Determining QCD matter viscosity from fluid dynamics with saturated minijet initial conditions in ultrarelativistic A+A collisions

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Paatelainen, et al, **Phys. Rev.** C87 044904 (2013)
Paatelainen, et al, **Phys. Lett.** B731 (2014)
Niemi, et al, work in progress

At ultrarelativistic energies semihard partons, gluon minijets, dominate particle production in A+A collisions

Calculational tools:

- Perturbative QCD
  - QCD parton scattering processes
    - ($2 \rightarrow 2$) LO & NLO
    - ($2 \rightarrow 3$) NLO
- Collinear factorization
  - Nuclear parton distribution functions (nPDFs)
- Gluon saturation
  - There exists a semihard scale (p_{sat}) controlling the particle production in the collision

Our goal:

Compute initial conditions for hydrodynamical evolution in A+A collisions from saturated minijet production

We compute the E_T production of minijets in A+A and Δy

$$\frac{\mathrm{d}E_T(p_0, \sqrt{s}, \Delta y, \mathbf{s}, \mathbf{b})}{\mathrm{d}^2\mathbf{s}} = T_A(\mathbf{s}+\mathbf{b}/2)T_A(\mathbf{s}-\mathbf{b}/2)\sigma\langle E_T\rangle_{p_0,\Delta y}$$

s = transverse position, **b** = impact parameter

- $T_A T_A$ accounts for the nuclear collision geometry (WS density)
- NLO cross section $\sigma\langle E_T\rangle_{p_0,\Delta y}$ for minijet E_T

$$\sigma\langle E_T\rangle_{p_0,\Delta y} = \frac{1}{2!}\int \mathrm{d}[\mathrm{PS}]_2 \frac{\mathrm{d}\sigma^{2\to 2}}{\mathrm{d}[\mathrm{PS}]_2} S_2 + \frac{1}{3!}\int \mathrm{d}[\mathrm{PS}]_3 \frac{\mathrm{d}\sigma^{2\to 3}}{\mathrm{d}[\mathrm{PS}]_3} S_3$$

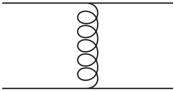
Differential partonic cross section at NLO

Collinear factorization, A+A collisions

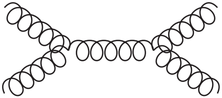
$$\frac{\mathrm{d}\sigma^{2\to n}}{\mathrm{d}[\mathrm{PS}]_{\mathrm{n}}} \sim \sum_{g,q,\bar{q}} f_{i/A}(x_1, Q^2, \mathbf{s}) \otimes f_{j/B}(x_2, Q^2, \mathbf{s}) \otimes |\mathcal{M}|^2$$

In LO we need:

- $|\mathcal{M}|^2(2 \to 2)$ for QCD parton processes $\mathcal{O}(\alpha_s^2)$



$qq' \to qq'$

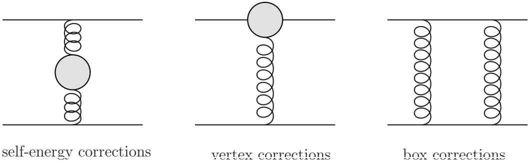


$gg \to gg$

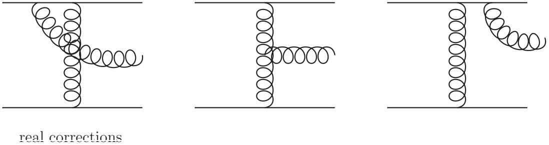
etc, ...

In NLO we need:

- $|\mathcal{M}|^2(2 \to 2)$ virtual corrections $\mathcal{O}(\alpha_s^3)$



- $|\mathcal{M}|^2(2 \to 3)$ real corrections $\mathcal{O}(\alpha_s^3)$



- UV renormalized $|M|^2$ in $4 - 2\epsilon$ dimensions
  [R.K Ellis & Sexton; My PhD thesis]

- IR/CL divergencies handled with NLO def. of PDFs & Ellis-Kunszt-Soper subtraction method

PDFs for each parton flavor i $(= g, q, \bar{q})$

$$f_{i/A}(x, Q^2, \mathbf{s}) \equiv R_i^A(x, Q^2, \mathbf{s}) f_i^p(x, Q^2)$$

R_i^A denotes the nuclear modification to the free proton PDF f_i^p

- f_i^p: CTEQ6 NLO parton densities
- R_i^A: EPS09s (**s** dependent) NLO nuclear modifications

EPS09s [Helenius, Eskola et al. JHEP (2012) 073]

Also, in the NLO cross section for minijets

$$\sigma\langle E_T\rangle_{p_0,\Delta y} = \frac{1}{2!}\int \mathrm{d}[\mathrm{PS}]_2 \frac{\mathrm{d}\sigma^{2\to 2}}{\mathrm{d}[\mathrm{PS}]_2} S_2 + \frac{1}{3!}\int \mathrm{d}[\mathrm{PS}]_3 \frac{\mathrm{d}\sigma^{2\to 3}}{\mathrm{d}[\mathrm{PS}]_3} S_3$$

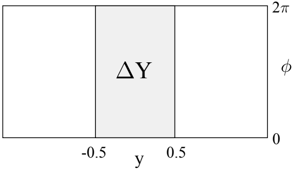
- Measurement functions S_2 and S_3 analogous to jet definition
- The measurement functions S_2 and S_3 fulfil the IR/CL safetines criteria: $S_3 \xrightarrow{IR,CL} S_2$

$\Rightarrow \sigma\langle E_T\rangle_{p_0,\Delta y}$ is a well defined IR/CL safe quantity

The measurement functions

$$S_n = E_{T,n} \times \Theta\left(\sum_{i=1}^{n=2,3} p_{T,i} \geq 2p_0\right) \times \Theta(E_{T,n} \geq \beta \times p_0)$$

- Rapidity acceptance Δy

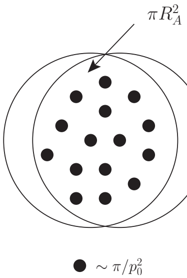


- Minijets E_T in Δy: $E_{T,n} = \sum_{i=1}^{n} p_{T,i}\Theta(y_i \in \Delta y)$
  - 1,2 or 3 minijets in Δy
- Hard scattering of partons
- Minimum amount of $E_{T,3} \geq \beta p_0$ in Δy
  - any $\beta \in [0, 1]$ IR/CL-safe

Minijet saturation in N_g

Geometrical gluon saturation

- original EKRT model [Eskola, Kajantie, Ruuskanen, Tuominen, NPB 570 (2000)]



- saturation of N_g when

$$N_g(p_0) \times \frac{\pi}{p_0^2} \sim \pi R_A^2, \qquad N_g \text{ is not IR/CL-safe!}$$

NEW: Saturation in minijet E_T production

$$\frac{dE_T}{\mathrm{d}^2\mathbf{s}\mathrm{d}y}(2 \to 2) \sim \frac{dE_T}{\mathrm{d}^2\mathbf{s}\mathrm{d}y}(3 \to 2)$$

- Using scaling law arguments:

$$(T_A g_A)^2 \frac{\alpha_s^2}{p_0} \sim (T_A g_A)^3 \left(\frac{\alpha_s}{p_0}\right)^3 \Rightarrow T_A g_A \sim \frac{p_{sat}^2}{\alpha_s} \Rightarrow \frac{dE_T}{\mathrm{d}^2\mathbf{s}\mathrm{d}y} \sim p_0^3$$

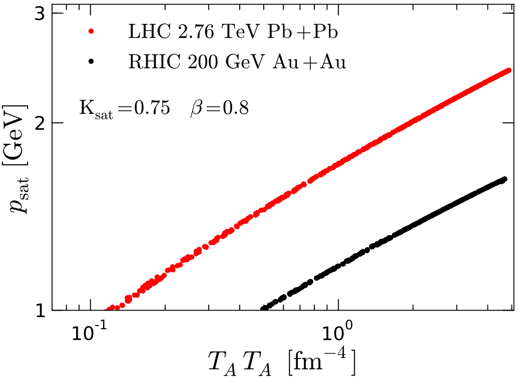
We obtain a saturation criterion for E_T (IR/CL safe)

$$\underbrace{\frac{\mathrm{d}E_T}{\mathrm{d}^2\mathbf{s}}(p_0, \sqrt{s}, ..., \beta)}_{= \text{NLO pQCD part}} = \left(\frac{K_{\mathrm{sat}}}{\pi}\right) p_0^3 \Delta y$$

and the saturation scale

$$\Rightarrow p_0 = p_{\mathrm{sat}}(\sqrt{s_{NN}}, A, \mathbf{b}, \mathbf{s}; \beta, K_{\mathrm{sat}})$$

Solve the saturation equation for $p_{\text{sat}}(\mathbf{b}, \mathbf{s})$ at different $\mathbf{b}$



- Observation: $p_{\text{sat}}(\mathbf{b}, \mathbf{s}) \propto [T_A(\mathbf{s} + \mathbf{b}/2)T_A(\mathbf{s} - \mathbf{b}/2)]^n$
- $p_{\text{sat}}(\mathbf{b}, \mathbf{s})$ can be parameterized!

Minijet initial conditions for hydro (3 steps)

step 1: Saturation scale $p_{\text{sat}}(\mathbf{s})$ gives:

- transverse profile of initial energy density $\epsilon(\mathbf{s}, \tau_{\text{sat}})$ at time $\tau_{\text{sat}} = 1/p_{\text{sat}}(\mathbf{s})$

$$\epsilon(\mathbf{s}, \tau_{\text{sat}}) = \frac{\mathrm{d}E_T(p_{\text{sat}}, \ldots, \beta)}{\mathrm{d}^2\mathbf{s}} \frac{1}{\tau_{\text{sat}}(\mathbf{s})\Delta y} = \frac{K_{\text{sat}}}{\pi} p_{\text{sat}}(\mathbf{s})^4$$

At this level two unknown parameters:

- K_{sat} in saturation condition $\sim \mathcal{O}(1)$
- $\beta \in [0, 1]$ in the def. of E_T measurement functions

step 2: Hydrodynamics needs $\epsilon(\mathbf{s}, \tau_0)$ at fixed proper time τ_0.

- We need prethermal evolution for $\tau_{\text{sat}} \to \tau_0$:

Free streaming (FS): conserves E_T

$$\epsilon(\mathbf{s}, \tau_0) = \epsilon(\tau_{\text{sat}} = 1/p_{\text{sat}}) \left(\frac{\tau_{\text{sat}}}{\tau_0} \right)$$

Bjorken scaling (BJ): conserves entropy

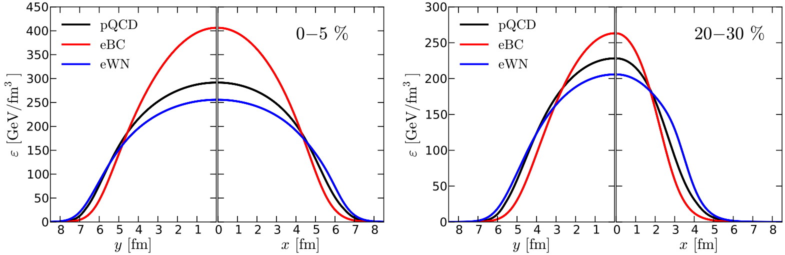
$$\epsilon(\mathbf{s}, \tau_0) = \epsilon(\tau_{\text{sat}} = 1/p_{\text{sat}}) \left(\frac{\tau_{\text{sat}}}{\tau_0} \right)^{4/3}$$

- $\tau_0 = 1/p_{\text{sat}}^{\text{min}} = 0.2$ fm $\quad (p_{\text{sat}}^{\text{min}} = 1 \text{ GeV} \gg \Lambda_{\text{QCD}})$

STEP 3: Saturation calculation extends only to

$$\epsilon_{\text{min}} = \left(\frac{K_{\text{sat}}}{\pi}\right) p_{\text{sat}}^{\text{min}}(\mathbf{s})^4$$

- Smoothly connect the computed ϵ-profile to $\epsilon \propto \rho_{\text{bin}}$ at the edge



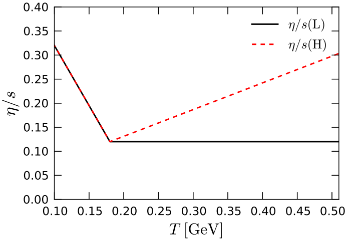
- Here $K_{\text{sat}} = 0.69$, $\beta = 0.9$ & BJ-evolution

Our hydro setup

2+1D relativistic viscous hydrodynamics (H. Niemi et al.)

Inputs:

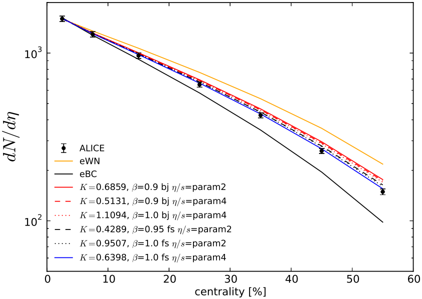
- Minijet initial conditions $\epsilon(\mathbf{s}, \tau_0), \tau_0 = 0.2$ fm
  - initial $\pi^{\mu\nu}$ & $\mathbf{v}_T$ are zero
- EoS: Based on lattice parametrization
  - by Petreczky & Huovinen (s95p-PCE175-v1)
  - freeze-out temperature $T_{\mathrm{f}} = 100$ MeV
- Temperature dependent $\eta/s(T)$ parametrizations:



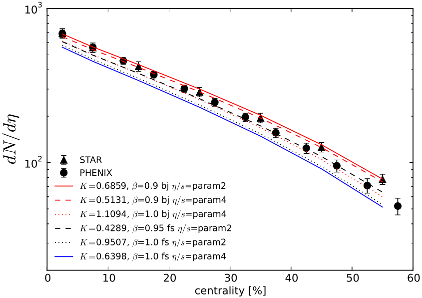
Centrality dependence of multiplicity at LHC & RHIC

- For given $\eta/s(T)$ & FS/BJ choose parameters $(K_{\mathrm{sat}}, \beta)$ such that the most central LHC multiplicity is reproduced

LHC



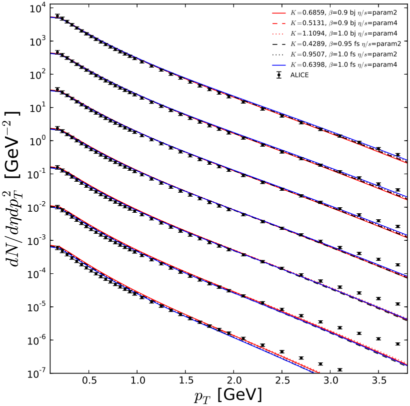
RHIC



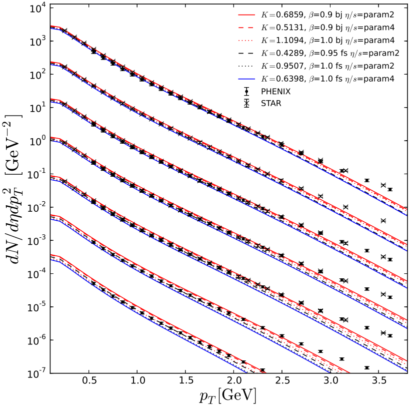
Paatelainen, Eskola, Niemi, Tuominen, PLB 731 (2014)

Charged particle p_T spectra vs centrality

LHC



RHIC

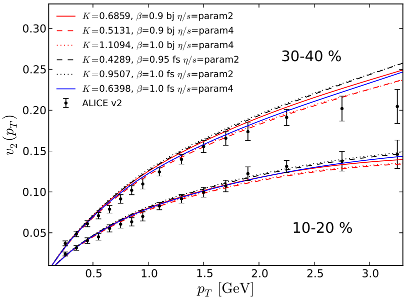


- better shape with PCE 175 MeV than 150 MeV

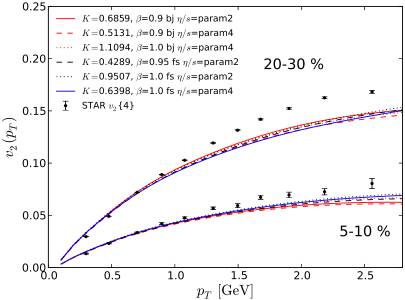
Elliptic flow $v_2(p_T)$

- Note: $\eta/s(T)$ same at RHIC and LHC!

LHC



RHIC



- Conclusion: good simultaneous agreement with low-p_T observables at LHC and RHIC $\Leftrightarrow$ constraints for $\eta/s(T)$

NLO improved EKRT – EbyE framework

Niemi, Eskola, Paatelainen, Tuominen (work in progress)

- Nucleon positions in A: sample WS distribution
- Around each nucleon, set a gluon transverse density

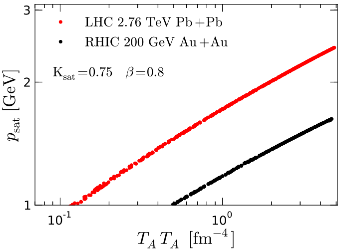
$$T_n(s) = \frac{1}{2\pi\sigma^2} e^{-s^2/2\sigma^2} \quad \text{with} \quad \sigma = 0.43 \text{ fm}$$

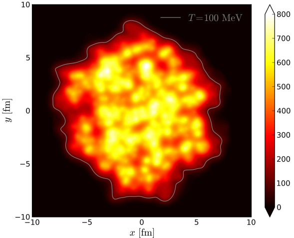
from HERA $\gamma^\star p \to J/\psi + p$ data

⇒ Thickness functions $T_{A1}(x,y)$ & $T_{A2}(x,y)$

⇒ $p_{\rm sat}$ from $p_{\rm sat} = p_{\rm sat}(T_{A1}T_{A2}) \Rightarrow \epsilon(x,y) \sim p_{\rm sat}^4$ like before

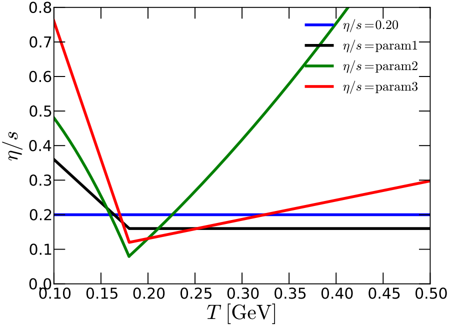
⇒ no need for $\sigma_{NN}^{\rm in}$; collision of gluon clouds



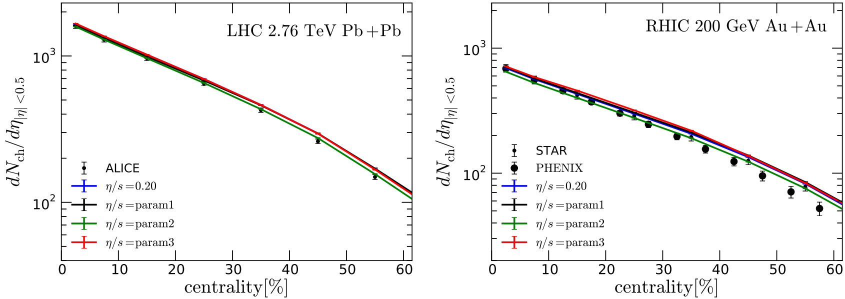


EbyE viscous hydro setup

- 2+1D EbyE viscous hydrodynamics (H. Niemi)
  - EoS: s95p-PCE175-v1
  - Initial $\pi^{\mu\nu}$ & $\mathbf{v}_T$ are zero
- Temperature dependent $\eta/s(T)$ parametrizations:

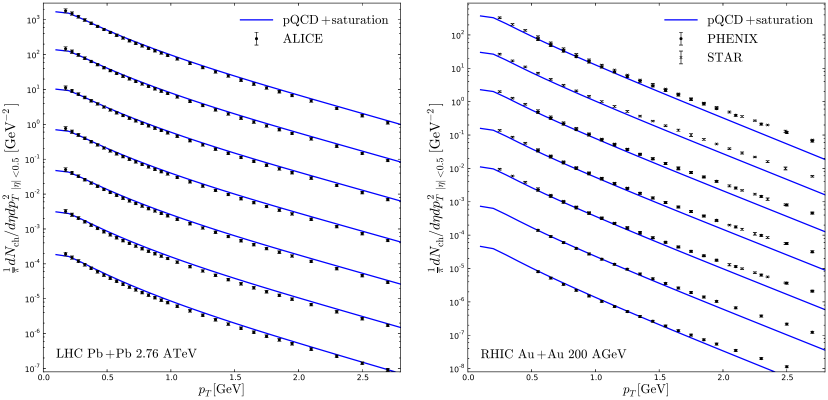


Centrality dependence of multiplicity at LHC & RHIC



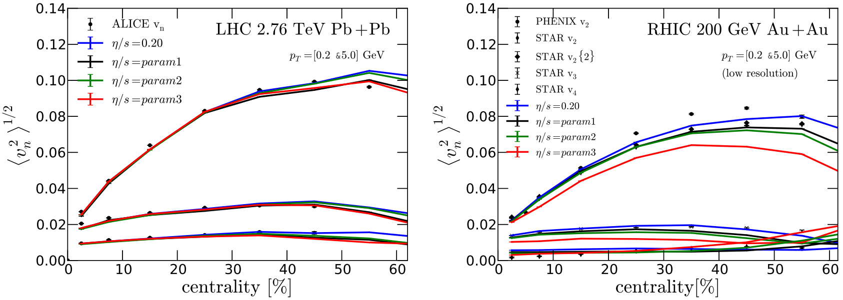
- (K_{sat}, β) fixed to give the most central LHC multiplicity!

Centrality dependence of p_T spectra at RHIC & LHC



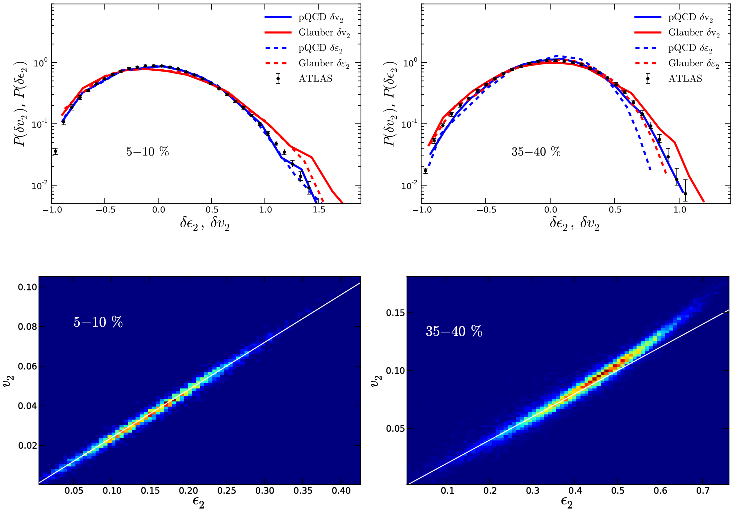
Flow coefficients v_n

- Simultaneous LHC & RHIC analysis constrains $\eta/s(T)$ & IS



- Viscous hydrodynamics is needed to get these right

- EbyE distributions of δv_2 & $\delta \epsilon_2$ at LHC constrain IS:



- nonlinear correlation is due to nonlinearity of hydro (no viscous effect)!
- pQCD + Saturation framework WORKS !

Summary

- Simultaneous, global, analysis of LHC and RHIC bulk observables – such as presented here – is vital (!) for pinning down the shear viscosity of QCD matter
- Our preliminary EbyE results, including the higher harmonics v_n and even their fluctuations, look very promising!
- Our minijet + saturation model presented here offers a useful counterweight to the current color-glass-condensate (small-x, high-$\sqrt{s}$ QCD) calculation of the QGP initial conditions

Back Up Slide:

$$v_n = \left\langle \cos(n(\phi - \Psi_n)) \right\rangle / \left\langle 1 \right\rangle,$$

where

$$\left\langle \cdots \right\rangle = \int \mathrm{d}p_T^2 \mathrm{d}\phi \frac{\mathrm{d}N}{\mathrm{d}y \mathrm{d}\phi \mathrm{d}p_T^2} (\cdots)$$

$$\epsilon_{n,2} = \left\langle \epsilon(\mathbf{s}) r^2 \cos(n(\phi - \Psi_n)) \right\rangle / \left\langle \epsilon(\mathbf{s}) r^2 \right\rangle$$

where

$$\left\langle \cdots \right\rangle = \int \mathrm{d}x \mathrm{d}y (\cdots)$$

For us $\epsilon_{2,2} = \epsilon_2$ and energy density $\epsilon(\mathbf{s})$ from minijet initial conditions.