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

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INTRO

We compute initial conditions for hydrodynamics in $A+A$

- Rigorous NLO pQCD calculation for E_T production from minijets (gluons)
- Saturation for E_T production (analogy to old EKRT model)

Apply viscous hydrodynamics

$\Rightarrow$ $\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}\eta}$, $\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}p_T\mathrm{d}\eta}$ and $v_2(p_T)$ simultaneously at LHC and RHIC

$\Longrightarrow$ Constrain the $\eta/s(T)$

Initial Conditions: Minijet E_T production

Minijet E_T production in $A{+}A$ and Δy

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

$\mathbf{s}$ = transverse position, $\mathbf{b}$ = impact parameter

Ingredients:

- $T_A T_A$ accounts for the nuclear collision geometry
- Collinear factorization, pQCD e.g. at LO

$$\sigma\langle E_T\rangle \propto \int_{p_0^2} \mathrm{d}p_T^2 p_T \int_{\Delta y} \mathrm{d}y_1 \mathrm{d}y_2 \sum_{ijk\ell} \underbrace{x_1 f_{i/A} \otimes x_2 f_{j/A}}_{\text{EPS09s+CTEQ6.1M}} \otimes \underbrace{\frac{\mathrm{d}\sigma^{ijk\ell}}{\mathrm{d}t}}_{\text{pQCD}}$$

Rigorous NLO pQCD computation of $\sigma\langle E_T\rangle$

$$\sigma\langle E_T\rangle = \frac{1}{2!}\int [\mathrm{DPS}]_2 \frac{\mathrm{d}\sigma^{2\to 2}}{[\mathrm{DPS}]_2} \tilde{S}_2(p_1,p_2) + \frac{1}{3!}\int [\mathrm{DPS}]_3 \frac{\mathrm{d}\sigma^{2\to 3}}{[\mathrm{DPS}]_3} \tilde{S}_3(p_1,p_2,p_3)$$

- Partonic $2 \to 2$ and $2 \to 3$ processes for LO & NLO corrections
  - 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
- The measurement functions $\tilde{S}_2$ and $\tilde{S}_3$ fulfil the IR/CL criteria $\Rightarrow$ $\sigma\langle E_T\rangle$ is a well defined IR/CL safe quantity

$$\tilde{S}_2 = \{\epsilon(y_1) + \epsilon(y_2)\} p_{T2}\ \Theta(p_{T2} \geq p_0)$$

$$\tilde{S}_3 = \{\epsilon(y_1) p_{T1} + \epsilon(y_2) p_{T2} + \epsilon(y_3) p_{T3}\}$$

$$\Theta(p_{T1} + p_{T2} + p_{T3} \geq 2p_0)\ \Theta(E_T \geq \beta \times p_0)$$

where $\epsilon(y_i) = 1$ if $y_i \in \Delta y$ otherwise $\epsilon(y_i) = 0$

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- $\tilde{S}_3 \to \tilde{S}_2$ at IR/CL limits

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- $\tilde{S}_3 \to \tilde{S}_2$ at IR/CL limits
- Def. E_T in Δy and $\Theta(\dots)$ hard scattering of partons

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- $\tilde{S}_3 \to \tilde{S}_2$ at IR/CL limits
- Def. E_T in Δy and $\Theta(\dots)$ hard scattering of partons
- $0 \leq \beta \leq 1$ defines the minimum amount of E_T in Δy carried by the partons
- Any $\beta \in [0, 1]$ is IR/CL safe, thus equally good – leave β free

Saturation criterion for E_T

Determine $p_0(\mathbf{s}) = p_{sat}(\mathbf{s})$ from local saturation criterion of E_T:

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

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

$$\frac{\mathrm{d}E_T}{\mathrm{d}^2\mathbf{s}}(p_0, \sqrt{s}, \Delta y, \mathbf{b}, \mathbf{s}, \beta) = \Delta y \left(\frac{K_{sat}}{\pi}\right) p_0^3$$

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

p_{sat} for $A \sim 200$ at LHC ~ 2 GeV and for RHIC ~ 1.3 GeV

HYDRODYNAMICS: 3 STEPS to initialize Hydro

STEP 1: Calculate initial energy density profile e at $\tau_{\rm sat} = 1/p_{\rm sat}(\mathbf{s})$

$$e(\mathbf{s}, \tau_{\rm sat}) = \left(\frac{\mathrm{d}E_T}{\mathrm{d}^2\mathbf{s}}\right) \frac{1}{\tau_{\rm sat}\Delta y} = \frac{K_{\rm sat}}{\pi} p_{\rm sat}(\mathbf{s})^4$$

STEP 2: Hydrodynamics needs $e(\tau_0)$ at fixed proper time τ_0. Prethermal evolution $\tau_{\rm sat} \to \tau_0$:

Free streaming (FS): conserves E_T	or	Bjorken scaling (BJ): conserves entropy

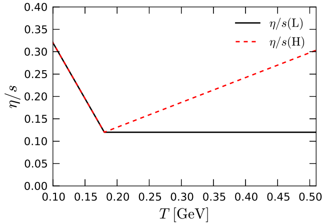
STEP 3: Continuation of $e(\tau_0)$ below $e_{\rm min}(p_{\rm sat} = 1\ \mathrm{GeV})$

Smoothly connect the computed e-profile to $e \propto \rho_{\rm bin}$

HYDRODYNAMICS: Hydro Evolution

2+1D viscous hydro (H. Niemi et al. & Denicol et al, PRD85 114047)

- EoS: Lattice parametrization by Petreczky & Huovinen (s95p-PCE175-v1)
- Hadron Resonance Gas (HRG) up to $m \sim 2\mathrm{GeV}$
- Temperature dependent η/s



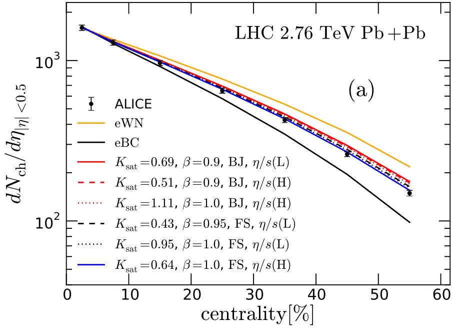
motivation from [H. Niemi et al Phys Rev C 86 014909 (2012)]

- Decoupling temperature $T_f = 100\mathrm{MeV}$
- Initial $\pi^{\mu\nu} = 0$ and $\mathbf{v} = 0$ (flow velocity)

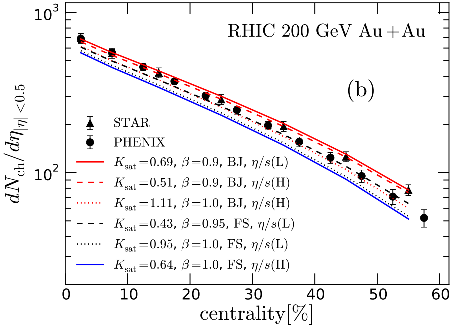
Centrality dependence of multiplicity at the LHC $\sqrt{s} = 2.76$ TeV and RHIC $\sqrt{s} = 200$ GeV

- Choose parameters $(K_{\rm sat}, \beta, \text{FS/BJ}, \eta/s)$ such that the most central LHC multiplicity is reproduced

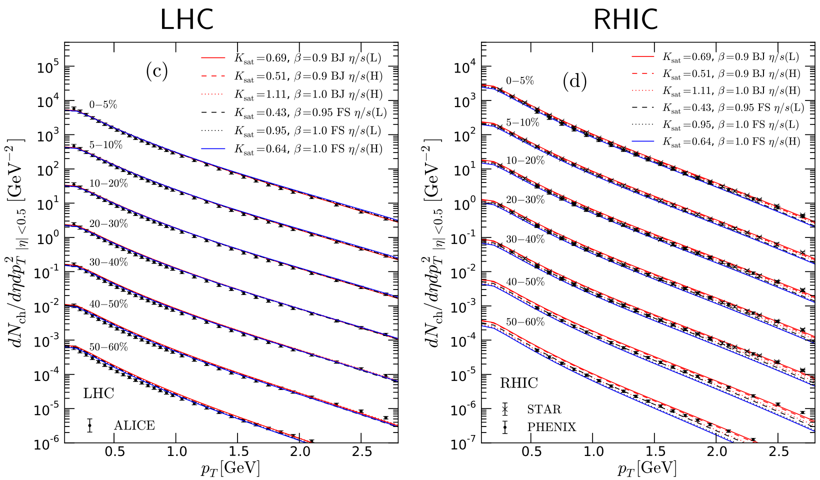
LHC



RHIC

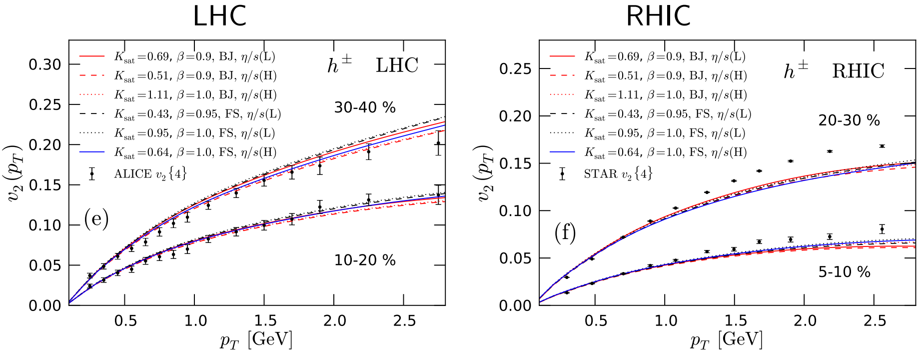


Charged particle p_T spectra VS Data at the LHC and RHIC



Elliptic flow $v_2(p_T)$ VS Data at the LHC and RHIC

- Good low-p_T agreement with the data at both LHC and RHIC
- Note: $\eta/s(T)$ same at RHIC and LHC



Summary and outlook

- NLO pQCD computation for E_T production from minijets in $A+A$
- Computation of the initial e-profiles at LHC and RHIC

  $\Rightarrow$ initial conditions for hydro
- Viscous hydro evolution

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

- Further studies: EbyE fluctuations $\Rightarrow$ study v_n's