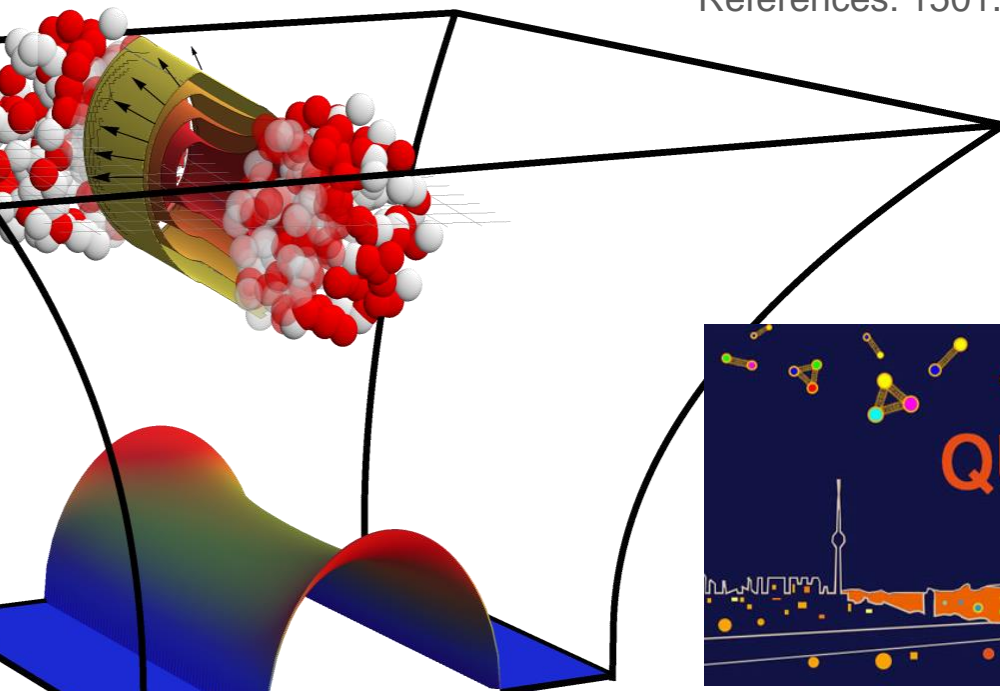




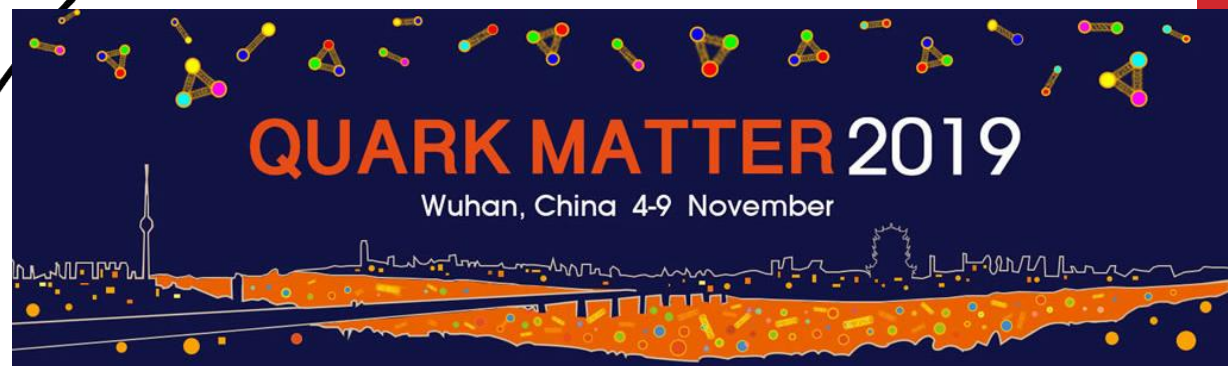
HOLOGRAPHIC COLLISIONS WITH BARYON NUMBER AT INTERMEDIATE COUPLING

HOLOGRAPHY BEYOND $\eta/s=1/4\pi$

Based on work Åsmund Folkestad, Sašo Grozdanov and Krishna Rajagopal
References: 1501.04952, 1507.08195, 1610.08976 (PRL), 1907.13134



Wilke van der Schee



OUTLINE

Holography to model QCD

- AdS/CFT: first principle non-perturbative QFT computations
- Limitations: QCD(-like) theory with intermediate coupling is hard

Baryon number is interesting: collision transparent?

- Not so at infinite coupling: baryon charge follows energy

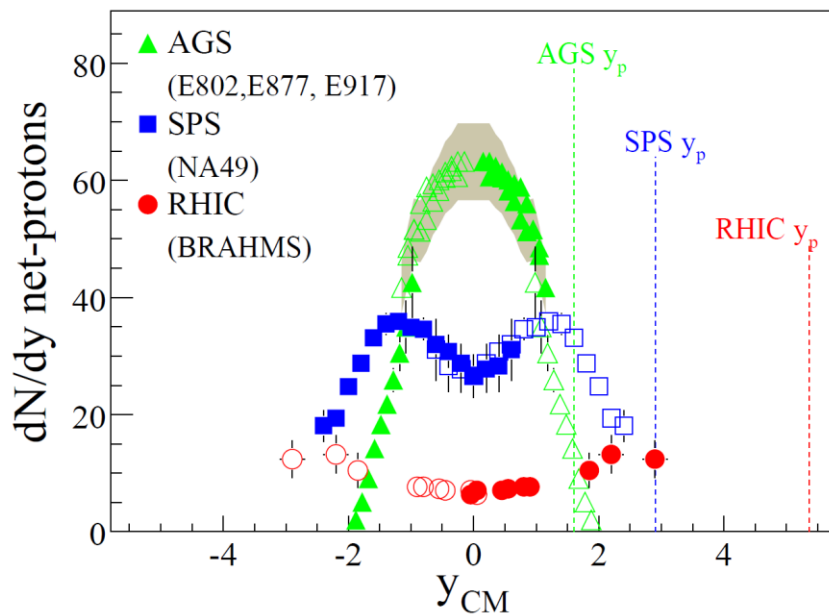
Finite coupling corrections, including baryon number

- Extra terms in the AdS Lagrangian
- Following baryon charge for thick and thin holographic collisions
 - Depending on extra parameter β : much more transparency

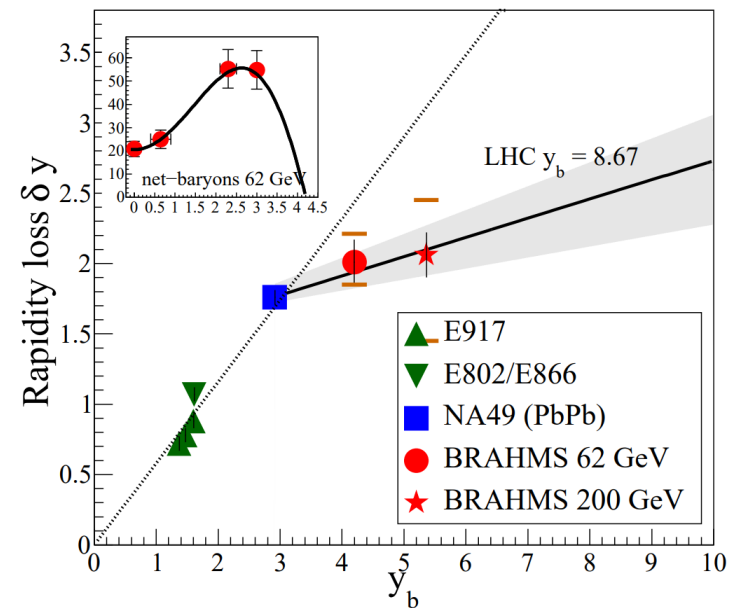
FOLLOWING BARYON NUMBER

Input: ~400 baryons, conserved: more protons than anti-protons

- Picture: transparent baryon flow, energy created at mid-rapidity
- Depending on beam rapidity (y_b) baryons lose 1 – 2.5 units of rapidity (δy)



(5, 17, 200) GeV



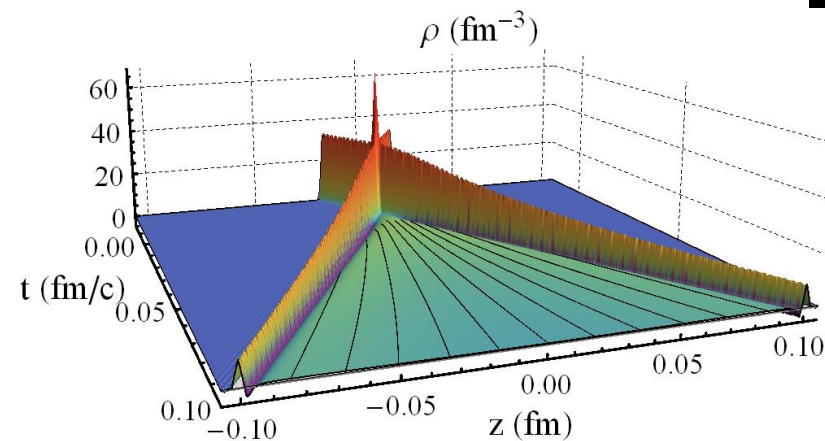
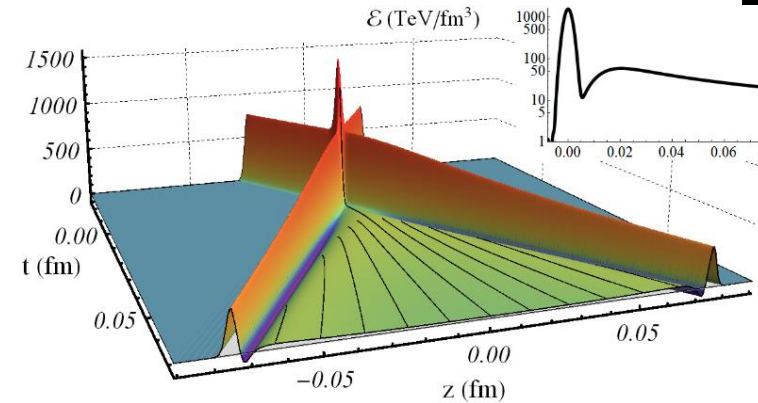
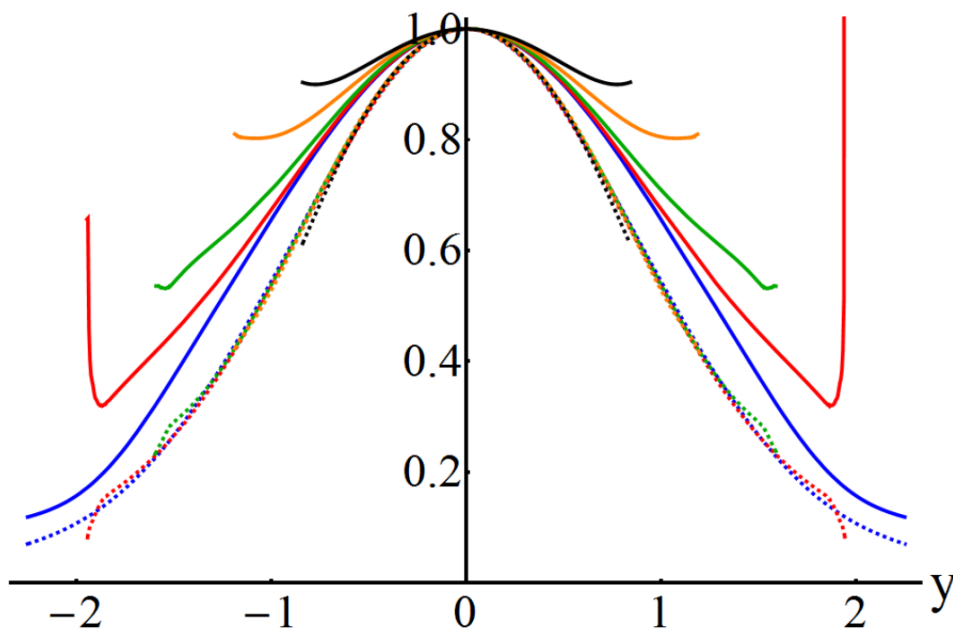
BRAHMS, Nuclear stopping and rapidity loss in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV (2009)

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

RAPIDITY PROFILE AT INFINITE COUPLING

- Collide shocks with energy and charge (=general conserved current)
- Charge rapidity (solid) similar to energy (dashed), but grows in time

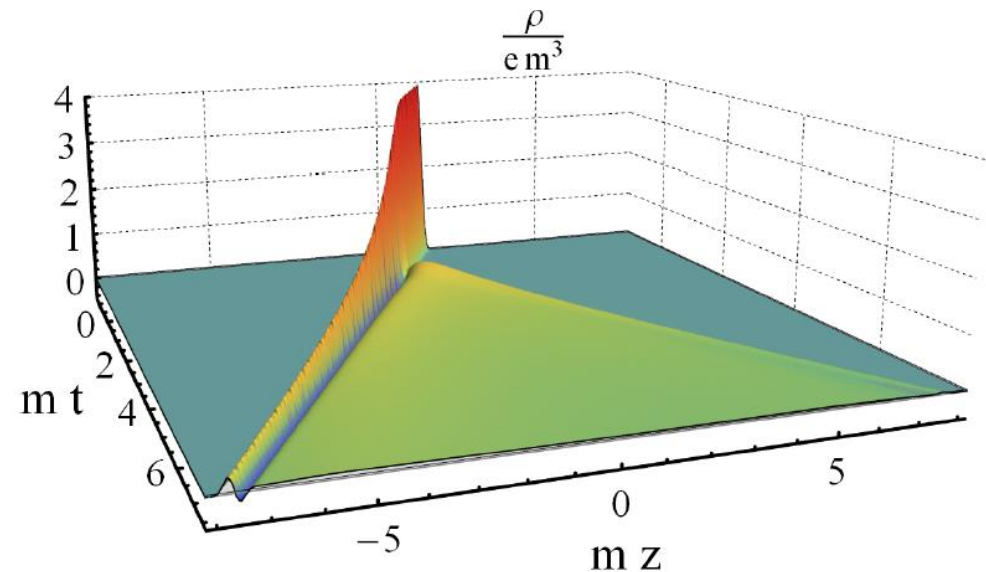
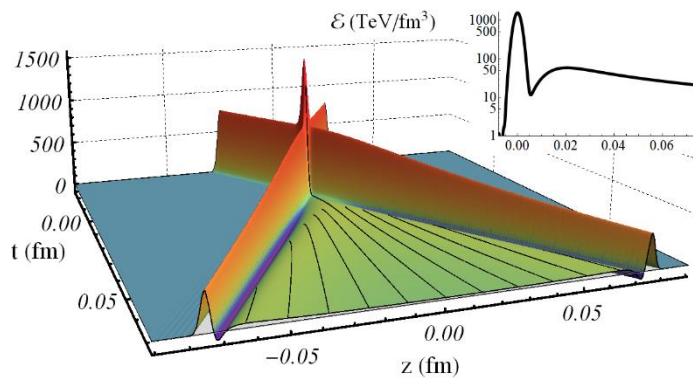
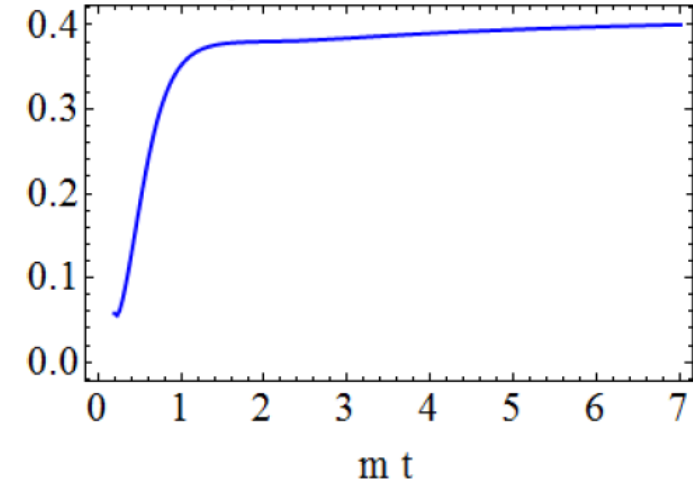
ρ_{loc} and \mathcal{E}_{loc} at $m\tau = \{1.5, 2.5, 3.5, 5, 6.5\}$



A QUANTITATIVE INSIGHT

- Collide shocks with energy and charge
- Now collide neutral with charged shock
- **41% of charge changes direction**
→ strong interactions

$$\int_0^{\infty} \rho dz / \int_{-\infty}^{\infty} \rho dz$$



ADS/CFT AND HOLOGRAPHY

Heavy ion physics: a weak/strong coupling interplay?

- A 'hybrid' approach: make a model inspired by strong and weak models
- Bolder approach: strong coupling entirely
 - Qualitative/quantitative trends can inspire better modelling
 - In either approach some amount of fitting is required

Here: try to bridge gap by including (important) corrections in AdS:

$$S = \frac{1}{2\kappa_5^2} \int d^5x \sqrt{-g} \left[R + \frac{12}{L^2} - \frac{\epsilon^2 L^2}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\lambda_{GB} L^2}{2} (R^2 - 4R_{\mu\nu} R^{\mu\nu} + R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}) \right. \\ \left. + \beta \epsilon^2 L^4 (R F_{\mu\nu} F^{\mu\nu} - 4R^{\mu\nu} F_{\mu\rho} F_{\nu}{}^{\rho} + R^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}) \right]$$

- With R Riemann tensor, F Maxwell field; two new couplings: λ_{GB} , β
- Bottom-up: field theory interpretation only known qualitatively

ADS/CFT AND HOLOGRAPHY

Here: try to bridge gap by including (important) corrections in AdS:

$$S = \frac{1}{2\kappa_5^2} \int d^5x \sqrt{-g} \left[R + \frac{12}{L^2} - \frac{\epsilon^2 L^2}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\lambda_{GB} L^2}{2} (R^2 - 4R_{\mu\nu} R^{\mu\nu} + R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}) \right. \\ \left. + \beta \epsilon^2 L^4 (R F_{\mu\nu} F^{\mu\nu} - 4R^{\mu\nu} F_{\mu\rho} F_{\nu}{}^{\rho} + R^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}) \right]$$

- Effect on i.e. transport coefficients and charge susceptibility:

$$\frac{\eta}{s} = \frac{1}{4\pi} \left[1 - 4\lambda_{GB} + O(\lambda_{GB}^2) + \frac{2}{3\pi^2} \frac{\mu^2}{T^2} (\lambda_{GB} + 3\beta) + \dots \right]$$

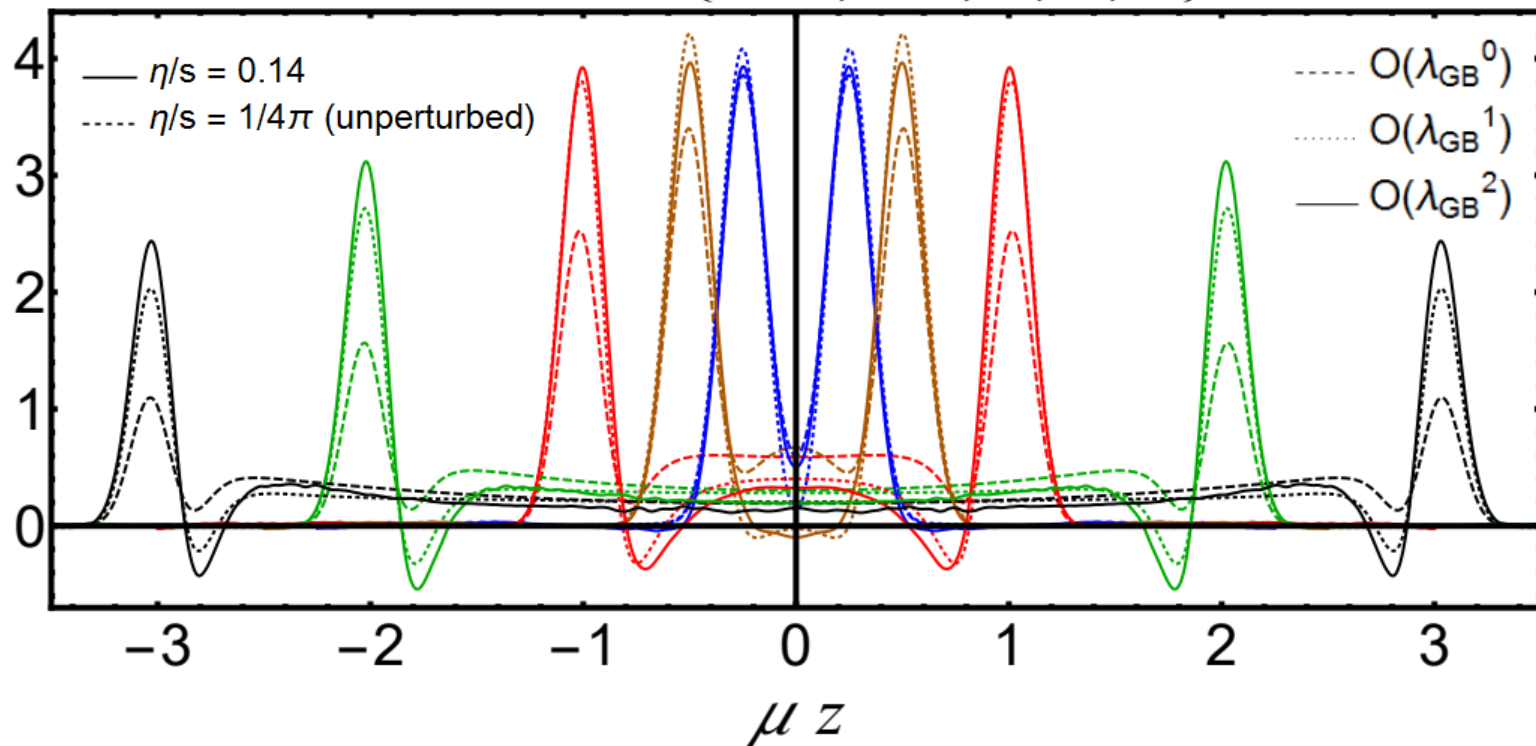
$$\chi = \left. \frac{\partial \rho}{\partial \mu} \right|_{\mu=0} = \frac{1}{2} \pi T^2 [1 + 3\lambda_{GB} + 16\beta]$$

- ‘Reasonable’ values are $\lambda_{GB} = -0.2$ and $\beta \in [0.08, 0.09]$
 - $\eta/s = 1.8/4\pi$ and $\frac{\chi}{\chi_0}|_{\text{QCD}} \in [0.8, 0.9]$
 - But all computations done perturbatively in λ_{GB} and β

COLLISIONS AT FINITE COUPLING - NARROW

- Results presented for, $\lambda_{GB} = -0.2$ i.e $\eta/s = 1.8/4\pi$ (solid)
- Initial condition constructed such that energy is the same

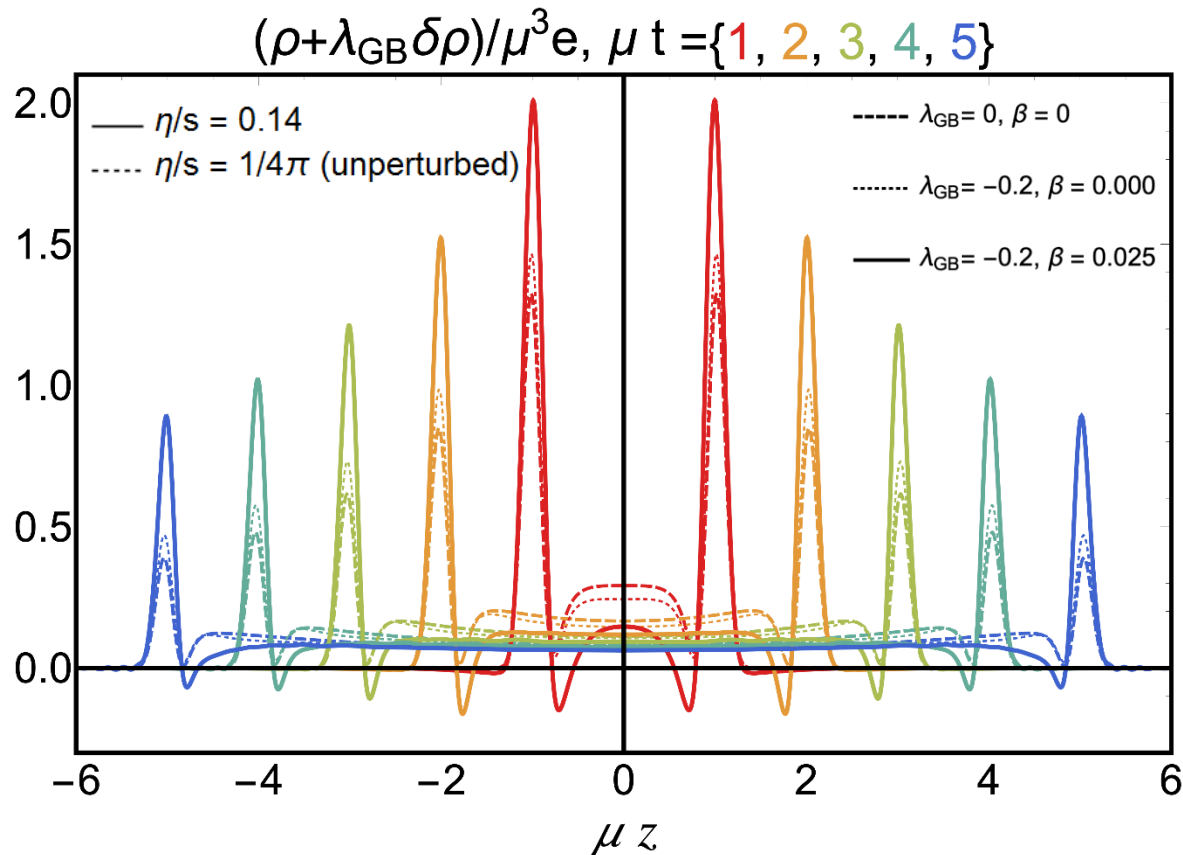
$$\mathcal{E}/\mu^4, \mu t = \{0.25, 0.5, 1, 2, 3\}$$



- Much more energy on lightcone (more transparent, less stopping)
- Energy in plasma flatter

BARYON CHARGE COLLISIONS

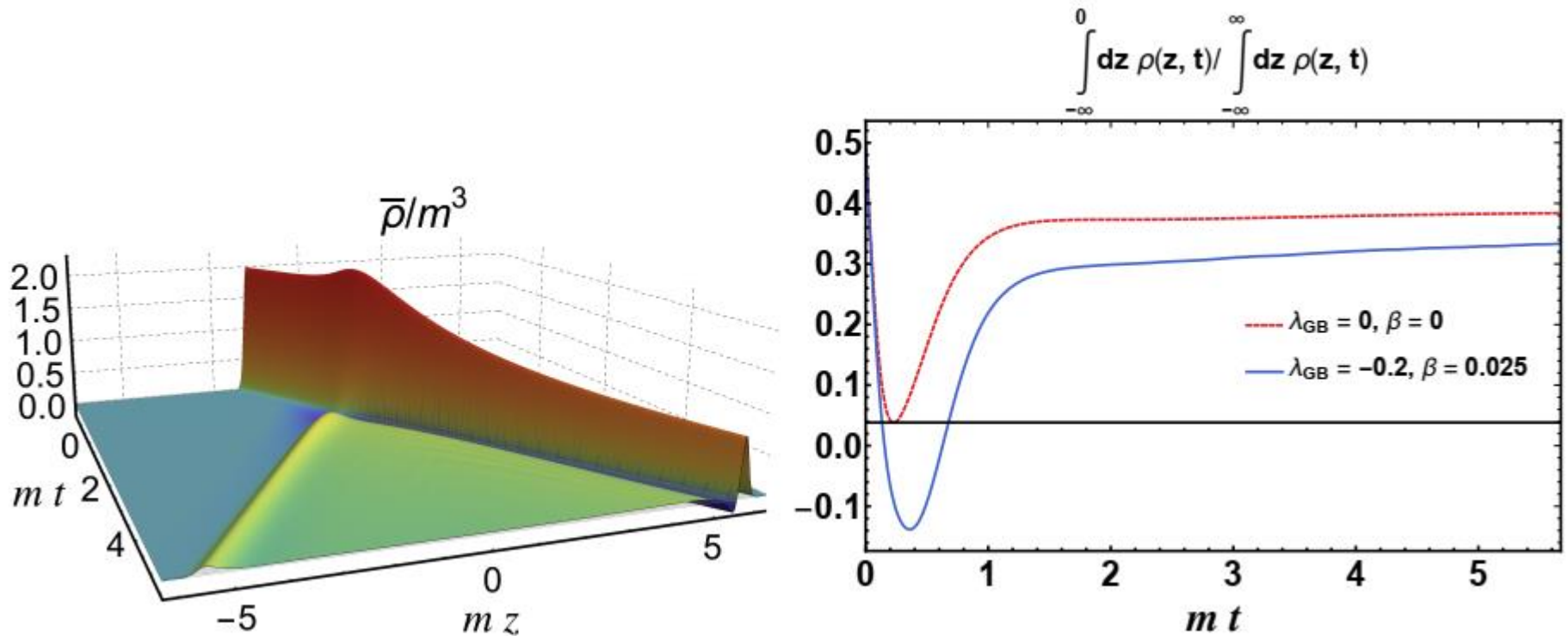
- Results presented for, $\lambda_{GB} = -0.2$ i.e $\eta/s = 1.8/4\pi$ (solid)
- Result strongly depends on β , especially on light-cone



- Much more baryon charge on light-cone (more transparent)

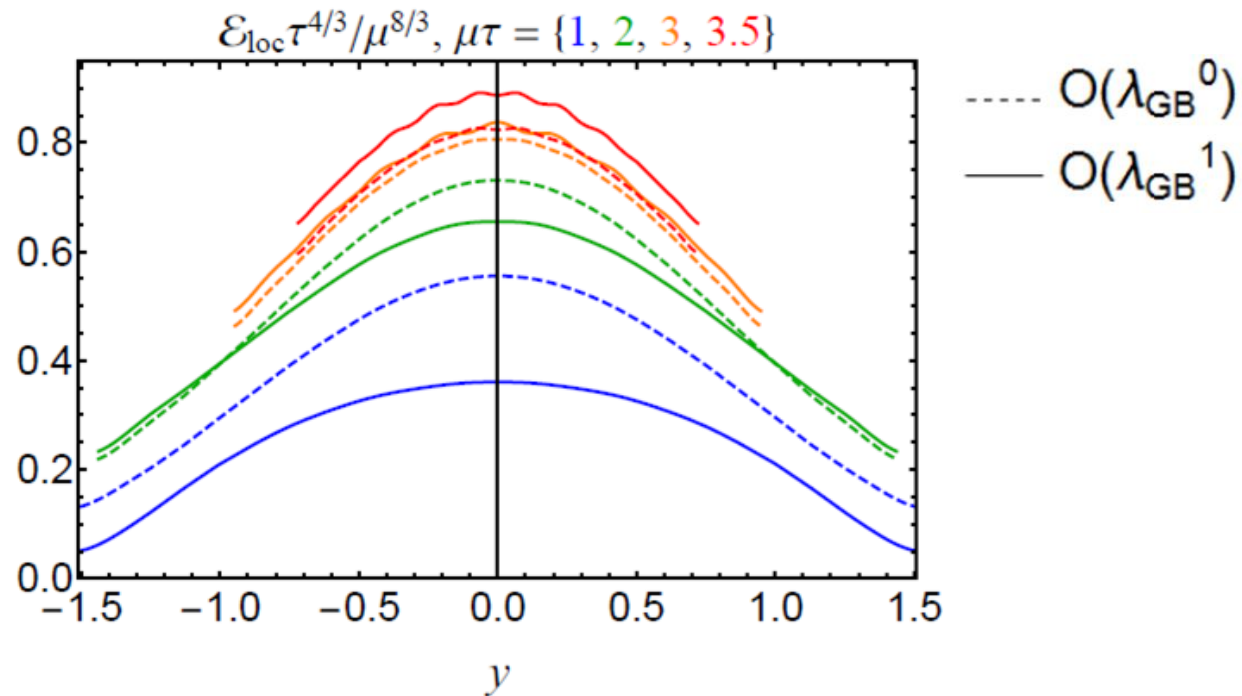
BOUNCING CHARGE

- With finite coupling corrections considerably less charge `bounces'



COLLISIONS AT FINITE COUPLING - RAPIDITY

- Initial rapidity shape differs from Gaussian



Narrow

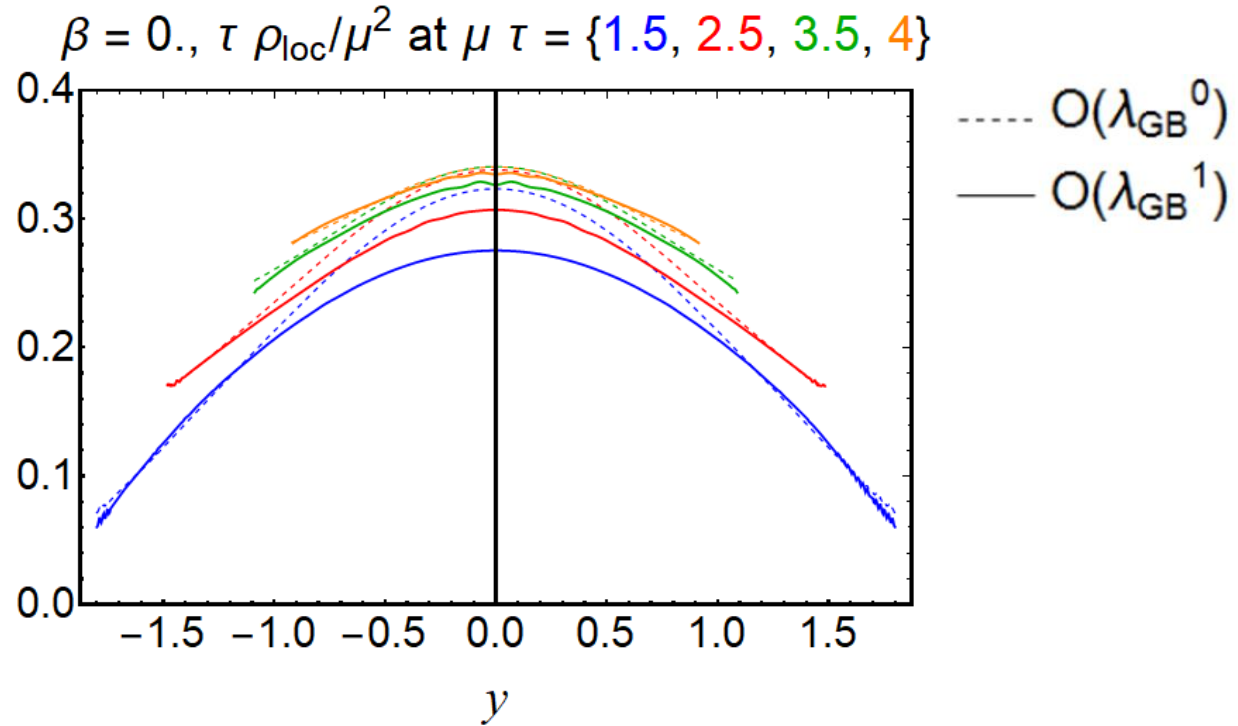
Wider and lower initially (energy on lightcone not shown)

Around time 3 similar

Later more entropy, similar width

CHARGE - RAPIDITY

- Rapidity shape similar at $\beta = 0$:

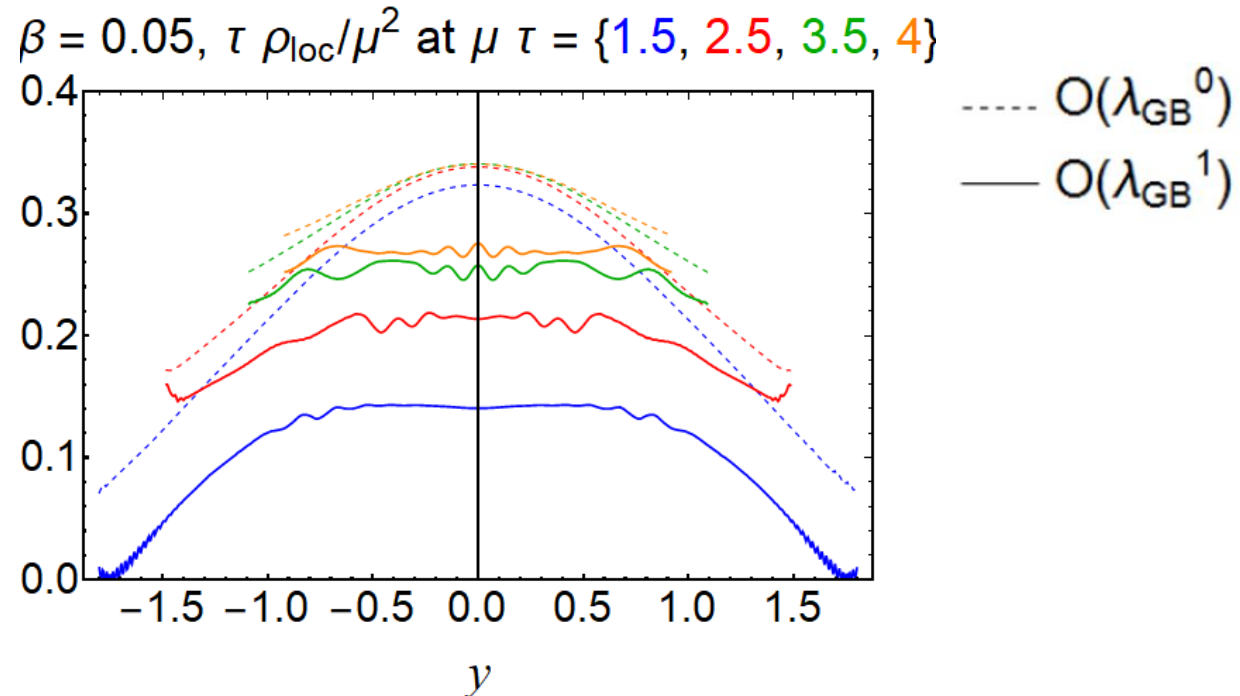


Narrow

Wider and lower initially, similar at $\mu \tau = 3.5$

CHARGE - RAPIDITY

- Rapidity shape at non-zero β considerably lower and perhaps wider:

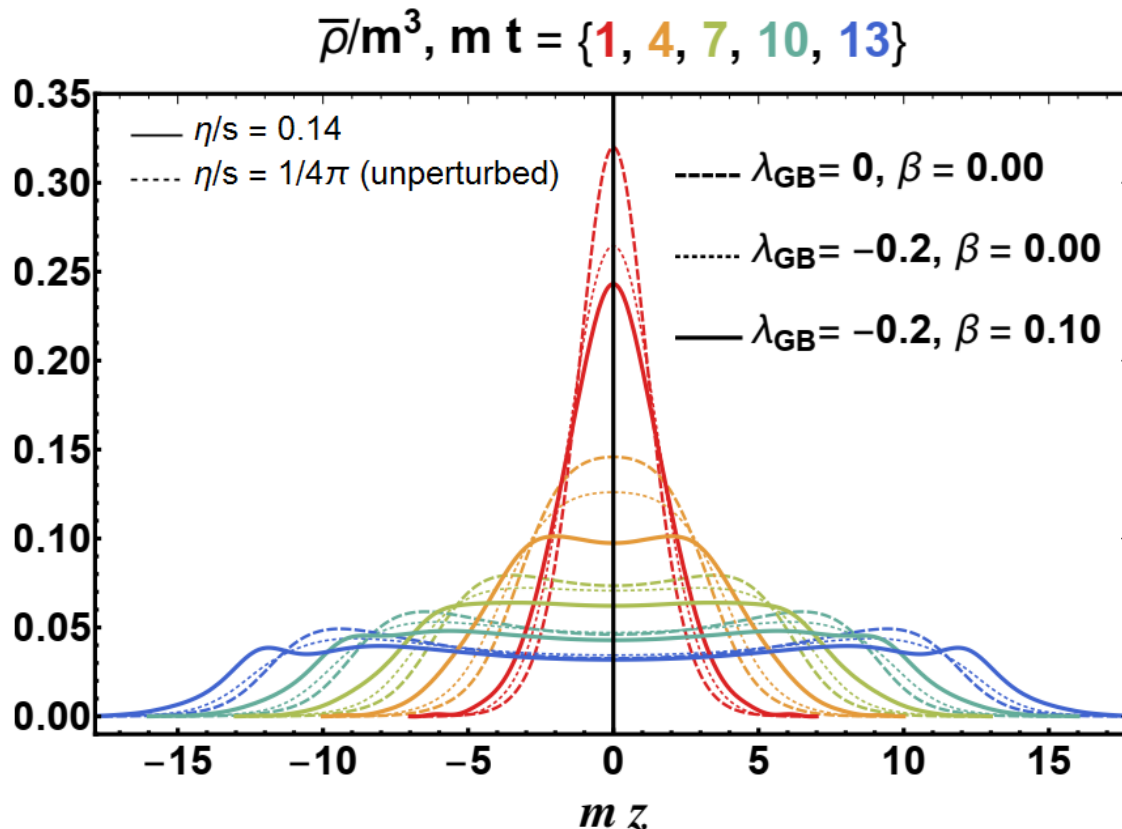


Narrow

Always lower, more baryon charge on the light-cone (total conserved)

WIDE SHOCK COLLISIONS

- Landau-like: hydrodynamic explosion



- Here larger β needed for similar effects as compared to narrow
 - Effects of $\beta = 0.1$ at edge of perturbative window

DISCUSSION

Holography and heavy ion collisions

- AdS/CFT essential tool for insights in strongly coupled matter
- Can we get closer to `realistic' baryon number transparency?

Holographic collisions at finite coupling

- New parameter β : `coupling between stress and (baryon) charge'
- Charge on light-cone: crucial dependence on β
- Rapidity spectrum charge plasma initially: wider and more transparent

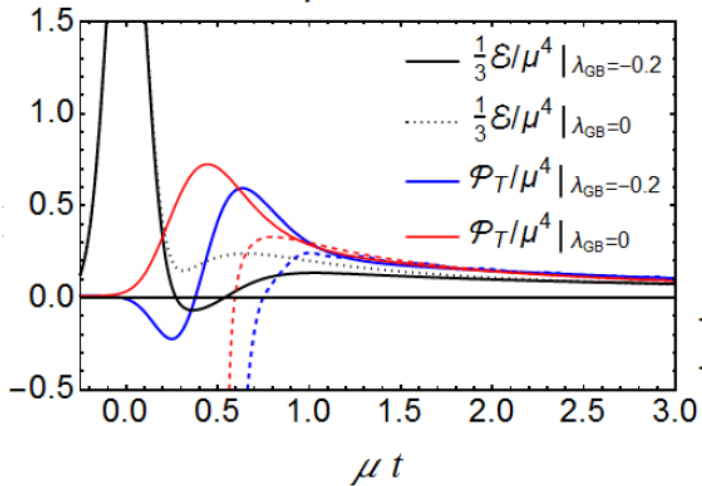
Outlook

- Improved models closer to QCD, include coupling changing with time

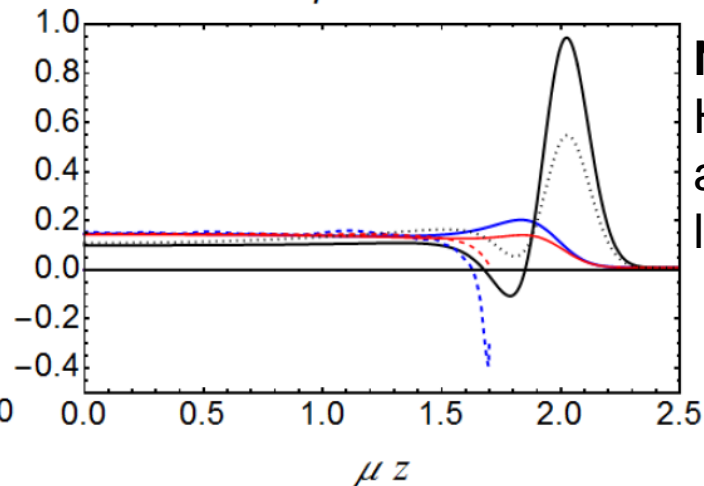
COLLISIONS AT FINITE COUPLING - HYDRO

- Hydro applies about 25% later for narrow shocks (subtler for wide)
 - Only transverse pressure: longitudinal from conformal symmetry
- Can be seen as either non-trivial check on viscosity or numerics...

$\mu z = 0.0$



$\mu t = 2.0$

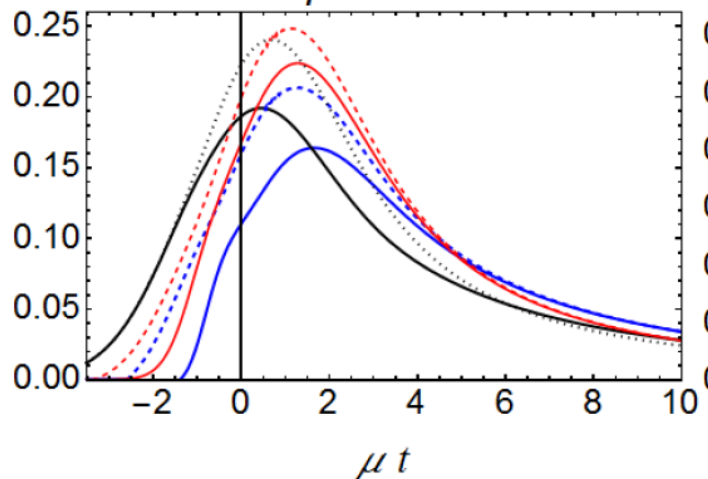


Narrow

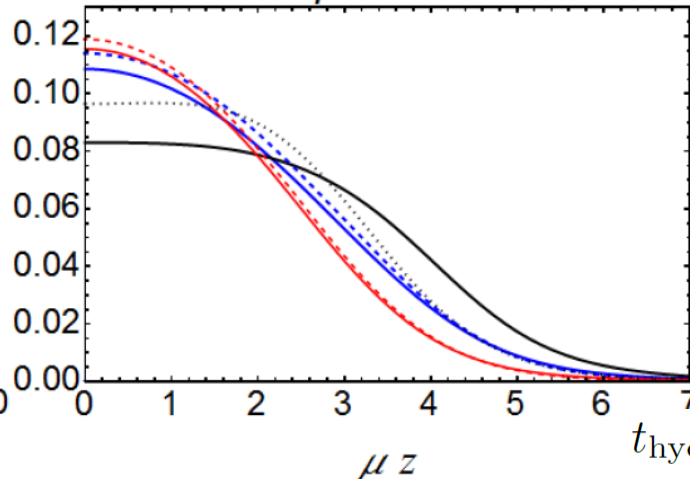
Hydro later (blue),
and further from
lightcone

$$t_{\text{hyd}} T_{\text{hyd}} = 0.41 - 0.52 \lambda_{GB}$$

$\mu z = 0.0$



$\mu t = 4.0$



Wide

Hydro later (blue),
and further from
lightcone, smaller
transverse pressure
early on, bigger later

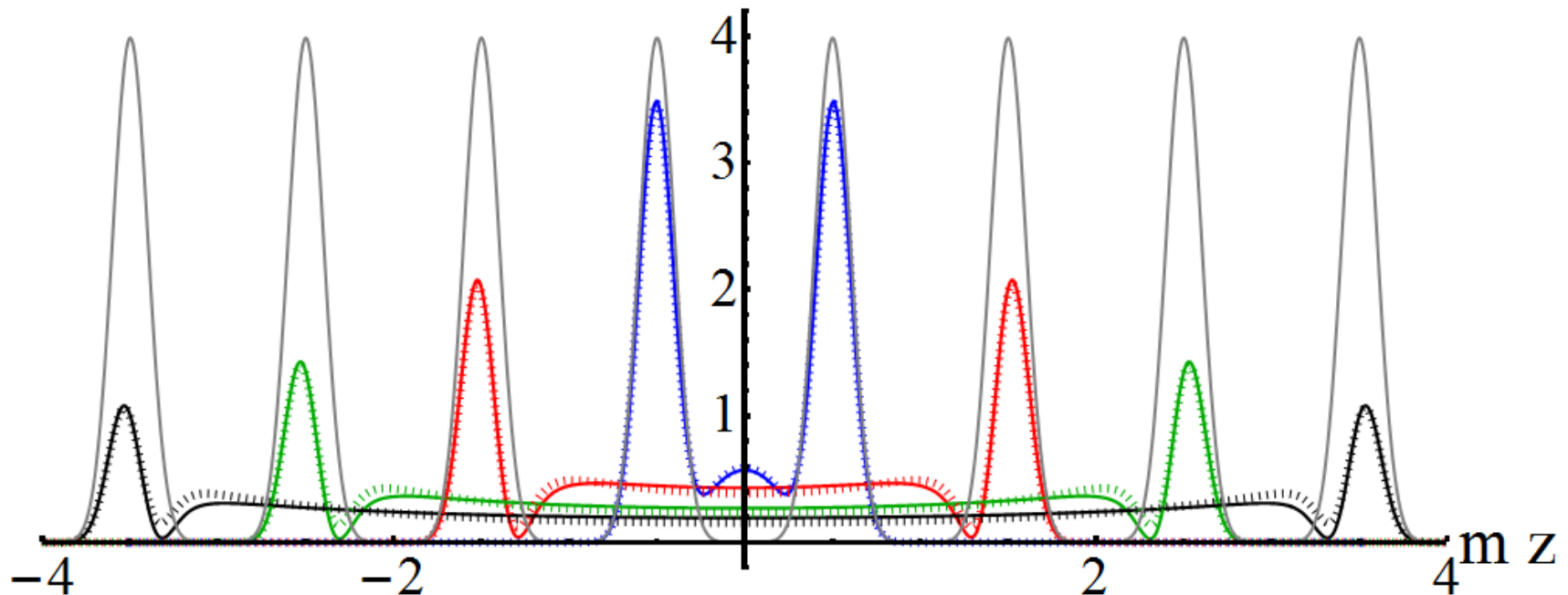
$$t_{\text{hyd}} T_{\text{hyd}} = 0.43 - 6.3 \lambda_{GB}$$

A PUZZLE: DECAY CHARGE ON LIGHT-CONE:

Charge (solid) and energy (dashed) decay exactly the same way

- Non-trivial from equations
- Charge distribution flatter in plasma

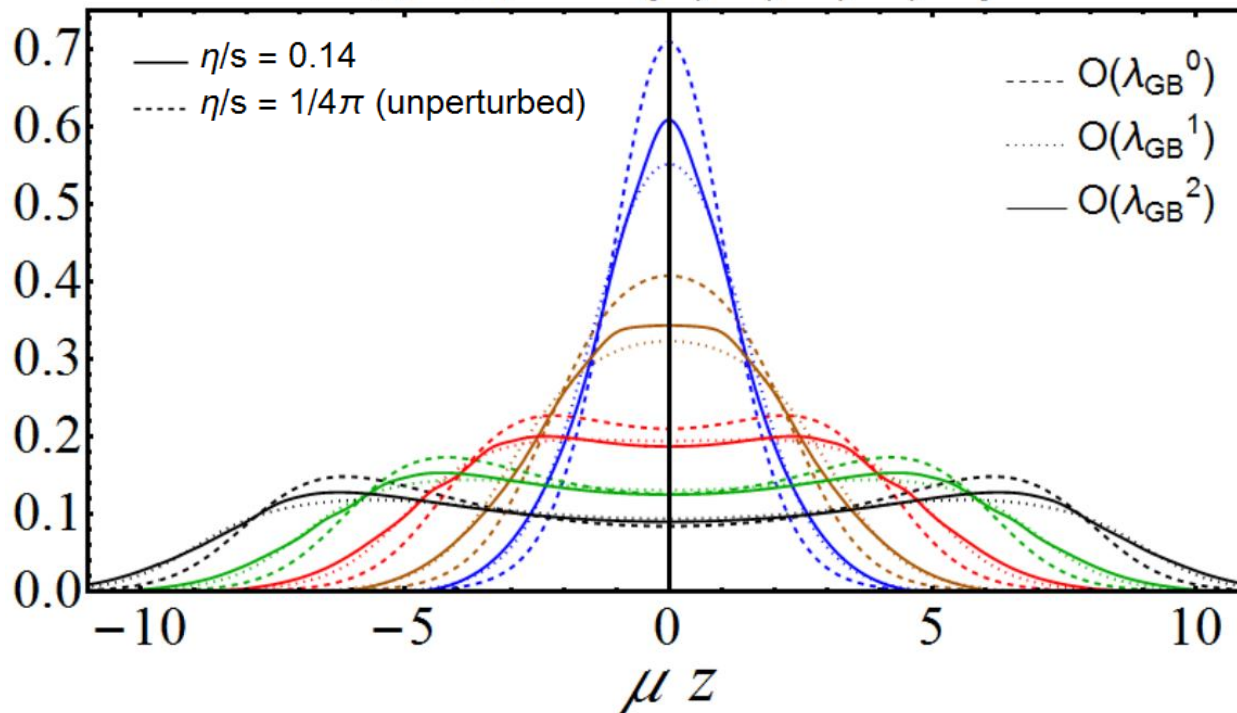
ρ/em^3 and \mathcal{E}/m^4 , $m t = \{0.5, 1.5, 2.5, 3.5\}$



COLLISIONS AT FINITE COUPLING - WIDE

- Results presented for, $\lambda_{GB} = -0.2$ i.e. $\eta/s = 1.8/4\pi$
- Initial condition constructed such that energy is the same

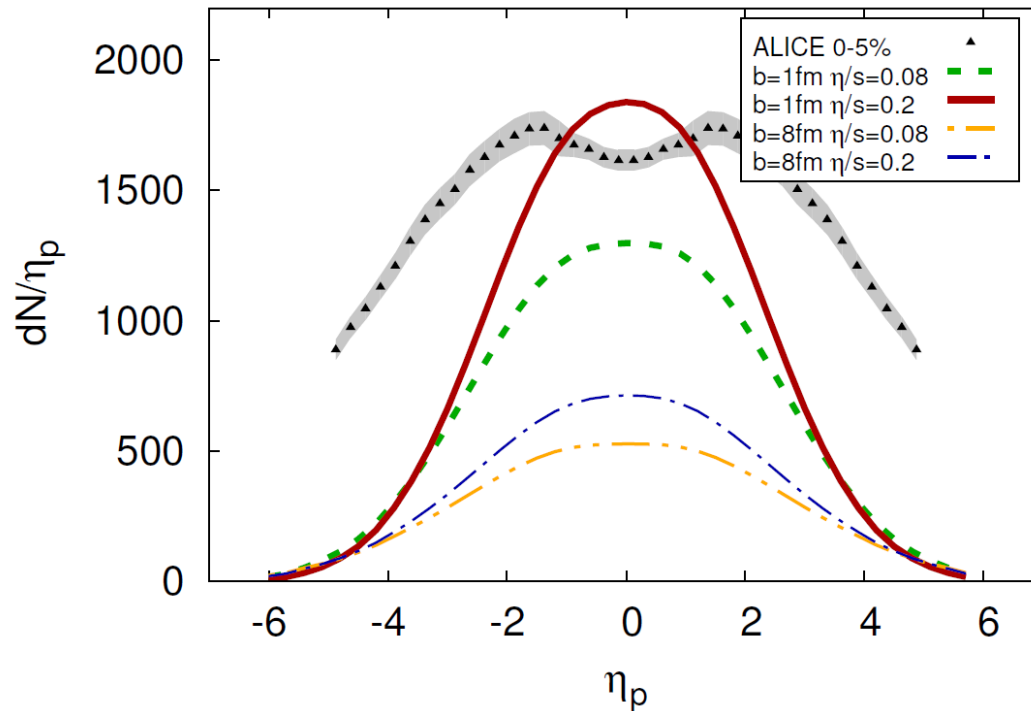
$$\mathcal{E}/\mu^4, \mu t = \{1, 3, 5, 7, 9\}$$



- Energy does not 'pile up', i.e. maximum 217% instead of 271%
- Also includes λ_{GB}^2 corrections (small opposite contribution)

RAPIDITY PROFILE + MUSIC

Particle spectra in longitudinal direction:

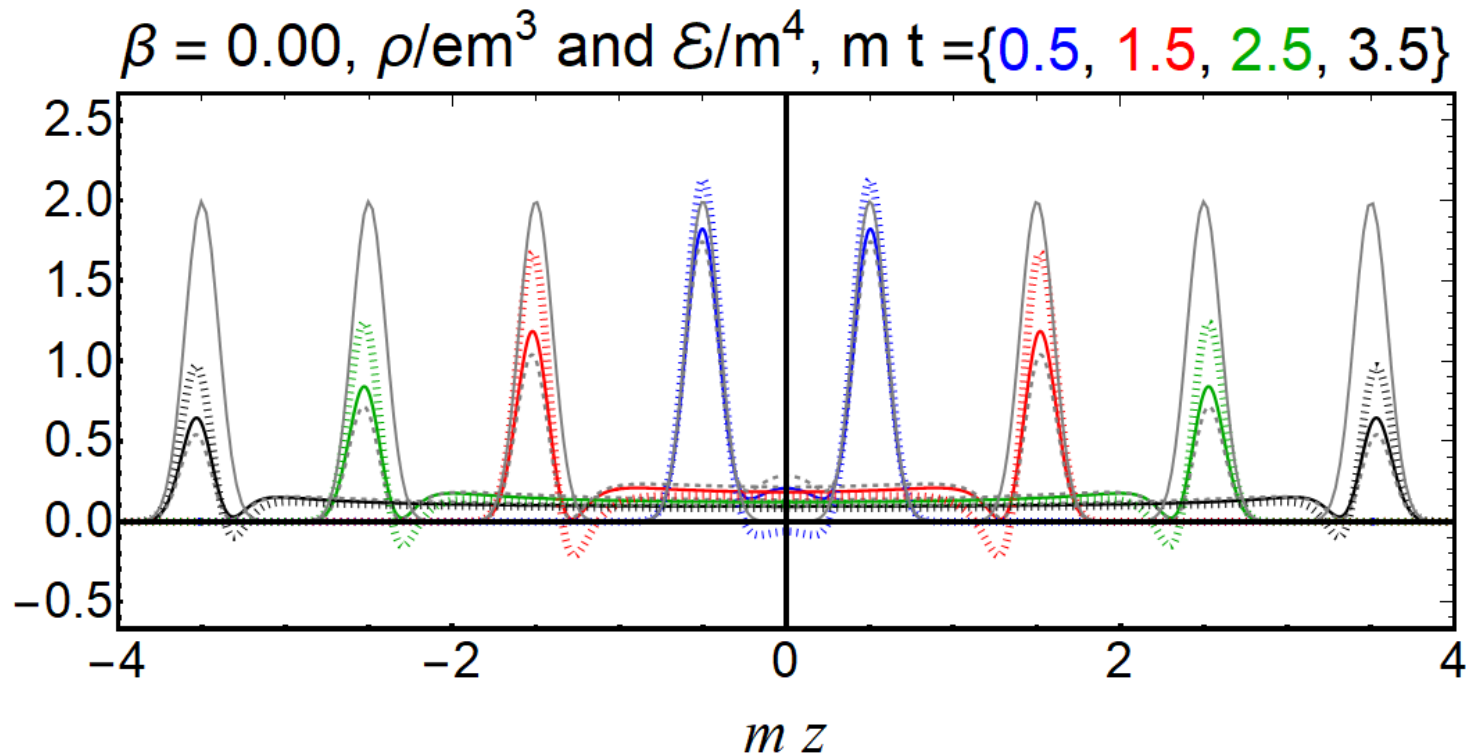


- Rescaled initial energy density by factor 20
- Profile is about 30% too narrow

DECAY CHARGE ON LIGHT-CONE:

Baryon charge (solid) and energy (dashed) decay differently

- $\beta = 0$: much more energy on light-cone, a bit more charge



DECAY CHARGE ON LIGHT-CONE:

Baryon charge (solid) and energy (dashed) decay differently

- $\beta = 0.05$: much more charge on light-cone

