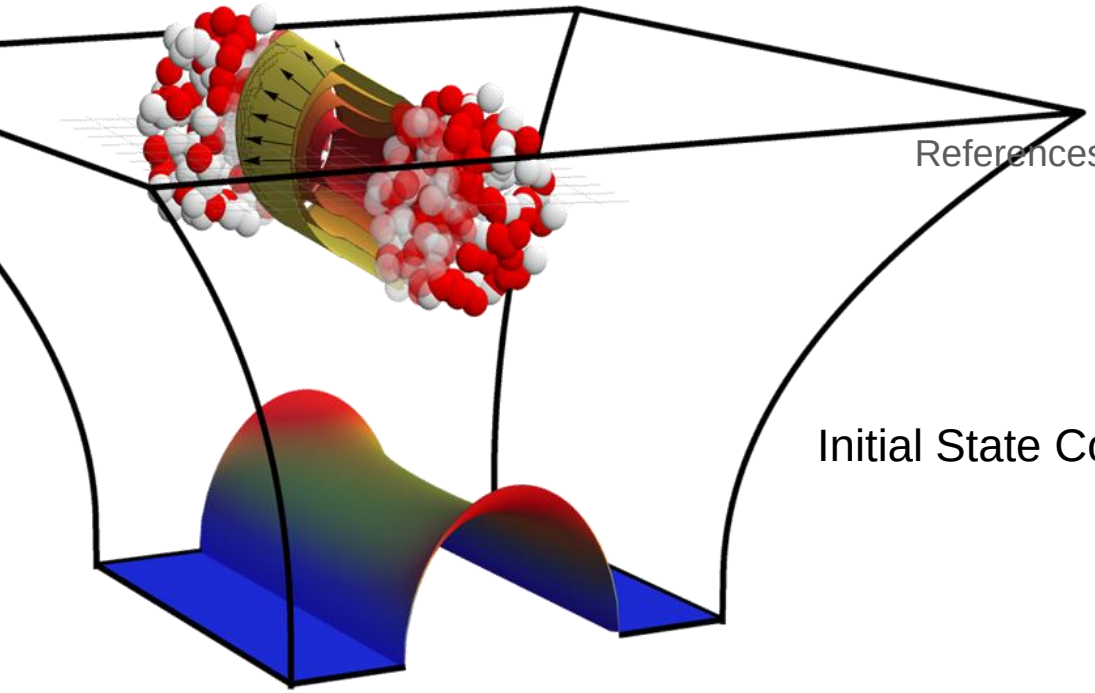
STRONG COUPLING QGP THERMALISATION WITH LONGITUDINAL DYNAMICS

TOWARDS MORE REALISTIC MODELS OF QGP FORMATION

Based on work with Michał Heller, David Mateos, Jorge Casalderrey, Miquel Triana, Paul Romatschke, Scott Pratt, Peter Arnold, Steve Gubser, Paul Chesler and Niki Kilbertus

New work with Björn Schenke

References: 1407.1849 (Thesis), 1408.2518, to appear



Wilke van der Schee

Initial State Conference, Napa, 7 December 2014

OUTLINE

AdS/CFT: initial state @ strong coupling

- Only approximate to QCD at intermediate coupling; simplified setting
- Goal: benchmark at `infinitely strong coupling'

Gravitational shock waves in AdS

- From Landau to Bjorken (but not quite)
- Coherence and a *universal Gaussian rapidity profile*
- To leading order, i.e. neglecting chemical potential, finite coupling etc

Preliminary results for matching with 3+1D hydro (MUSIC)

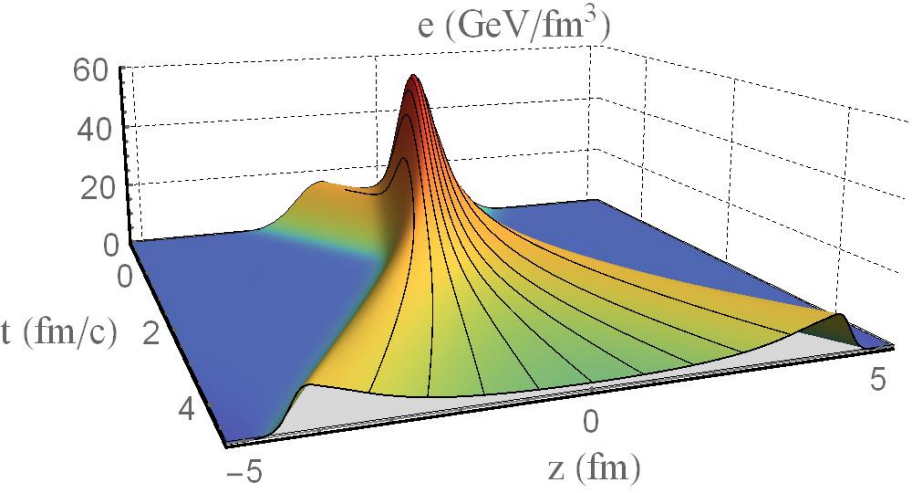
- Use longitudinal physics from AdS/CFT
- Use conventional transverse physics (Glauber + universal pre-flow)

SHOCK WAVES – A DYNAMICAL CROSS-OVER

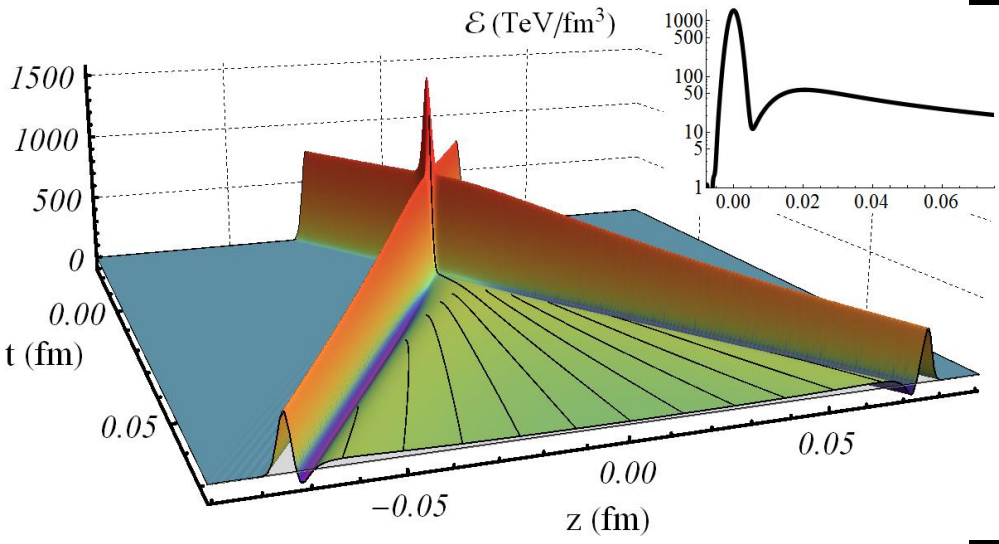
Colliding lumps of energy at infinite coupling, neglecting transverse dynamics

Low energy: Landau model, i.e. reasonably dN/dy (see work Peter Steinberg)

$\sqrt{s_{NN}} = 19.3\,\mathrm{GeV}$



$\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$



Benchmarks: $T_{\max} = 440\ \mathrm{MeV}$ $T_{\max} = 2.6\ \mathrm{GeV}$

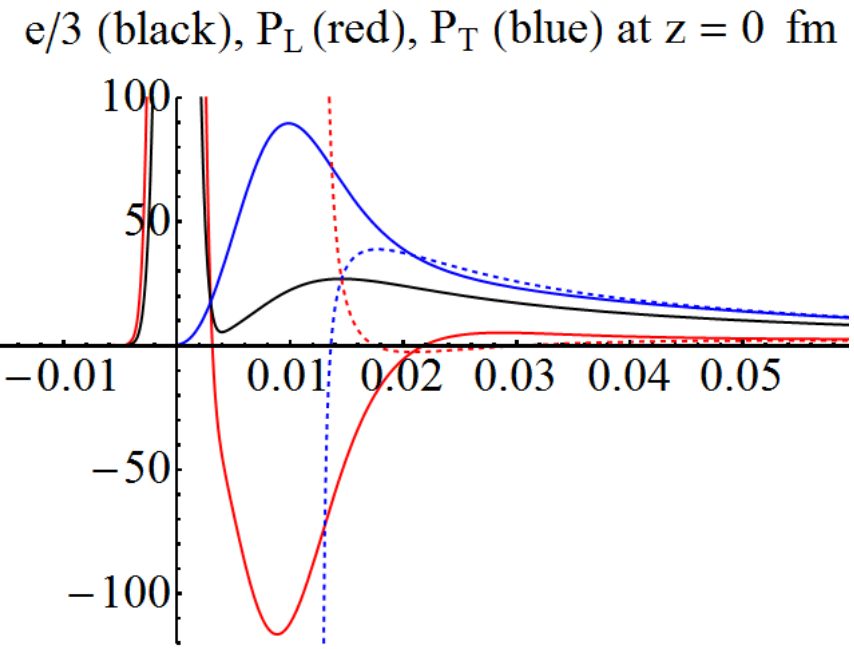
J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, From full stopping to transparency in a holographic model of heavy ion collisions (2013)

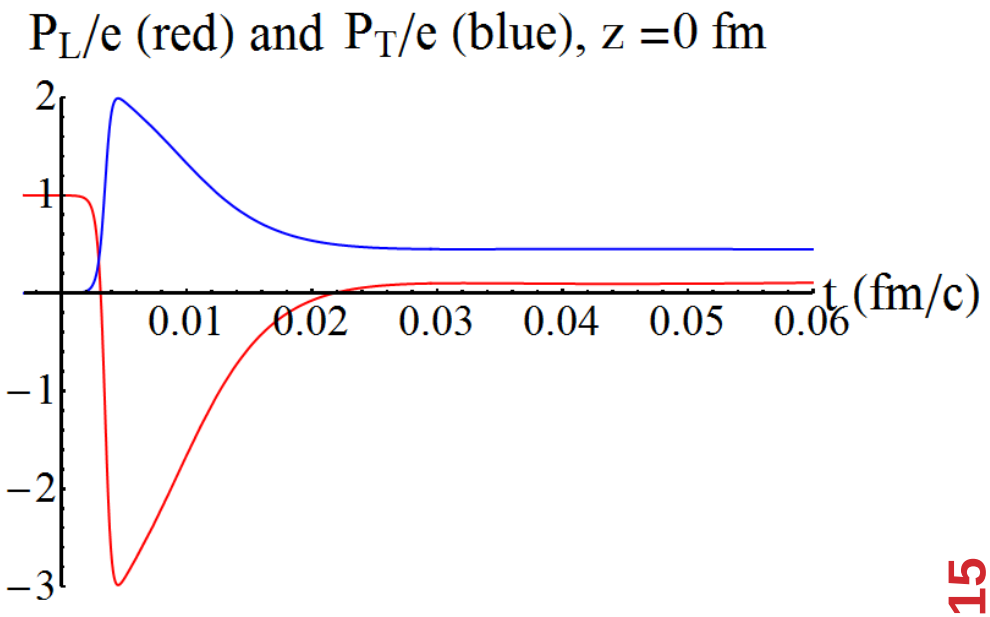
THERMALISATION/PRESSURES

Pressures, energy starts at zero, grows (unique to holography?)

Thermalises very fast (hydro applies in perhaps 0.02 fm/c)

- Thermalisation = relaxation non-hydro modes
- Gradients + viscous corrections are big



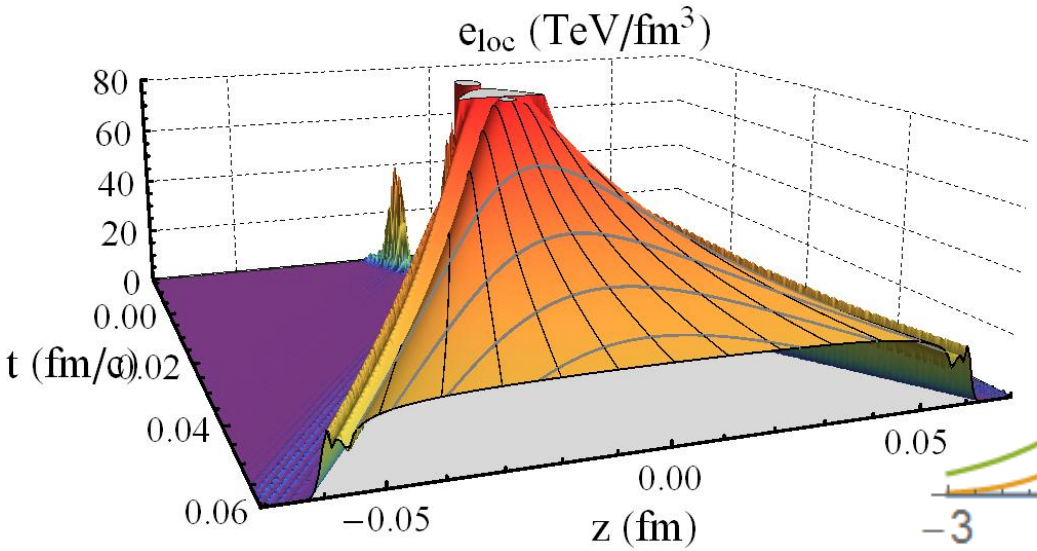


M.P. Heller, R.A. Janik and P. Witaszczyk, Hydrodynamic Gradient Expansion in Gauge Theory Plasmas (2013)

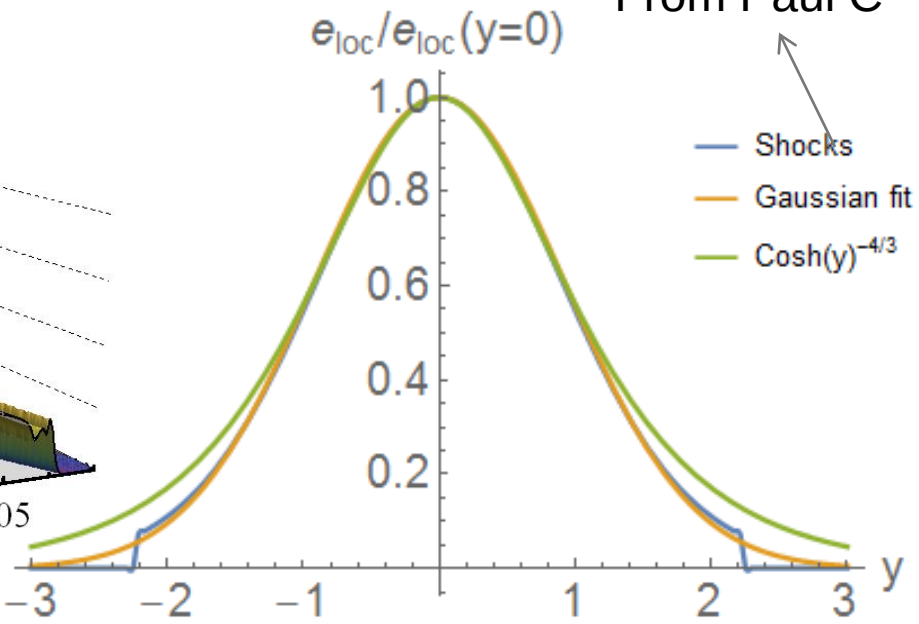
Work in progress with Paul Chesler and Niki Kilbertus (to appear)

A UNIVERSAL GAUSSIAN RAPIDITY PROFILE

Local energy density, flat in *z*, Gaussian in rapidity



From Paul C



Why Gaussian? Don't know, but robust computation.

DIMENSIONAL ANALYSIS 1.0

$\sqrt{e_L(x_\perp)e_R(x_\perp)}$

Only one scale in problem: $\mu^3 \sim e_\perp(\mathrm{GeV/fm}^2) \sim \sqrt{s_{NN}}$

$e_\perp(r=0) \approx 2.5\ \mathrm{TeV/fm}^2 = (0.04\ \mathrm{fm})^{-3} = (4.6\ \mathrm{GeV})^3$

- **Idea: during thermalisation no transverse scale either!**
  - I.e. thermalisation time << 0.1 fm, transverse scale >> 0.1 fm
  - No QCD scale is assumption

- **Corollary: entropy production (fm^{-2}):** $\mu^2 \sim \sqrt{s_{NN}}^{2/3}$

  Limitation of holography?

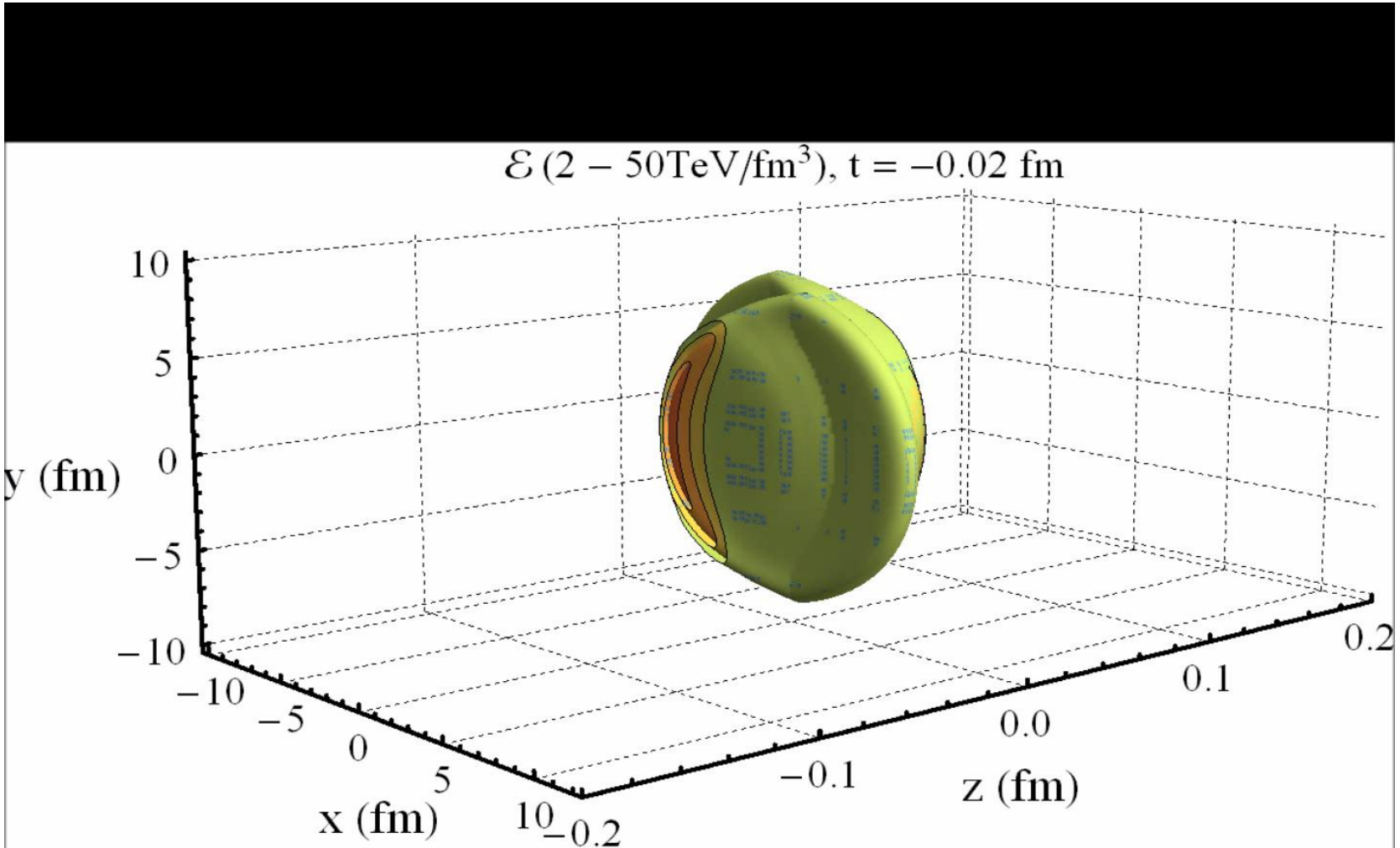
More non-trivial:

- **rapidity profile + Bjorken velocity (shift to c.o.m.!)**
- **fast thermalisation → decoupling of transverse dynamics**

COLLIDING TWO NUCLEI:

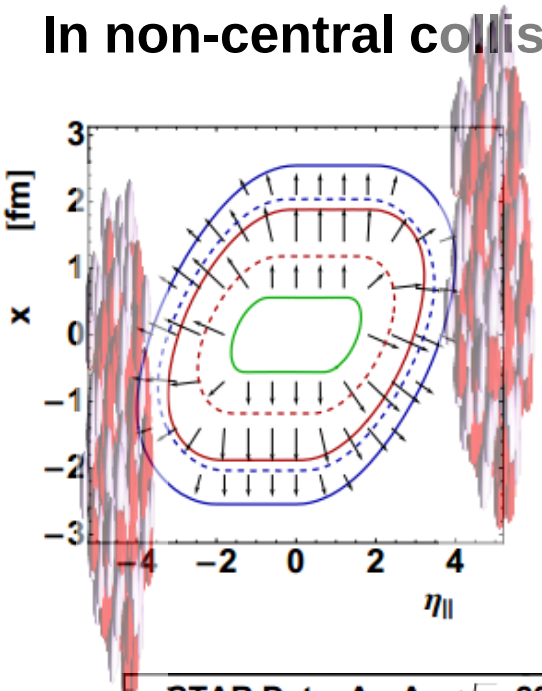
Locally in transverse plane: use shock waves (i.e. Gaussian rapidity)

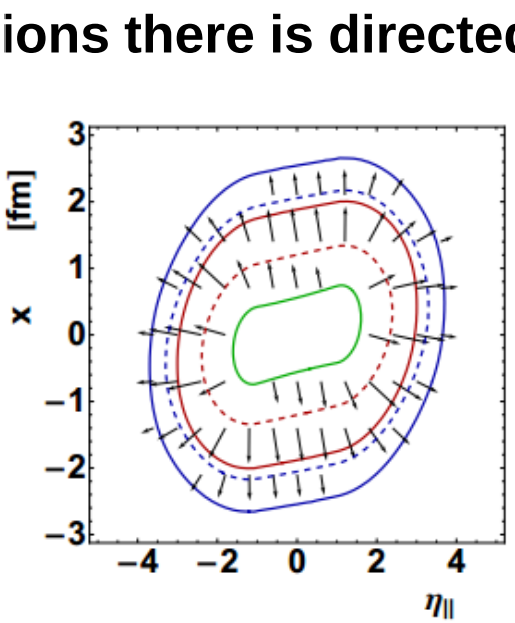
→ Go and run hydro (MUSIC) and get particle spectra ☺

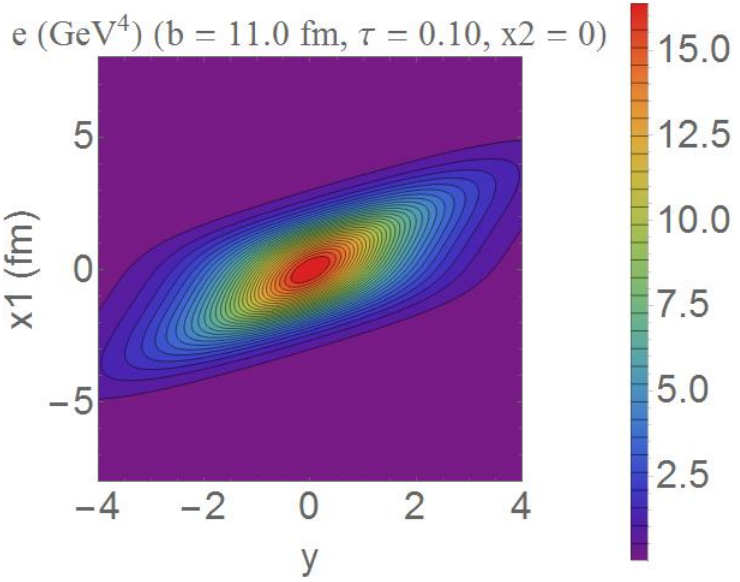


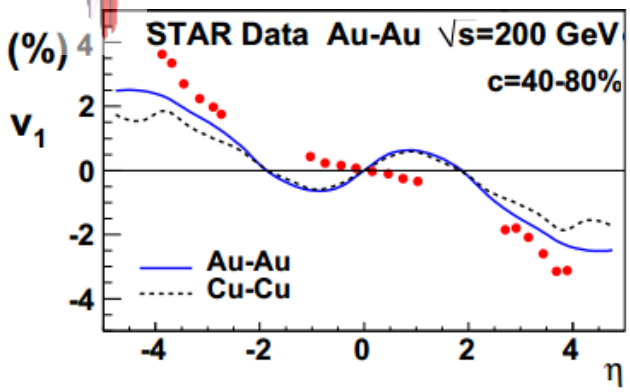
DIRECTED FLOW AND LONGITUDINAL DYNAMICS

In non-central collisions there is directed flow:







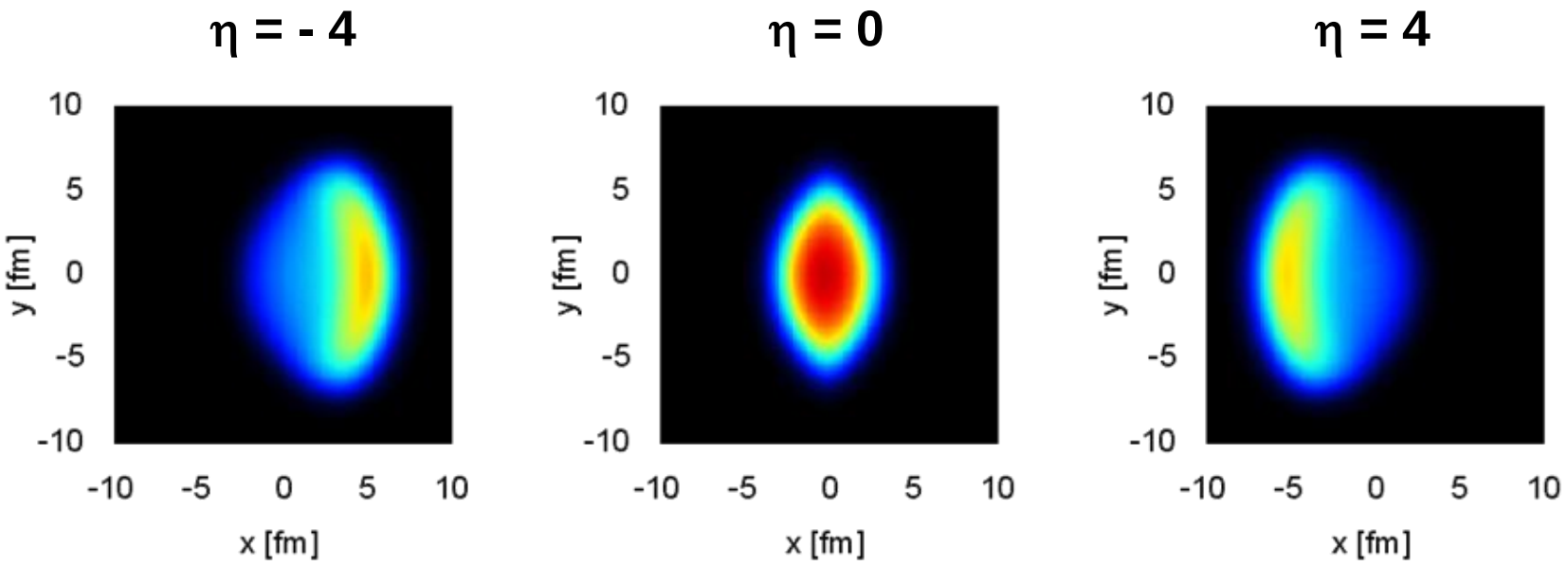


- ‘Standard’ boost-invariant coherent model conflicts with experiment
  - Either tilt,
  - Or use narrow Gaussian rapidity profile

P. Bozek, I. Wyskiel, Directed flow in ultrarelativistic heavy-ion collisions (2010)

Work in progress with Björn Schenke (to appear)

MUSIC RESULTS



Impact parameter 8 fm, time 0.1 fm/c to 10 fm/c

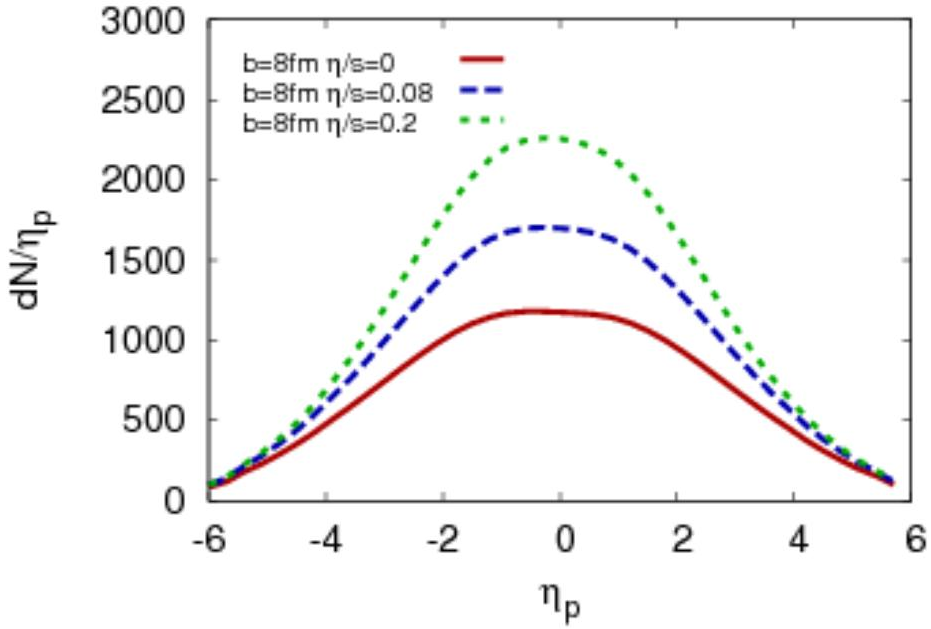
Initial flow in transverse plane by `universal pre-flow': $v_i = -\frac{1}{3}\tau\,\partial_i e/e$

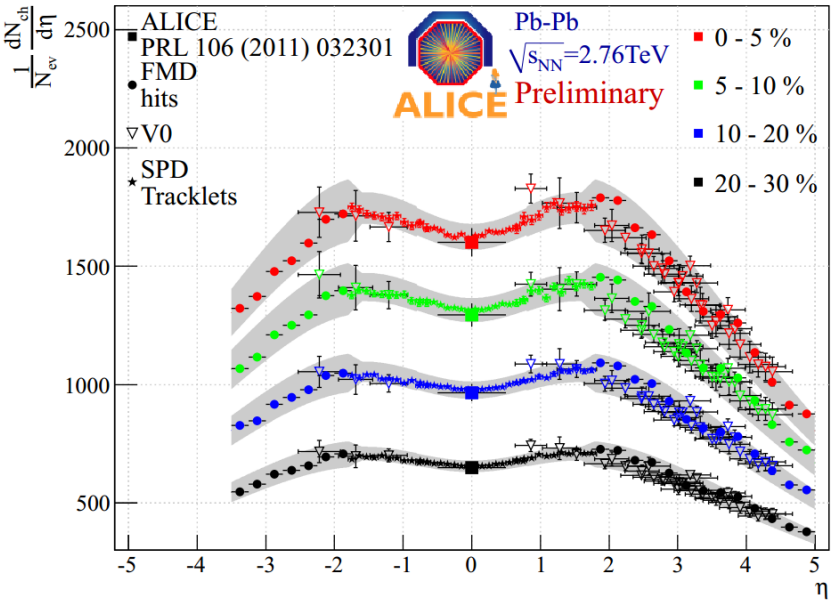
J. Vredevoogd and S. Pratt, Universal flow in the first stage of relativistic heavy ion collisions (2009)
WS, P. Romatschke and S. Pratt, Fully Dynamical Simulation of Central Nuclear Collisions (2013)

Work in progress with Björn Schenke (to appear)

MUSIC RESULTS, PRELIMINARY

Particle spectra in longitudinal direction:





Fluctuations can change profile

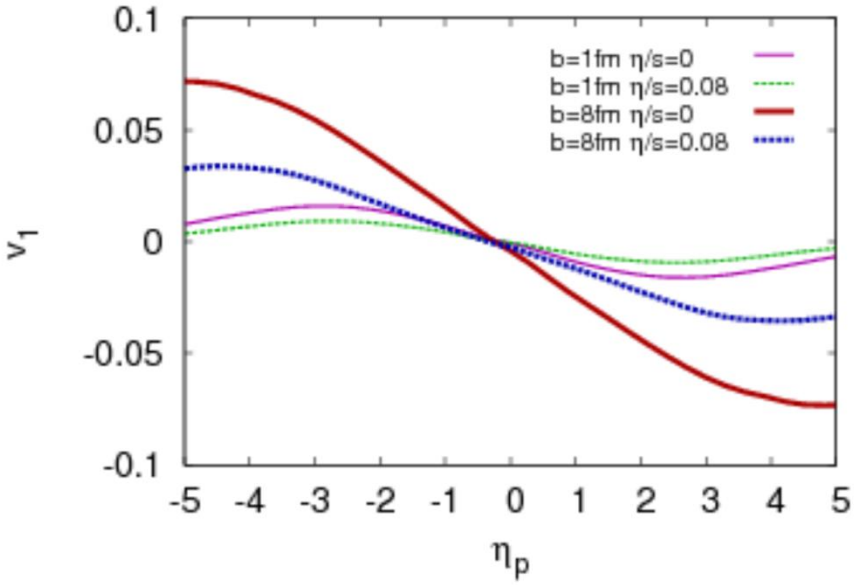
Work in progress

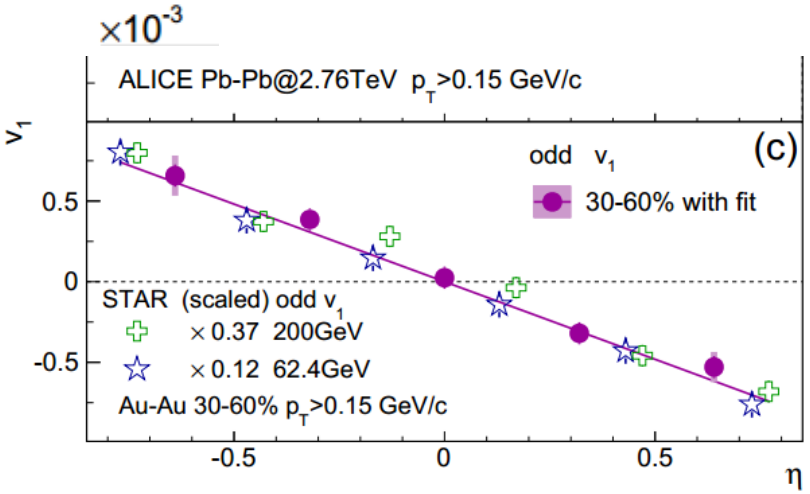
ALICE, Bulk Properties of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV measured by ALICE (2011)

Work in progress with Björn Schenke (to appear)

MUSIC RESULTS, PRELIMINARY

Directed flow: right ball-park values





Note: somewhat subtle to measure; event-plane etc

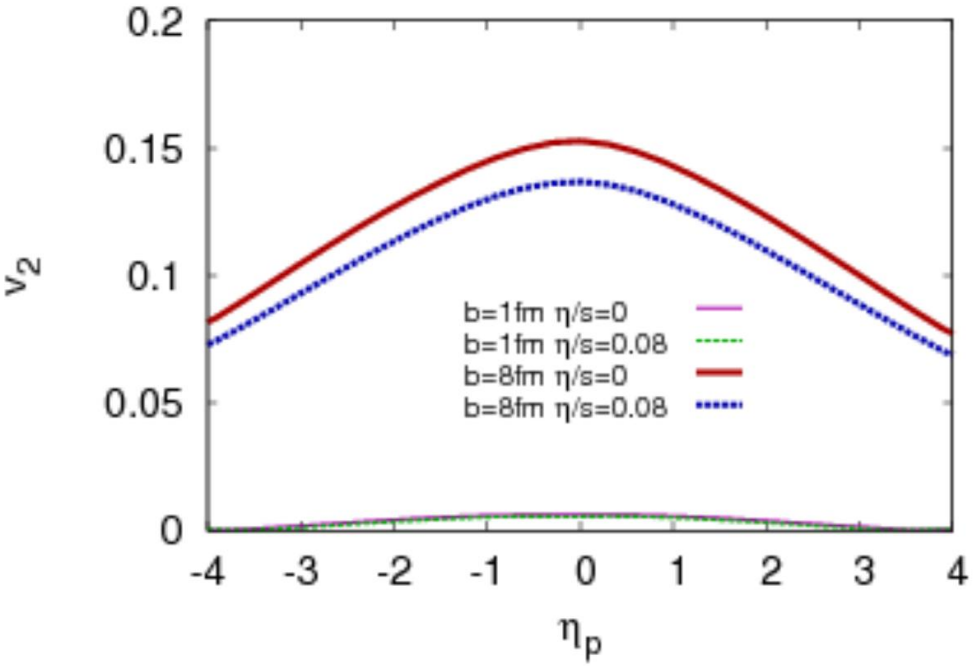
Could be very sensitive to viscosity

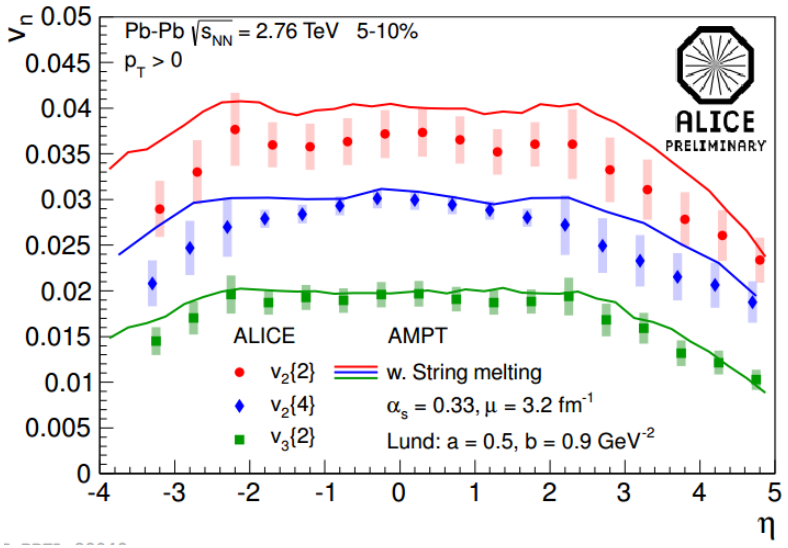
ALICE, Directed flow of charged particles at mid-rapidity relative to the spectator plane in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (2013)

Work in progress with Björn Schenke (to appear)

MUSIC RESULTS, PRELIMINARY

Elliptic flow: work in progress



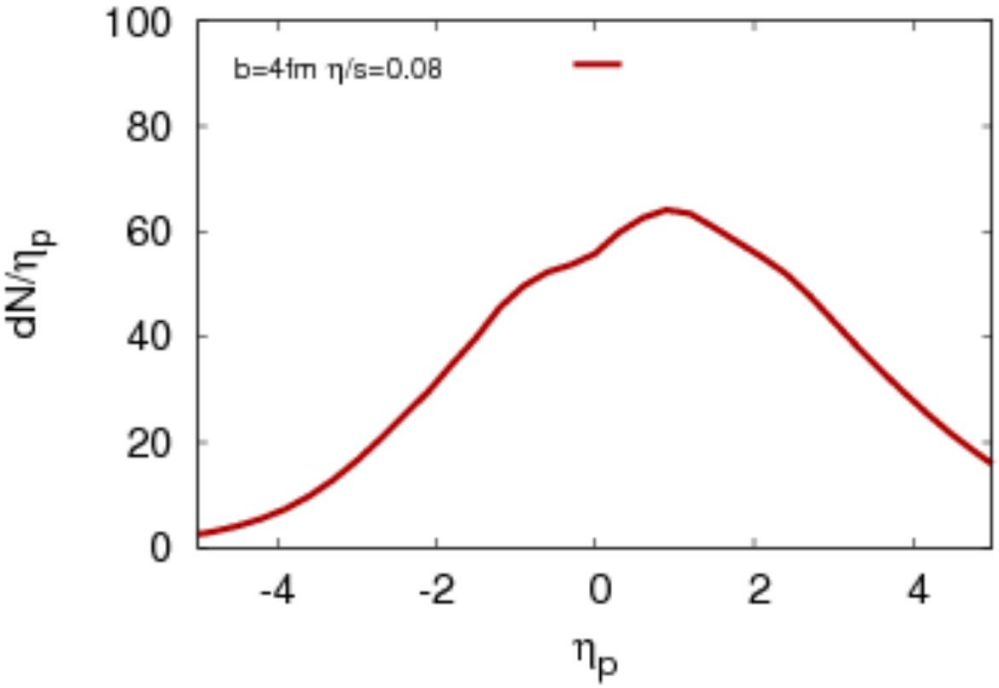


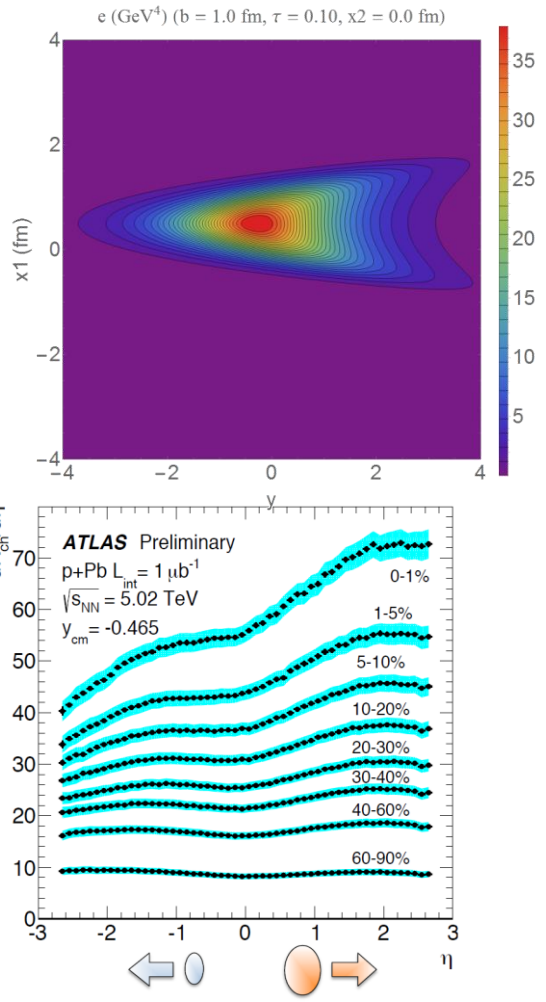
p-Pb: EVEN MORE NON-TRIVIAL?

Shift rapidity profile to local c.o.m.

Correct shape, a bit too narrow again

- See also old article by Peter Steinberg

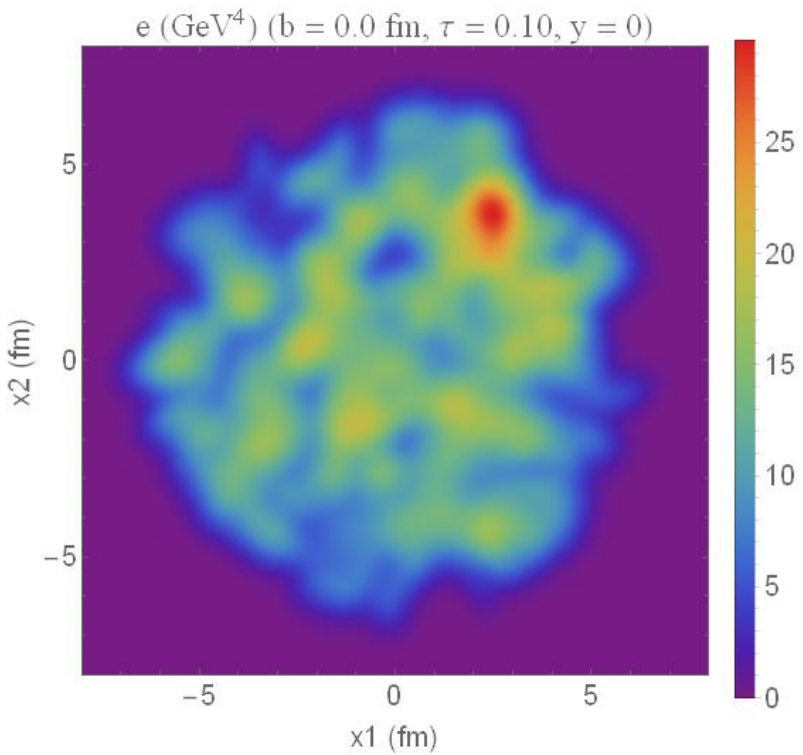


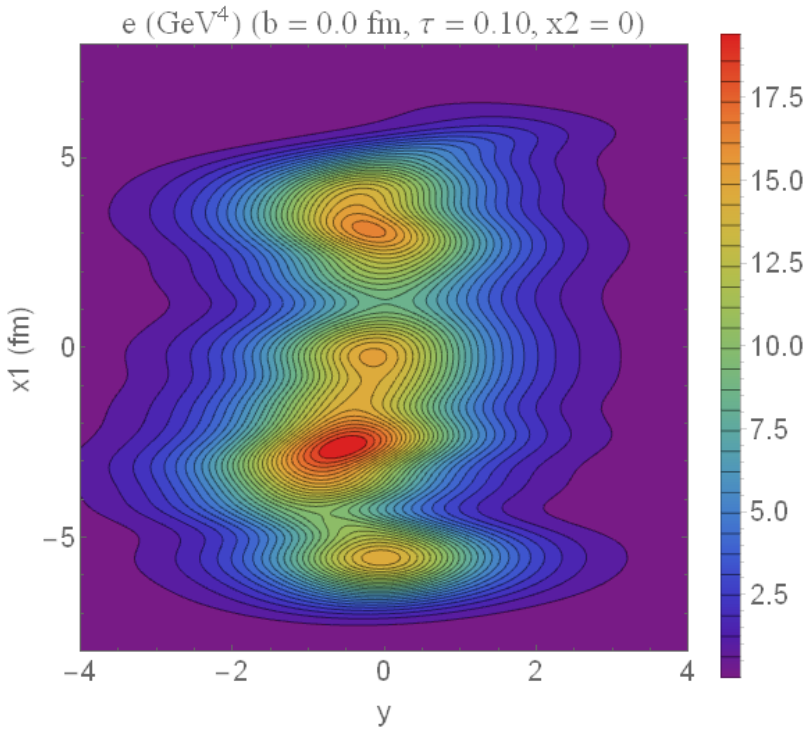


P. Steinberg, Inclusive Pseudorapidity Distributions in p(d)+A Collisions Modeled With Shifted Rapidity Distributions (2007)

EVENT-BY-EVENT

Single events are not smooth spheres: large fluctuations





More non-trivial:

- **rapidity distribution widens**
- **average energy density goes down**

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DISCUSSION

A universal rapidity profile

- Initial state: Gaussian rapidity profile, with Bjorken velocity
- AdS/CFT: simple and strong predictions: fits data??

AdS/CFT plus MUSIC 3+1 hydro very exciting: stay tuned ☺

- Directed flow as function of rapidity
- p-Pb energy just Gaussian shifted in rapidity?
- Test different transverse plane models?
- Rapidity dependence perhaps not studied enough?

Future is open: *correct for infinite coupling approximation*, finite baryon density, non-conformal theories, confining theories……