



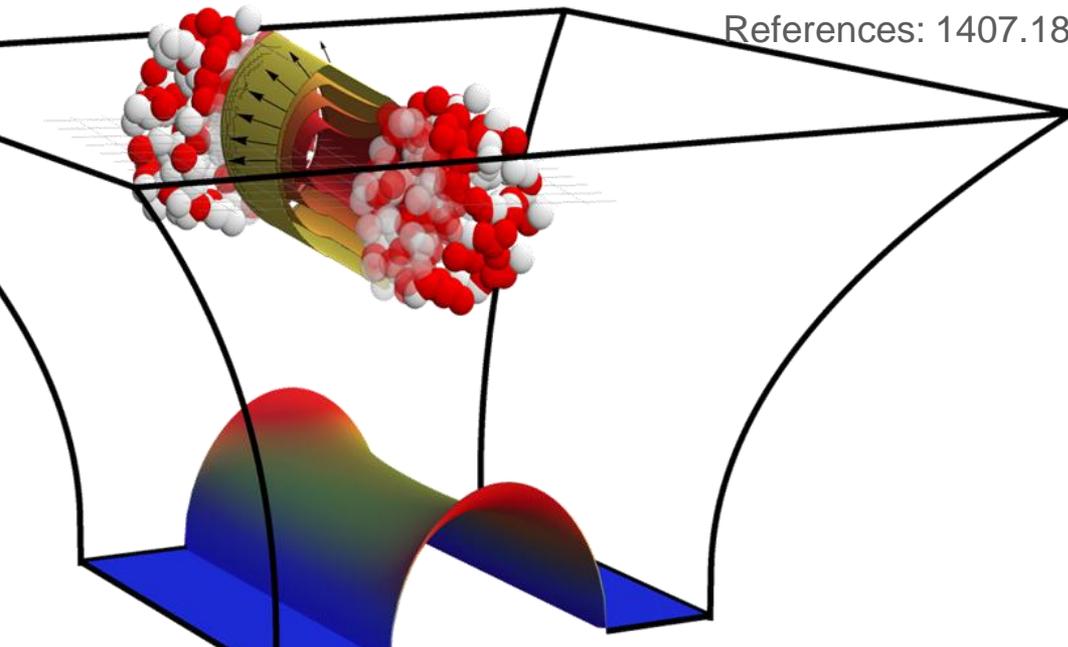
STRONG COUPLING QGP THERMALISATION WITH LONGITUDINAL DYNAMICS

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, Paul Chesler and Steve Gubser,

New work with Björn Schenke

References: 1407.1849 (Thesis), 1408.2518, 1410.7408, to appear



Wilke van der Schee

Seminar BNL, 23 January 2015

OUTLINE

AdS/CFT: heavy ion 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 rapidity profile*
- To leading order, i.e. neglecting chemical potential, finite coupling etc

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

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

KEY HEAVY ION PHYSICS:

Surprising (?): quark-gluon plasma is a fluid!

- An almost ideal fluid

Experiment: billions of Pb or Au collisions

- Each has $\sim 1000(0)$ particles at RHIC (LHC)
- Study correlations, v_2 , but also v_3 etc
- \rightarrow very constraining data set!

Still lot of theoretical uncertainty

- Initial state (!), viscosity, jet observables



Pb+Pb @ $\sqrt{s} = 2.76$ ATeV

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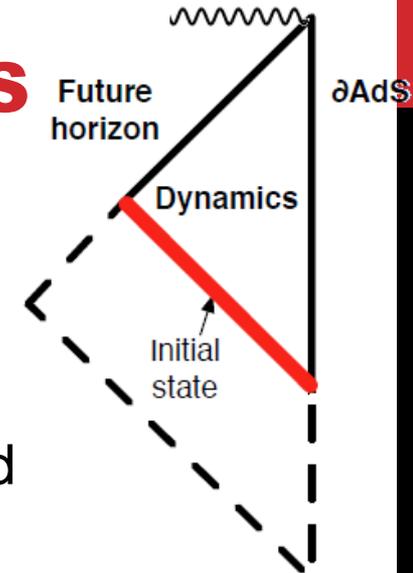
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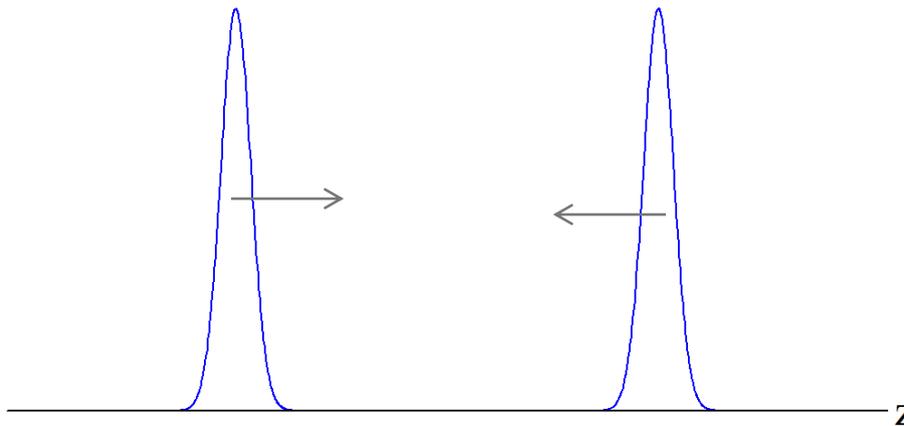
SHOCK WAVES – INITIAL CONDITIONS

Field theory interpretation:

- Start with energy as function of space
- Demand that it moves with speed of light
- \rightarrow quantum state/AdS geometry is completely fixed



Homogeneous in transverse plane (gradients small)

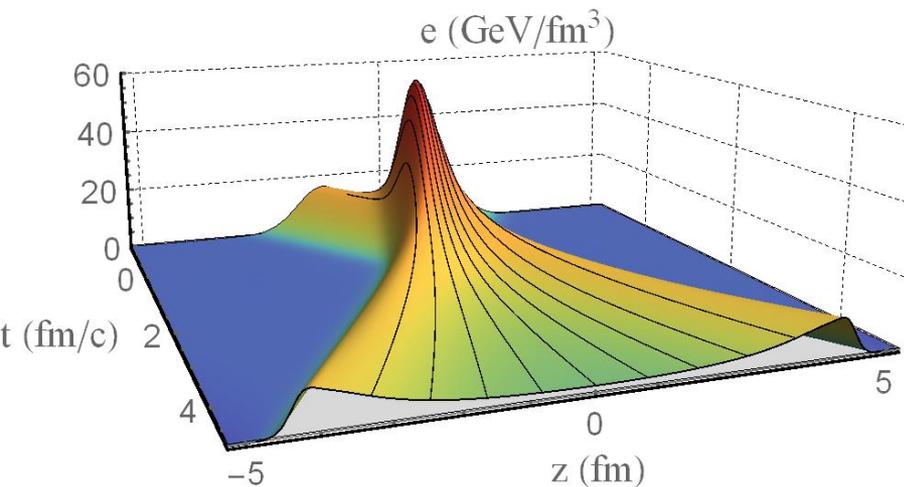


SHOCK WAVES – A DYNAMICAL CROSS-OVER

Colliding lumps of energy at infinite coupling, neglecting transverse dynamics

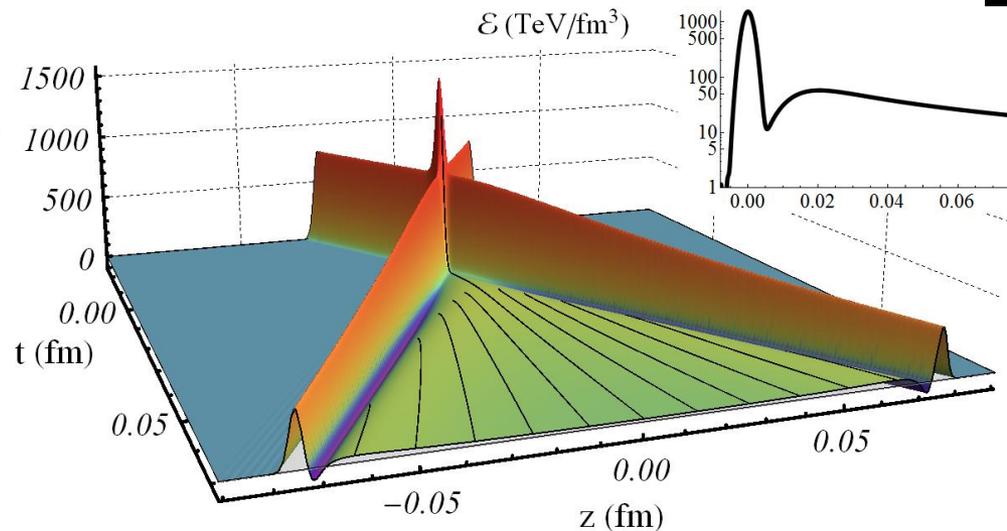
Low energy: Landau model, i.e. reasonably dN/dy (see work Peter Steinberg)

$$\sqrt{s_{NN}} = 19.3 \text{ GeV}$$



Benchmarks: $T_{\text{max}} = 440 \text{ MeV}$

$$\sqrt{s_{NN}} = 2.76 \text{ TeV}$$



$T_{\text{max}} = 2.6 \text{ GeV}$

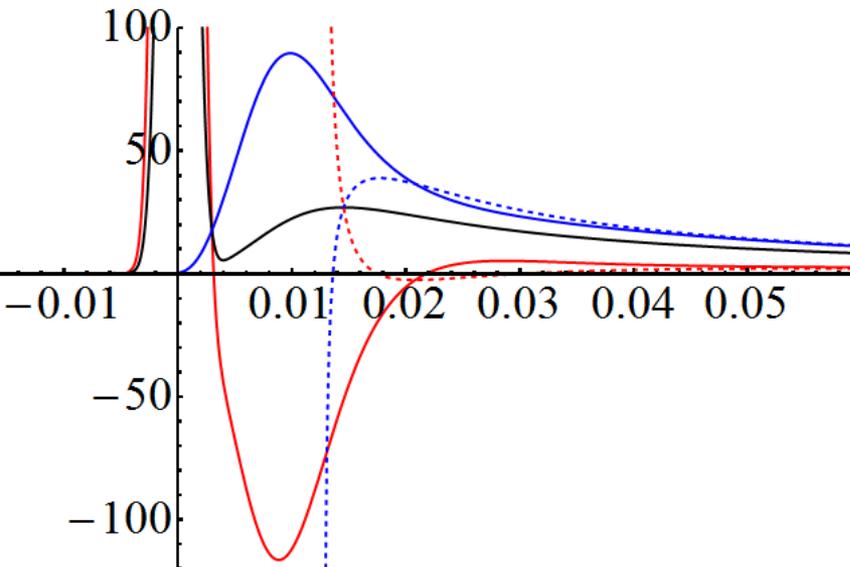
THERMALISATION/PRESSURES

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

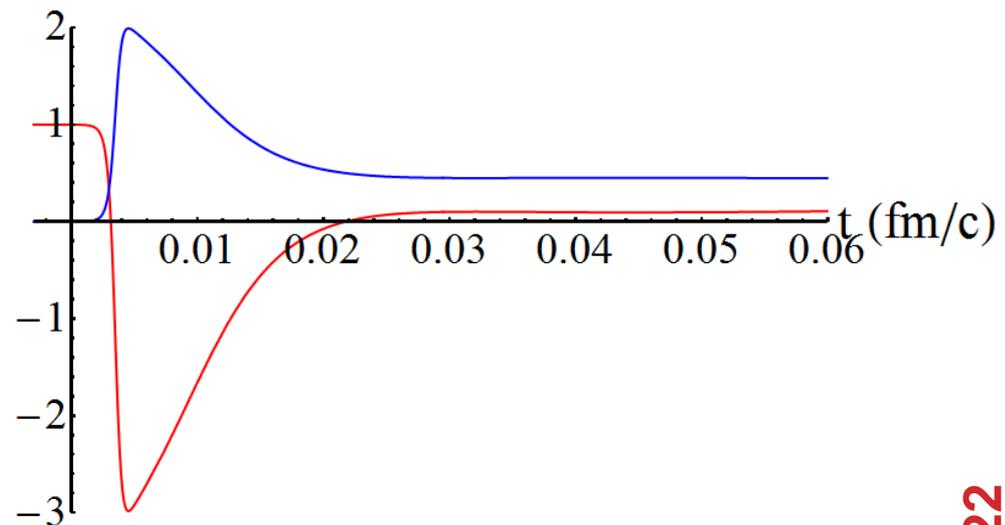
Thermalises very fast (hydro applies in perhaps 0.02 fm/c)

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

$e/3$ (black), P_L (red), P_T (blue) at $z = 0$ fm



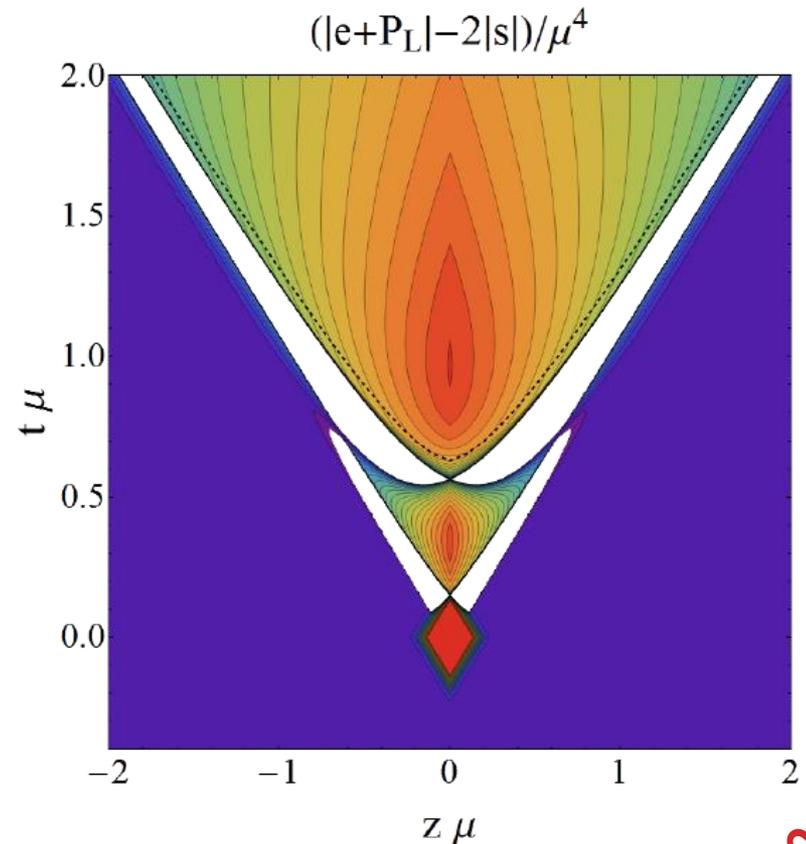
P_L/e (red) and P_T/e (blue), $z = 0$ fm



REGIONS WITHOUT A REST FRAME (THIN SHOCKS)

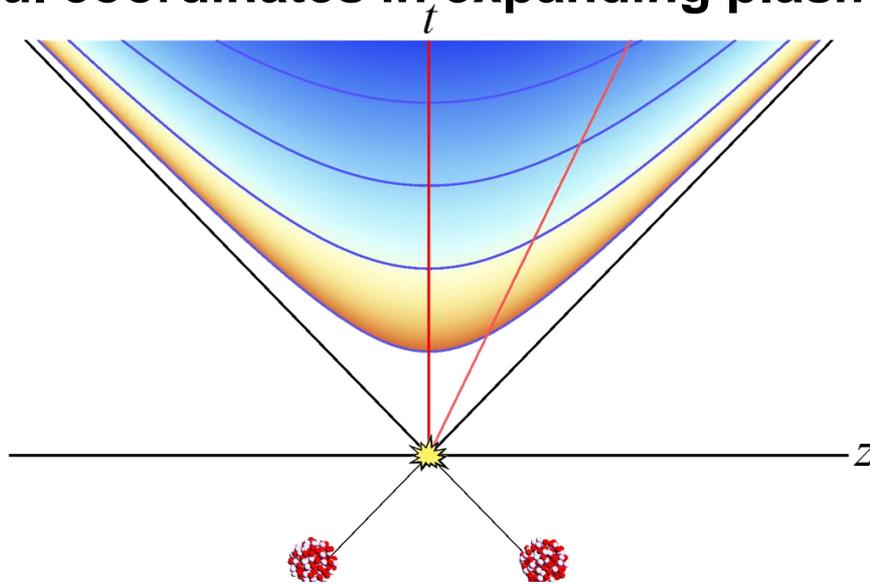
Work with Paul Romatschke and Peter Arnold (1408.2518)

- **Regions with negative energy density**
- **Regions where no Lorentz boost can diagonalise stress tensor!**
 - Also found in other systems
- **But no pathologies: well-defined quantum phenomenon**
 - Still curious: possibly present in HIC! (consequences??!)



RAPIDITIES AND *INITIAL STATE BI*

Useful coordinates in expanding plasmas:



$$t = \tau \cosh y$$

$$z = \tau \sinh y$$

Weak coupling: interactions follow charge

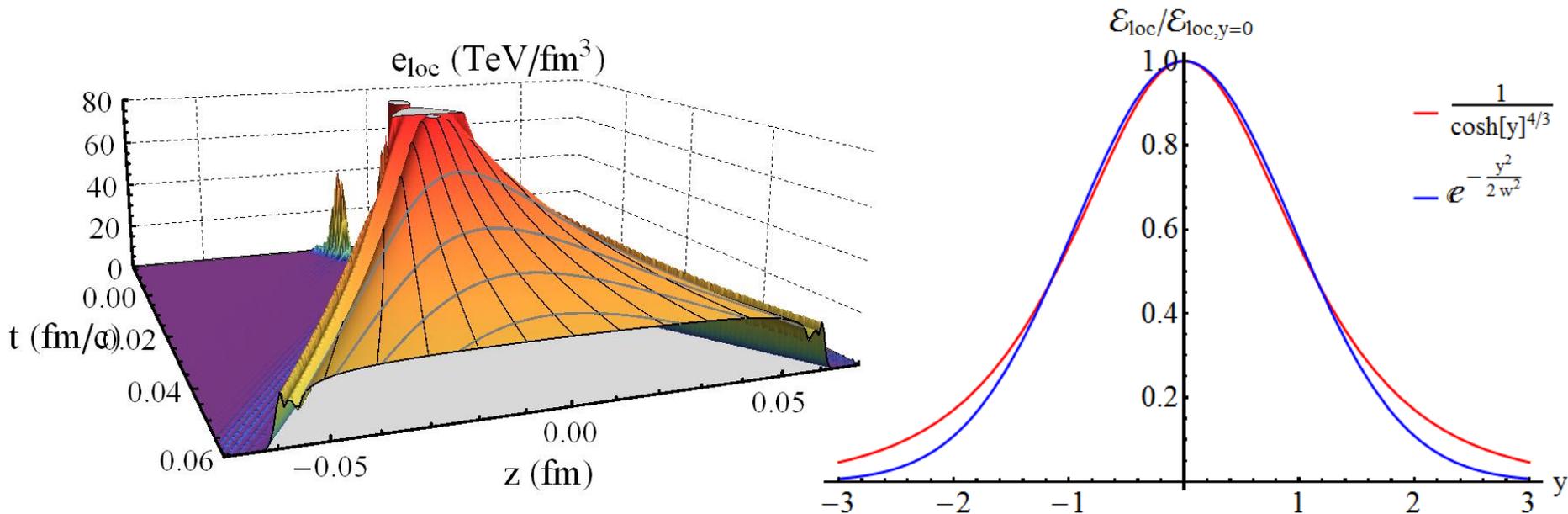
- Boost-invariant if moving on light-cone

Strong coupling: interactions follow energy

- Receives γ -factor on boosting, even if $v \approx c$

A UNIVERSAL RAPIDITY PROFILE

Local energy density, flat in z , Gaussian-like in rapidity



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

DIMENSIONAL ANALYSIS 1.0



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

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

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

- **Idea: during thermalisation no (local) transverse scale either!**
 - I.e. thermalisation time $\ll 0.1 \text{ fm}$, transverse scale $\gg 0.1 \text{ fm}$
 - 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 \rightarrow decoupling of transverse dynamics**

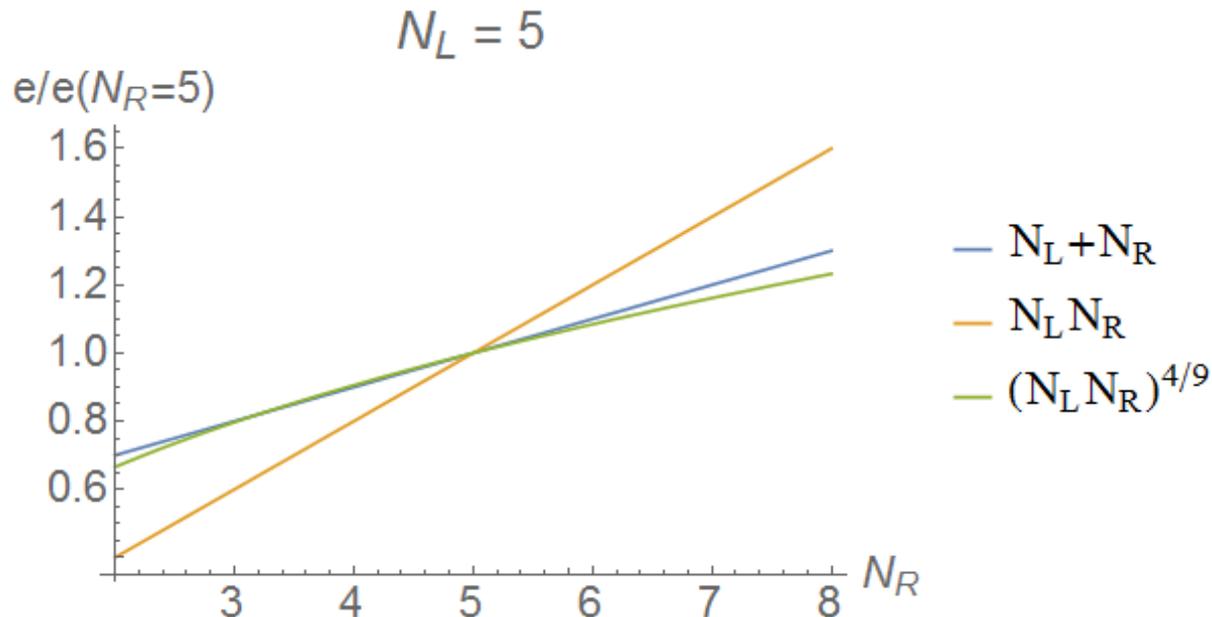
WOUNDED VS BINARY

$$\mu^3 \sim e_{\perp}(\text{GeV}/\text{fm}^2) \sim \sqrt{s_{NN}}$$

- **Produced energy at mid-rapidity:**

$$e(y=0) \sim \mu^{8/3} \tau^{-4/3} \sim (\sqrt{e_L e_R})^{8/9}$$

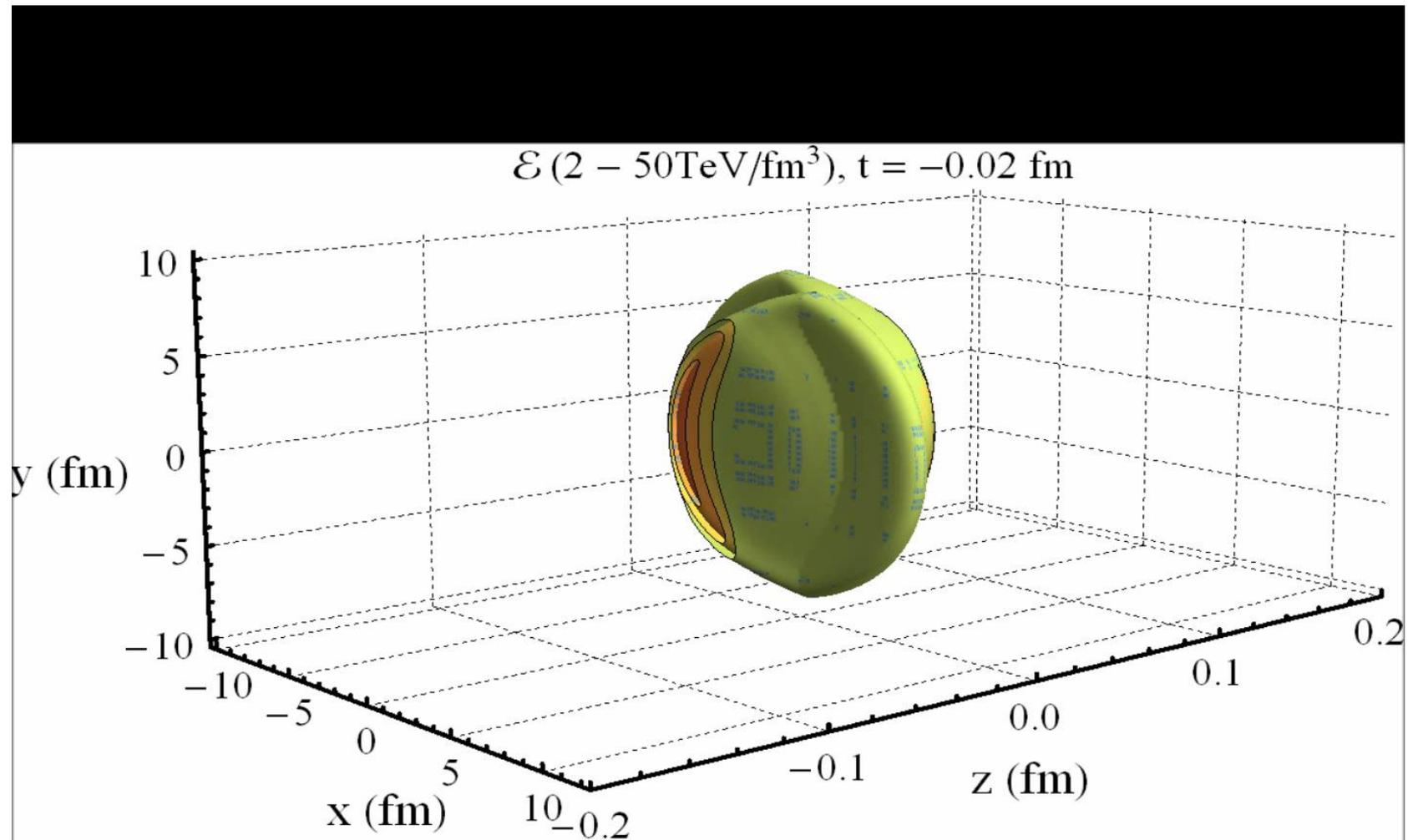
I.e. no “wounded” or “binary” scaling (but close to wounded in AA(!))



COLLIDING TWO NUCLEI:

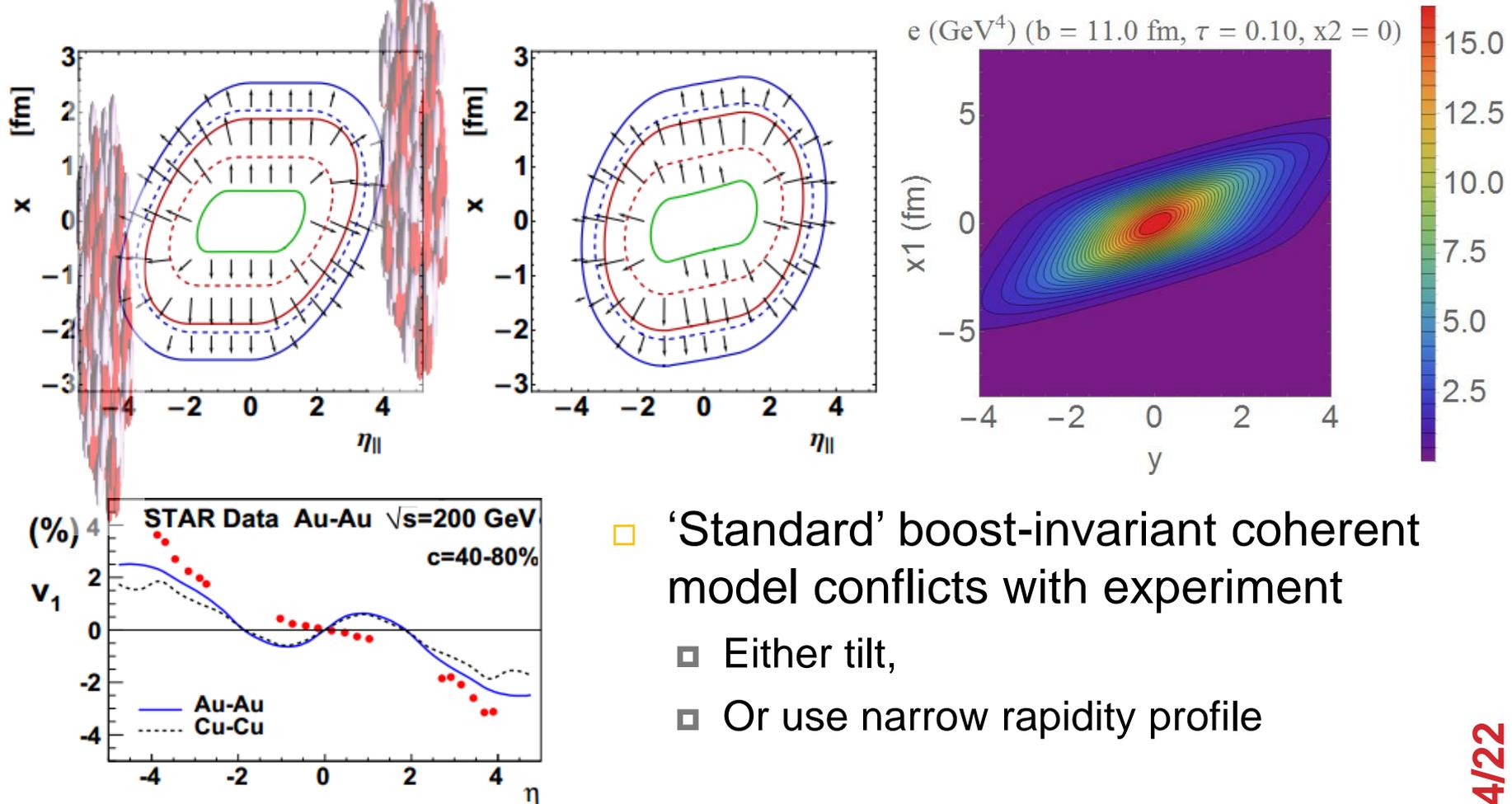
Locally in transverse plane: use shock waves (i.e. Gaussian rapidity)

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



DIRECTED FLOW AND LONGITUDINAL DYNAMICS

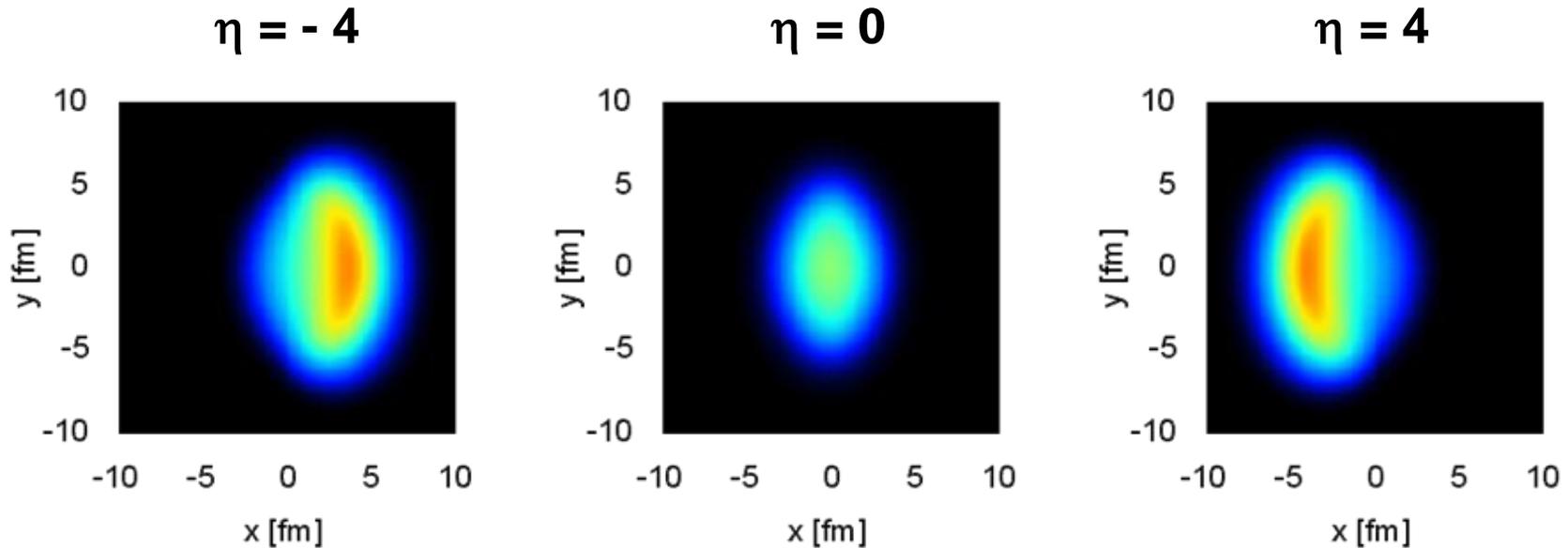
In non-central collisions there is directed flow:



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

Work in progress with Björn Schenke (to appear)

MUSIC RESULTS



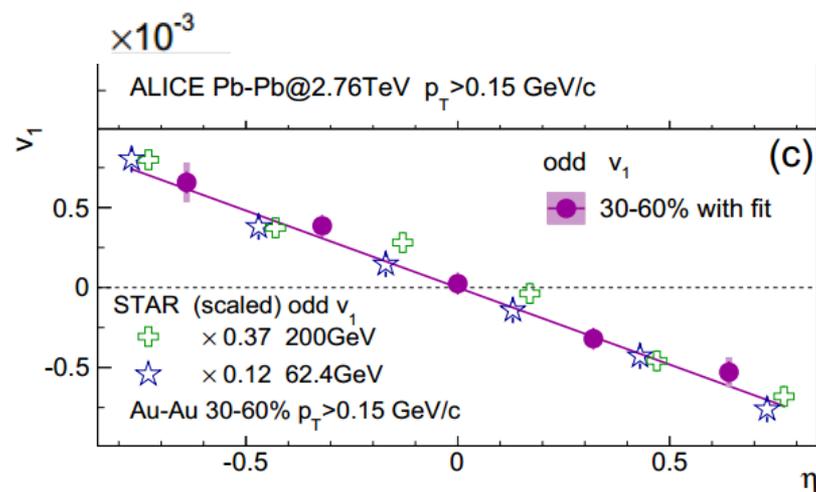
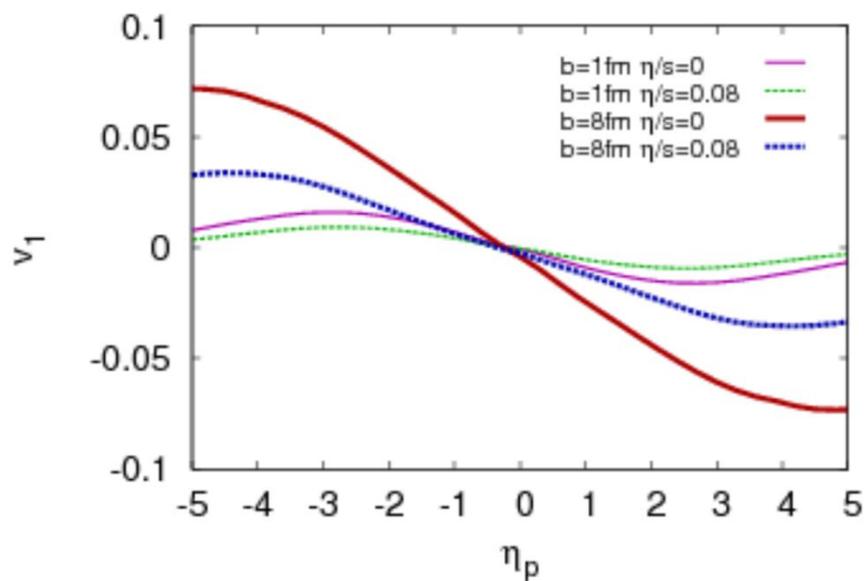
Impact parameter 8 fm, time 0.1 fm/c to 10 fm/c

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

Work in progress with Björn Schenke (to appear)

MUSIC RESULTS, PRELIMINARY

Directed flow: right ball-park values



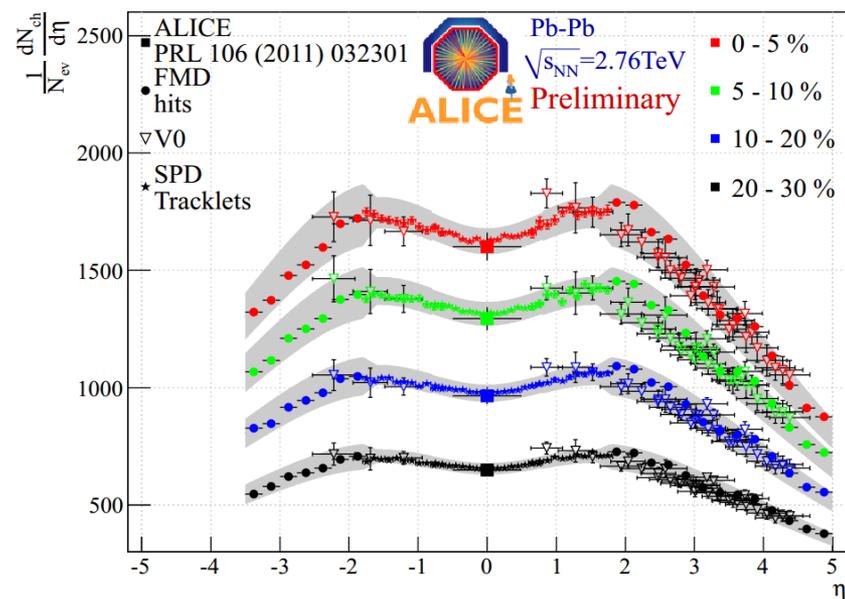
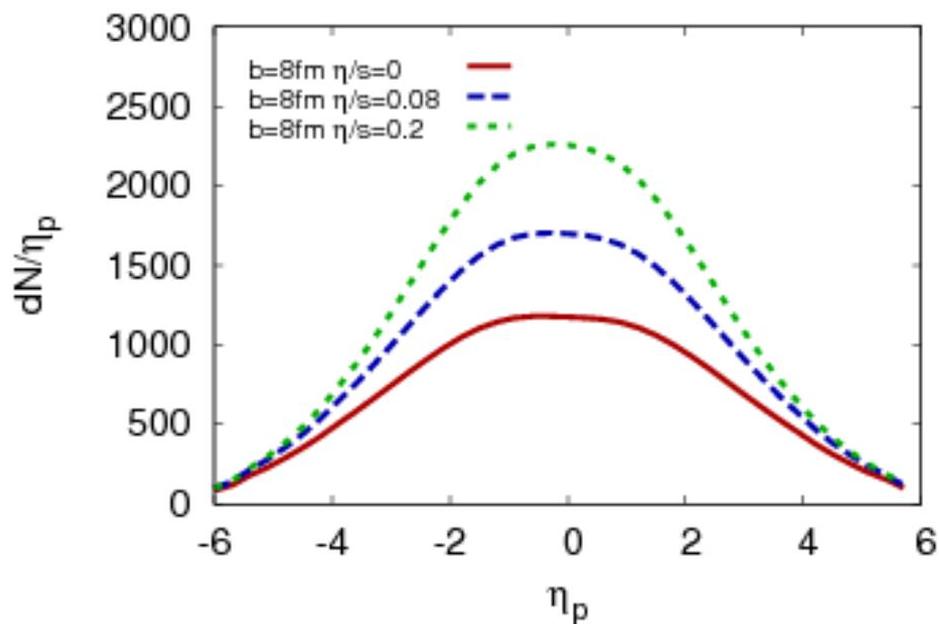
Note: somewhat subtle to measure; event-plane etc

Could be very sensitive to viscosity

Work in progress with Björn Schenke (to appear)

MUSIC RESULTS, PRELIMINARY

Particle spectra in longitudinal direction:



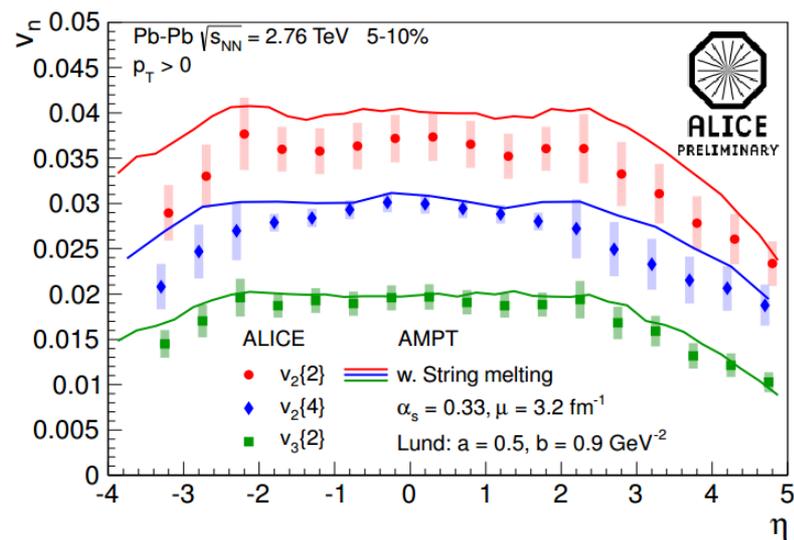
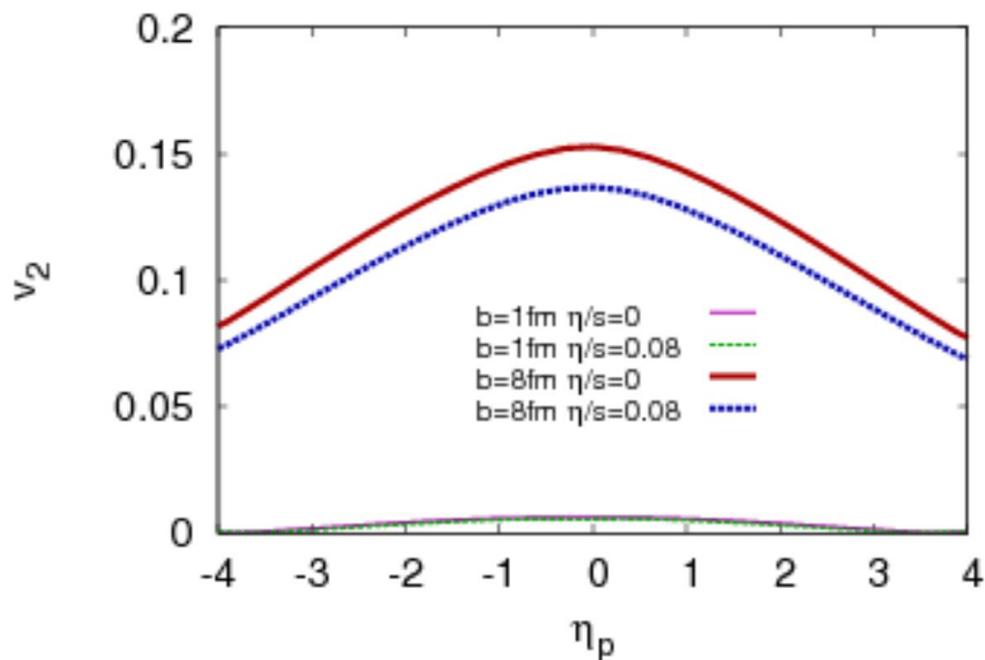
Fluctuations can change profile

Work in progress

Work in progress with Björn Schenke (to appear)

MUSIC RESULTS, PRELIMINARY

Elliptic flow: work in progress

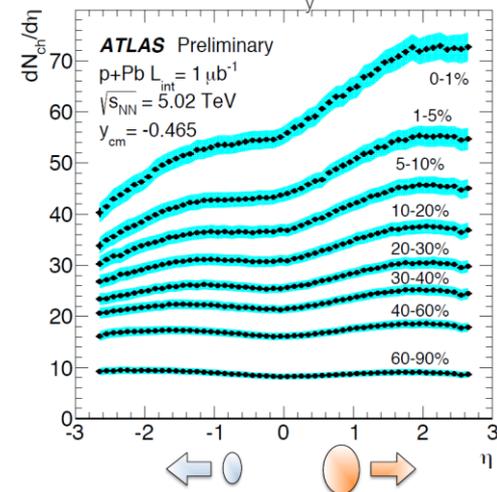
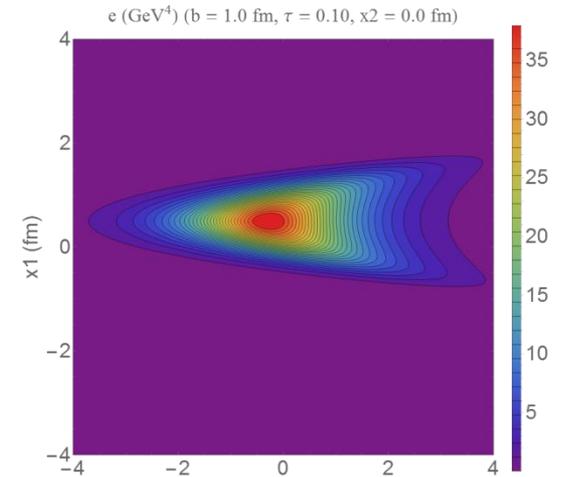
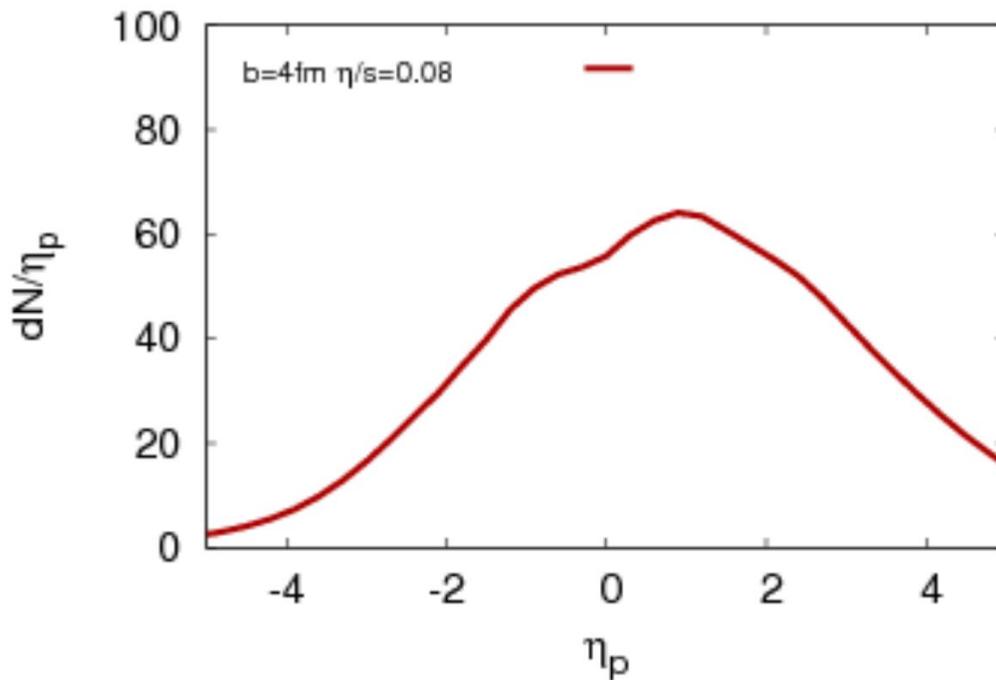


p-Pb: EVEN MORE NON-TRIVIAL?

Shift rapidity profile to local c.o.m.

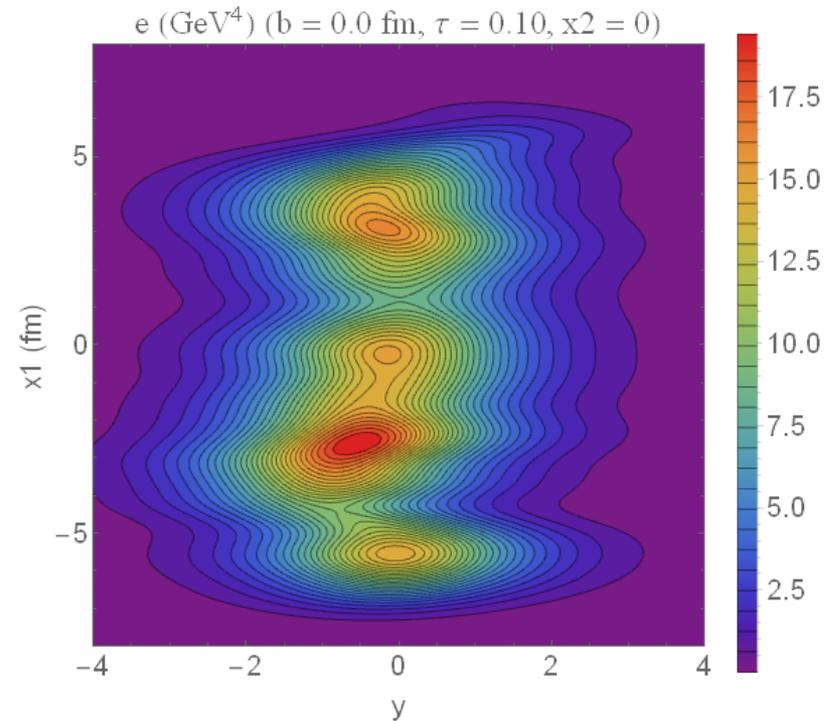
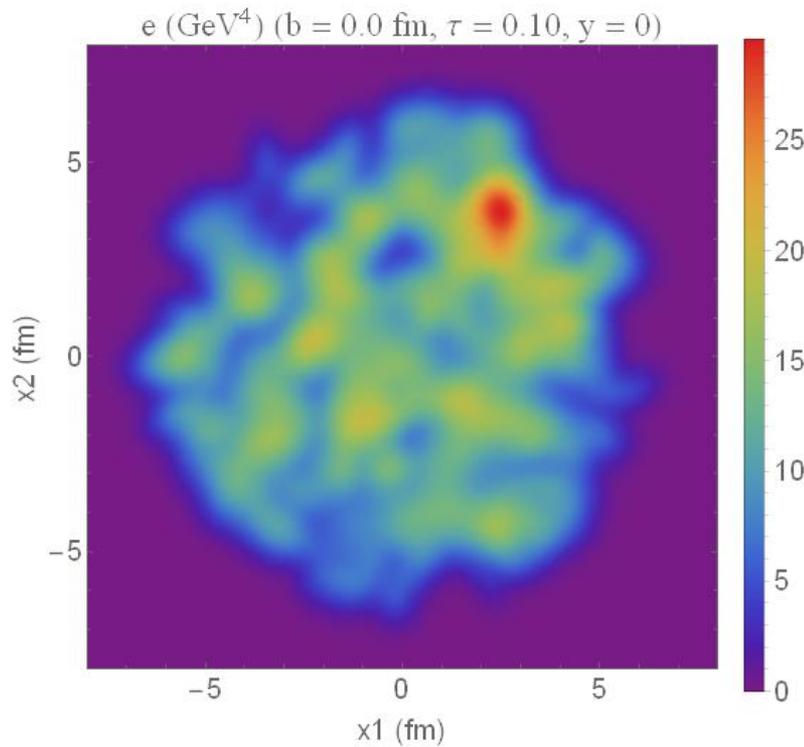
Correct shape, a bit too narrow again

- See also old article by Peter Steinberg



EVENT-BY-EVENT

Single events are not smooth spheres: large fluctuations

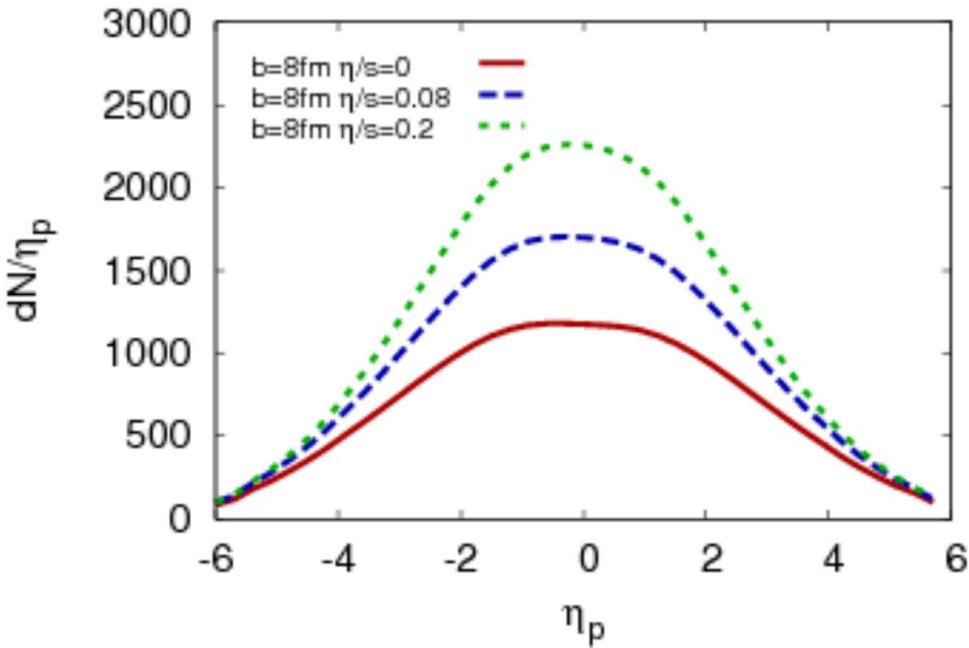


More non-trivial:

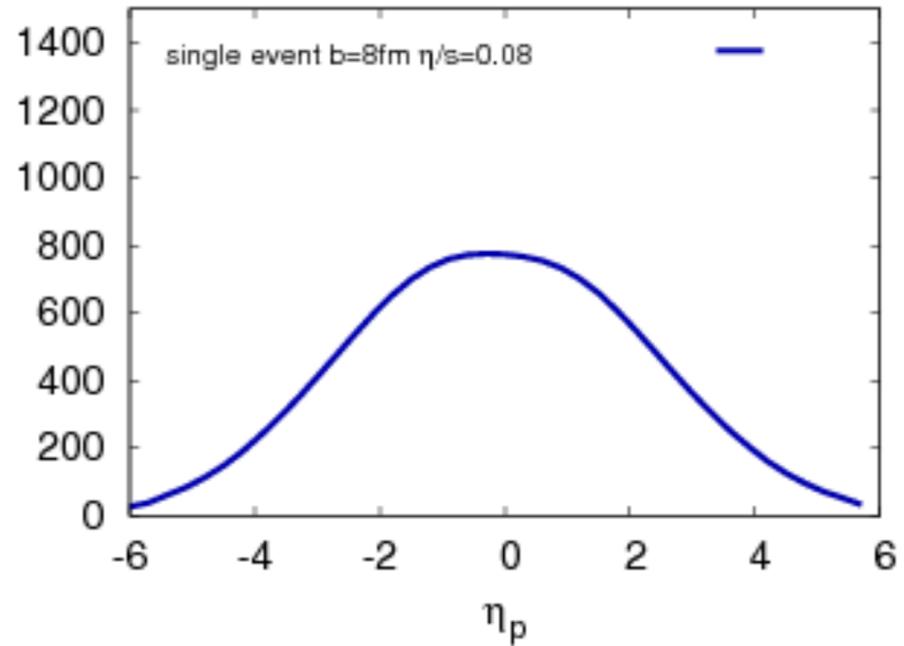
- rapidity distribution widens
- average energy density goes down

EVENT-BY-EVENT

Without fluctuation:



With fluctuation:



Big decrease in total multiplicity

- relates back to old computations by Gubser/Pufu/Yarom/Lin/Shuryak
- i.e. $dN/d\eta$ very sensitive to energy distribution of a nucleon

DISCUSSION

A universal rapidity profile

- Initial state: universal 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? Fluctuations?
- Rapidity dependence perhaps not studied enough?

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