EKRT-model predictions for 5.02 TeV Pb+Pb collisions at the LHC

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Results from:
Outline

- Compute EbyE fluctuating EKRT initial state for hydro evolution in A+A collisions from saturated NLO pQCD minijet production

- Describe space-time evolution of QCD-matter with 2+1D viscous hydrodynamics, Event-by-Event

- Compare with LHC & RHIC data for bulk (low $p_T$) observables, to
  - Test the initial state calculation & its predictive power
  - Determine QCD matter $\eta/s(T)$

- New: EKRT predictions for LHC run II 5.02 TeV Pb+Pb collisions
Initial state calculation: step I

Compute the initial minijet ($p_T = \text{a few GeV}$) $E_T$ production in A+A and $\Delta y$

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

- $T_A T_A$ accounts for the nuclear collision geometry (WS density)

- $s = \text{transverse position } (x, y), \quad b = \text{impact parameter}$
- $\sigma\langle E_T \rangle = E_T$-weighted minijet cross section
Computation of $\sigma\langle E_T \rangle$ in NLO

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

Partonic cross sections $\frac{d\sigma^{2\to n}}{d[PS]_n}$ at NLO

- Collinear factorization in A+A
- pQCD in $2 \to 2$ and $2 \to 3$ scatterings

$$\frac{d\sigma^{2\to n}}{d[PS]_n} \sim \sum_{g,q,\bar{q}} f_{i/A}(x_1, Q^2, s_1) \otimes f_{j/A}(x_2, Q^2, s_2) \otimes |M|^2(2 \to n)$$
PDFs for each parton flavor $i \ (= g, q, \bar{q})$

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

- $f_i^p$: CTEQ6M NLO parton densities
- $R_i^A$: EPS09s ($s$ dependent) NLO nuclear modifications
  Helenius, Eskola et al. JHEP 1207 (2012) 073

- $s$ dependence of the nPDFs is quite weak near the centres of $A$
Measurement functions $S_2$ and $S_3$ for computing minijet $E_T$ in NLO

- Analogous to jet production;

$$S_n = \left[ \sum_{i=1}^{n} p_{T,i} \Theta(y_i \in \Delta y) \right] \times \Theta \left( \sum_{i=1}^{n} p_{T,i} \geq 2p_0 \right) \times \Theta \left( E_{T,n} \geq \beta \times p_0 \right)$$

- IR/CL safeness: $S_3 \rightarrow S_2$ at IR & CL limits

- Any $\beta$ in $[0, 1]$ is OK but a free parameter [RP et al., PRC87 (2013) 4, 044904]

These $S_n$ + nPDFs: Well defined NLO computation of minijet $E_T$!
Initial state calculation: step II

**Conjecture:** minijet $E_T$ production saturates when

\[
\frac{dE_T}{d^2sdy}(2 \rightarrow 2) \sim \frac{dE_T}{d^2sdy}(3 \rightarrow 2) \sim \text{H.O.}
\]

- Using scaling law arguments (LO $\alpha_s$):

\[
(T_{AgA})^2 \frac{\alpha_s^2}{p_0} \sim (T_{AgA})^3 \left( \frac{\alpha_s}{p_0} \right)^3 \Rightarrow T_{AgA} \sim \frac{p_0^2}{\alpha_s} \Rightarrow \frac{dE_T}{d^2sdy} \sim p_0^3
\]

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

\[
\frac{dE_T}{d^2s}(p_0, \sqrt{s}, \ldots, \beta) = \left( \frac{K_{sat}}{\pi} \right) p_0^3 \Delta y
\]

= NLO pQCD part

- and the saturation scale $p_0 = p_{\text{sat}}(\sqrt{s_{NN}}, A, b, s; \beta, K_{\text{sat}})$
Solve the saturation equation for $p_{\text{sat}}(b, s)$ at different $b$

\[ p_{\text{sat}}(b, s) \propto [T_A(s + b/2)T_A(s - b/2)]^n \]

- Observation: $p_{\text{sat}}$ scales with $T_A T_A$

\[ C(a + T_A T_A)^n - b C a^n \]

- $p_{\text{sat}}(b, s)$ can be parameterized! [RP et al. PLB 731 (2014) 126]
Initial state calculation: step III

Include the EbyE fluctuations arising from the fluctuating nucleon configurations

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

\[
T_n(s) = \frac{1}{2\pi\sigma^2} e^{-\frac{s^2}{2\sigma^2}}, \quad \sigma = 0.43 \text{ fm from HERA } \gamma^* p \rightarrow J/\Psi + p \text{ data}
\]

In each event the nuclear thickness function \( T_A(s) = \sum_i^A T_n(|s - s_i|) \)

- Collisions of gluon clouds

Key point: fluctuations for \( p_{\text{sat}} = p_{\text{sat}}(T_A T_A) \)
Transverse profile of initial energy density \( \epsilon(s, \tau_{\text{sat}}) \) at time \( \tau_{\text{sat}}(s) = 1/p_{\text{sat}}(s) \)

\[
\epsilon(s, \tau_{\text{sat}}) = \frac{dE_T(p_{\text{sat}}, \ldots, \beta)}{d^2s} \frac{1}{\tau_{\text{sat}}(s) \Delta y} = \frac{K_{\text{sat}}}{\pi} p_{\text{sat}}(s)^4
\]

Here \( p_{\text{sat}}^{\text{min}} = 1 \text{ GeV} \gg \Lambda_{\text{QCD}} \)

Below \( p_{\text{sat}}^{\text{min}} \) smoothly connect the computed \( \epsilon \)-profile to \( \epsilon \propto \rho_{\text{bin}} \)

"Pre-thermal" evolution from \( \tau_{\text{sat}}(s) \) to \( \tau_0 = 1/p_{\text{sat}}^{\text{min}} = 0.2 \text{ fm} \)

\[
\epsilon(s, \tau_0) = \epsilon(s, \tau_{\text{sat}}) \left( \frac{\tau_{\text{sat}}}{\tau_0} \right)^{4/3}
\]

done with 1D Bjorken hydro at each \( s \)
Viscous Hydrodynamics [Niemi et al]

Run 2+1 D (2nd order) dissipative hydro, Event-by-Event

\[ \partial_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = \varepsilon u^{\mu} u^{\nu} + (P + \Pi)(g^{\mu\nu} - u^{\mu} u^{\nu}) + \pi^{\mu\nu} \]

- Neglect the bulk pressure \( \Pi = 0 \): \( \Pi \propto \zeta = \text{bulk viscosity} \)
- Keep the shear stress \( \pi^{\mu\nu} \): \( \pi^{\mu\nu} \propto \eta = \text{shear viscosity} \)

Evolution equation for \( \pi^{\mu\nu} \) from kinetic theory [Denicol, et al., PRD85 (2012) 114047]

\[ \tau_\pi \dot{\pi}^{(\mu\nu)} + \pi^{\mu\nu} = 2\eta \sigma^{\mu\nu} + \cdots \]

QCD EoS: Based on lattice parametrization [Huovinen,Petreczky,NPA837 (2010) 26]

- s95p-PCE175-v1 chemical freeze-out at \( T_{\text{chem}} = 175 \text{ MeV} \)
- kinetic freeze-out \( T_f = 100 \text{ MeV} \)

Initial \( \pi^{\mu\nu}(s, \tau_0) \) and transverse flow \( \mathbf{v}_T(s, \tau_0) \) set to zero
We study the temperature dependence of shear viscosity $\eta/s$

Map the possible temperature dependence of $\eta/s(T)$ with these parametrizations, reproducing the measured $v_2$ at LHC

Comparison with LHC and RHIC data

Centrality dependence of $N_{ch}$ at mid-rapidity

- Only one (0-5%) LHC point ($K_{\text{sat}}, \beta$) is fitted, the rest is prediction.

Our computed initial transverse densities are under control

Centrality dependence of 2,3-particle cumulant flow coefficients $v_n$

- LHC $v_n$ well reproduced by all these $\eta/s(T)$
- Simultaneous LHC & RHIC analysis very important!
- Constraints for $\eta/s(T)$: small $\eta/s$ in the HRG (0.2 & param1) seems favored

Correlations of 2 Event-plane angles OK, for centralities $< 40 - 50\%$

*Again small $\eta/s$ in the HRG (0.2 & param1) seems favored!*

**EKRT predictions** for 5.02 TeV LHC Pb+Pb


- Centrality & cms-energy dependence of $N_{ch}$

Data: ALICE collaboration, arXiv:1512.06104
EKRT predictions for 5.02 TeV LHC Pb+Pb


Centrality & cms-energy dependence of $N_{ch}$

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Ratio of the flow coefficients $v_n\{2\}$ at 5.02 TeV and 2.76 TeV


- Higher harmonics $n > 2$ more sensitivity to $\eta/s(T)$
- Constraints for $\eta/s(T)$

Ratio of the flow coefficients $v_n\{2\}$ at 5.02 TeV and 2.76 TeV


Higher harmonics $n > 2$ more sensitivity to $\eta/s(T)$

Constraints for $\eta/s(T)$

Correlations of two EP angles for charged hadrons in 5.02 TeV Pb+Pb

- Small changes in the magnitude of 2 EP correlations from 2.76 TeV to 5.02 TeV


Conclusions & Outlook

The EbyE NLO EKRT framework

- Successfully explains the LHC and RHIC bulk observables in A+A collisions
- Has clear predictive power in cms energy, centrality, A
- Is a promising tool for getting a controlled estimate of the QCD matter shear viscosity

Our "best" estimate currently for $\eta/s(T)$

But this is not yet a true error band, statistical global analysis needed (talk by S. Moreland)

Next ... 

- Study also bulk viscosity effects
- Improve the pre-thermal evolution (combine EKRT & EKT [A. Kurkela])
Also centrality dependence of the average $p_T$ for pions, kaons and protons looks OK

Our QCD matter EoS is under (sufficient) control but essentially no constraints for $\eta/s(T)$ from here, either

Relative EbyE fluctuations of elliptic flow at LHC come out beautifully

- To reproduce these measurements, need EbyE hydro: initial $\varepsilon_2$ correlates nonlinearly with final state $v_2$
- No sensitivity to $\eta/s(T)$
- Constraints to the initial state
- Our initial states are in control!!

Correlations of 2 Event-plane angles OK, for centralities $< 40 - 50\%$

- Since $P(\delta v_n)$ constrain our ISs independently of $\eta/s$, these correlations give further constraints for $\eta/s(T)$ and simultaneously test the validity of the EbyE viscous framework!

Even the correlations of 3(!) Event-plane angles similarly OK

\[ \langle \cos(2\Psi_2 + 3\Psi_3 - 5\Psi_5) \rangle_{SP} \]

\[ \langle \cos(2\Psi_2 + 3\Psi_3 - 5\Psi_5) \rangle_{SP} \]

\[ \langle \cos(2\Psi_2 - 3\Psi_3 + 4\Psi_4) \rangle_{SP} \]

\[ \langle \cos(2\Psi_2 - 3\Psi_3 + 4\Psi_4) \rangle_{SP} \]

\[ \langle \cos(-10\Psi_2 + 6\Psi_3 + 4\Psi_4) \rangle_{SP} \]

\[ \langle \cos(-10\Psi_2 + 6\Psi_3 + 4\Psi_4) \rangle_{SP} \]

LHC 2.76 TeV Pb+Pb

\[ p_T = [0.5...5.0] \text{ GeV} \]

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\[ \eta/s = 0.20 \]

\[ \eta/s = \text{param1} \]

\[ \eta/s = \text{param2} \]

\[ \eta/s = \text{param3} \]

\[ \eta/s = \text{param4} \]

ATLAS

\[ \nu_n = \left\langle \cos(n(\phi - \Psi_n)) \right\rangle / \left\langle 1 \right\rangle, \]

where

\[ \left\langle \cdots \right\rangle = \int d\rho_T^2 d\phi \frac{dN}{dy d\phi dp_T^2} (\cdots) \]

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

where

\[ \left\langle \cdots \right\rangle = \int dx dy (\cdots) \]

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

\[ \left\langle \cos(k_1 \Psi_1 + \cdots + nk_n \Psi_n) \right\rangle_{SP} \equiv \]

\[
\frac{\left\langle \nu_1^{k_1} \cdots \nu_n^{k_n} \cos(k_1 \Psi_1 + \cdots + nk_n \Psi_n) \right\rangle_{ev}}{\sqrt{\left\langle \nu_1^{2k_1} \right\rangle_{ev} \cdots \left\langle \nu_n^{2k_n} \right\rangle_{ev}}} \]