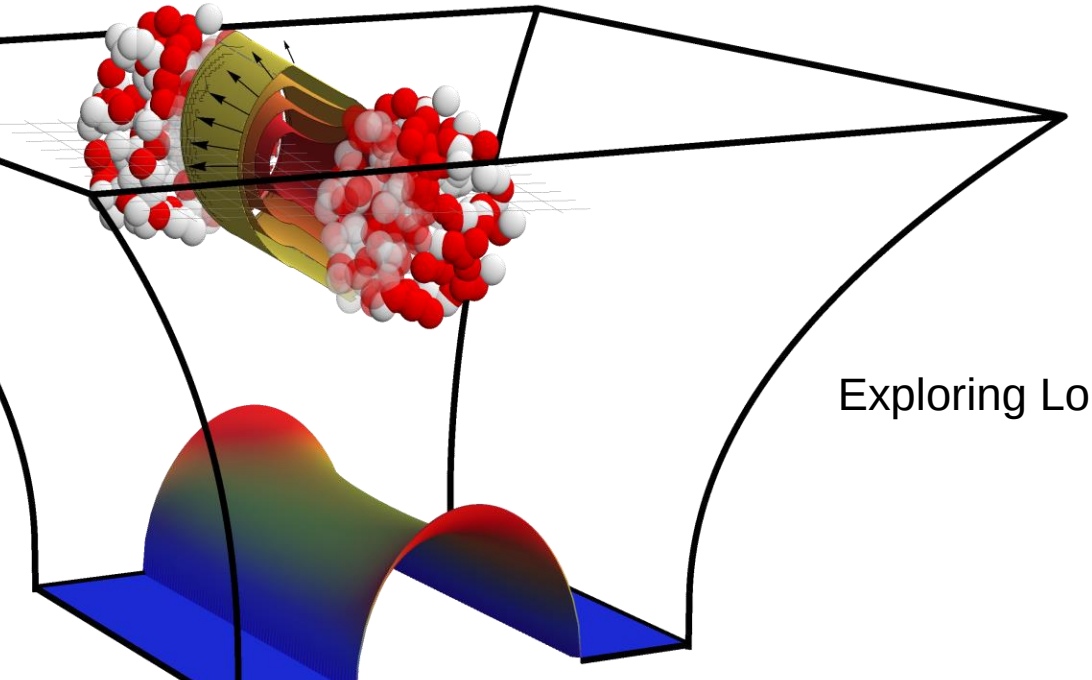
RAPIDITY DEPENDENCE IN HOLOGRAPHIC HEAVY ION COLLISIONS

TOWARDS MORE REALISTIC MODELS OF QGP FORMATION

Based on work with Michał Heller, David Mateos, Jorge Casalderrey-Solana, Miquel Triana, Paul Romatschke, Scott Pratt, Peter Arnold, Paul Chesler, Steve Gubser and Björn Schenke

References: 1407.1849 (Thesis), 1507.02548 (JHEP), 1507.06789 (PRC)



Wilke van der Schee

Exploring Longitudinal Dynamics in HIC at RHIC
Brookhaven, 20 January 2016

HEAVY IONS AT STRONG COUPLING

Not necessarily close to QCD (uncontrolled approximation)

- Different field content: perhaps not so bad in thermal phase?
- Initial stage at high energy, i.e. weak or intermediate coupling

Goal: use AdS/CFT in quantitative models for quark-gluon plasma

- First to leading order, i.e. *infinite coupling benchmark*
- A lot of room for improvement
  (confinement, intermediate coupling, etc)

New:

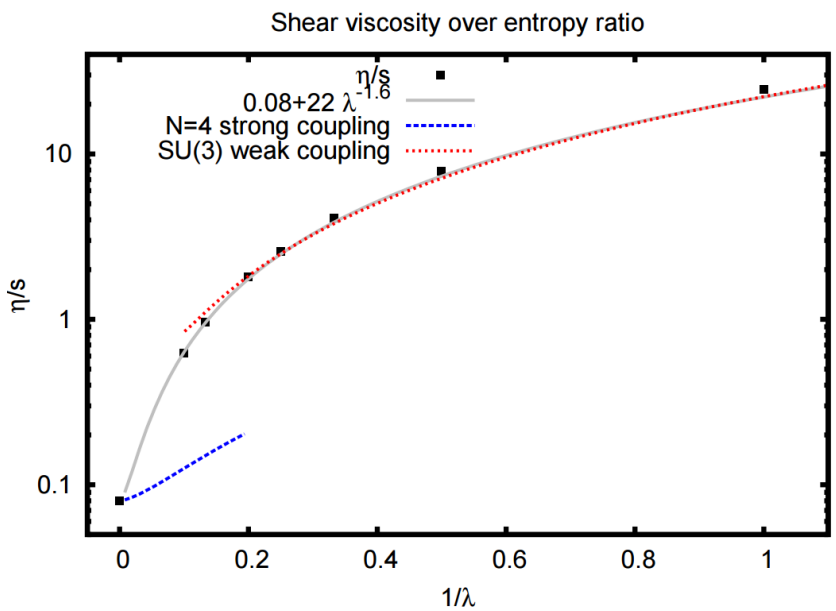
- Colliding holographic ions with a conserved charge, rapidity profile
- Influence of fluctuations on rapidity profile

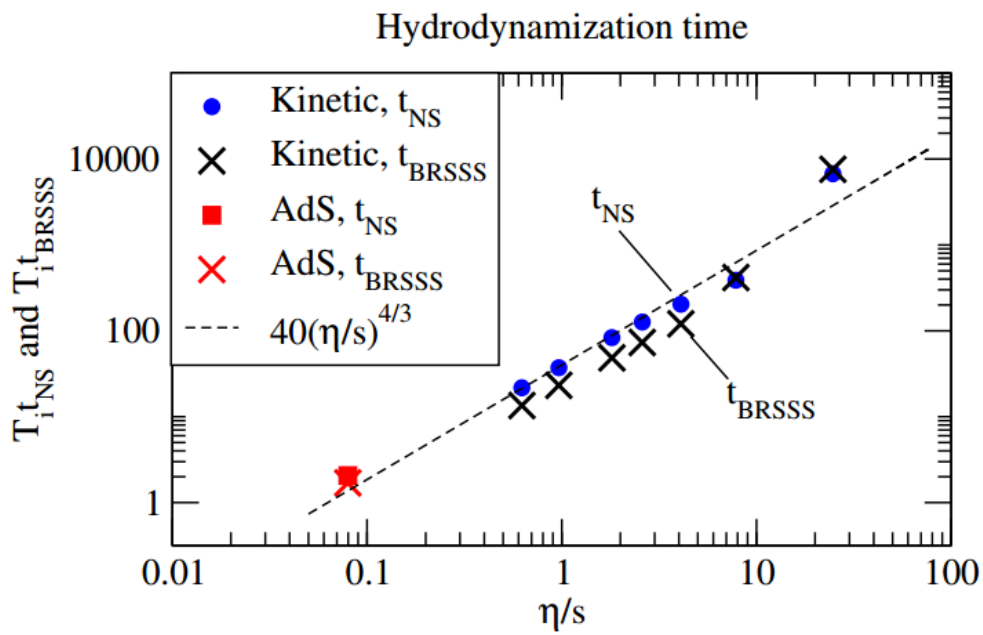
With Liam Keegan, Aleksi Kurkela, Paul Romatschke and Yan Zhu (1512.05347)

BRACKETING THE REAL WORLD?

Advertisement of recent work

- Apples-to-apples of kinetic theory versus AdS/CFT
- Start with thermal state
- Pulse of curved spacetime: go from homogeneous to boost-invariant



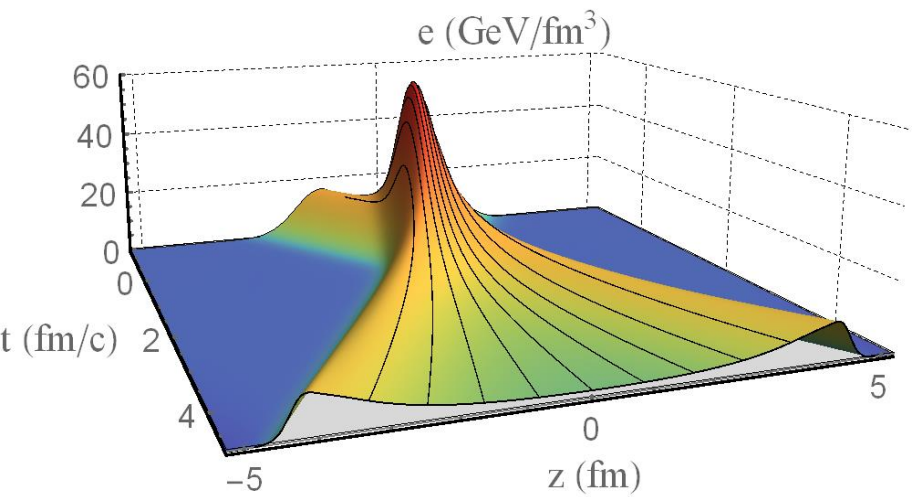


Now: longitudinal dynamics

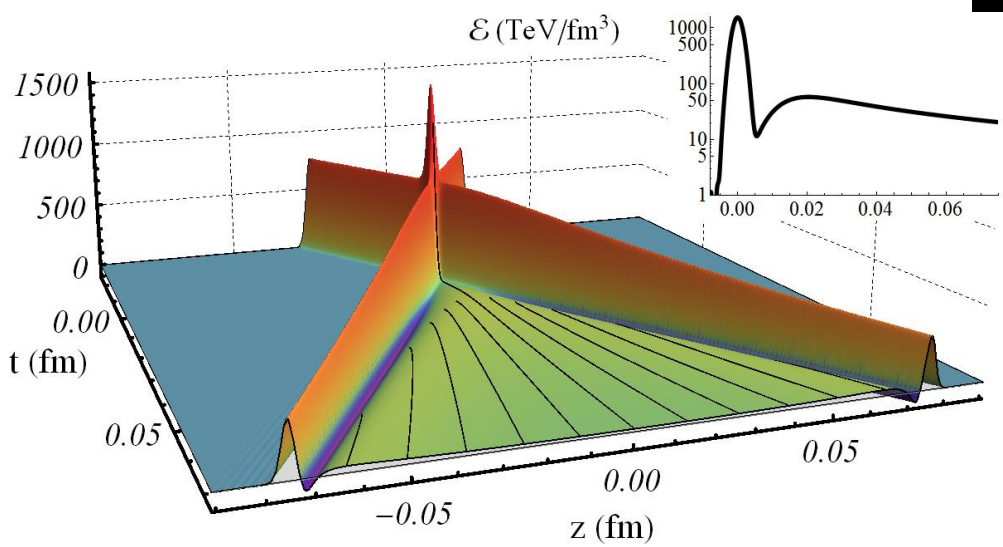
SHOCK WAVES – A DYNAMICAL CROSS-OVER

Colliding lumps of energy at infinite coupling, neglecting transverse dynamics

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



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

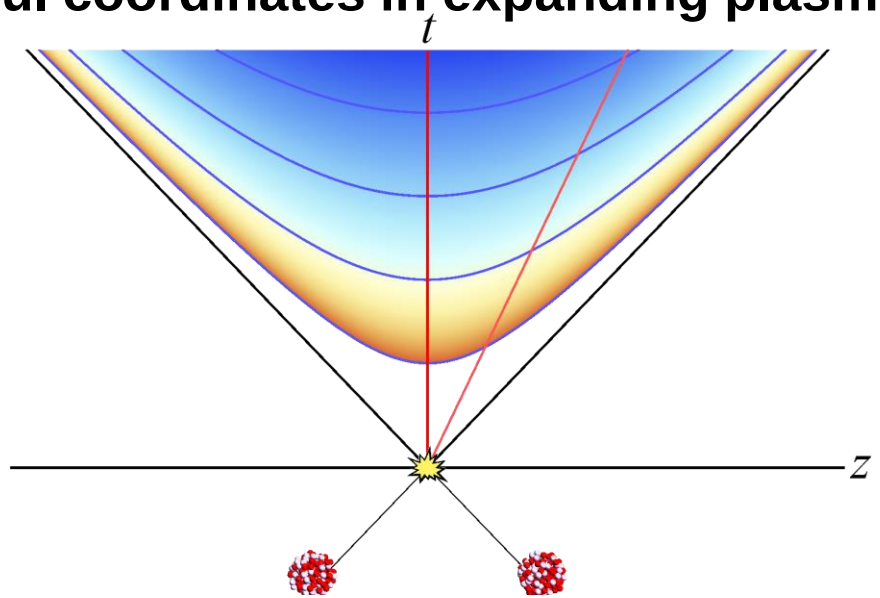


Benchmarks: $T_{\max} = 440\ \mathrm{MeV}$ $T_{\max} = 2.6\ \mathrm{GeV}$

P.M. Chesler and L.G. Yaffe, Holography and colliding gravitational shock waves in asymptotically AdS_5 spacetime (2010)
J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, From full stopping to transparency in a holographic model of heavy ion collisions (2013)

RAPIDITIES AND *INITIAL STATE* BI

Useful coordinates in expanding plasmas:



$$t = \tau \cosh y$$

$$z = \tau \sinh y$$

Weak coupling: interactions follow charge

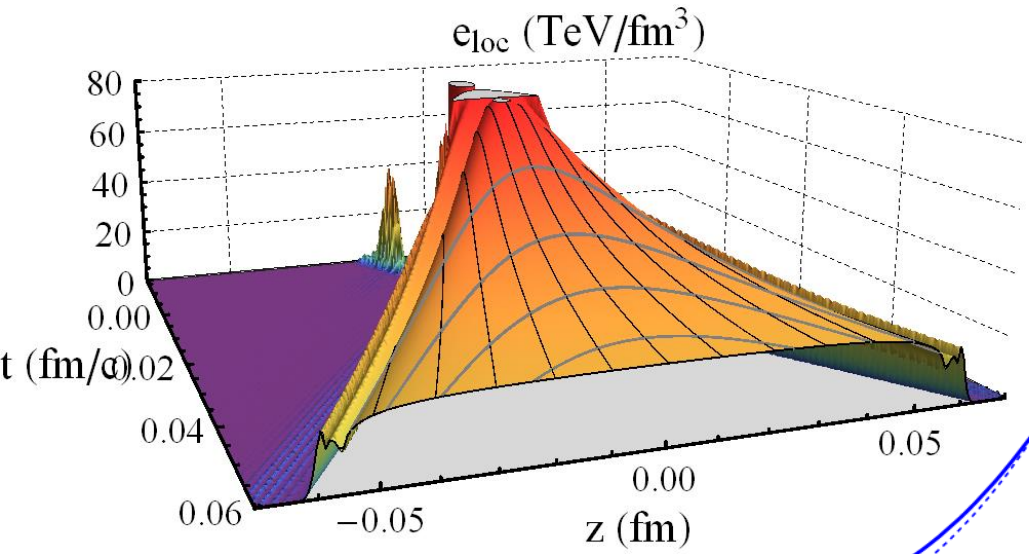
- Boost-invariant if moving on light-cone

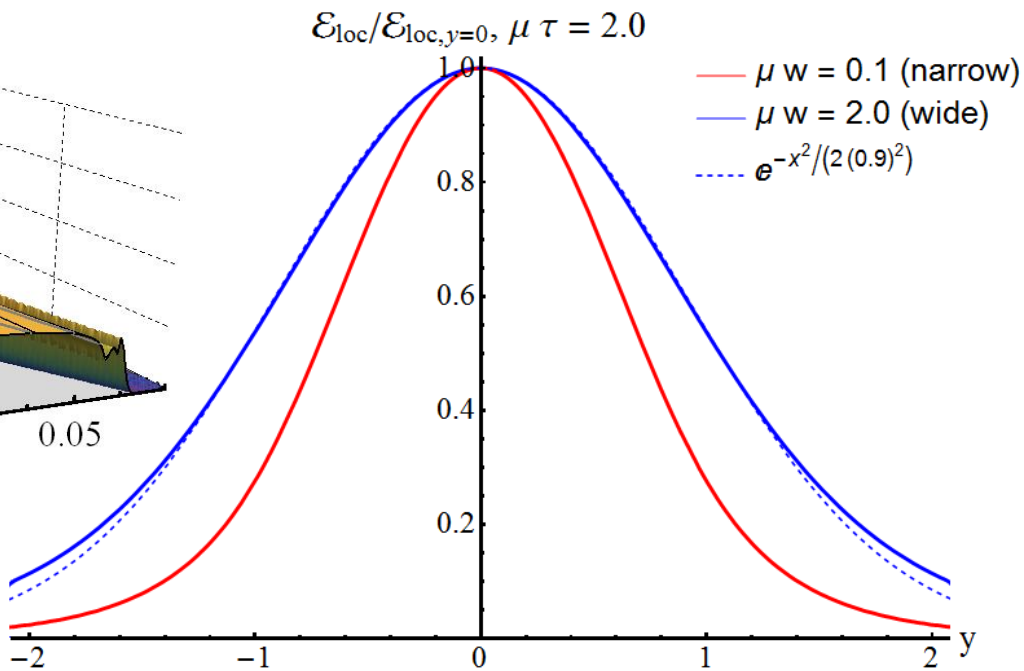
Strong coupling: interactions follow energy

- Receives γ-factor on boosting, even if v ≈ c

A UNIVERSAL RAPIDITY PROFILE

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





Universal profile at high energies (compare with pQCD)

J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, Longitudinal coherence in a holographic model of asymmetric collisions (2013)
P.M. Chesler, N. Kilbertus and WS, Universal hydrodynamic flow in holographic planar shock collisions (2015)

OFF-CENTRAL COLLISIONS

Everything depends only on: $\mu^3 \sim e_\perp(\mathrm{GeV}/\mathrm{fm}^2) \sim \sqrt{s_{NN}}$

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

More non-trivial:

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

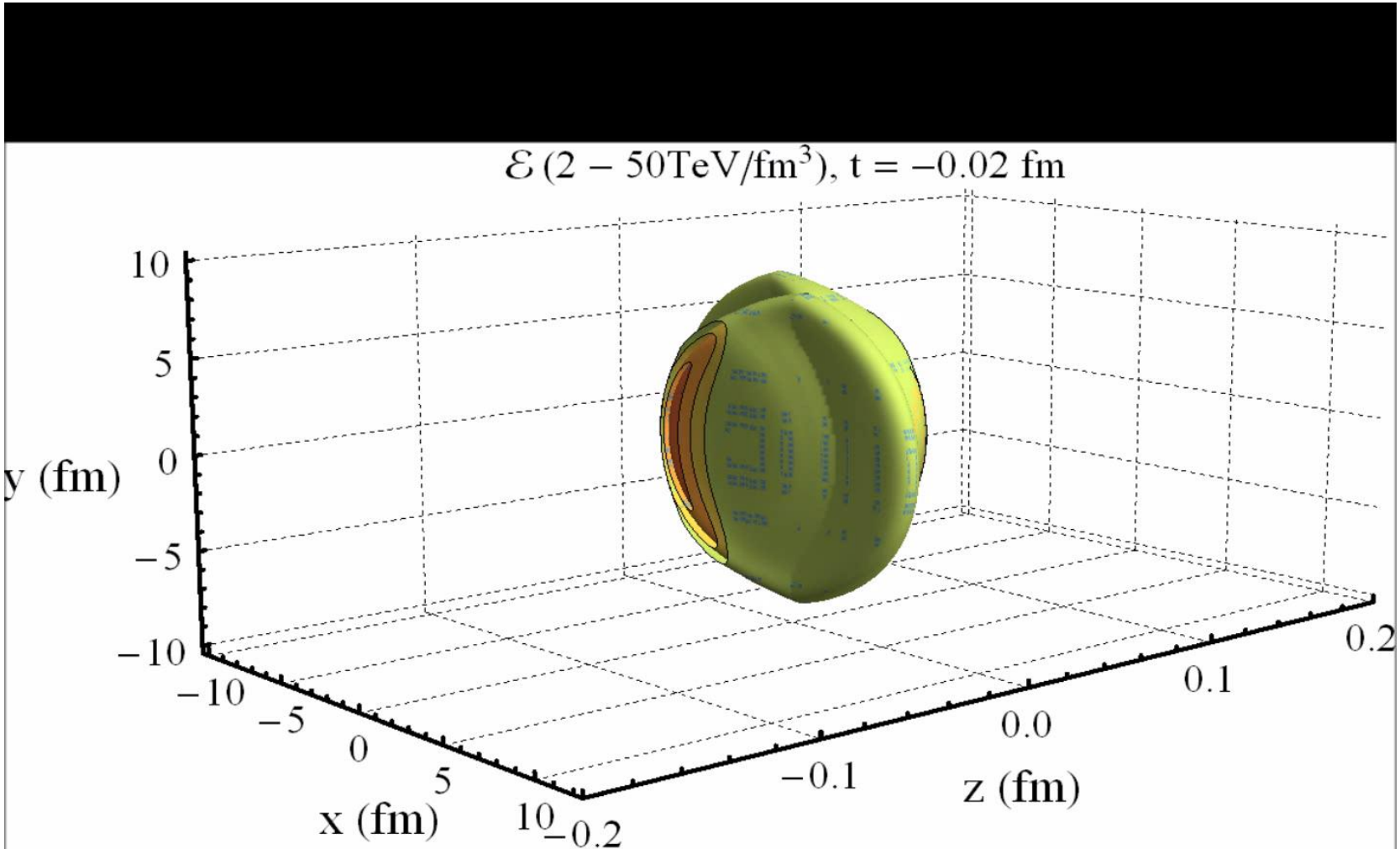
Take favourite model for transverse plane:

- **Here integrated Wood-Saxon (no fluctuations)**
- **Does not follow from AdS**

COLLIDING TWO NUCLEI:

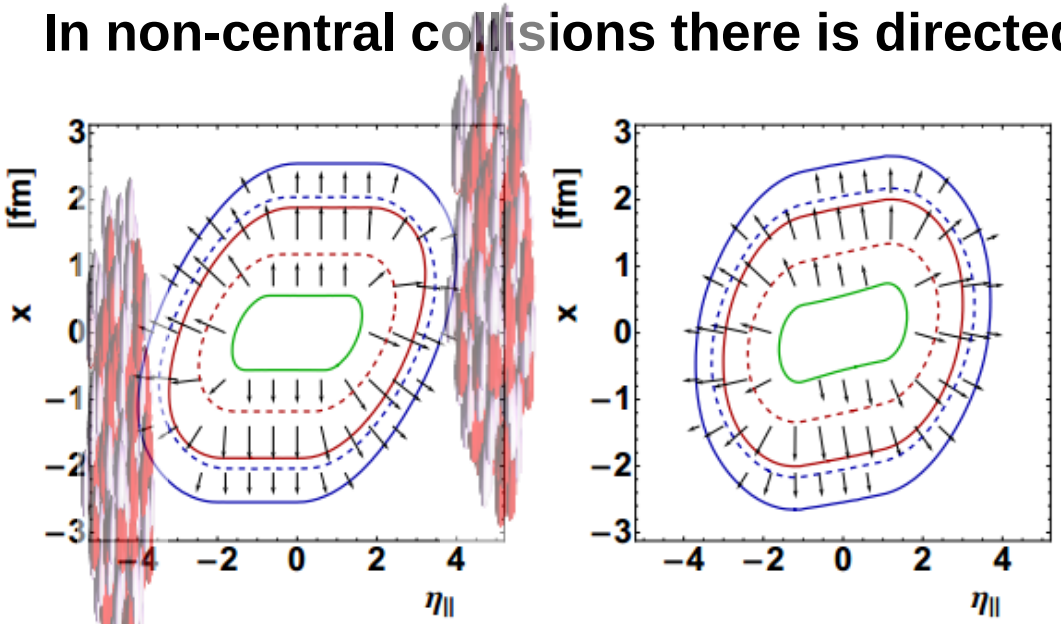
Locally in transverse plane: use shock waves (i.e. Gaussian rapidity)

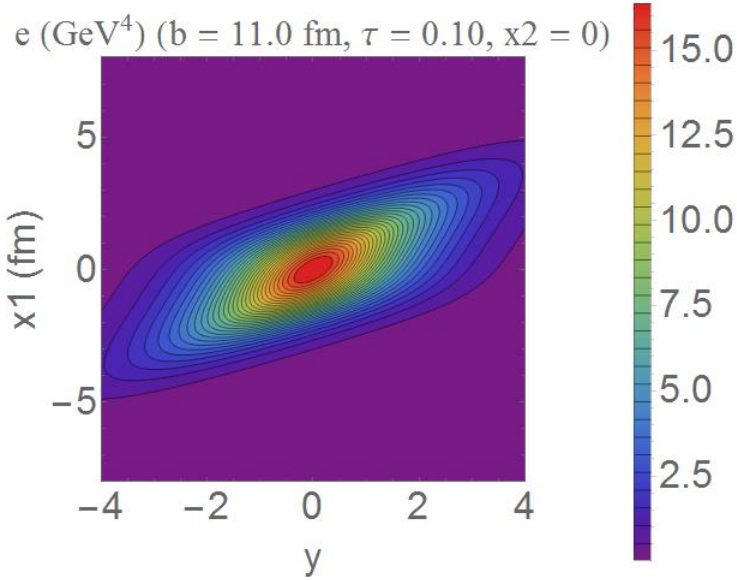
→ Go and run hydro (MUSIC) and get particle spectra ☺

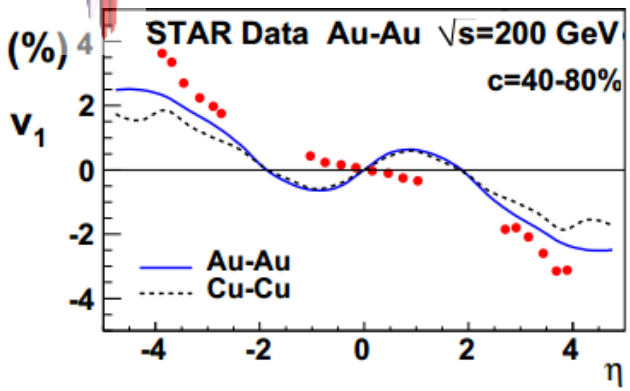


DIRECTED FLOW AND LONGITUDINAL DYNAMICS

In non-central collisions there is directed flow:





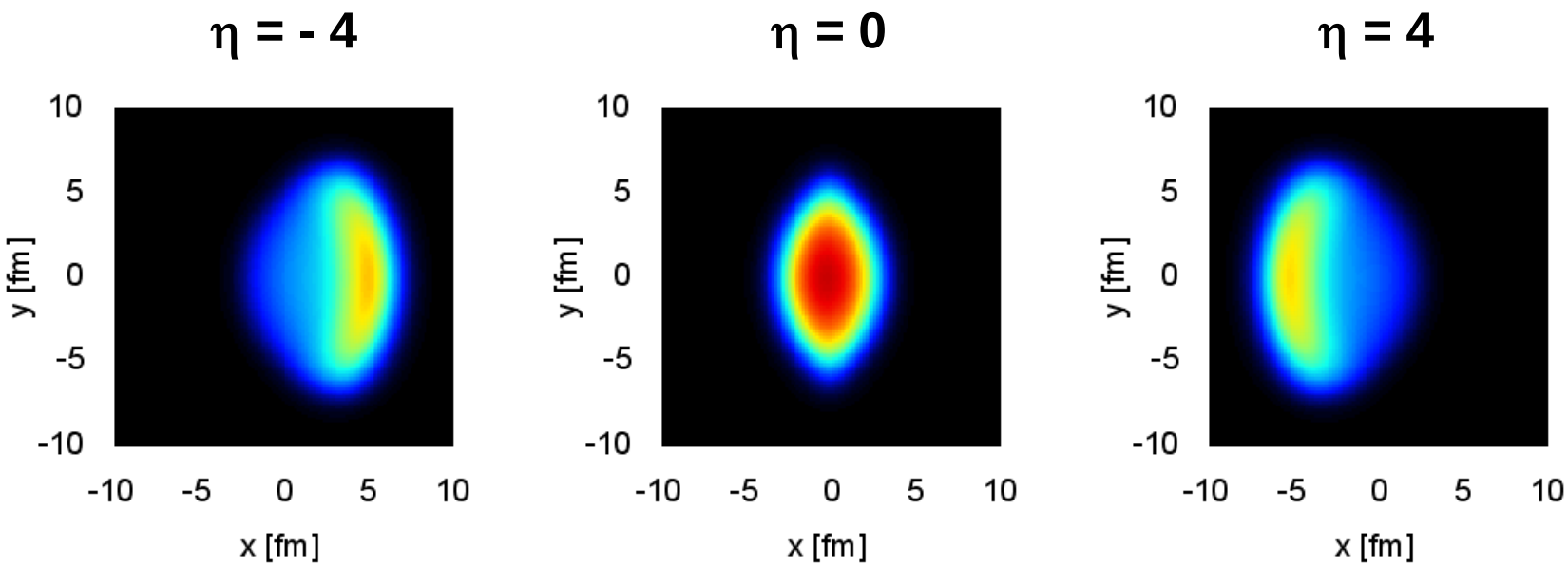


- ‘Standard’ boost-invariant coherent model conflicts with experiment
  - Either tilt,
  - Or use narrow rapidity profile

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

With Björn Schenke (to appear soon)

MUSIC RESULTS



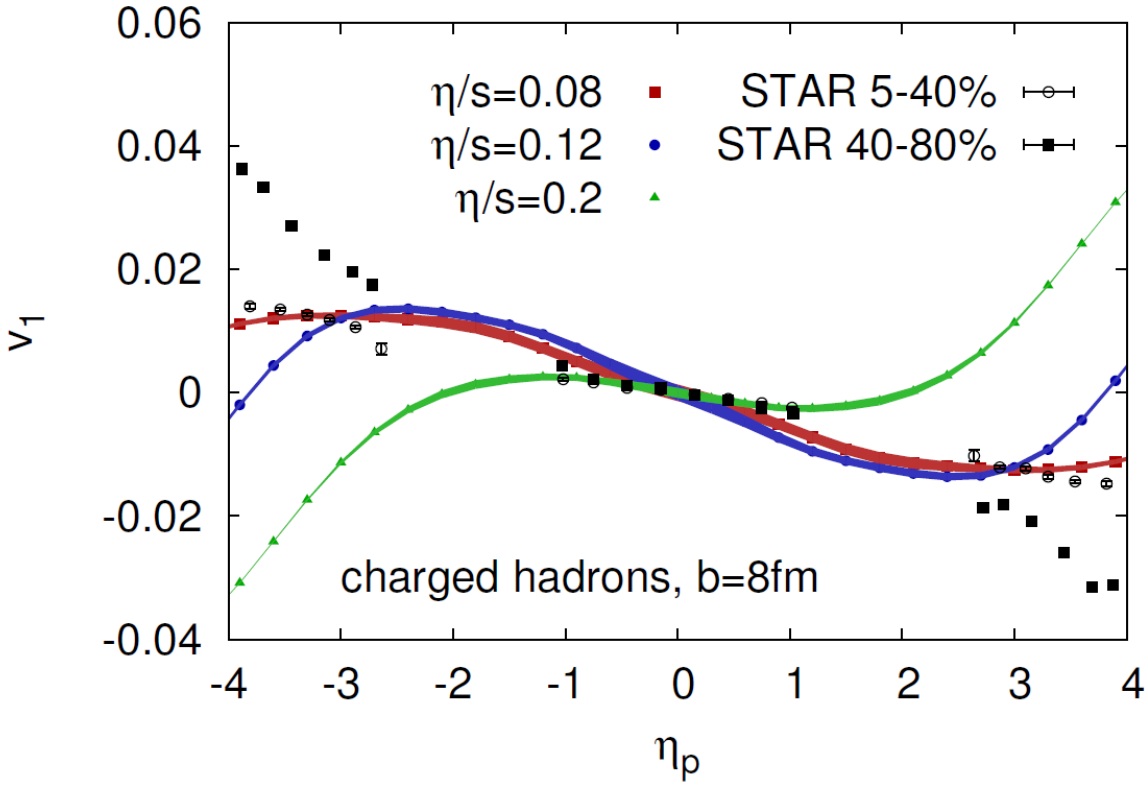
Impact parameter 8 fm, time 0.1 fm/c to 10 fm/c

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)

MUSIC RESULTS, RHIC

Directed flow: right ball-park values

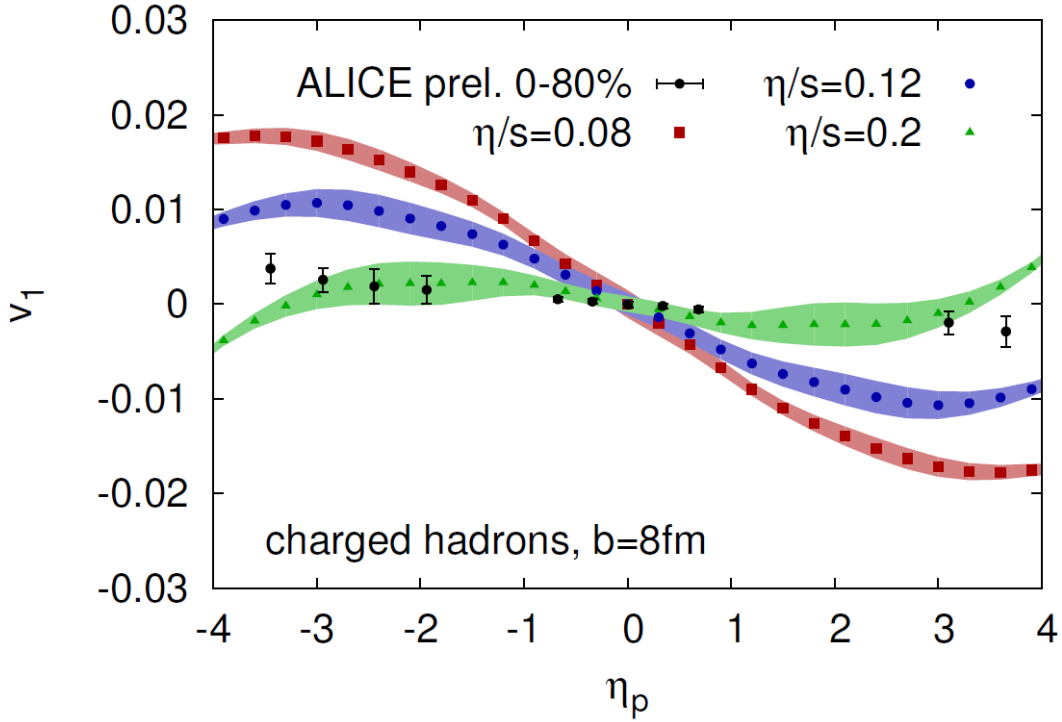


Note: somewhat subtle to measure; event-plane etc

Could be very sensitive to viscosity

MUSIC RESULTS, LHC

Directed flow: right ball-park values



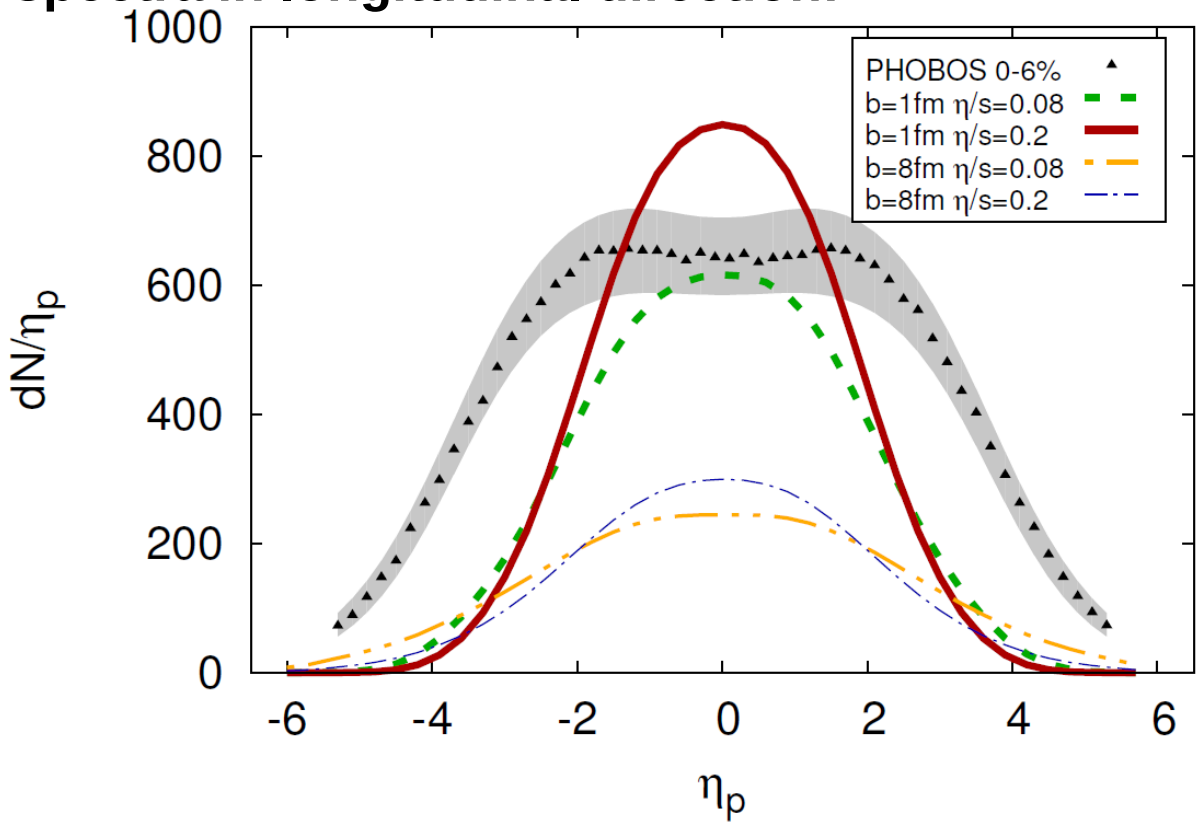
Note: somewhat subtle to measure; event-plane etc

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)

MUSIC RESULTS, RHIC

Particle spectra in longitudinal direction:

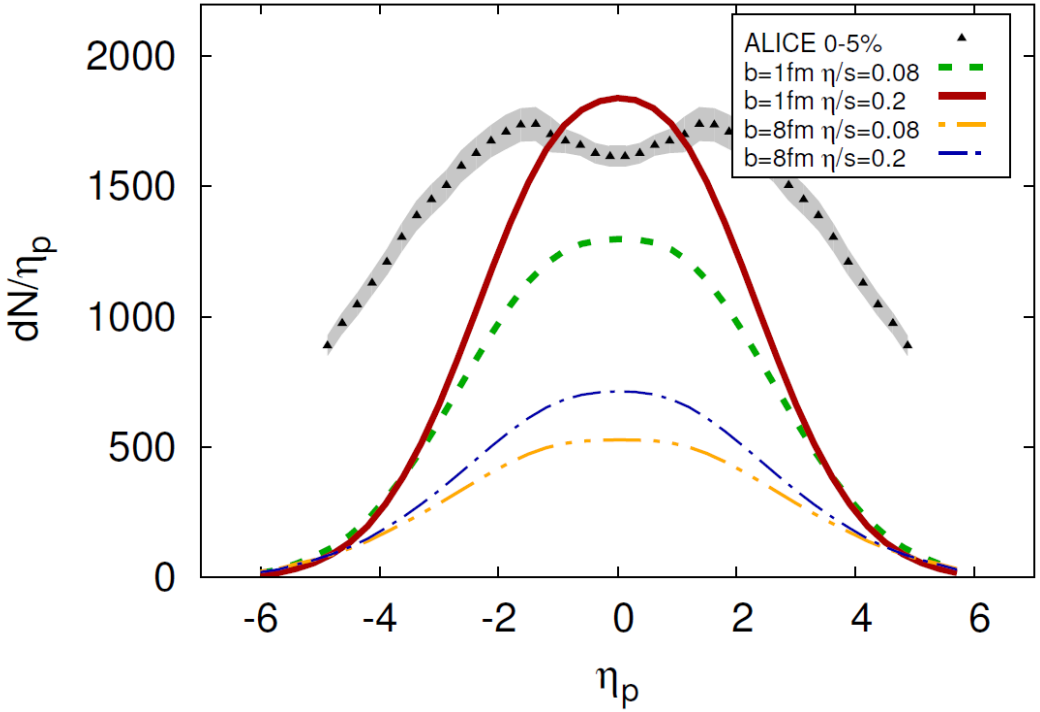


Width comes out too narrow, rescaled initial energy by factor 6

Includes `dynamical cross-over' (i.e. non-universal rapidity)

MUSIC RESULTS, LHC

Particle spectra in longitudinal direction:

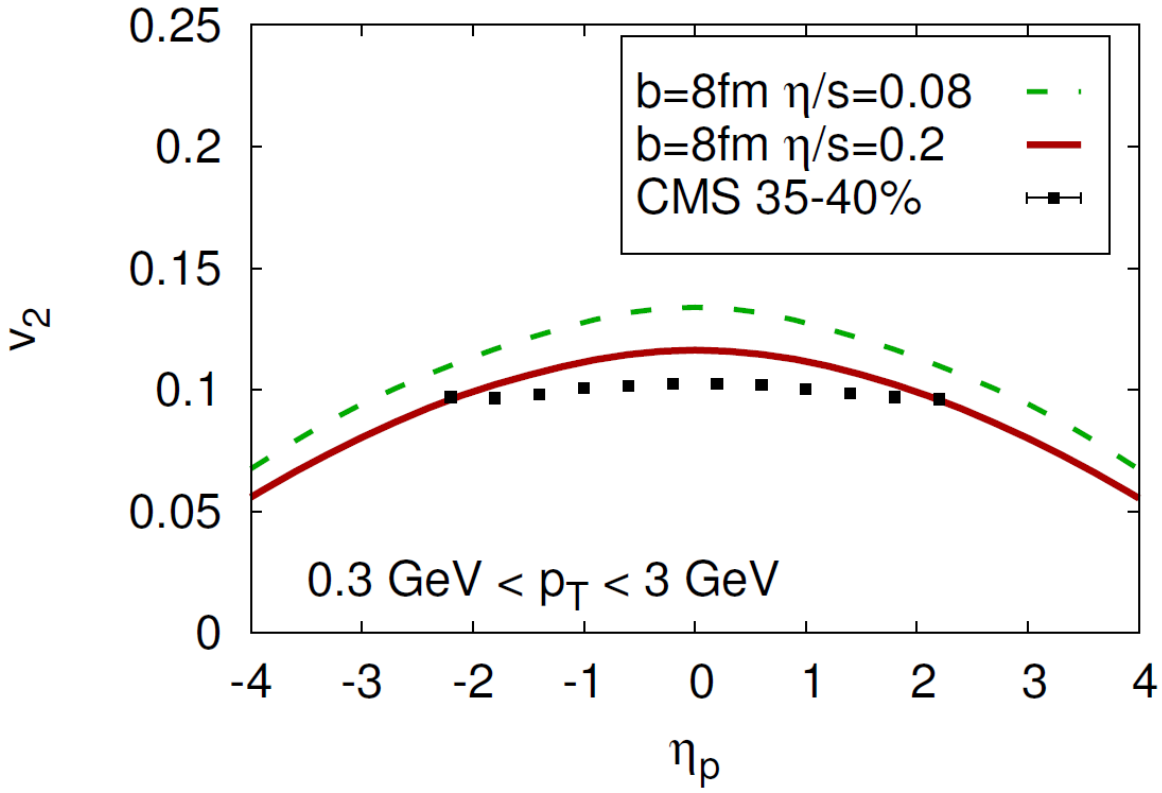


- **Rescaled initial energy density by factor 20 (fit total N)**
- **Profile is significantly too narrow**
- **Fluctuations will change profile**

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

MUSIC RESULTS, ELLIPTIC FLOW

Elliptic flow: also right order of magnitude, but a bit too narrow

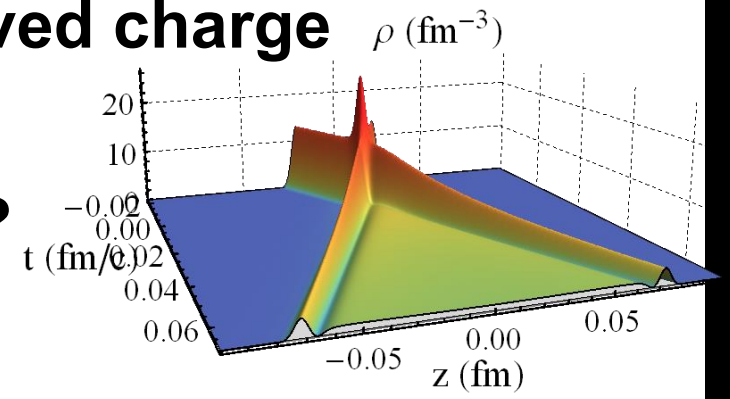


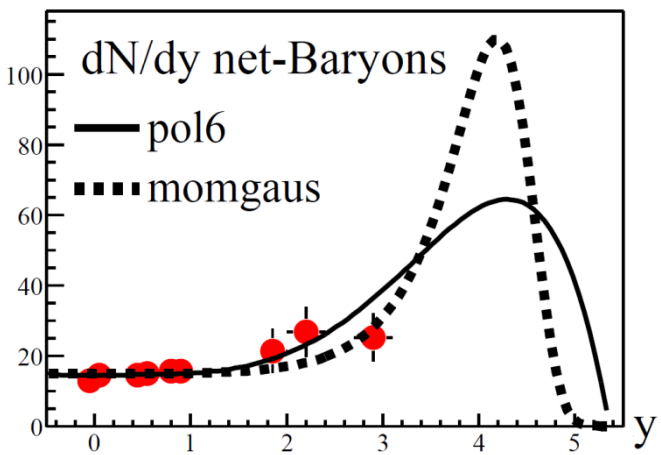
BARYON NUMBER AND CONSERVED CHARGE

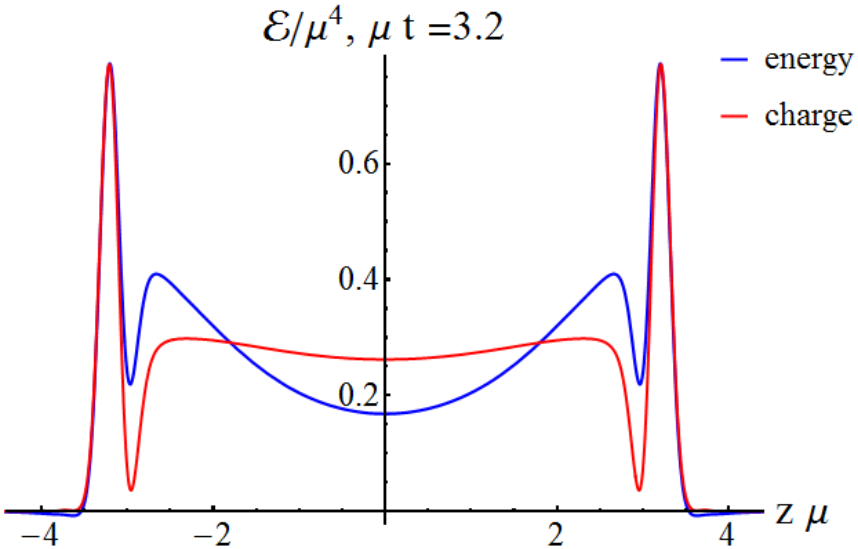
Pure gravity doesn't have conserved charge

- Add vector field

Does net charge end up at high y?







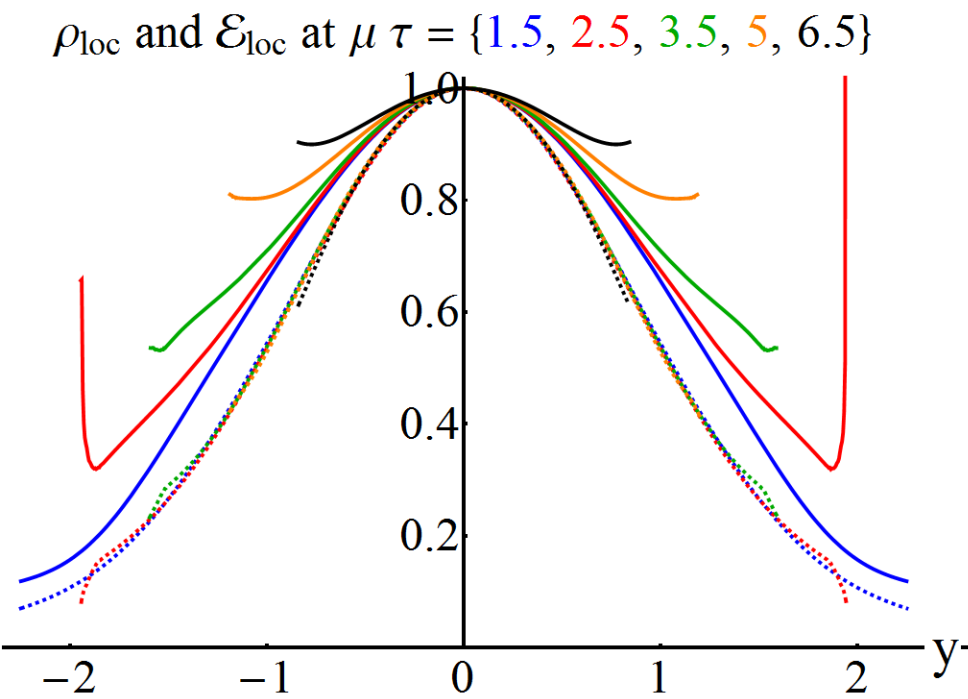
BRAHMS, Nuclear Stopping in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV(2003)

J. Casalderrey-Solana, D. Mateos, W. van der Schee and M. Triana, Holographic heavy ion collisions with a conserved charge (soon)

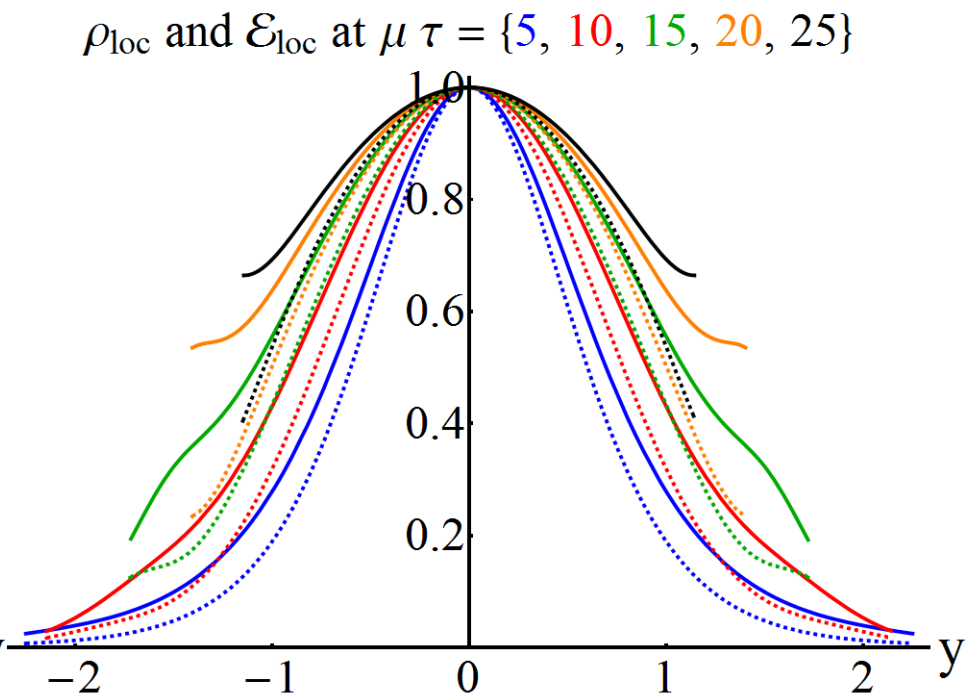
INITIAL RAPIDITY PROFILE OF CHARGE

Local charge behaves very differently from energy (dashed)

- Narrow: *charge* profile widens, develops new maximum
- Wide: charge and energy widen similarly (=hydrodynamics)



Narrow/high energy

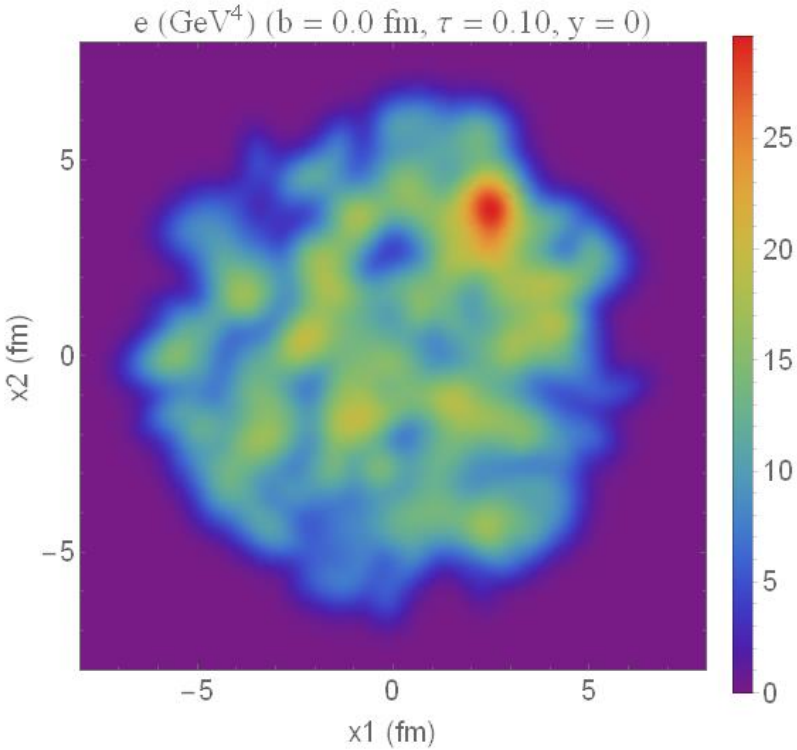


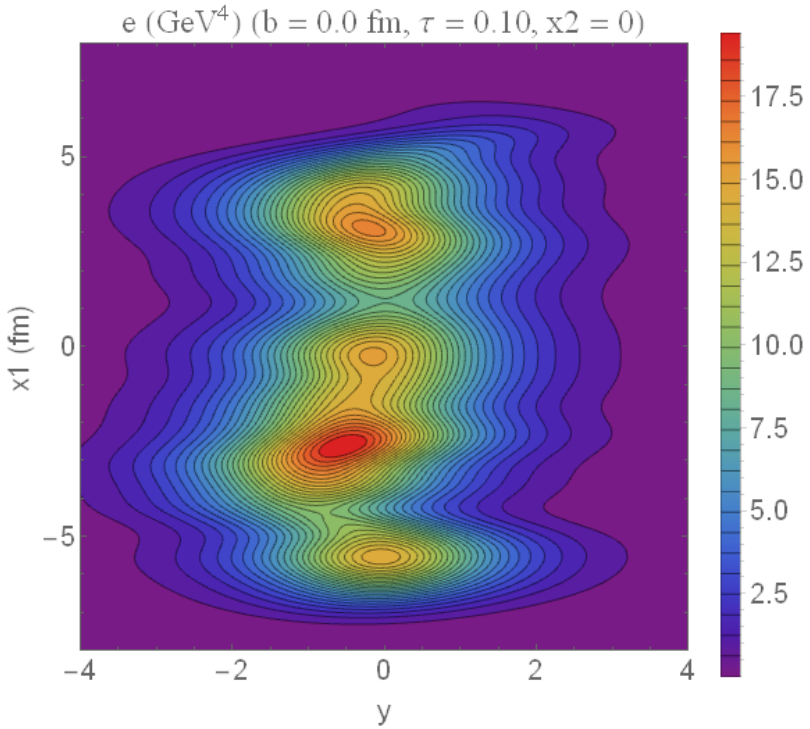
Wide/low energy

J. Casalderrey-Solana, D. Mateos, W. van der Schee and M. Triana, Holographic heavy ion collisions with a conserved charge (soon)

EVENT-BY-EVENT

Single nuclei are not smooth spheres: large fluctuations



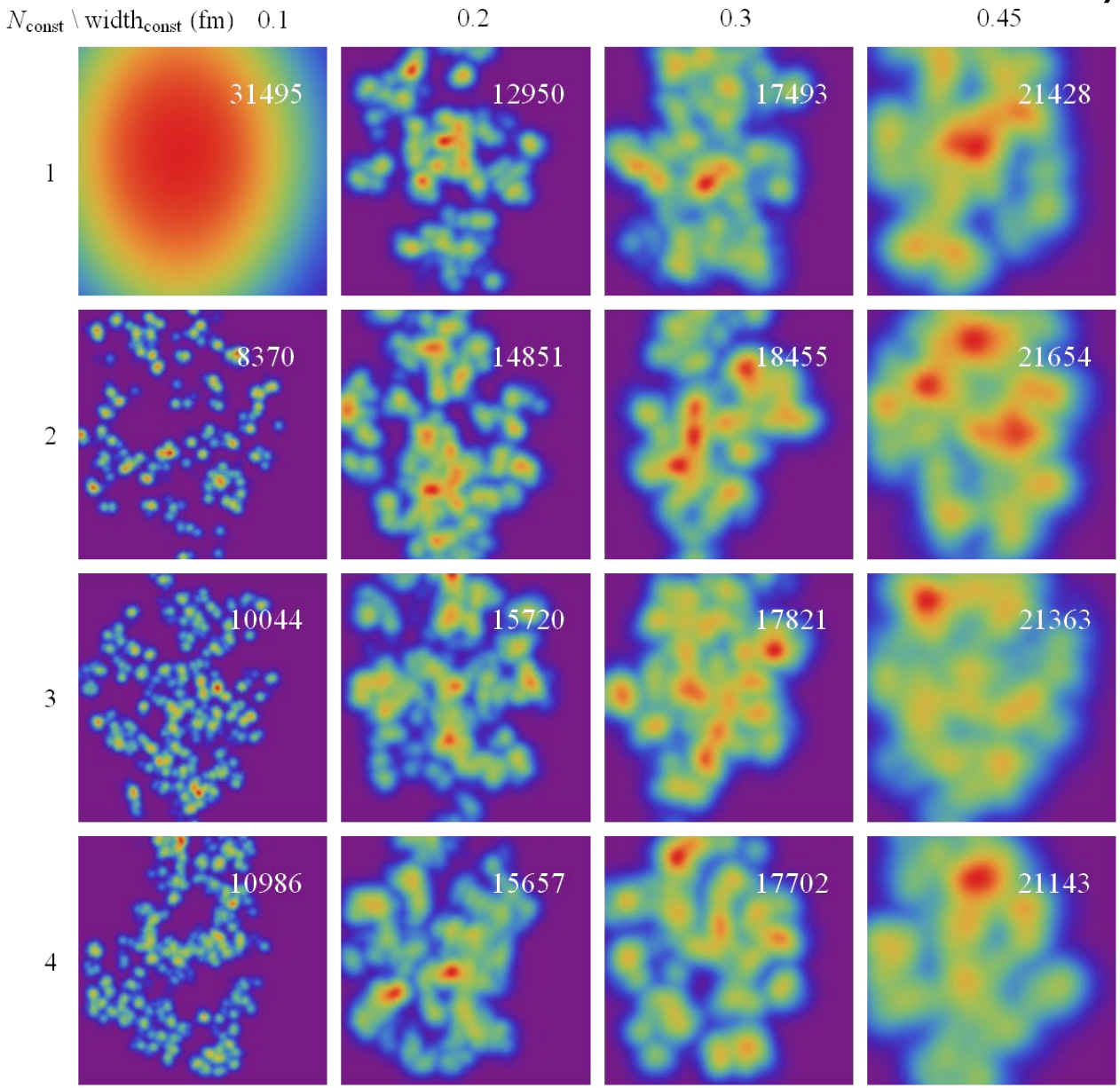


More non-trivial:

- **rapidity distribution widens (a bit)**
- **average energy density goes down (quite a lot)**

EVENT-BY-EVENT

Unknown: nucleon structure: # constituents, width constituent



20-30%

Total N_{ch} in white (7300 from ALICE)

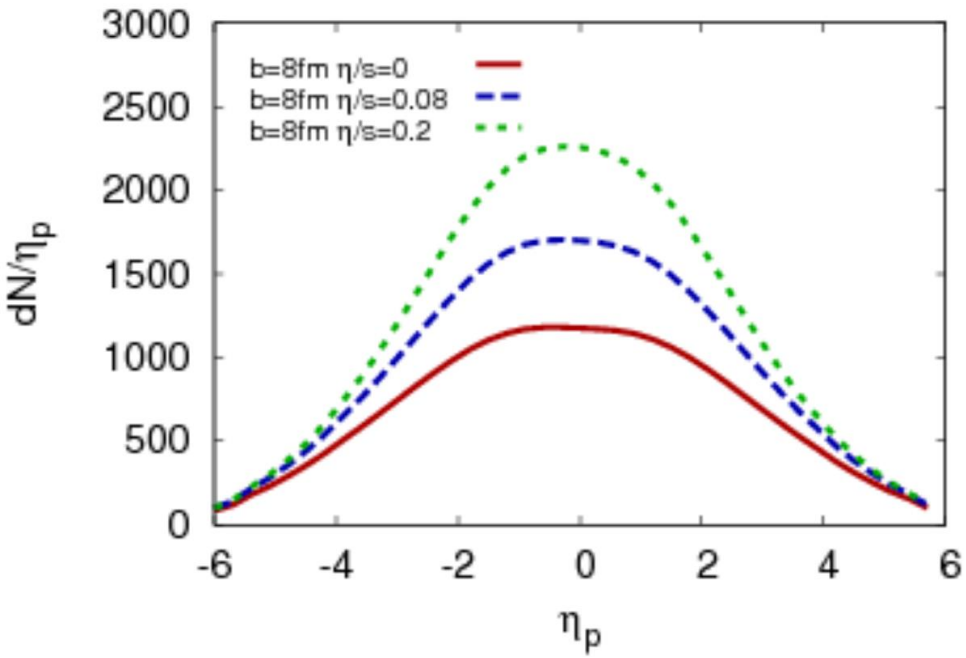
(from initial entropy)

Averaged: top-left

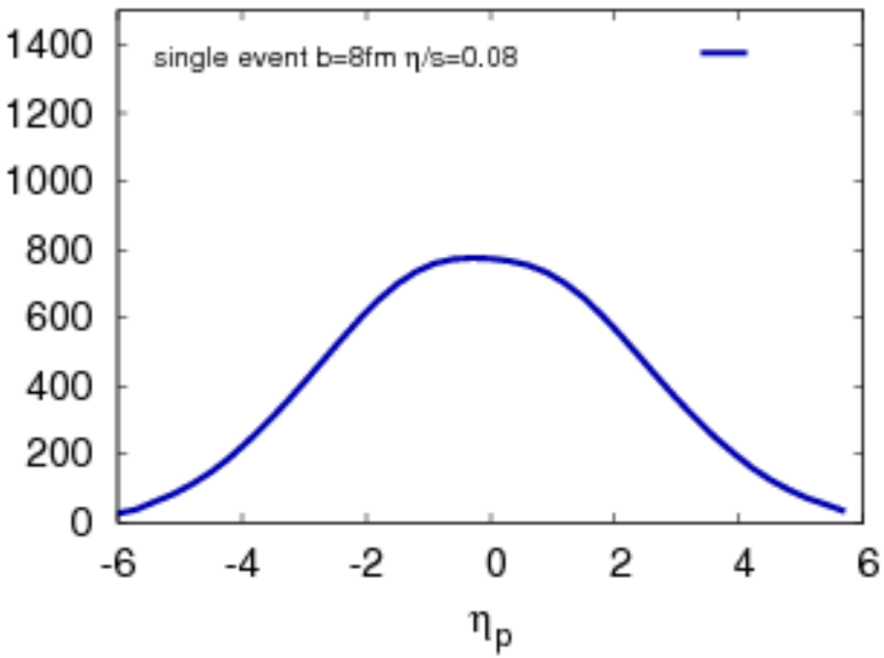
Implications for v_n?

EVENT-BY-EVENT

Without fluctuation:



With fluctuation:

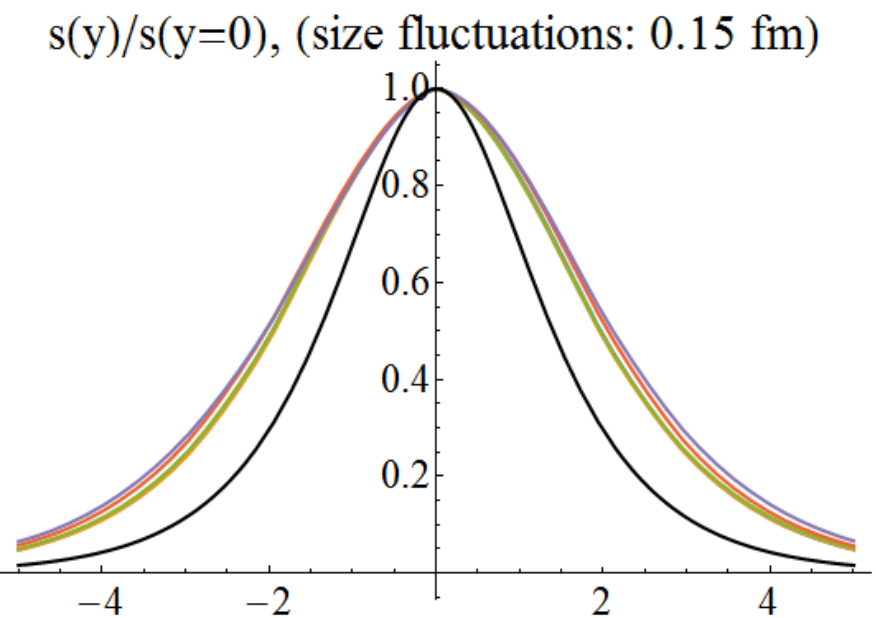


Big decrease in total multiplicity

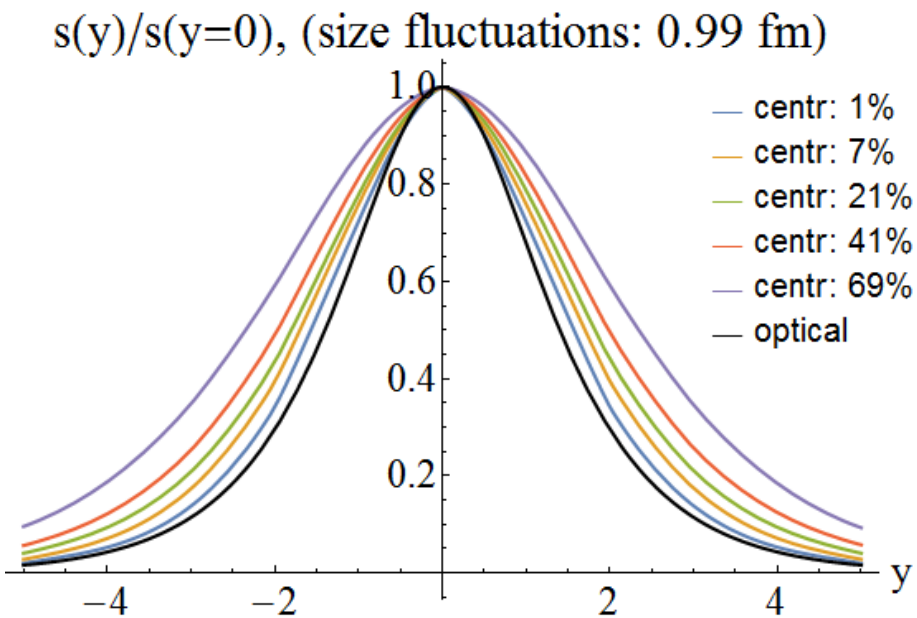
- **relates back to old computations by Gubser/Pufu/Yarom/Lin/Shuryak**
- **i.e. dN/dη very sensitive to energy distribution of a nucleon**

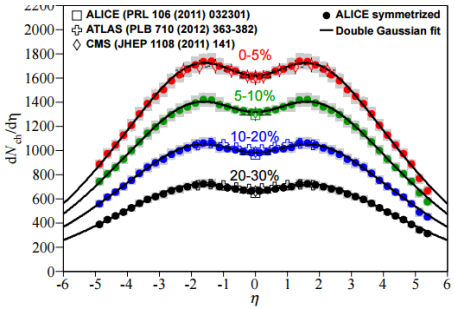
EVENT-BY-EVENT, INITIAL PROFILE

With large fluctuations:



With small fluctuations:





- **Fluctuations make profile wider**
- **More pronounced for either large fluctuations, or more off-central collisions**

ALICE, Centrality dependence of the pseudorapidity density distribution for charged particles in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (2013)

Wilke van der Schee, MIT

DISCUSSION

Longitudinal dynamics key for dynamics from AdS/CFT

- Initial state: universal rapidity profile, with Bjorken velocity
- Conserved charge as a function of rapidity
- AdS/CFT: simple and strong predictions: fits some data??
  - Keep in mind caveats when using AdS/CFT, lots of room for improvement

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

- Directed flow as function of rapidity
- Test different transverse plane models? p-Pb collisions? Fluctuations?
- Rapidity dependence perhaps not studied enough?

Future is open: *correct for infinite coupling approximation (width of Gaussian get wider?)*, non-conformal theories, confining theories, probes like jets……