2013-14 Bulk Working Group Report

Michael Strickland
Kent State University

2014 JET Collaboration Meeting

June 17, 2014

Active Bulk Working Group (BWG) Members

- **Duke University:**
  Steffen Bass, Berndt Mueller (PIs); S. Cao, J.S. Moreland, G-Y. Qin, C.E. Coleman-Smith
- **Kent State University:**
  Michael Strickland (PI, Convener); R. Ryblewski, M. Nopush
- **Lawrence Berkeley Laboratory:**
  Xin-Nian Wang (PI); A. Buzzatti
- **McGill University:**
  Charles Gale and Sangyong Jeon (PIs)
- **Ohio State University:**
  Ulrich Heinz (PI); D. Bazow, J. Liu, M. Martinez, C. Plumberg, Z. Qiu, and C. Shen
- **Purdue University:**
  Denes Molnar (PI); D. Sun, D. Hemphill, and Z. Wolff
- **Texas A&M University:**
  Che-Ming Ko, Rainer Fries (PIs); G. Chen, S. Ozonder, T. Song.
- **University of Colorado, Boulder:**
  Paul Romatschke (PI); T. Gorda and M. Habich
- **Wayne State University:**
  Abhijit Majumder (PI)
- **China and Germany**:
  H. Song, H. Peterson

The raison d'être of the Bulk WG

- The Bulk WG consists of twelve PIs and twenty ancillary personnel from nine U.S. and international institutions.
- The Bulk Evolution Working Group provides quantitative modeling of the bulk medium evolution to enable accurate calculation of hard probe observables.
- As part of this mission, we strive to make the most realistic end-to-end simulations of QGP bulk medium evolution and use these to constrain bulk parameters.
- According to our 2013-14 annual report, members of the bulk working group published over 20 papers related to bulk evolution in the QGP.
- We also organize regular online seminars that facilitate the exchange of information between group members.

Bulk WG Online Seminars 2013-14

1. C. Shen, *Photon emission from nearly equilibrated relativistic heavy-ion collisions I*, March 6, 2013.
2. U. Heinz, Z. Qui, and C. Shen, *Flow angle fluctuations and anisotropic flow angles*, March 20, 2013.
3. C. Shen, *Photon emission from nearly equilibrated relativistic heavy-ion collisions II*, Oct 15, 2013.
4. U. Heinz, C. Shen, and Jia Liu, *Stabilizing second-Order viscous hydrodynamics simulations*, Oct 29, 2013.
5. G.-Y. Chen and Rainer Fries, *Initial Flow Of Gluon Fields in Heavy Ion Collisions*, Nov 12, 2013.
6. M. Strickland, *NLO anisotropic hydrodynamics*, Nov 26, 2013.
7. C. Young, *Thermal noise in heavy-ion collisions*, Dec 10, 2013.
8. M. Strickland, *Resummed QCD thermodynamics at finite temperature and chemical potential*, Feb 10, 2014
9. W. Florkowski, *A new formulation of leading order anisotropic hydrodynamics*, Feb 24, 2014.
10. M. Martinez, *About the Gubser solution in hydrodynamics*, March 10, 2014.
11. J. Bernhard, *QGP parameter extraction via a global analysis of event-by-event flow coefficient distributions*, March 24, 2014.
12. W. Van der Schee, *Collisions in ADS: The Road to Experiments: Towards more realistic models of the QGP thermalization,* April 21, 2014

* Meetings related to organization and discussions are not listed above.

Advances in the 2013-14 (Alphabetical)

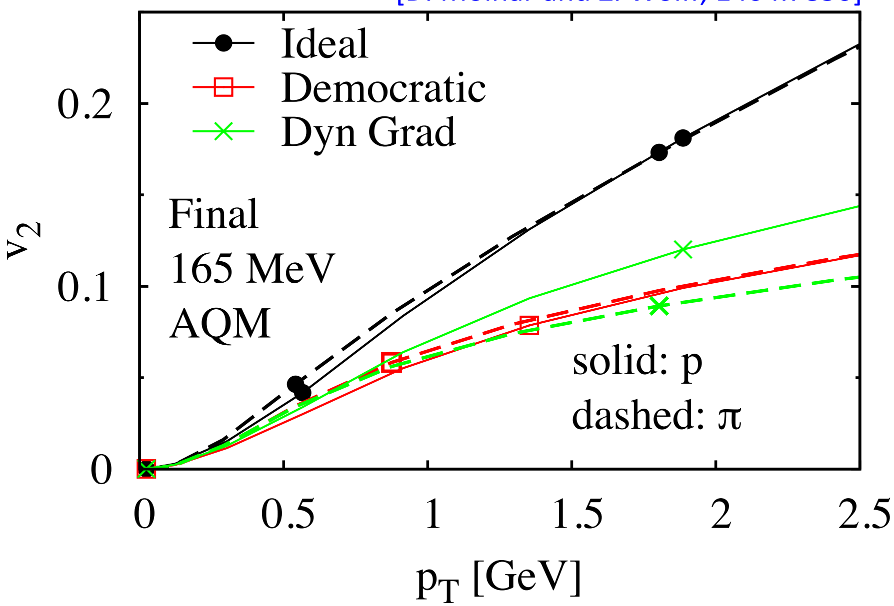
- **Anisotropic Hydrodynamics (KSU & OSU)**
- Elliptic and triangular flow in d-Au collisions and p-Pb collisions (WSU & Duke)
- **Exact solutions of linearized transport in 0+1d and 1+1d (KSU & OSU)**
- Electromagnetic radiation (OSU & McGill)
- Event plane correlations in Pb+Pb collisions at LHC (LBNL)
- Hydrodynamic Flow in Small Systems (CUB)
- **iEBE-VISHNU hydrodynamic code package (OSU)**
- Initial Conditions from Classical Gluon Fields (TAMU)
- Lattice Boltzmann Solvers (Colorado)
- The Little Bang fluctuation spectrum (OSU)
- **Matching AdS/CFT pre-equilibrium dynamics and viscous hydro (CUB)**
- Radiative energy loss in evolving bulk medium (Purdue)
- Radiative transport (Purdue)
- **Rapidity Structure of Colliding Sheets of Color Glass (TAMU)**
- **Self-consistent freezeout (Purdue)**

Self-consistent freezout

- A challenge in generating particle spectra from viscous hydrodynamics calculations is to determine $\chi_j(p/T)$ for all particle species j.
- Standard practice is to assume quadratic momentum dependence with a universal coefficient for all hadron species (aka "democratic Grad" ansatz).
- This introduces uncontrolled errors into the comparison of hydrodynamic and hydrodynamics+ transport calculations and data.
- The Purdue group developed a self-consistent approach based on linearized transport theory.
- Result provides viscous corrections that depend on microscopic interactions in the hadron gas.

Group calculated the momentum dependence of viscous corrections for different hadron gases, and implemented feeddown (RESO) from resonance decays.

[D. Molnar and Z. Wolff, 1404.7850]



[Purdue Group]

Rapidity Structure of Colliding Sheets of Color Glass

- CGC energy density

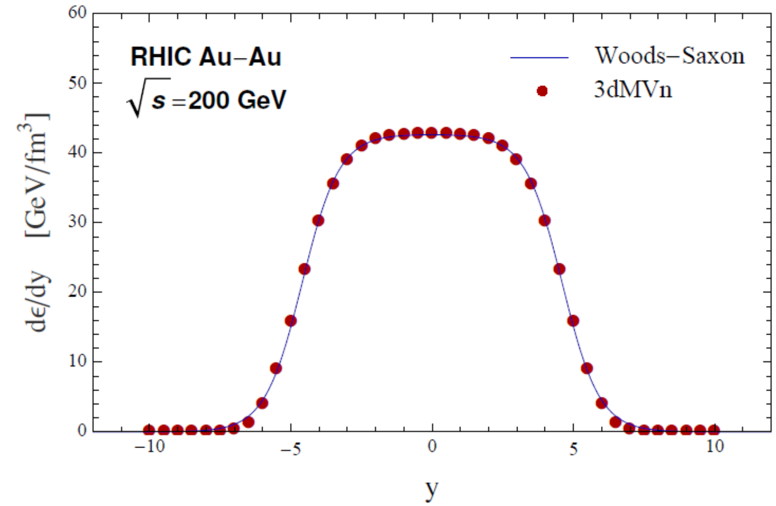
$$\varepsilon_0 = \frac{g^6 N_c \left(N_c^2 - 1\right)}{8\pi} \mu_1 \mu_2 \ln^2 \frac{Q^2}{m^2}$$ [T. Lappi, 2006]

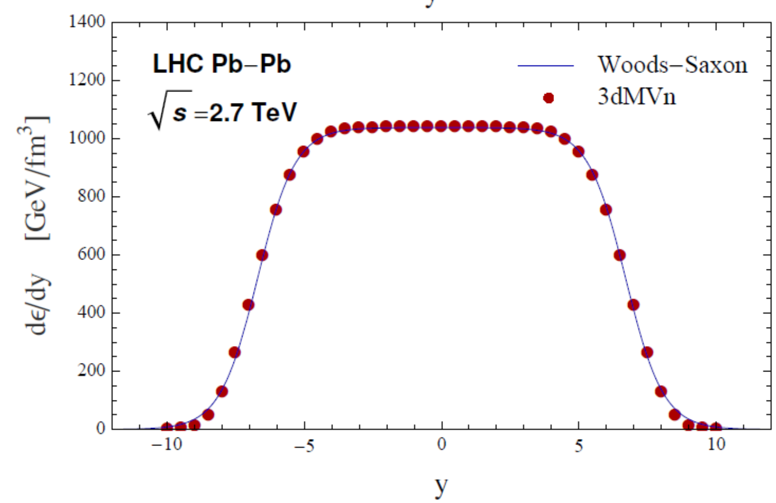
  - Independent of rapidity ⇒ strict boost-invariance, nuclei on the lightcone
- Real nuclei are slightly off the light cone:
  - Classical gluon distributions calculated by Lam and Mahlon.

    [C.S. Lam, G. Mahlon, PRD 62 (2000)]
- Nuclear collisions off the light cone:
  - Use Lappi's techniques with the Lam-Mahlon gluon distributions.
  - Approximations valid for R_A/γ (passing time) << $1/Q_s$ (CGC internal time scale)
- New initial energy densities respecting kinematic realities!

[S. Ozonder, R. Fries, PRC 89 (2014)]

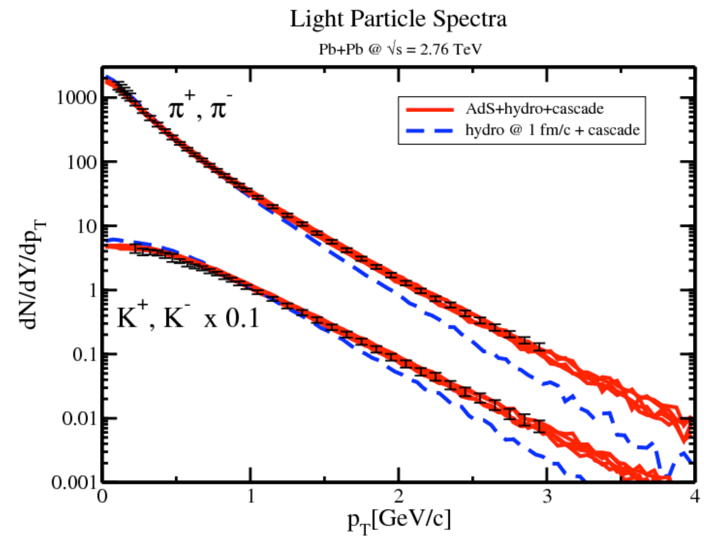
[S. Ozonder, R. Fries, PRC 89 (2014)]

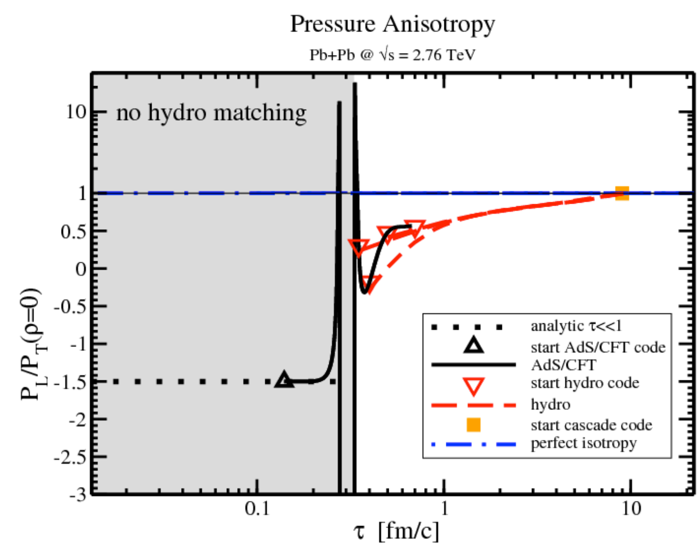




AdS/CFT pre-eq dynamics + viscous hydro

- First "complete" simulation of all collision stages (only 1+1d though)
- Shockwave collision implemented in AdS/CFT with numerical solution
- Includes initial radial flow from first principles
- Allows for smooth matching between pre-equilibrium dynamics and viscous hydro
- Successful description of particle spectra for central collisions
- Study finds strong initial momentum-space anisotropies even when including transverse expansion





[W. van der Schee, P. Romatschke, S. Pratt, PRL 111 (2013)]

[Colorado Group]

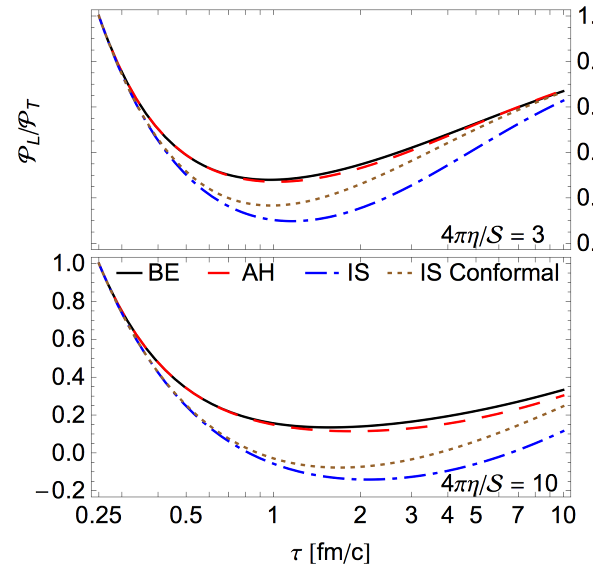
iEBE-VISHNU hydrodynamic code package

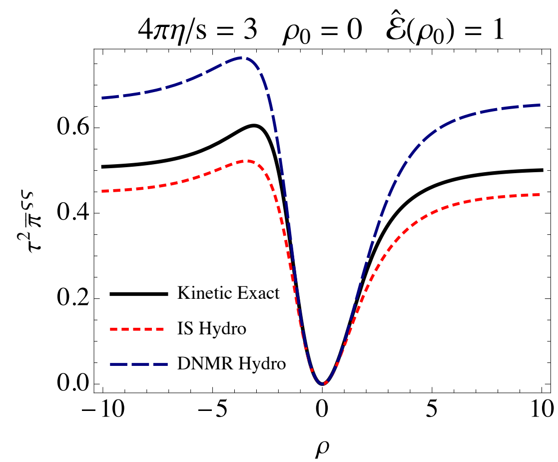
- iEBE-VISHNU = A Python-based interactive program package that allows users to perform event-by-event hydrodynamic simulations for heavy-ion collisions.
- Package includes modules for
  - Fluctuating initial density profile
  - 2+1d hydro evolution with the OSU code VISH2+1
  - Computation of spectra and anisotropic flow coefficients from the Cooper-Frye spectra (including all resonance decays if desired)
  - Monte-Carlo sampling the Cooper-Frye spectra to obtain input for the UrQMD cascade ("spectra sampler")
  - Python-based analysis module + SQLite database to store event-by-event runs
  - Computation any soft hadron observable, if desired
- New module for thermal photon emission
- More details can be found in Chun Shen's talk

[OSU group + Jonah Bernhard (Duke)]

Exact solutions of linearized transport

- It is possible to <u>exactly</u> solve the 0+1d kinetic equation in the RTA.
  [W. Florkowski, R. Ryblewski, and MS, PRC 88 (2013)]
- Solutions now available for massless (conformal) and massive (non-conformal) systems.
- These solutions allow one to test different viscous hydrodynamics approximations. It is a bit restricted, since we have 0+1d, but still quite useful in practice.
- 0+1d result shows that Israel-Stewart second-order hydro is markedly worse than the full Grad-14 method. Grad-14 second-order viscous hydro is inferior to aHydro.
- Exact solutions now extended to 1+1d case with Gubser flow for arbitrary η/S.
  [G. Denicol, U. Heinz, J. Noronha, M. Martinez, and MS, forthcoming]
- Resulting exact 1+1d solutions allow one to test codes in both small and large η/S limits!



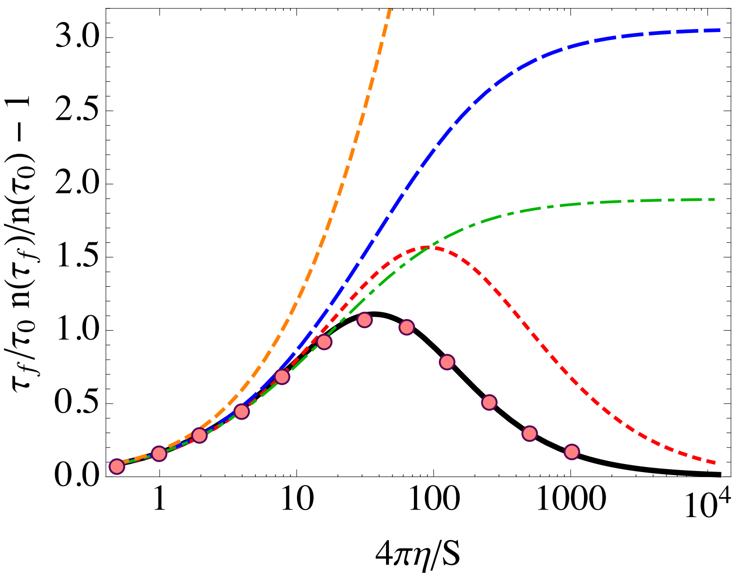


[KSU & OSU groups]

Anisotropic Hydrodynamics

- QGP is not isotropic in LRF → large corrections to ideal hydrodynamics primarily due to strong longitudinal expansion
- Anisotropic hydrodynamics builds in momentum-space anisotropies in the local rest frame from the beginning
- The goal is to create a quantitatively reliable viscous-hydro code that more accurately describes
  - Early time dynamics
  - Dynamics near the transverse edges of the overlap region
  - Temperature-dependent and potentially large η/S
- Recent advances include NLO aHydro for conformal systems and extension of LO aHydro to massive systems → bulk viscous effects

Conformal Entropy Production (0+1d)



Points = Exact 0+1d Boltzmann Solutions
Black Solid Line = NLO aHydro
Red Dashed Line = LO aHydro
Green Dash-Dotted Line = 3rd Order CE vHydro
Blue Dashed Line = 14-moment vHydro (DNMR)
Orange Dashed Line = Israel-Stewart vHydro

NLO aHydro:
[D. Bazow, U. Heinz, and M. Strickland, 1311.6720]
Exact Solution:
[W. Florkowski, R. Ryblewski, and MS, PRC 88 (2013)]

[KSU & OSU groups]

The to-do list for the next year – Pt I

- After some discussions with the bulk WG members, I have come up with a to-do list for the next year.
- I have also taken the liberty to add some things that I find particularly interesting.
- The list I present is by no means a prioritized list.

- Complete event-by-event all-stage dynamical simulations with fluctuating initial conditions
- Completion of the jet quenching module (jet shower MC) and couple it with iEBE (mostly work needed by the jet WG)
- Completion and publication of the iEBE documentation and the code package (mostly done already)
- 2+1d and 3+1d NLO aHydro with fluctuating ICs (aka vaHydro)
- Lots of uncertainties associated with freeze-out. This is important for how we fix the physical parameters that are used at all times during the bulk evolution. Needs some critical attention.

The to-do list for the next year – Pt II

- Anisotropic freezeout; instead of using linearly-corrected distribution functions, use anisotropically deformed distribution functions
- Systematic studies of pre-equilibrium dynamics on final observables
- Implementation and testing of the self-consistent initial conditions (flow & rapidity dependence) from the CGC
- More studies of the impact of viscous (anisotropic) corrections to electromagnetic signatures → necessary for experimental determination of the degree of isotropization of the QGP
- Work needed on elimination of instabilities in the relativistic Lattice Boltzmann solvers; work in progress at Colorado to implement "f0 stabilization"
- Squeeze B. Schenke hard to provide 2+1d and 3+1d MUSCL-based hydro as an alternative to the current VISHNU hydro module. Important to test dependence of results on the underlying hydro module.

Bulk WG to-do list beyond the next year

- Viscous hydro approach & codes are being improved and methods for extending their range of applicability are progressing nicely.
- Event-by-event hydro code produced by this collaboration needs to be updated and <u>maintained</u> going forward. This requires continued funding in order to support the groups that will be in charge of this.
- Options for modules for various pieces need to be more flexible so that we can better determine the effect of different model assumptions in each stage.
- Large shear corrections (pressure anisotropies) can effect non-flow observables <u>including jet quenching</u>. This needs a concerted drive from the top to make systematic and realistic calculations.
- There have been significant advances recently in our understanding of pre-eq and dilute-region dynamics, but there is still some uncertainty. We need further theoretical and phenomenological work on this front.

Thanks for your attention

"Hey, Sisyphus, when you've got a minute I'd like to discuss this progress report with you."