FROM FLUCTUATING MINIJET INITIAL STATE TO GLOBAL OBSERVABLES IN AA COLLISIONS AT LHC AND RHIC

Risto Paatelainen
U. of Santiago de Compostela

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...work in progress/to be published soon

with **K.J Eskola**[(a,b)], **H. Niemi**[(a,b)], **K. Tuominen**[(b,c)]
[(a)]U. of Jyväskylä, [(b)]Helsinki Institute of Physics
[(c)]U. of Helsinki

Intro & this work:

Part I: Compute fluctuating IS for hydrodynamical evolution in A+A collisions from saturated minijet production

- Roots in the old EKRT model
- NLO pQCD calculation for E_T production from minijets
- Now our IS calculation includes the EbyE fluctuations arising from the fluctuating nucleon configurations
- Saturation for E_T

Part II: Apply 2+1D EbyE viscous hydro

- Study the bulk observables to constrain the IS & $\eta/s(T)$ simultaneously at LHC & RHIC

Minijet E_T production in A+A and Δy

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

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

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

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

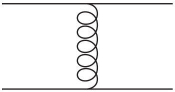
Differential partonic cross section at NLO

Framework of collinear factorization in A+A collisions

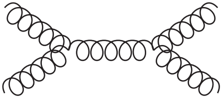
$$\frac{\mathrm{d}\sigma^{2\to n}}{\mathrm{d[PS]_n}} \sim \sum_{g,q,\bar{q}} f_{i/A}(x_1, Q^2, \mathbf{s}) \otimes f_{j/A}(x_2, Q^2, \mathbf{s}) \otimes |\mathcal{M}|^2$$

In LO we need:

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



$qq' \to qq'$

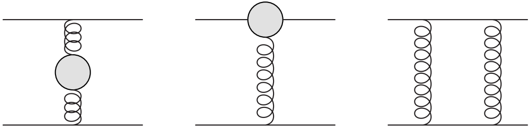


$gg \to gg$

etc, ...

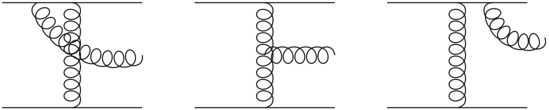
In NLO we need:

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



self-energy corrections   vertex corrections   box corrections

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



real 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

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

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

- f_i^p: free proton PDFs from NLO CTEQ6
- R_i^A: EPS09s ($\mathbf{s}$ dependent) NLO nuclear modifications
  - EPS09s [Helenius, et al. JHEP 1207 (2012) 073]

The measurement functions S_2 & S_3

- S_n's analogous to jet definition (jet cone,...)

For minijet $\sigma\langle E_T\rangle_{p_0,\Delta y}$ the S_n's define:

$$S_n = \underbrace{\left[\sum_{i=1}^{n} p_{T,i}\Theta(y_i \in \Delta y)\right]}_{\text{Minijet } E_T \in \Delta y} \times \underbrace{\Theta\left(\sum_{i=1}^{n} p_{T,i} \geq 2p_0\right)}_{\text{Hard scat. of partons}} \times \underbrace{\Theta(E_{T,n} \geq \beta \times p_0)}_{\text{Minimum } E_T \in \Delta y}$$

- S_n's fulfil the IR/CL safeness criteria: $S_3 \xrightarrow{IR,CL} S_2$

Note: any $\beta \in [0,1]$ IR/CL-safe [R.P et al, **PRC** 87 044904 (2013)]

Saturation in minijet E_T production

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

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

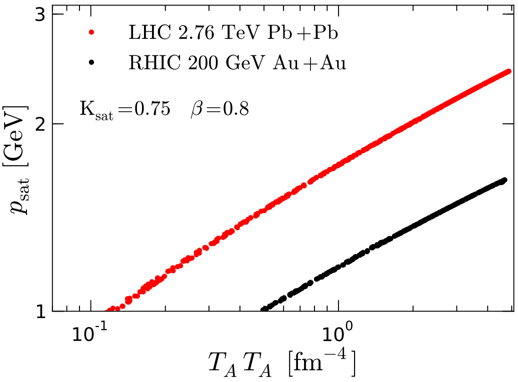
We obtain a **saturation criterion** for E_T (IR/CL safe)

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

and the **saturation scale**

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

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



[R.P et al., **PLB** 731 (2014)]

- Observation: $p_{\mathrm{sat}}(\mathbf{b}, \mathbf{s}) \propto [T_A(\mathbf{s} + \mathbf{b}/2) T_A(\mathbf{s} - \mathbf{b}/2)]^n$
- K_{sat} & β dependence of $p_{\mathrm{sat}}(\mathbf{b}, \mathbf{s})$ can be parameterized!
- Fixing K_{sat} & β through LHC data becomes possible, especially EbyE!

EbyE fluctuating nuclear collision geometry

- Nucleon positions in A_1 and A_2: sample WS distribution
- For IS calculation we also need the spatial gluon densities inside the nucleons
  - 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 $T_{A_{1/2}}(\mathbf{s}) = \sum_{i=1}^{A_{1/2}} T_n(|\mathbf{s} - \mathbf{s}_i|)$
- essentially no need for $\sigma_{NN}^{\rm in}$; collision of gluon clouds

Minijet initial conditions for hydro

Saturation scale $p_{\rm sat}(\mathbf{s})$ gives:

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

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

At this level two unknown parameters:

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

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

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

Bjorken scaling (BJ): conserves entropy

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

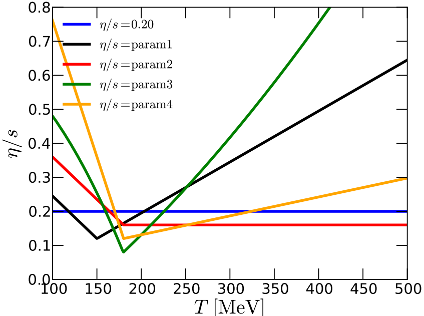
- $\tau_0 = 1/p_{\mathrm{sat}}^{\mathrm{min}} = 0.2$ fm $\quad (p_{\mathrm{sat}}^{\mathrm{min}} = 1\ \mathrm{GeV} \gg \Lambda_{\mathrm{QCD}})$

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

Our hydrodynamic setup

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

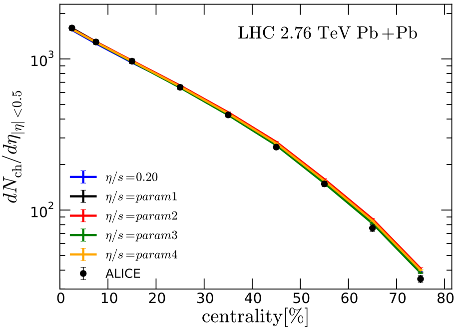
- Minijet initial conditions $\epsilon(\mathbf{s}, \tau_0)$ & $\tau_0 = 0.2$ fm
- Initial $\pi^{\mu\nu} = 0, \mathbf{v}_T = 0$ & $T_{\rm dec} = 100$ MeV
- EoS: Based on lattice parametrization (s95p-PCE175-v1) [**NPA** 837, 26 (2010)]
- Temperature dependent η/s

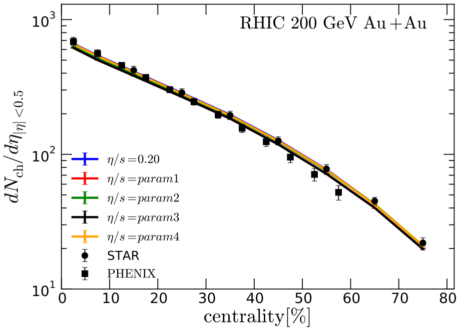


EbyE Results :

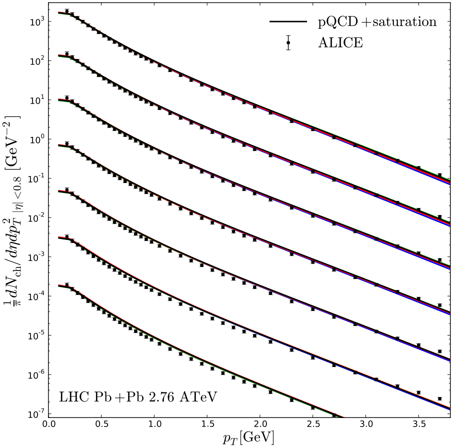
Centrality dep. of multiplicity at LHC & RHIC

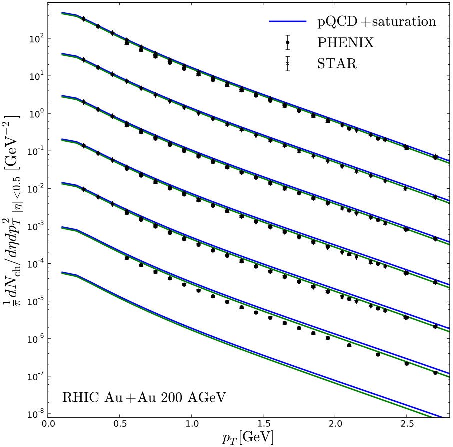
- For given $\eta/s(T)$, BJ and $\beta = 0.8$ choose parameter $K_{\rm sat}$ such that the most central LHC multiplicity is reproduced





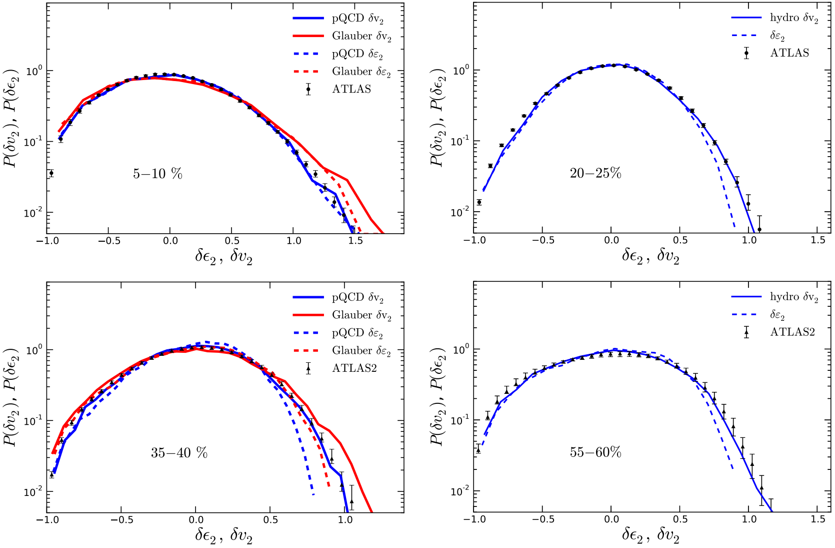
Charged particle p_T spectra at LHC & RHIC





EbyE distributions of δv_2 and $\delta \epsilon_2$ at LHC

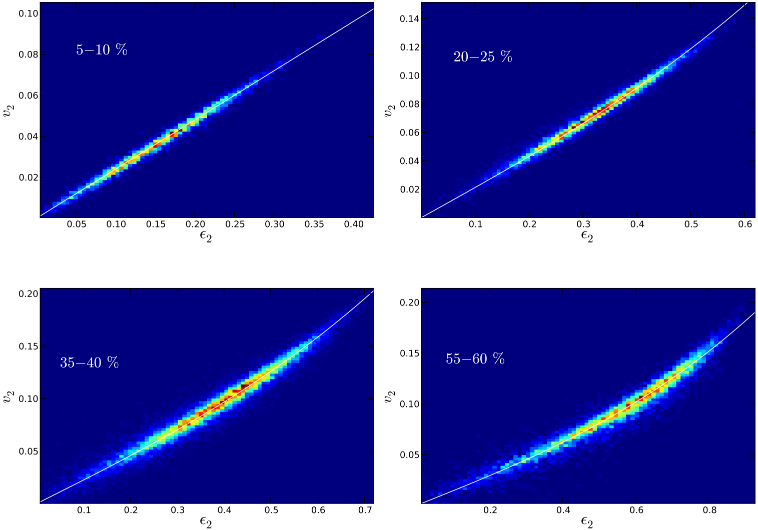
- constraint for initial state, not a viscous effect!



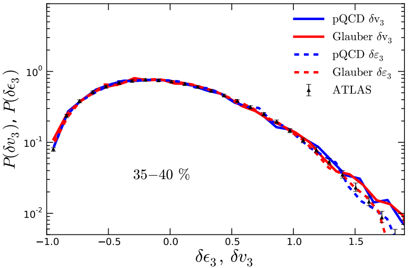
- pQCD + sat. framework WORKS & hydro is NEEDED!

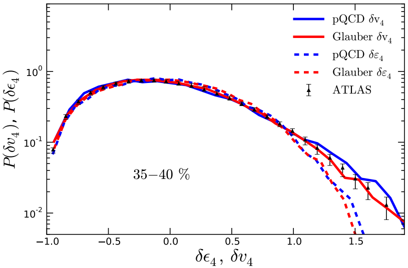
EbyE distributions of δv_2 and $\delta \epsilon_2$ at LHC

- nonlinear correlation is due to nonlinearity of hydro



EbyE distributions of $\delta v_{3,4}$ and $\delta\epsilon_{3,4}$ at LHC

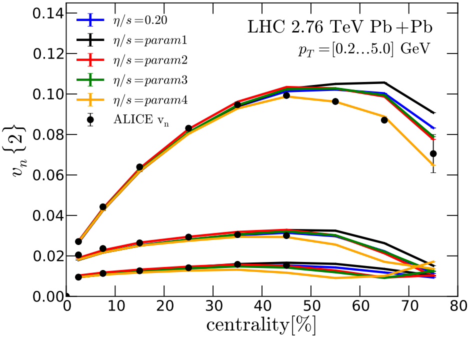


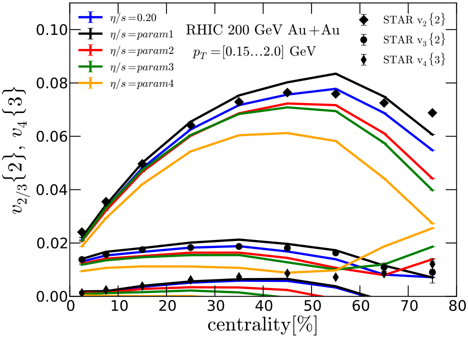


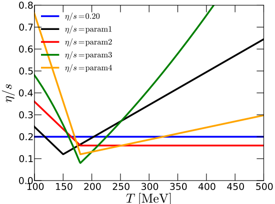
- also these are well reproduced!

Flow coefficients $v_n\{2\}$ and $v_4\{3\}$

- The shown $\eta/s(T)$ parametrizations are chosen so that they reproduce the LHC v_n's



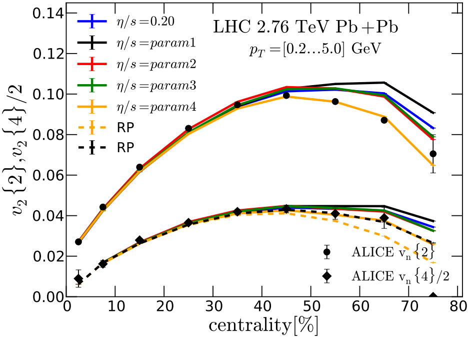


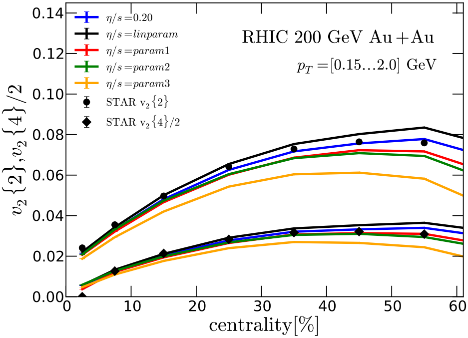


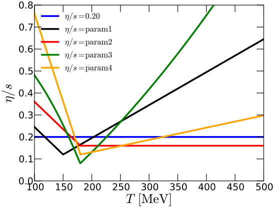
$$v_n\{2\} \equiv \langle v_n^2 \rangle_{\text{ev}}^{1/2}$$

$$v_4\{3\} \equiv \frac{\langle v_2^2 v_4 \cos(4[\Psi_2 - \Psi_4]) \rangle_{\text{ev}}}{\langle v_2^2 \rangle_{\text{ev}}}$$

Flow coefficients $v_2\{2\}$ and $v_2\{4\}$



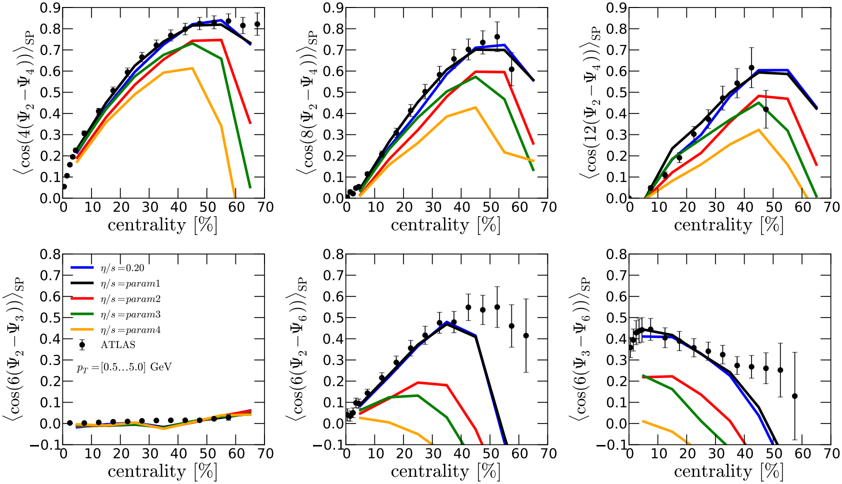


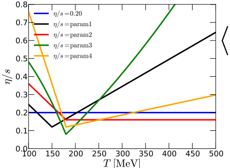


$$v_n\{2\} \equiv \langle v_n^2 \rangle_{\text{ev}}^{1/2}$$

$$v_n\{4\} \equiv \left(2\langle v_n^2 \rangle_{\text{ev}}^2 - \langle v_n^4 \rangle_{\text{ev}}\right)^{1/4}$$

Event plane correlations at LHC





$$\langle\cos(k_1\Psi_1+\ldots+nk_n\Psi_n)\rangle_{\rm SP}\equiv \frac{\langle v_1^{k_1}\ldots v_n^{k_n}\cos(k_1\Psi_1+\cdots+nk_n\Psi_n)\rangle_{\rm ev}}{\sqrt{\langle v_1^{2k_1}\rangle_{\rm ev}\ldots\langle v_n^{2k_n}\rangle_{\rm ev}}}$$

Summary

- Presented a new EbyE framework for NLO pQCD + saturation & viscous hydro (to be published soon)
- The computed $\sqrt{s}$ and centrality dependence of $dN_{ch}/d\eta$ agree very well with LHC and RHIC data $\Rightarrow$ predictive power!
- Also p_T spectra come out rather well, assuming a high $T_{\rm ch}$
- Most direct constraints for the IS come from the v_2 fluctuations and the ratio v_2/v_3 – both are now very well reproduced!
- LHC v_n's alone do not stringently constrain the T-dependence of η/s: we tested a wide range of $\eta/s(T)$
- Further constraints for $\eta/s(T)$ from the v_n's at RHIC and the EP correlations at the LHC
  - $\eta/s = 0.2$ (blue) and param1 with minimum at $T = 150$ MeV (black) and small hadronic η/s work best in our framework
- Very promising results but we should keep in mind the uncertainties when ruling out a large hadronic viscosity: peripheral collisions and large hadronic $\eta/s \Rightarrow$ large δf at decoupling $\Rightarrow$ applicability of hydro ?