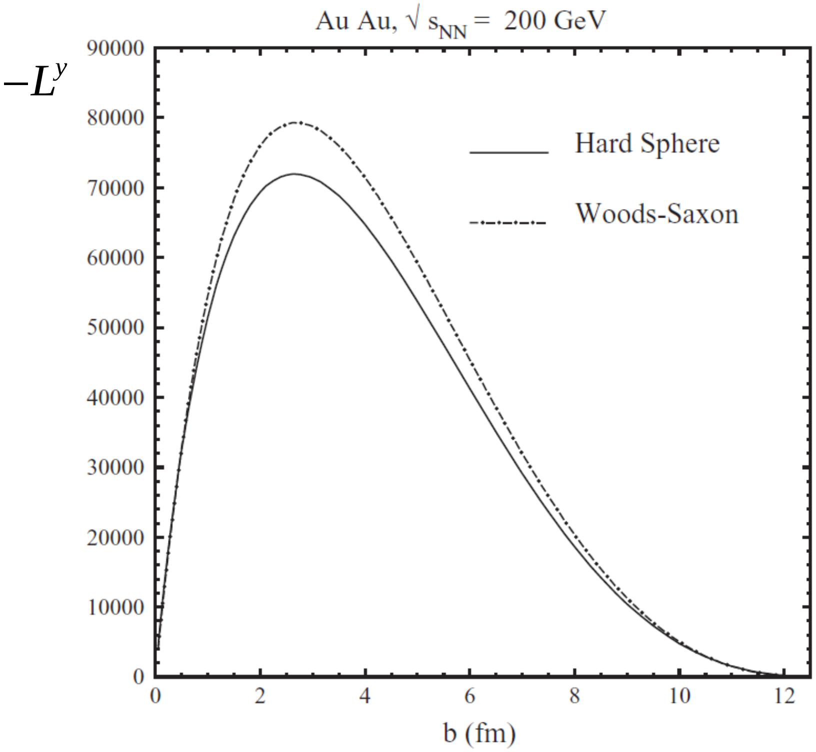




M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Angular momentum





$$L^y \sim 10^7 \hbar \text{ @ LHC } ?$$

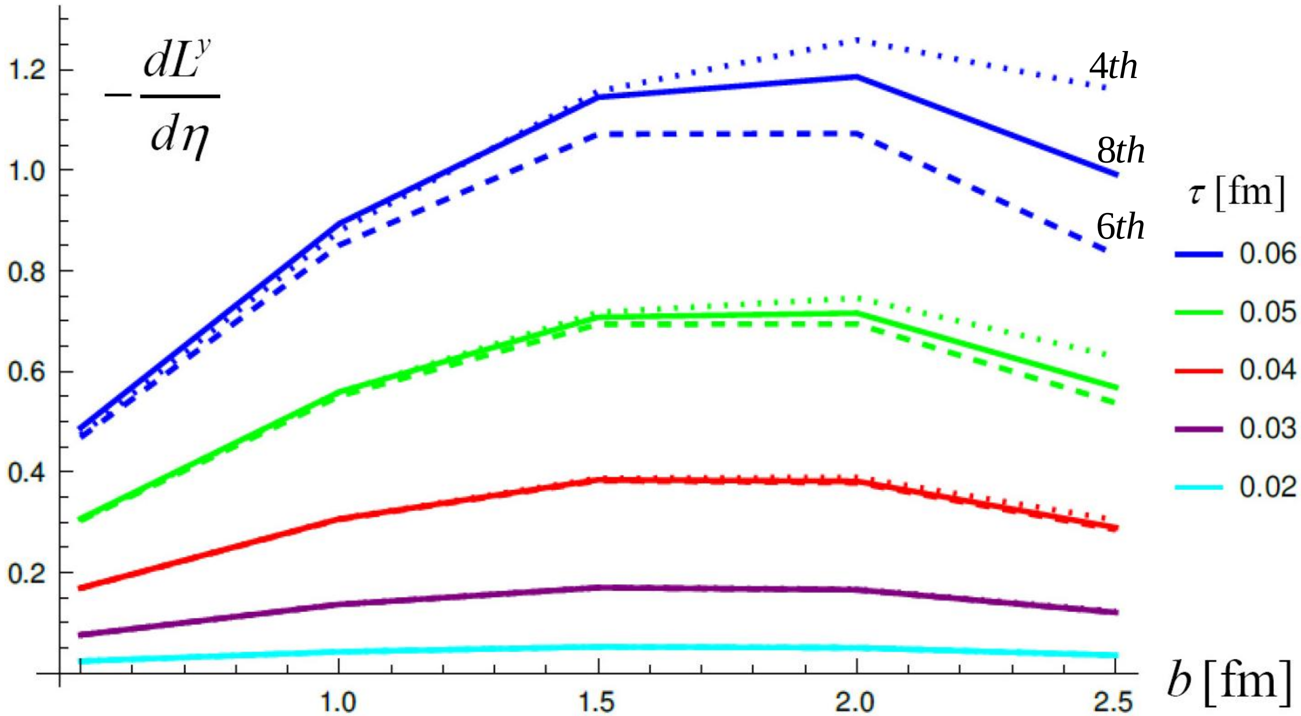
F. Becattini, F.Piccini, J. Rizzo, Physical Review C **77**, 024906 (2008)

Angular momentum cont.

Pb-Pb collisions at b = 2 fm

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

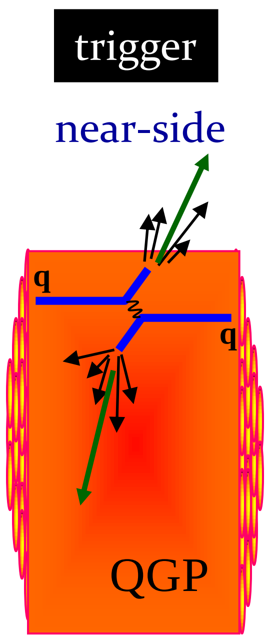
Milne coordinates

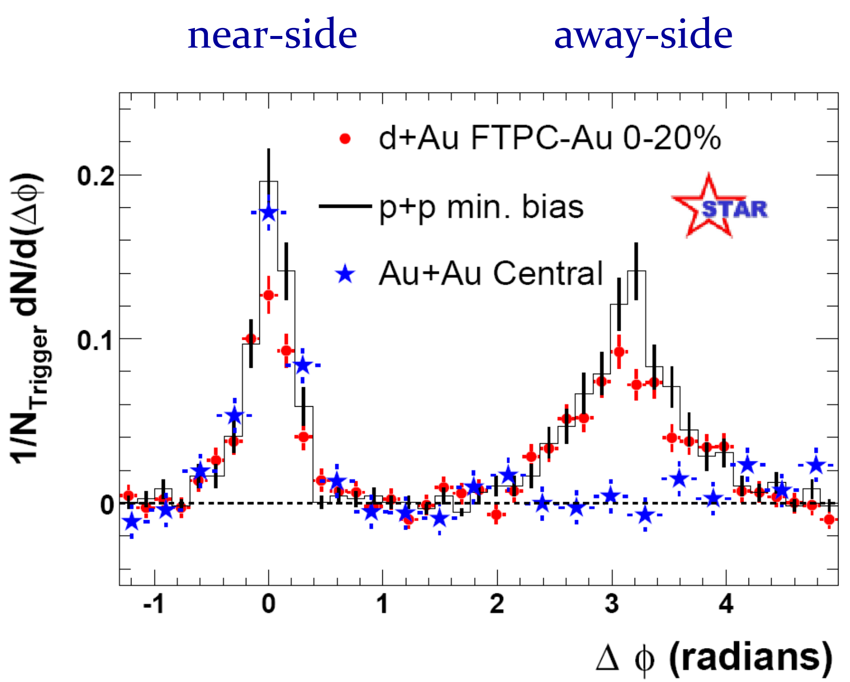


Glasma does not rotate!

M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Jet quenching



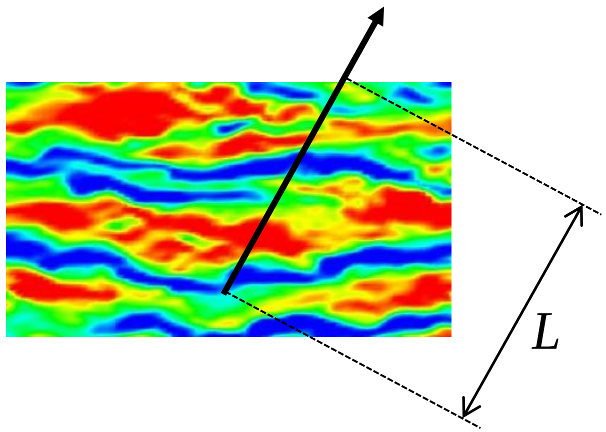


Away-side jet is suppressed
in central collisions!

J. Adams et al. [STAR Collaboration], Nucl. Phys. **A757**, 102 (2005)

Jet quenching in glasma

How hard probes propagate through the glasma?



$$\frac{dE}{dx}, \ \hat{q} \ ?$$

$\frac{dE}{dx}$ - collisional energy loss

$\hat{q}$ - transverse momentum broadening

$$\frac{dE^{\mathrm{rad}}}{dx} = -\frac{1}{8}\alpha_s N_c \hat{q} L$$ - radiative energy loss

St. Mrówczyński, European Physical Journal A **54**, 43 (2018)

M. Carrington, A. Czajka & St. Mrówczyński, Nuclear Physics A **1001**, 121914 (2020)

M. Carrington, A. Czajka & St. Mrówczyński, Physics Letters B **834**, 137464 (2022)

M. Carrington, A. Czajka & St. Mrówczyński, Physical Review C **105**, 064910 (2022)

M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Fokker-Planck equation

- Transport of hard probes can be described using the Fokker-Planck equation.

$$\underbrace{\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)}_{\text{drift}} n(t,\mathbf{r},\mathbf{p}) = \underbrace{\left(\nabla_p^i X^{ij}(\mathbf{v})\nabla_p^j + \nabla_p^i Y^i(\mathbf{v})\right)}_{\text{collisions}} n(t,\mathbf{r},\mathbf{p})$$

$n(t,\mathbf{r},\mathbf{p})$ - distribution function of hard probes $\qquad \mathbf{v}\equiv\frac{\mathbf{p}}{E_{\mathbf{p}}}, \quad \nabla_p^i \equiv \frac{\partial}{\partial p_i}$

$$X^{ij}(\mathbf{v}),\ Y^i(\mathbf{v}) \quad \Rightarrow \quad \begin{cases} \dfrac{dE}{dx} = -\dfrac{\mathrm{v}^i}{\mathrm{v}} Y^i(\mathbf{v}) & \text{collisional energy loss} \\ \hat{q} = \dfrac{2}{\mathrm{v}}\left(\delta^{ij} - \dfrac{\mathrm{v}^i \mathrm{v}^j}{\mathrm{v}^2}\right) X^{ji}(\mathbf{v}) & \text{momentum broadening} \end{cases}$$

$$n(t,\mathbf{r},\mathbf{p}) = n_{\mathrm{eq}}(\mathbf{p}) \sim e^{-\frac{E_{\mathbf{p}}}{T}} \quad \Leftrightarrow \quad \boxed{Y^j(\mathbf{v}) = \frac{\mathrm{v}^i}{T} X^{ij}(\mathbf{v})}$$

solves FK equation

Fokker-Planck equation cont.

Boltzmann equation

Diffusive approximation

$$p >> \Delta p$$

p – momentum of a hard probe

Δp – momentum transfer in a single collision

$\Downarrow$

Fokker-Planck equation

- A Fokker-Planck equation for glasma can be derived using the *quasilinear* method known in plasma physics.

Fokker-Planck equation of a hard probe in glasma

- Lorentz force $\mathbf{F} \equiv g\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$

- $$\left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla\right) n(t,\mathbf{r},\mathbf{p}) = \left(\nabla_p^i X^{ij}(\mathbf{v}) \nabla_p^j + \nabla_p^i Y^i(\mathbf{v})\right) n(t,\mathbf{r},\mathbf{p})$$

- $$X^{ij}(\mathbf{v}) = \frac{1}{N_c} \int_0^t dt' \left\langle F^i(t,\mathbf{r}) F^j(t',\mathbf{r} - \mathbf{v}(t-t'))\right\rangle, \qquad Y^j(\mathbf{v}) = \frac{\mathrm{v}^i}{T} X^{ij}(\mathbf{v})$$

- The collision term is given by field correlators $\left\langle E^i E^j \right\rangle, \left\langle B^i E^j \right\rangle, \left\langle B^i B^j \right\rangle$

- Gauge covariance requires: $\left\langle E_a^i(t,\mathbf{r}) E_a^j(t',\mathbf{r}')\right\rangle \;\to\; \left\langle E_a^i(t,\mathbf{r})\, \Omega_{ab}(t,\mathbf{r} \,|\, t',\mathbf{r}')\, E_b^j(t',\mathbf{r}')\right\rangle$

$$\Omega(t,\mathbf{r} \,|\, t',\mathbf{r}') \equiv P \exp\left[ig \int_{(t',\mathbf{r}')}^{(t,\mathbf{r})} ds_\mu A^\mu(s) \right]$$

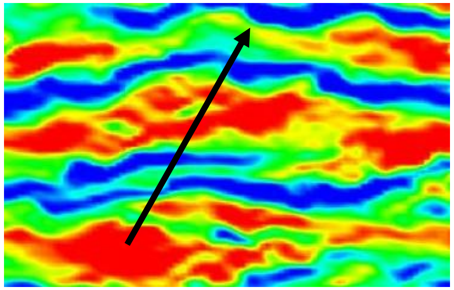
St. Mrówczyński, European Physical Journal A **54**, 43 (2018)

Transport of hard probes in glasma

$$\boxed{\begin{aligned} X^{ij}(\mathbf{v}) = \frac{g}{N_c}\int_0^t dt' \Big\{ \big\langle E^i(t,\mathbf{r}) E^j(t',\mathbf{r}')) \big\rangle + \varepsilon^{jkl} \mathrm{v}^k \big\langle E^i(t,\mathbf{r}) B^l(t',\mathbf{r}')) \big\rangle \\ + \varepsilon^{ikl} \mathrm{v}^k \big\langle B^l(t,\mathbf{r}) E^j(t',\mathbf{r}')) \big\rangle + \varepsilon^{ikl}\varepsilon^{jmn} \mathrm{v}^k \mathrm{v}^m \big\langle B^l(t,\mathbf{r}) B^n(t',\mathbf{r}')) \big\rangle \Big\} \end{aligned}}$$

$$\mathbf{r}' \equiv \mathbf{r} - \mathbf{v}(t - t')$$

$$\begin{cases} \hat{q} = \dfrac{2}{\mathrm{v}}\left(\delta^{ij} - \dfrac{\mathrm{v}^i \mathrm{v}^j}{\mathrm{v}^2} \right) X^{ji}(\mathbf{v}) \\[2ex] \dfrac{dE}{dx} = -\dfrac{\mathrm{v}^i \mathrm{v}^j}{\mathrm{v}T} X^{ij}(\mathbf{v}) \end{cases}$$



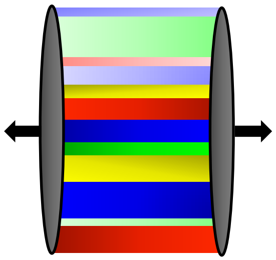
St. Mrówczyński, European Physical Journal A **54**, 43 (2018)

Rough estimate

Density of energy accumulated in the fields

$$\varepsilon_{\text{field}} = \frac{1}{2}\Big(\big\langle E_a^i E_a^i \big\rangle + \big\langle B_a^i B_a^i \big\rangle\Big)$$

E & *B* fields along the axis *z*



Density of energy released in a central collision

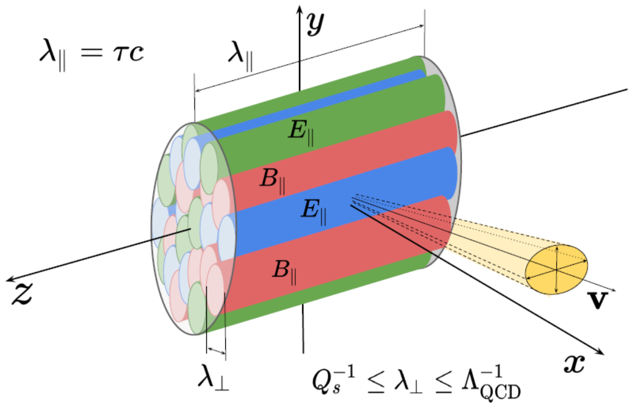
$$\varepsilon_{\text{coll}} = \frac{c_{\text{inel}} A\sqrt{s}}{\pi R_A^2 l}$$

$$\varepsilon_{\text{coll}} = \varepsilon_{\text{field}} \Longrightarrow \begin{cases} -\dfrac{dE}{dx} \sim (0 \div 10) \quad \left[\dfrac{\text{GeV}}{\text{fm}}\right] \\ \hat{q} \sim 10 \quad \left[\dfrac{\text{GeV}^2}{\text{fm}}\right] \end{cases}$$

$$c_{\text{inel}} = 0.5, \quad A = 200, \quad \sqrt{s} = 5\,\text{TeV}, \quad l = 1\,\text{fm}$$

St. Mrówczyński, European Physical Journal A **54**, 43 (2018)

Hard probes in glasma - $\hat{q}$



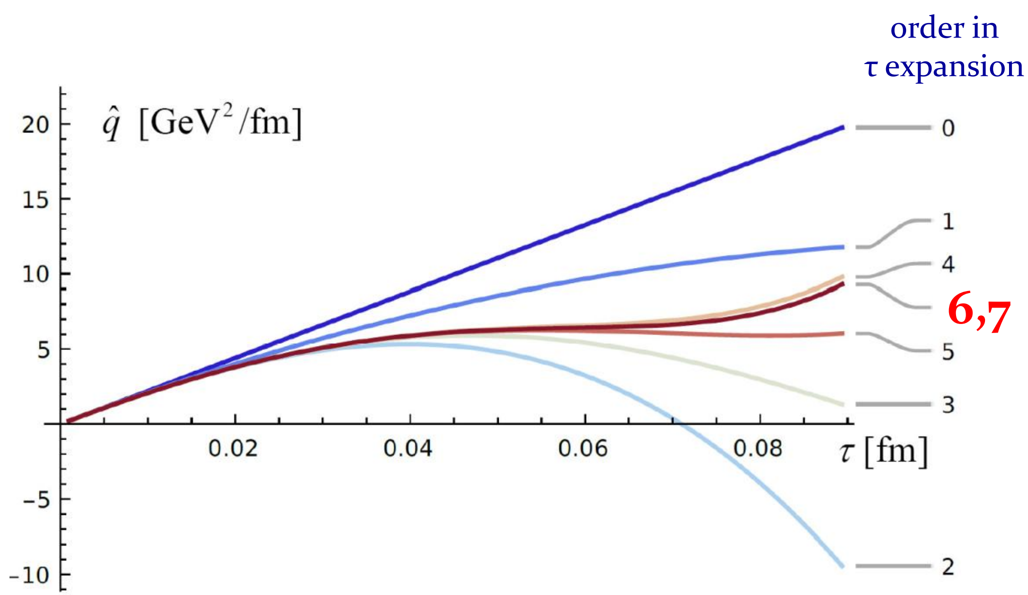
$$\hat{q} = \frac{2}{\mathbf{v}}\left(\delta^{ij} - \frac{\mathbf{v}^i\mathbf{v}^j}{\mathbf{v}^2}\right)X^{ji}(\mathbf{v})$$

$N_c = 3, \quad g = 1$

$Q_s = 2$ GeV

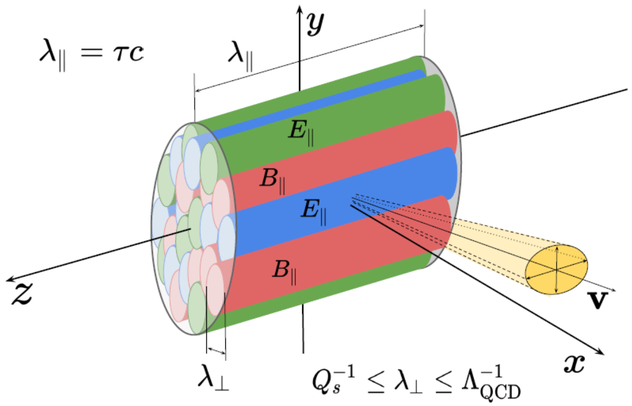
$m = 0.2$ GeV

$\mathrm{v} = \mathrm{v}_\perp = 1$

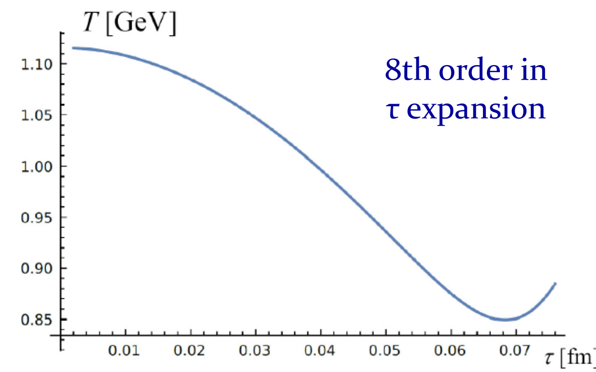


M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Hard probes in glasma - $\frac{dE}{dx}$



$$\frac{dE}{dx} = -\frac{1}{T}\frac{v^i v^i}{v} X^{ij}(\mathbf{v})$$

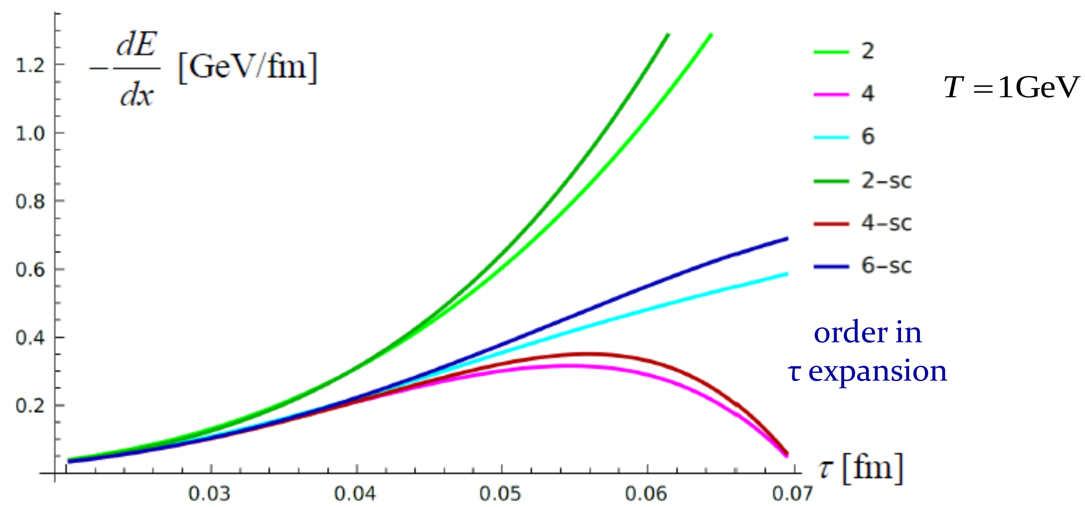


$N_c = 3, \quad g = 1$

$Q_s = 2$ GeV

$m = 0.2$ GeV

$v = v_\perp = 1$



M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, Phys. Rev. C **108**, 054903 (2023)

Glasma impact on jet quenching

Glasma

$\hat{q}_{\max} = 6 \ \text{GeV}^2 / \text{fm}$

$t_{\max} = 0.06 \ \text{fm}$

Equilibrium QGP

$\hat{q} = 3T^3$

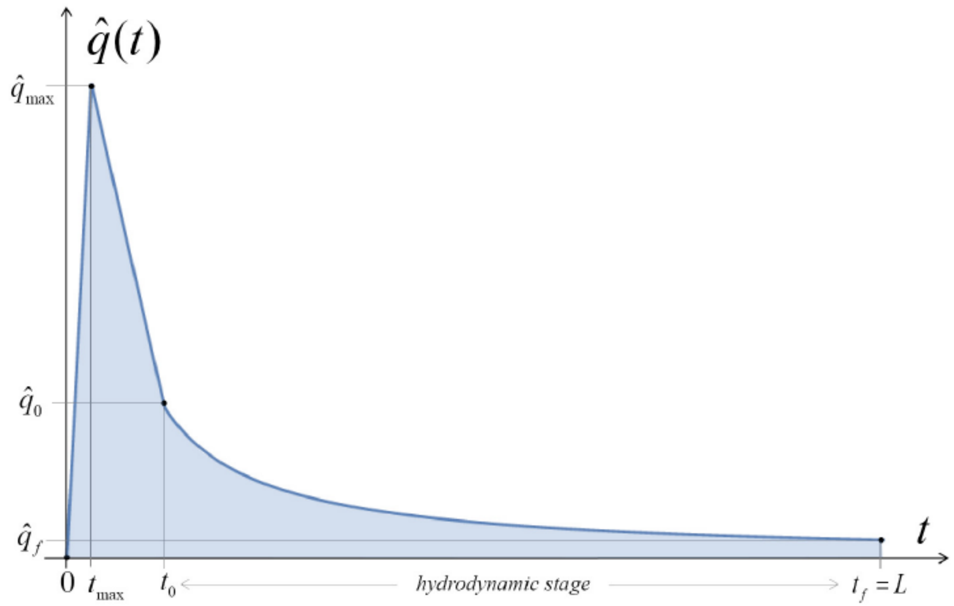
$t_0 = 0.6 \ \text{fm}$

$T_0 = 450 \ \text{MeV}$

$\hat{q}_0 = 1.4 \ \text{GeV}^2 / \text{fm}$

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

$L = 10 \ \text{fm}$



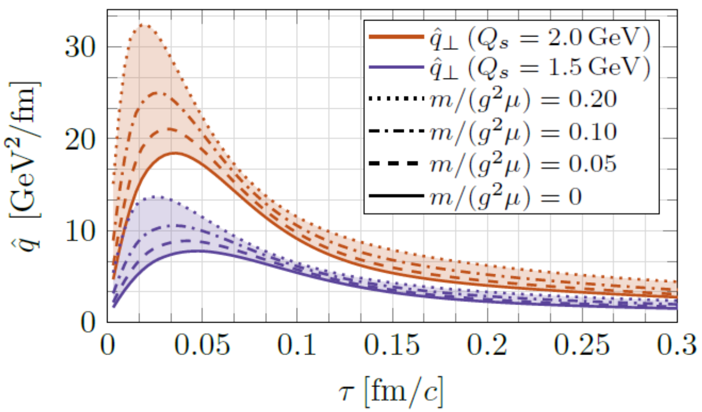
$$\Delta p_T^2 \Big|^{\text{non-eq}} = \int_0^{t_0} dt \, \hat{q}(t)$$

$$\Delta p_T^2 \Big|^{\text{eq}} = \int_{t_0}^{L} dt \, \hat{q}(t)$$

$$\frac{\Delta p_T^2 \Big|^{\text{non-eq}}}{\Delta p_T^2 \Big|^{\text{eq}}} = 0.93$$

S. Cao et al. [JETSCAPE], Physical Review C **104**, 024905 (2021),
C. Shen, U. Heinz, P. Huovinen and H. Song, Physical Review C **84**, 044903 (2011).

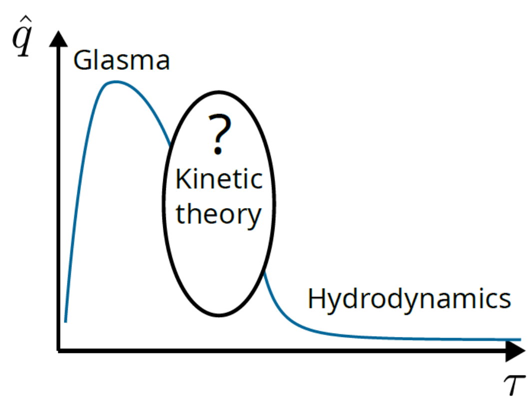
Glasma impact on jet quenching cont.



Full simulations of glasma

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

D. Avramescu, V. Băran, V. Greco, A. Ipp, D.I. Műller & M.Ruggieri, Phys. Rev. D **107**, 114021 (2023)



Kinetic theory interpolates between glasma and equilibrium QGP

K. Boguslavski, A. Kurkela, T.Lappi, F. Lindenbauer & J.Peuron, arXiv:2303.12595

Conclusions

- The glasma evolves in a hydrodynamic-like way.
- The glasma's orbital momentum is small,
  the system does not rotate.
- Momentum broadening and energy loss in the glasma
  are significantly bigger than in equilibrated QGP.
- In spite of its short lifetime the glasma provides
  a significant contribution to the jet quenching.