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ArXiv: 1311.xxxx

From Full Stopping to Transparency in a Holographic Model of Heavy Ion Collisions

Jorge Casalderrey-Solana

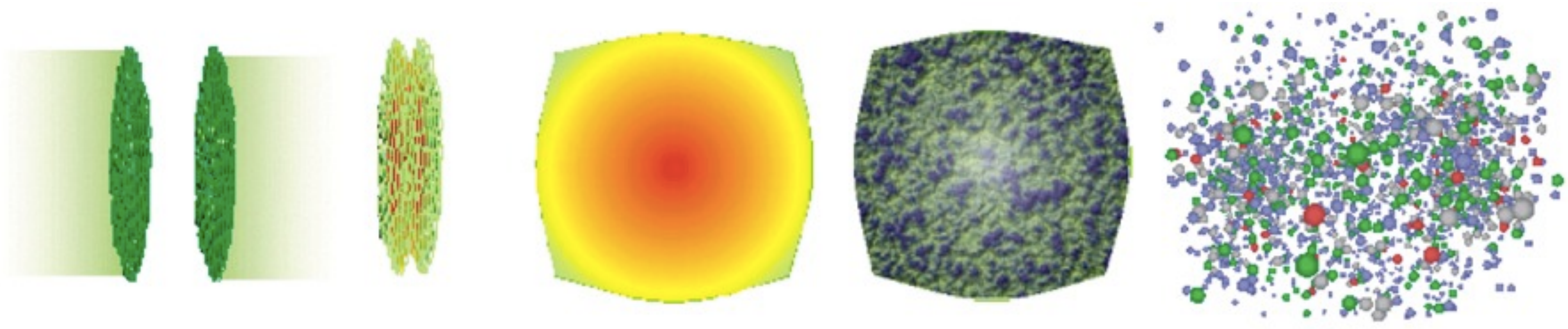
in collaboration with M. Heller, D. Mateos and W. van der Schee

MARIE CURIE ACTIONS

UNIVERSITAT DE BARCELONA

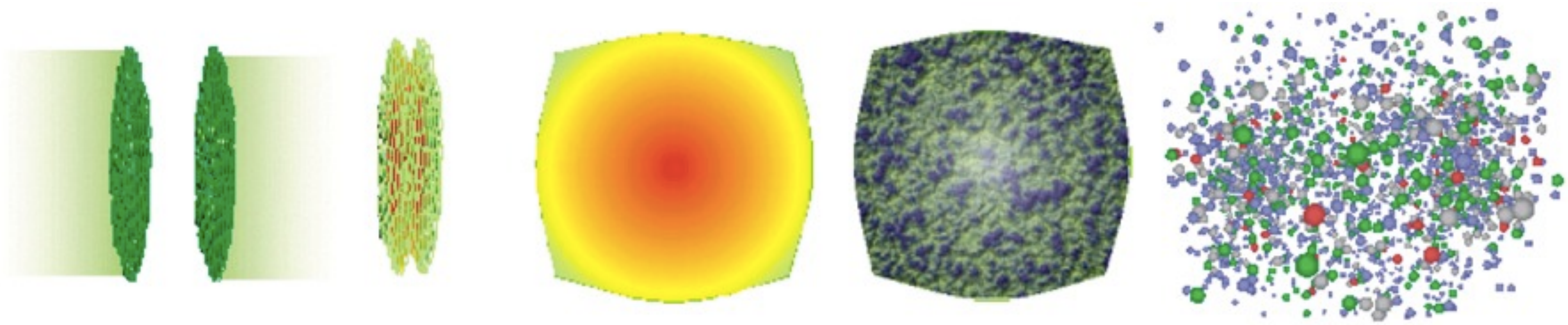
PEOPLE

From Initial to Final State in Holography



Initial State Collision Out-of-equilibrium Collective expansion Final stage

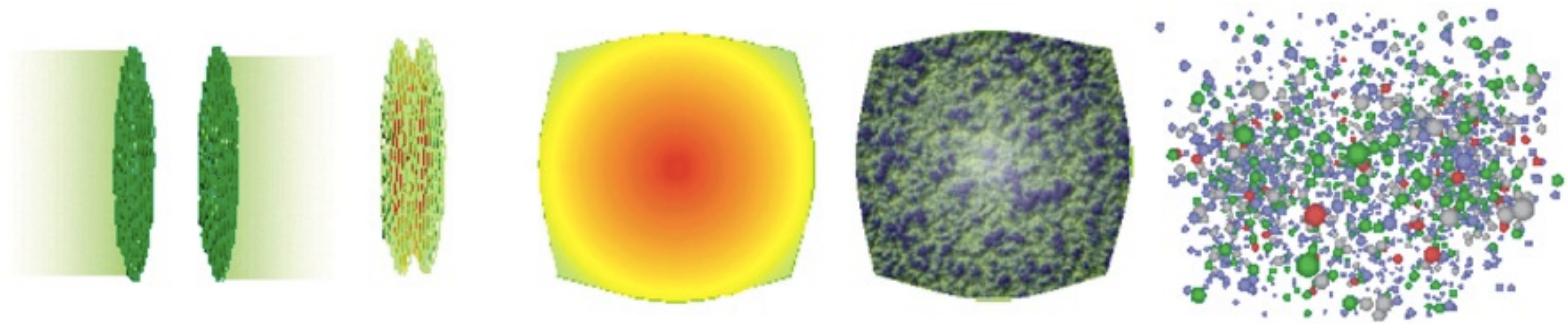
From Initial to Final State in Holography



Initial State | Collision | Out-of-equilibrium | Collective expansion | Final stage

Properties of nuclei
Small x partons
Saturation effects

From Initial to Final State in Holography

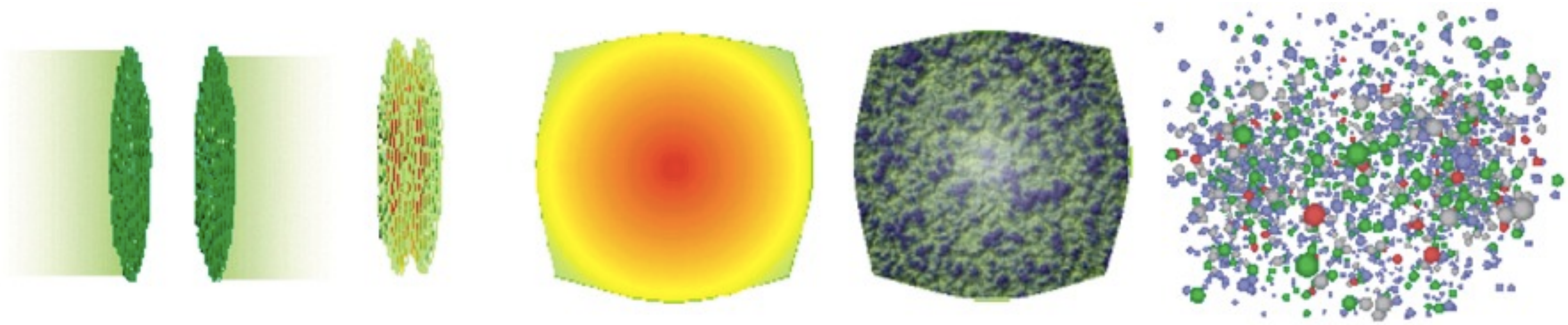


Initial State | Collision | Out-of-equilibrium | Collective expansion | Final stage

Initial State → Properties of nuclei; Small x partons; Saturation effects

Collective expansion → Hydrodynamics; Strongly coupled fluid

From Initial to Final State in Holography



Initial State → Properties of nuclei, Small x partons, Saturation effects

Collision → Liberation of partons, Perturbation theory

Out-of-equilibrium

Collective expansion → Hydrodynamics, Strongly coupled fluid

Final stage

Properties of nuclei
Small x partons
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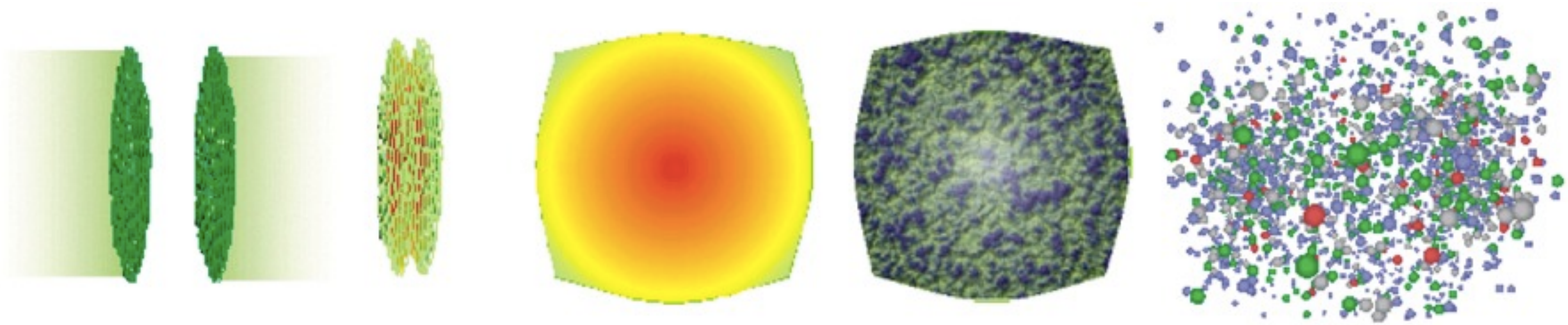
Liberation of partons
Perturbation theory

Hydrodynamics
Strongly coupled fluid

From Initial to Final State in Holography



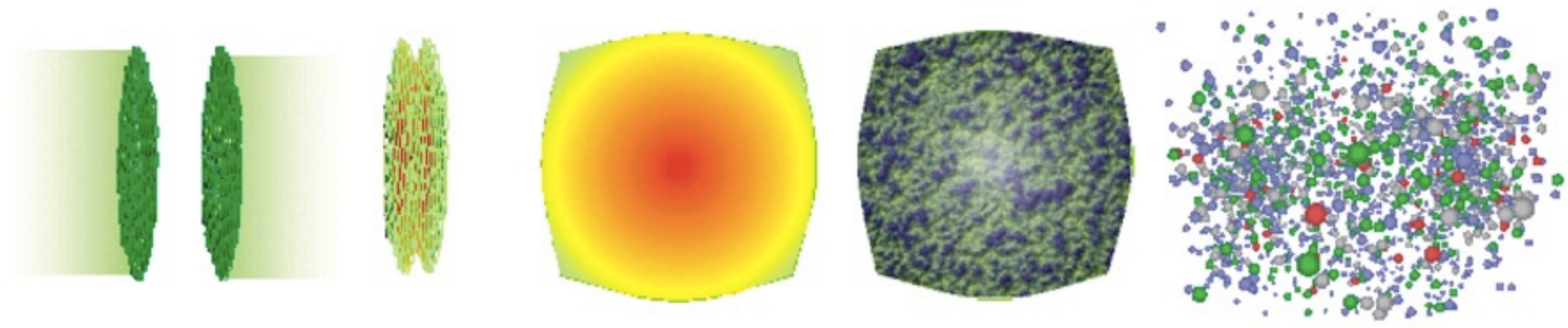
Initial State — Collision — Out-of-equilibrium — Collective expansion — Final stage

Initial State →
- Properties of nuclei
- Small x partons
- Saturation effects

Collision →
- Liberation of partons
- Perturbation theory ?

Collective expansion →
- Hydrodynamics
- Strongly coupled fluid

From Initial to Final State in Holography



Initial State → **Properties of nuclei** / Small x partons / Saturation effects

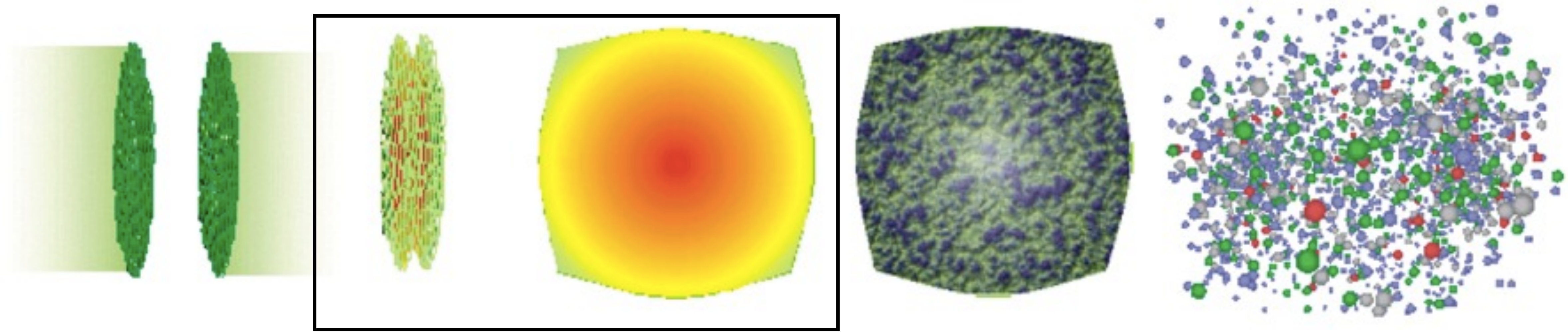
Collision → **Liberation of partons** / Perturbation theory ?

Out-of-equilibrium → **Thermalization, Isotropization, Hydrodynamization (hard for pQCD)**

Collective expansion → **Hydrodynamics** / Strongly coupled fluid

Final stage

From Initial to Final State in Holography



Initial State → Properties of nuclei; Small x partons; Saturation effects

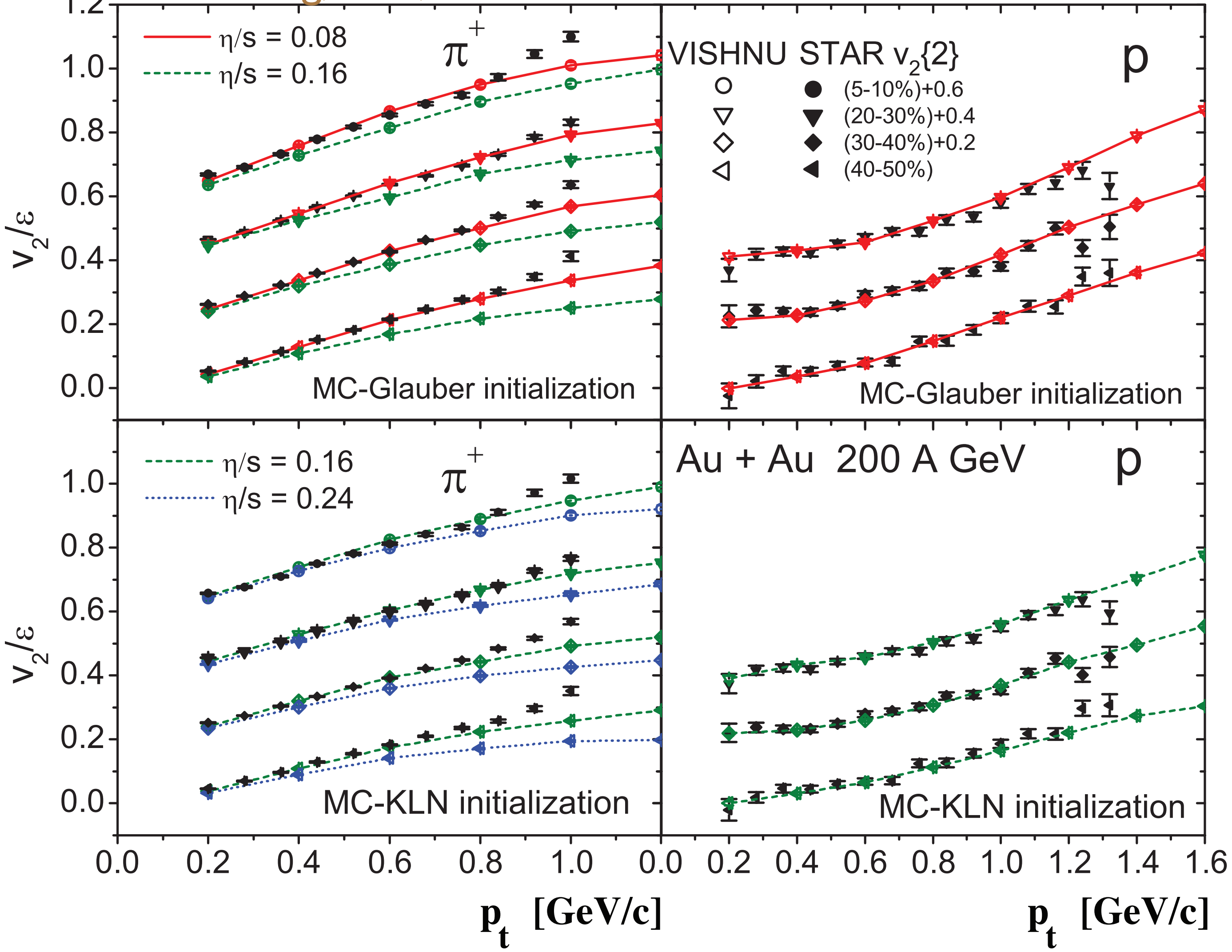
Collision → Liberation of partons; Perturbation theory ?

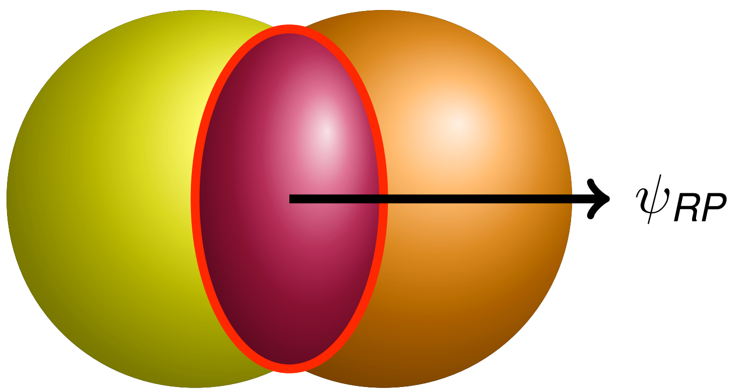
Out-of-equilibrium → Thermalization, Isotropization, Hydrodynamization (hard for pQCD)

Collective expansion → Hydrodynamics; Strongly coupled fluid

Final stage

Hydrodynamics and Heavy Ion Collision





$$v_2 \equiv \langle \cos 2(\phi - \psi_{RP}) \rangle \propto \varepsilon \equiv \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

ε depends on the model for nuclear density

- Hydro describes well flow data for different species

A very good liquid strongly coupled!

$$1 < 4\pi \frac{\eta}{s} < 2.5$$

(Son,Bass, Heinz, Hirano, Shen 11)

predicted by AdS/CFT!

(Policastro, Son, Starinets 01)

(Transverse) Fluctuations

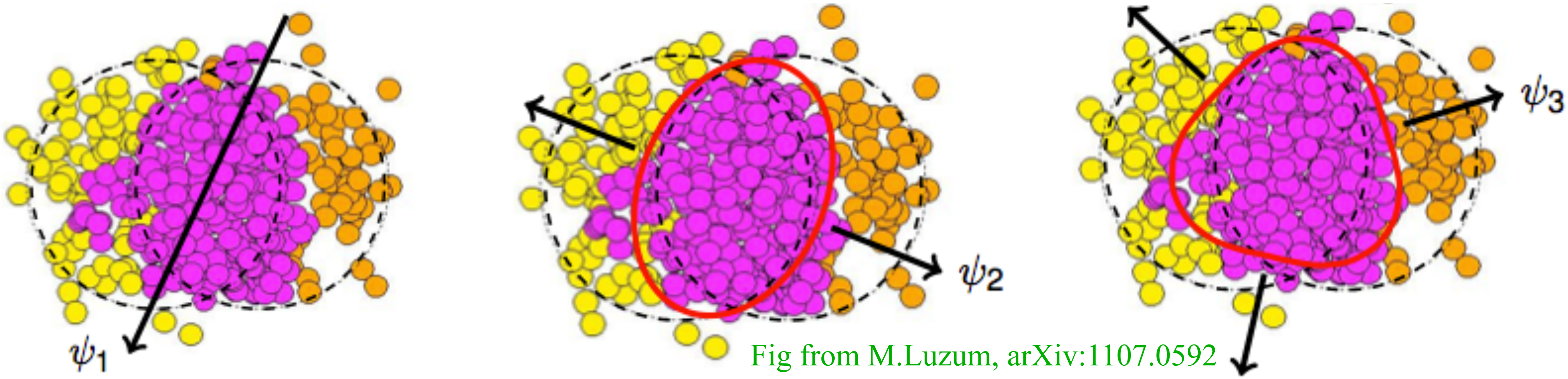
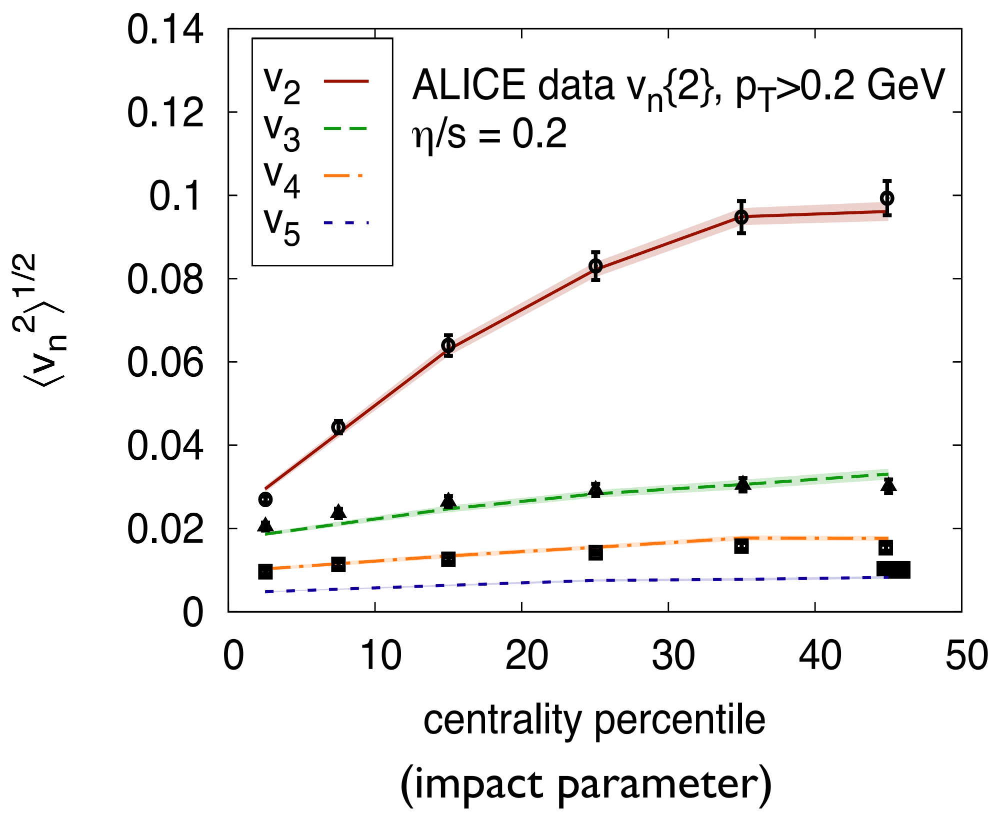
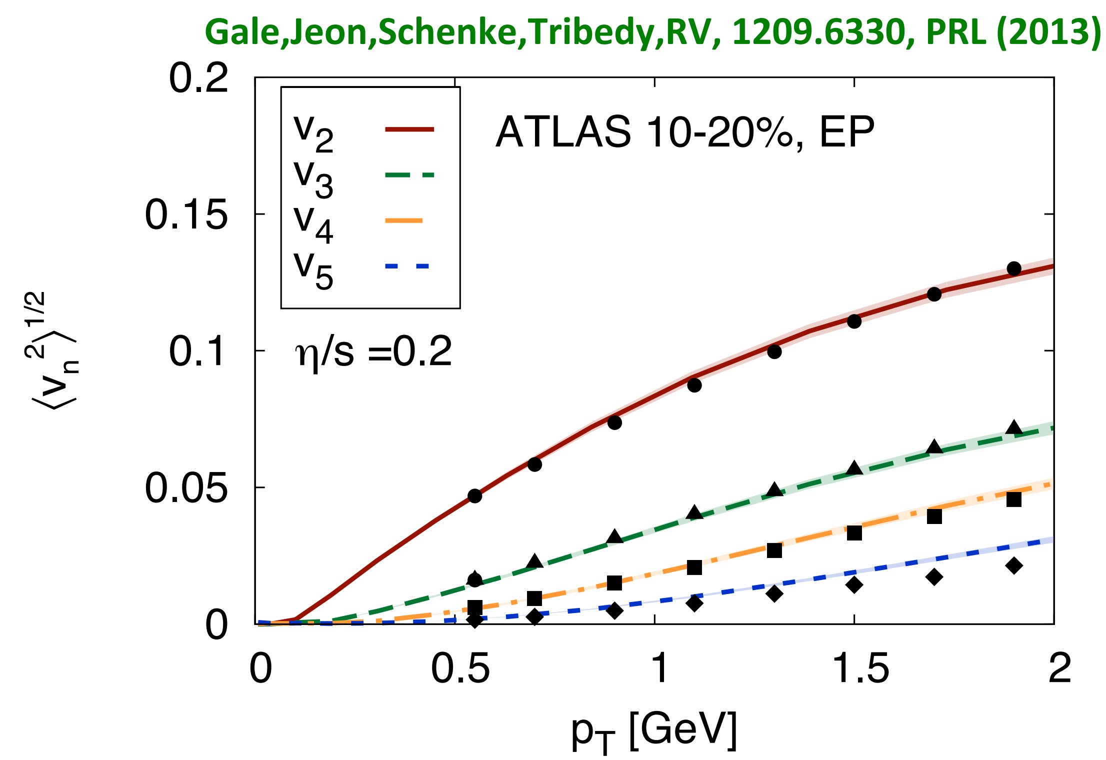


Fig from M.Luzum, arXiv:1107.0592

- Large event by event fluctuations ⇒ non-trivial hydro response

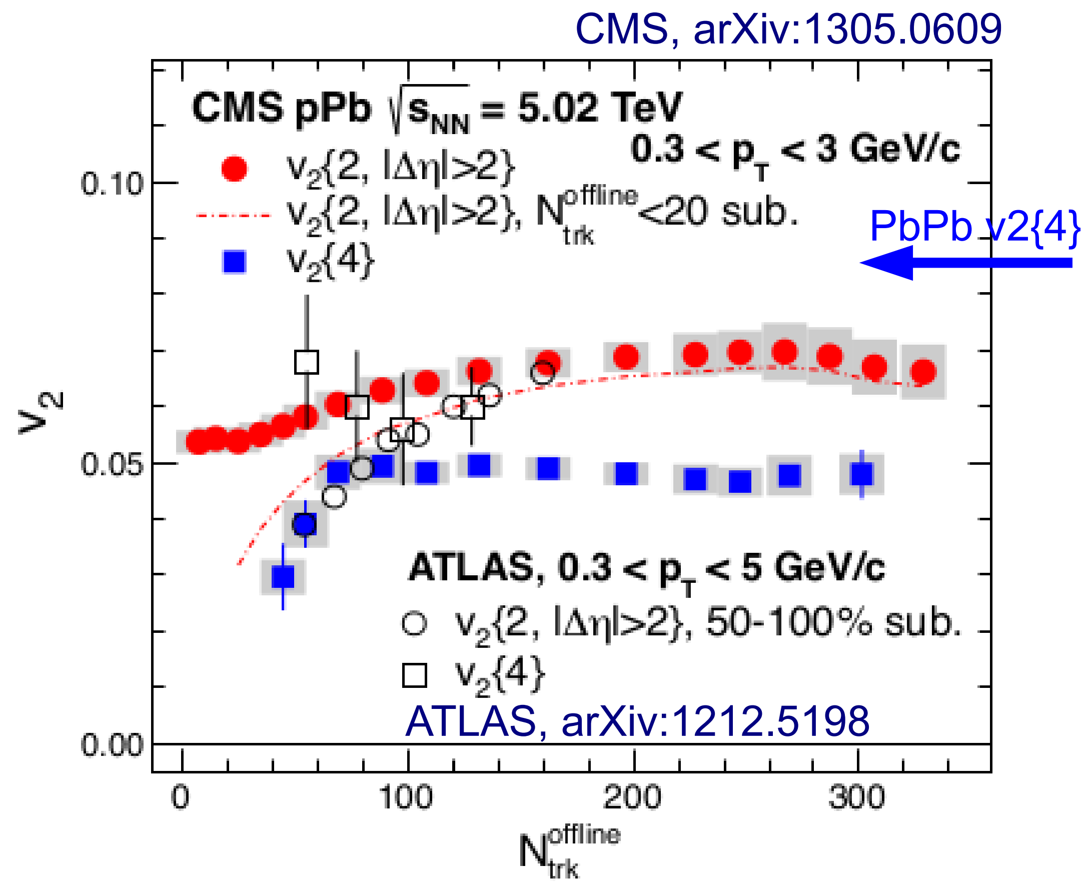
(Transverse) Fluctuations

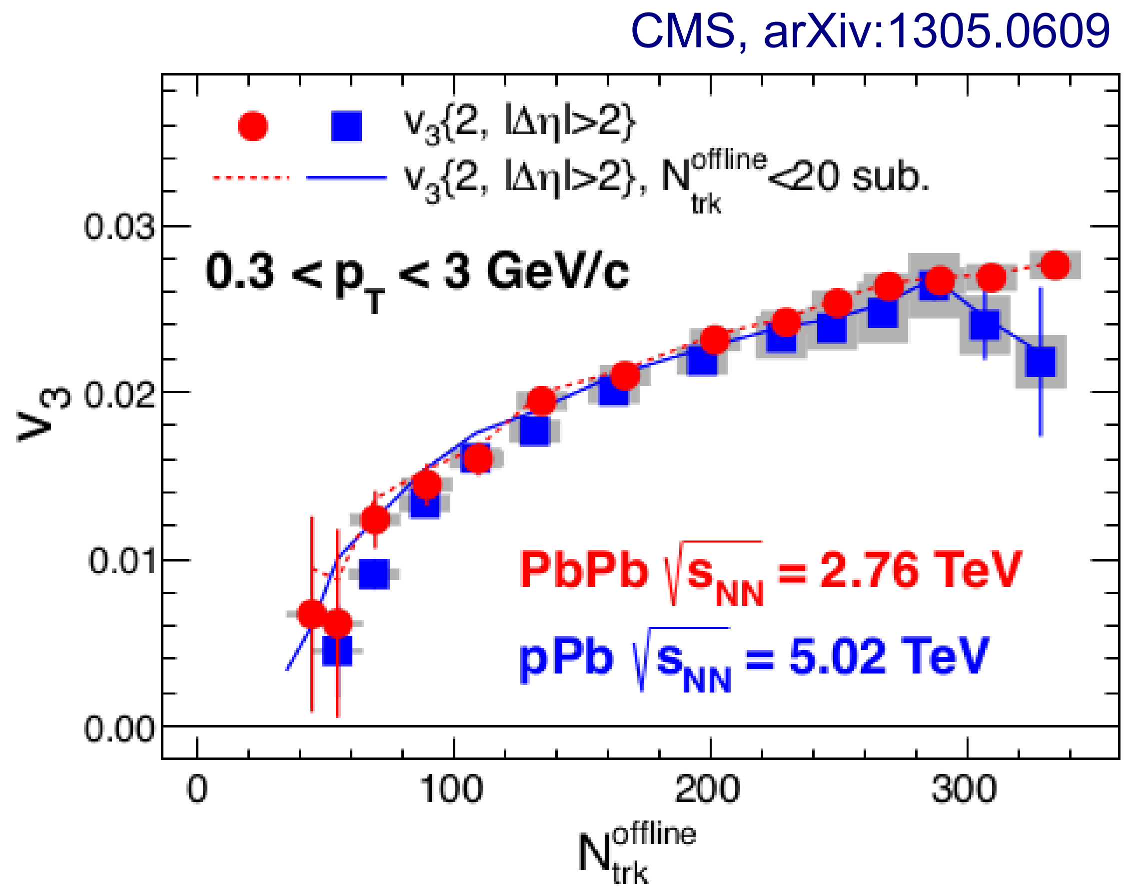




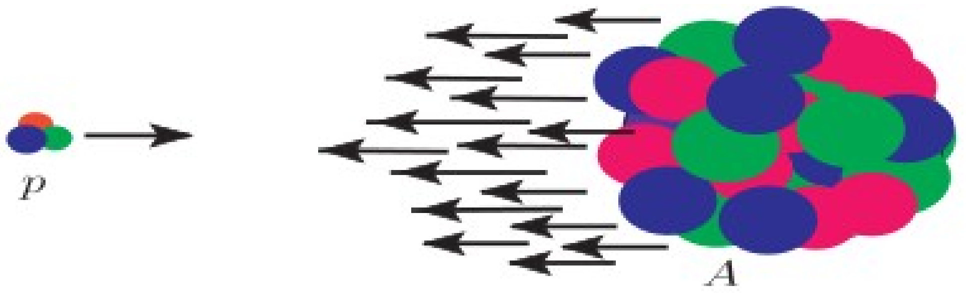
- Large event by event fluctuations ⇒ non-trivial hydro response
- Hydro + initial condition models can describe data
- New program to extract viscosities.
  - ➤ Focus on constraining initial state

Flow in p-Pb!



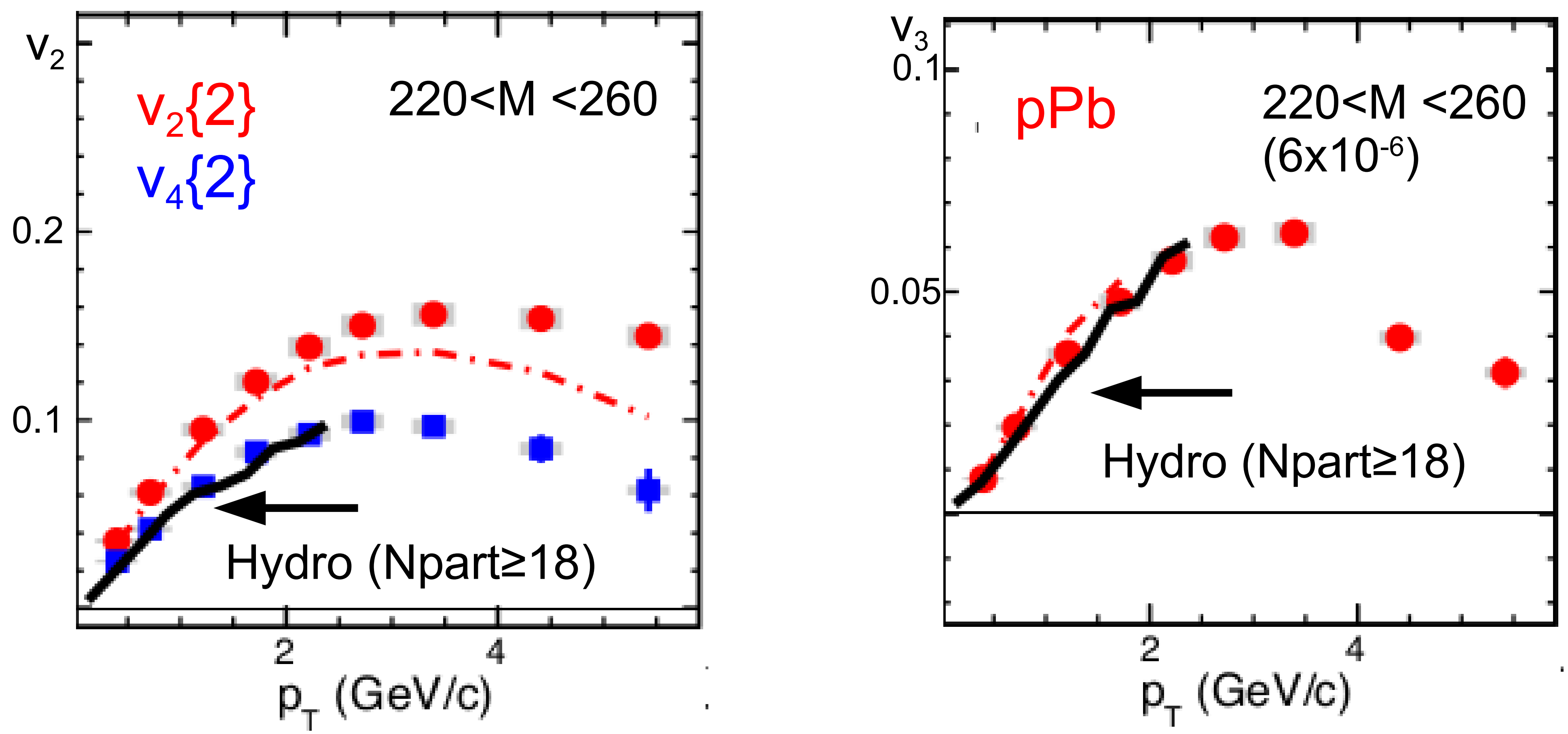


- Flow effects are large!
  - ➤ v_2 smaller than PbPb (different shape)
  - ➤ v_3 same as in PbPb (same fluctuations)



Flow in p-Pb!

Bozek arXiv:1112.0915



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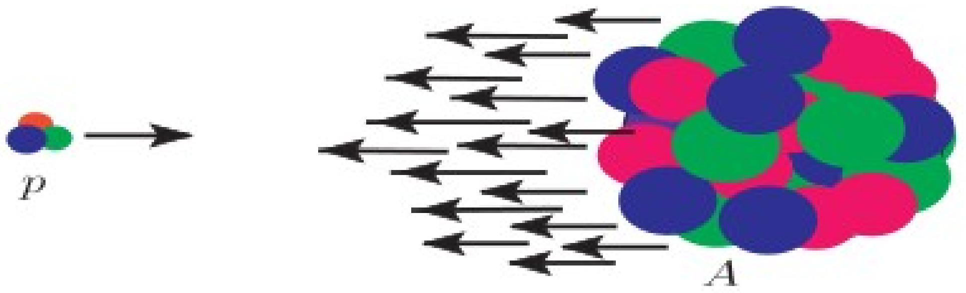
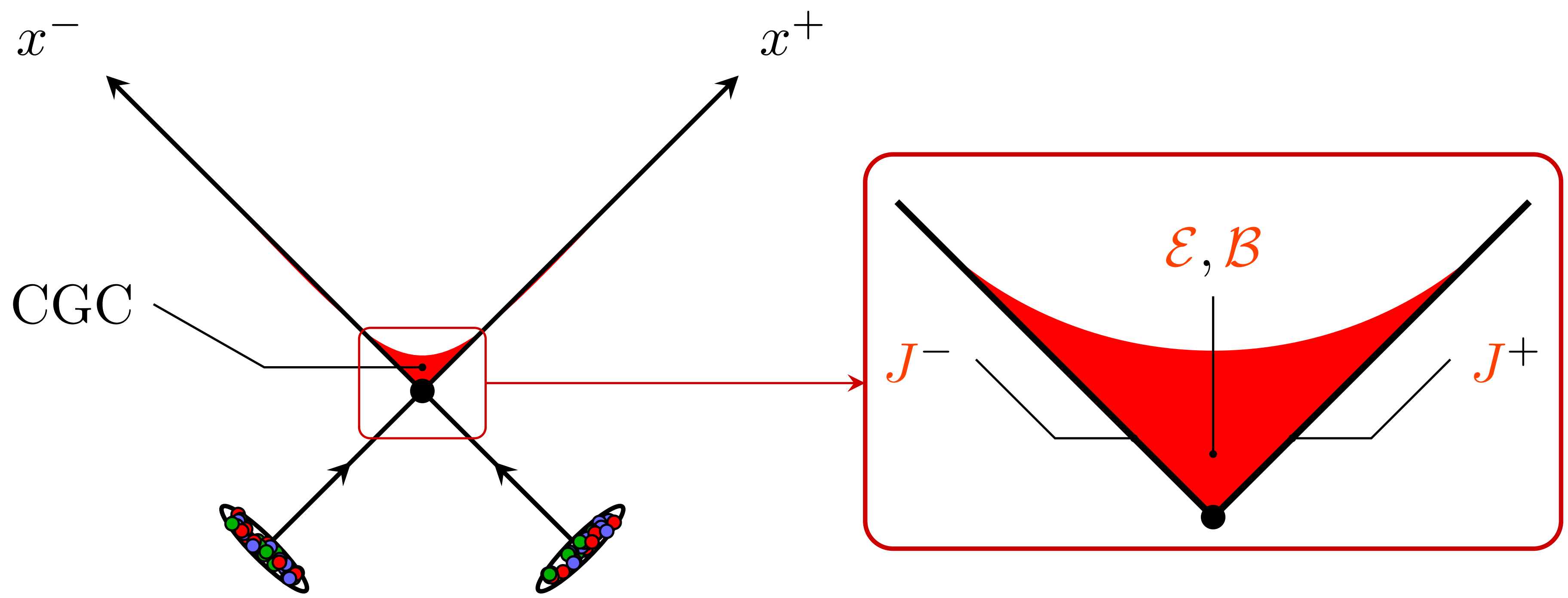


- Hydrodynamics predicts both these flows!

despite of smaller system ⇒ larger gradients

Initial Conditions and the CGC

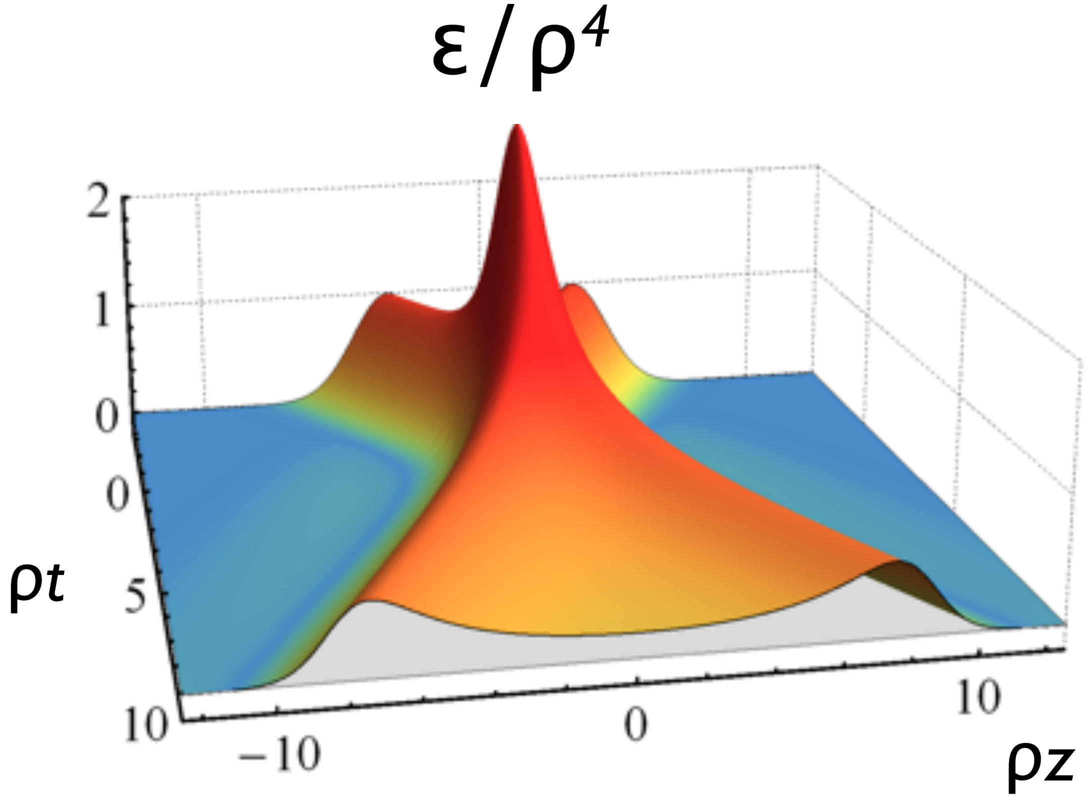


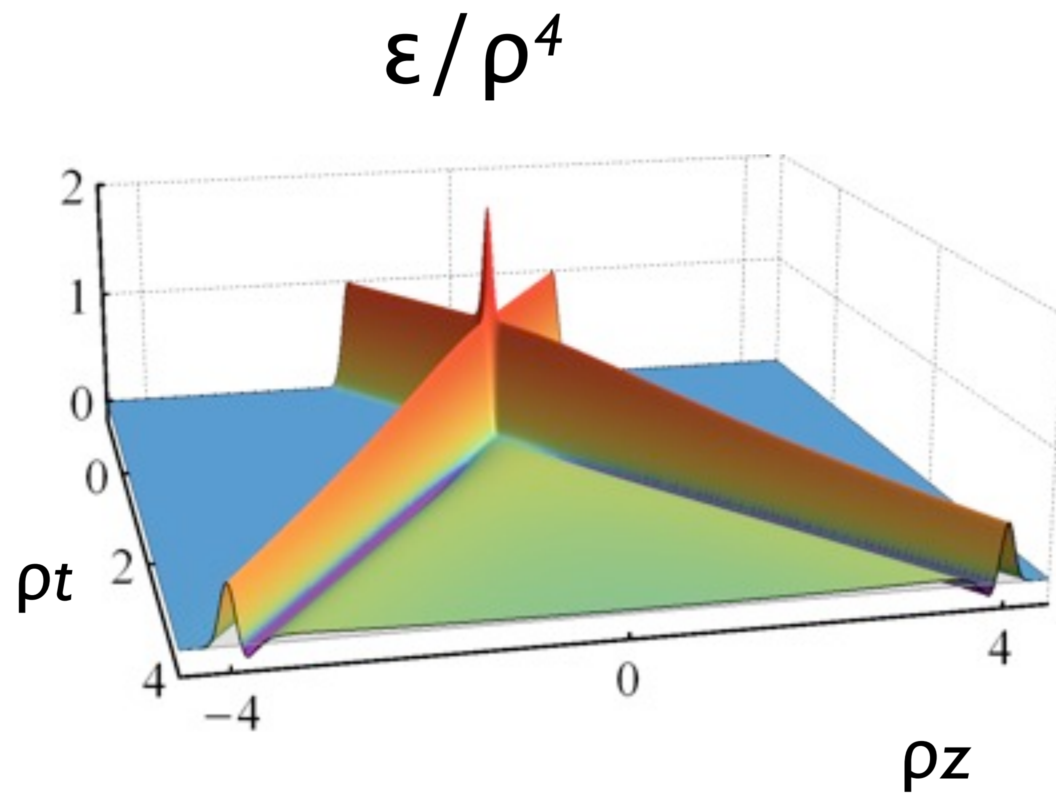
- Small x partons ⇒ Saturation physics
  - ➤ Typical size of partons $1/Q_s$ (perturbative scale)
  - ➤ Large occupation numbers $1/\alpha_s(Q_s)$ ⇒ classical fields
- Phenomenologically:

$$Q_s^{LHC} \sim 3 - 4\,\mathrm{GeV}$$ Albacete, Dumitru, Fujii, Nara 12

➤ Not terribly perturbative, still room for strong coupling effects

Shock Collisions at Different Energies





Holographic collision of two gaussian shocks

(Chesler & Yaffe 11)

(Albacete, Kovchegov and Taliotis 08, Grumiller & Romatschke 08)

ρ: *maximum energy density*

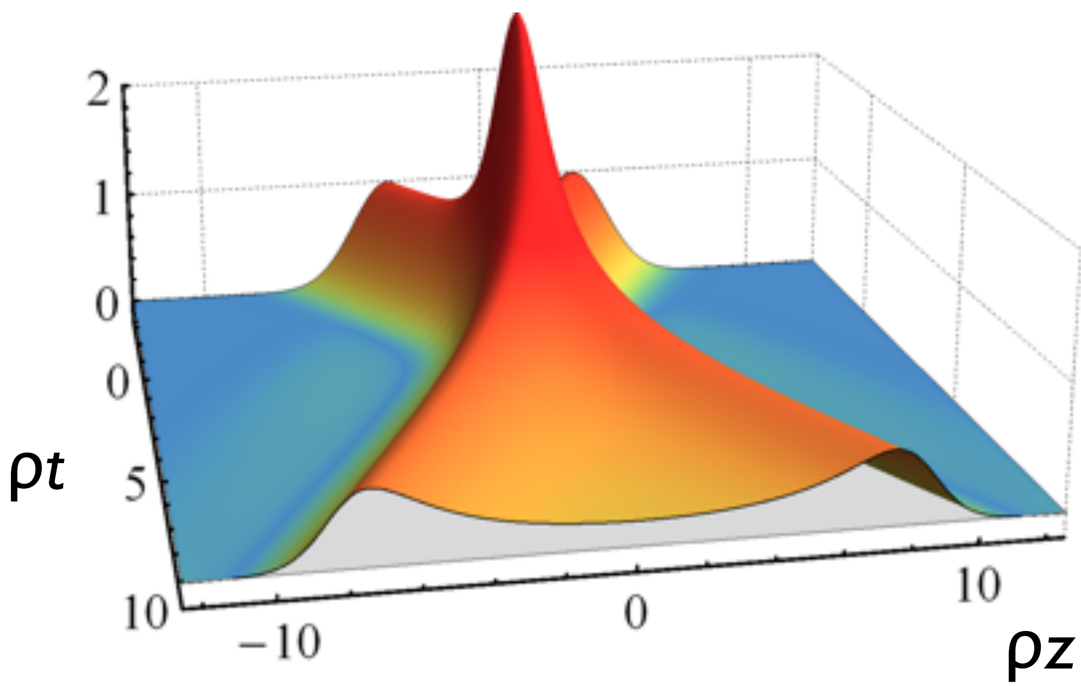
ω: *width of the gaussian*

proxy for shock energy ω~ 1/E

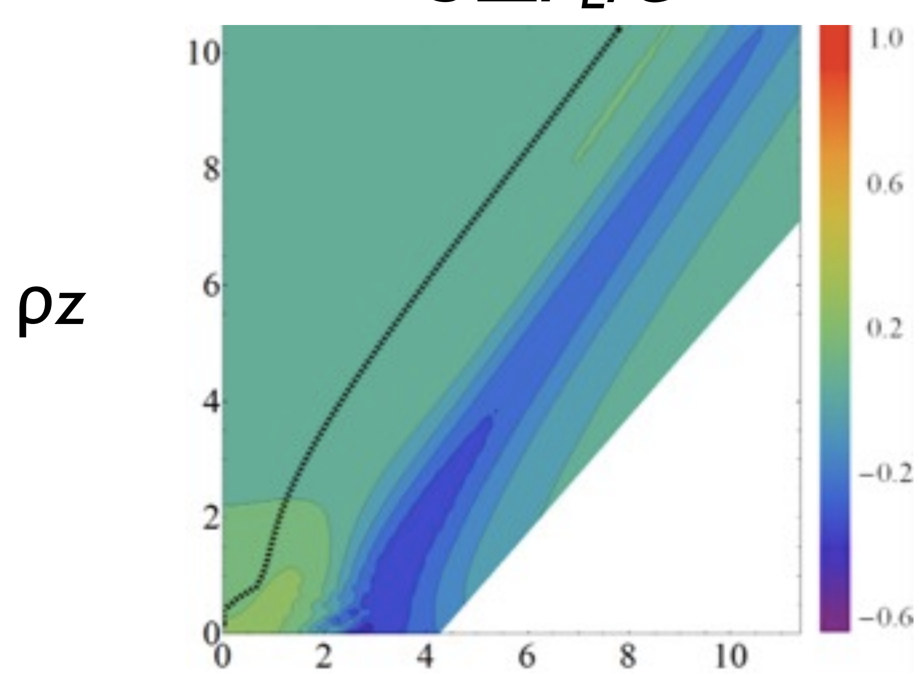
μ: *energy per transverse area*

Low Energy Shocks

ε / ρ^4



$3\Delta P_L/\varepsilon$



- ➤ The shocks merge and stall
- ➤ No propagation in light-cone
- ➤ Dynamics well approximated by viscous hydrodynamics

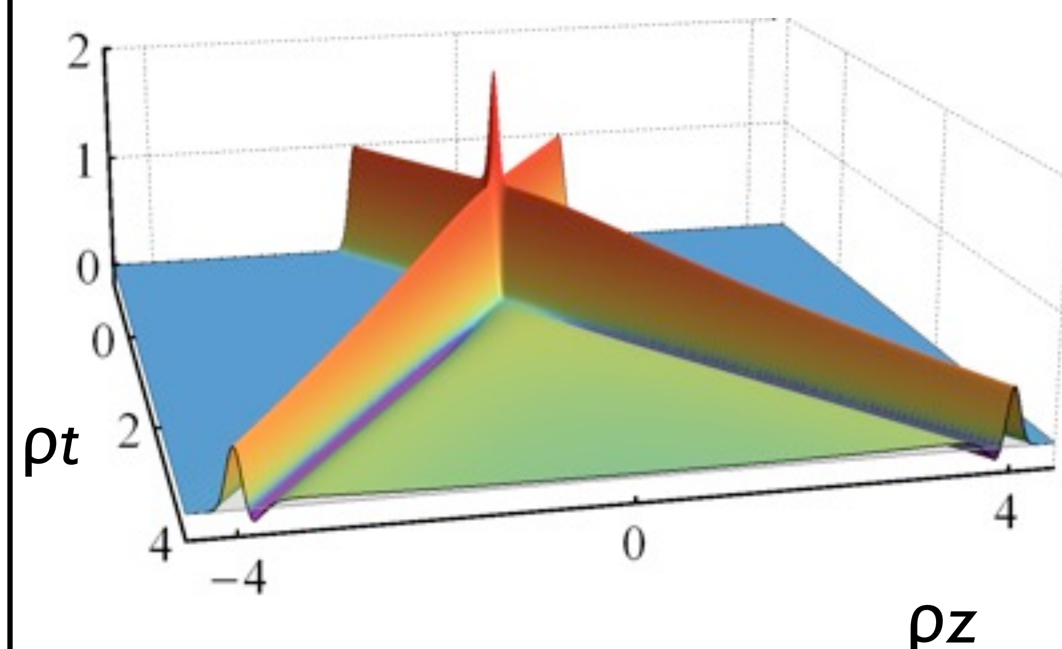
High energy shocks

- Shocks pass through each other

Transparency

- Some energy remains in the light-cone
- Disturbed remnant shocks do not behave hydrodynamically
- They decay after the collision
- Hydrodynamic plasma is formed in the central rapidity region

ε/ρ^4



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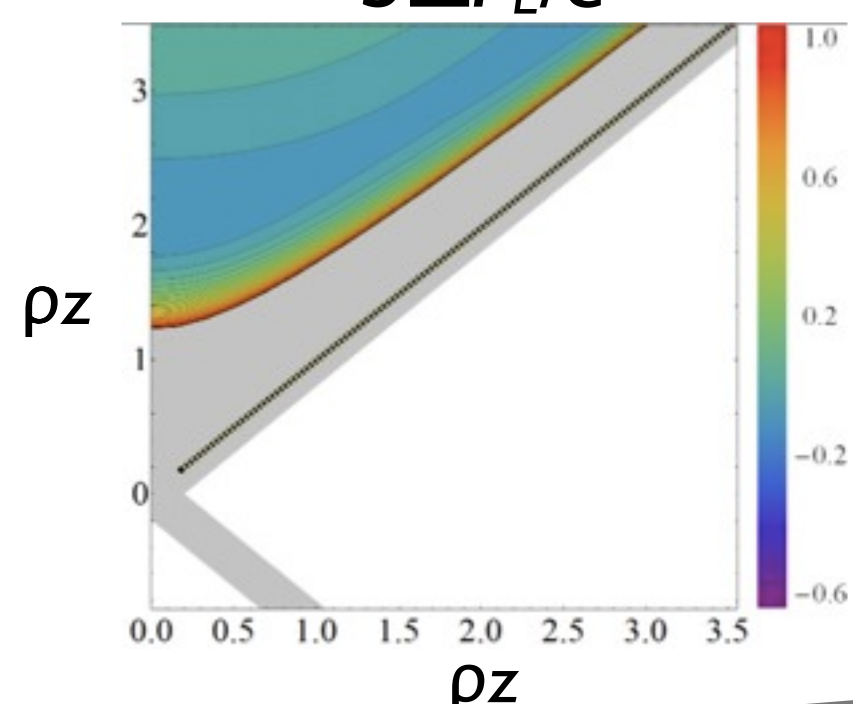
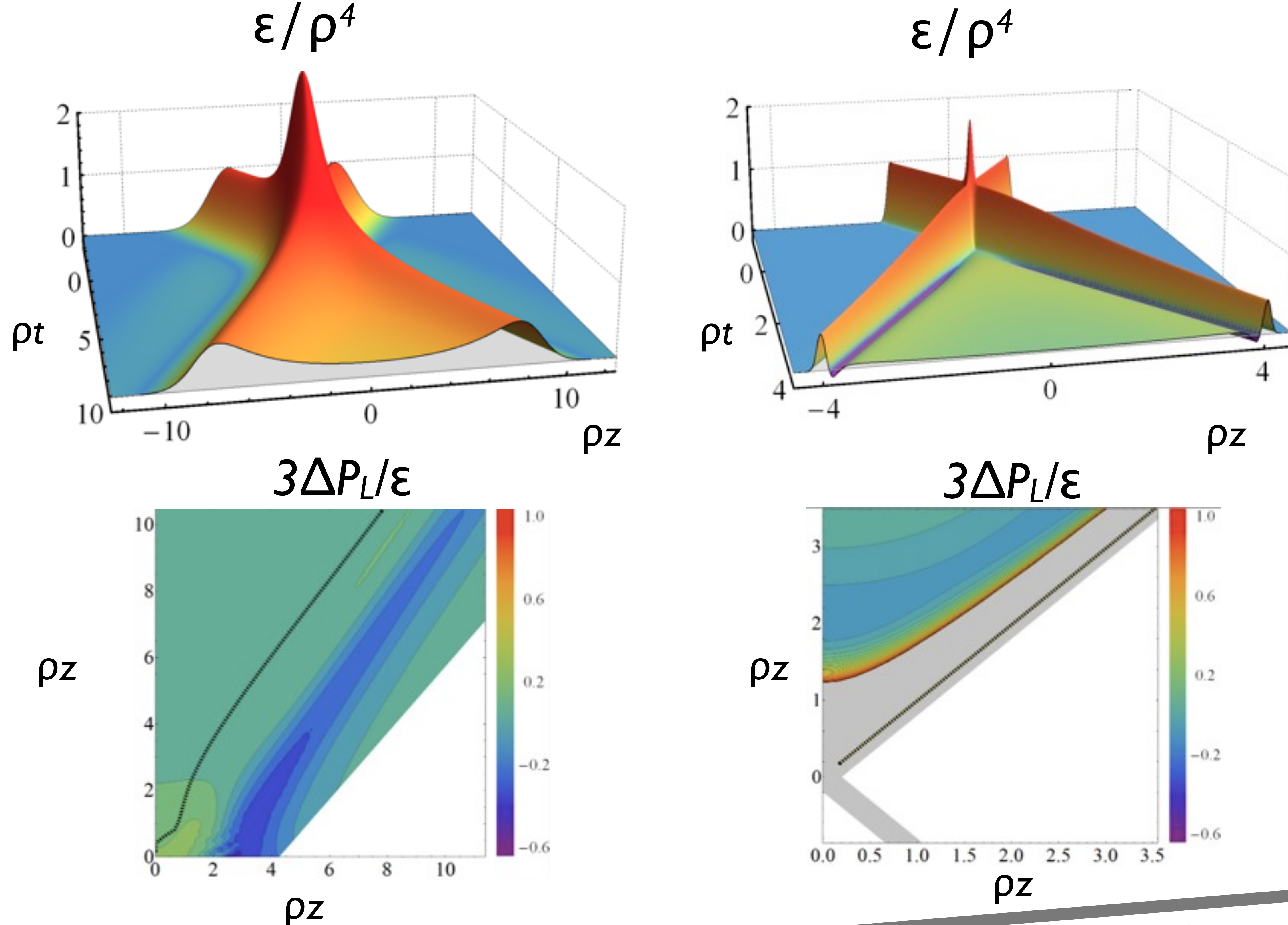


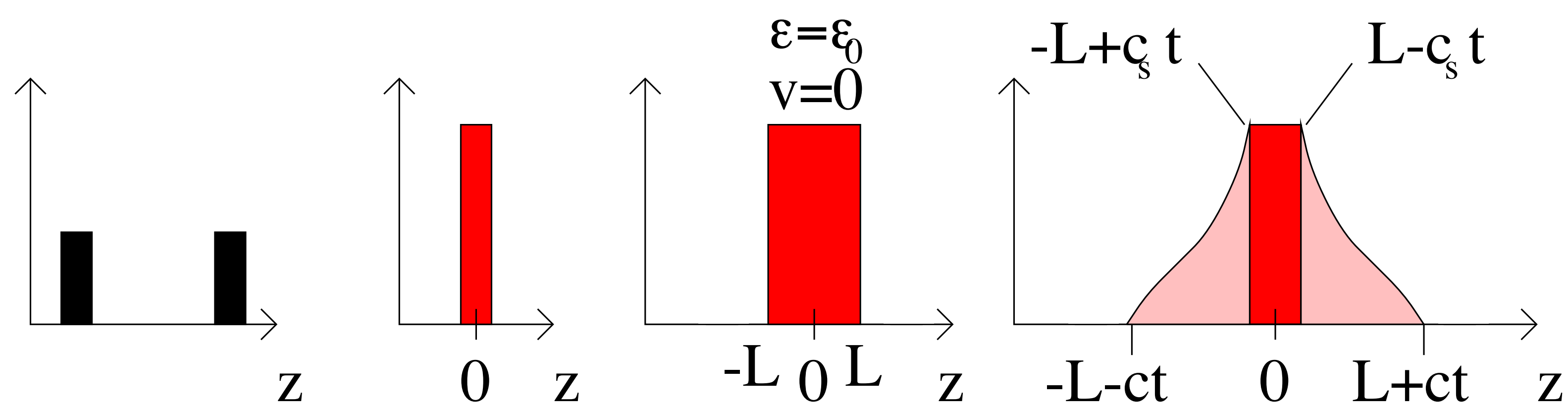
A Dynamical Cross Over



Jorge Casalderrey-Solana

Landau vs Bjorken

- Landau model: All energy is stopped + hydro explosion

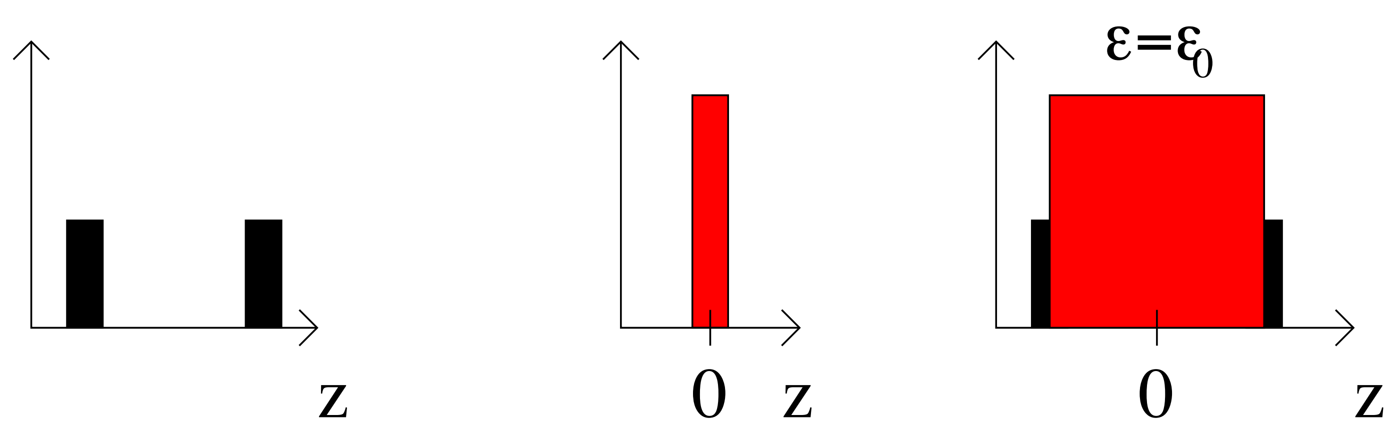


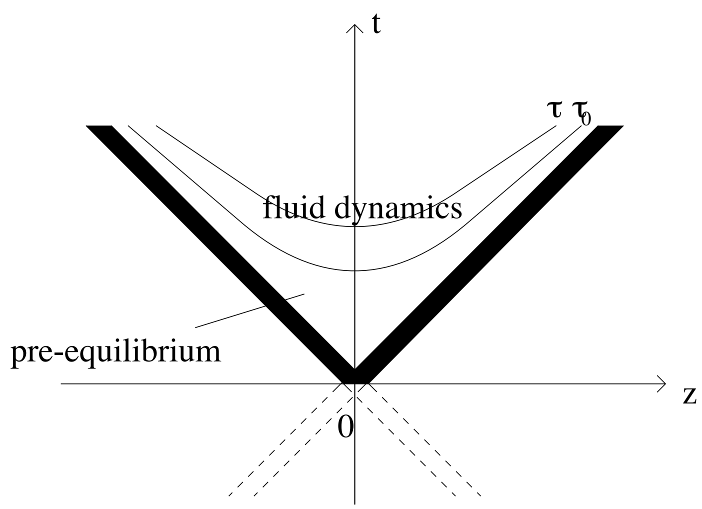
(predicts a gaussian distribution in rapidity)

$t = \tau\ \mathrm{Cosh}(\eta_{st})$

$z = \tau\ \mathrm{Sinh}(\eta_{st})$

- Bjorken: matter produced at all rapidities

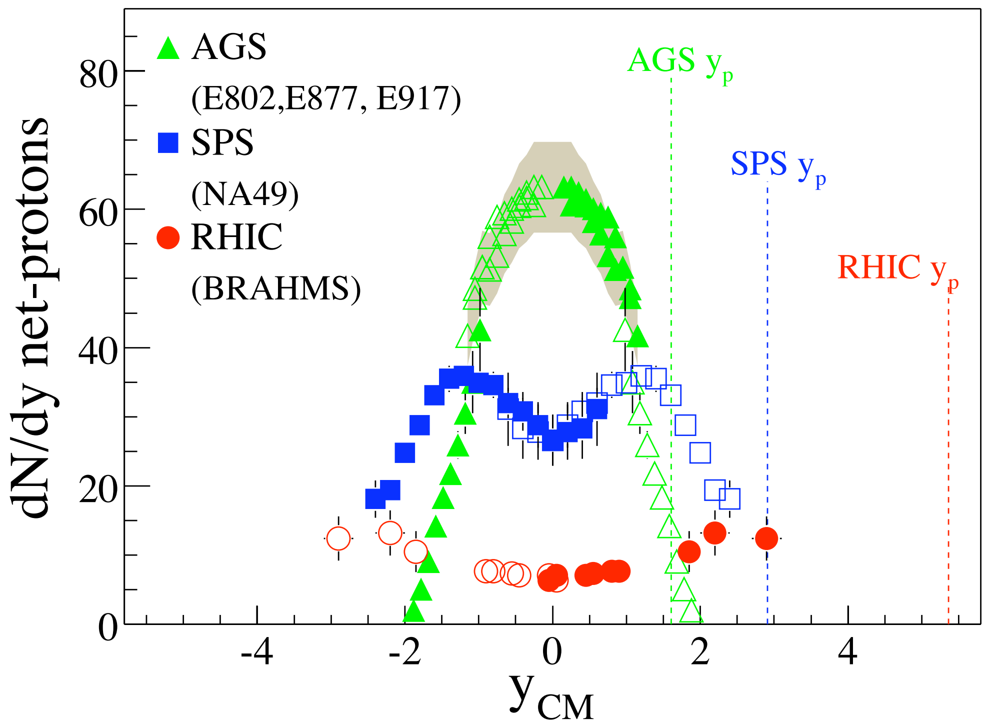




Boost invariant flow

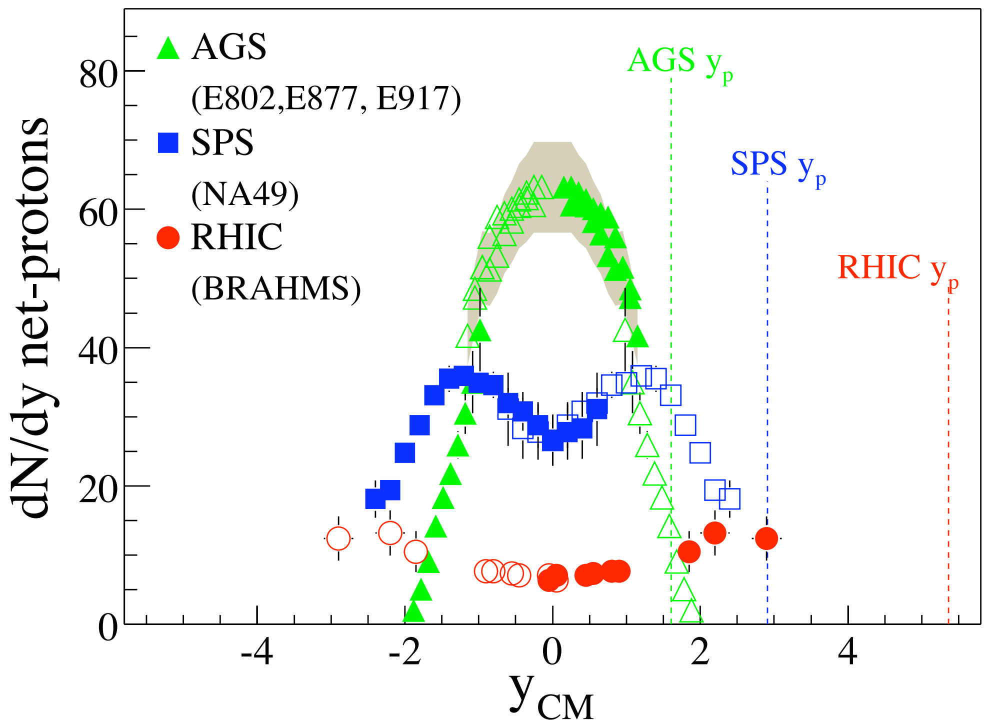
Fluid rapidity = space time rapidity

Landau vs Bjorken



Baryons are not stopped
(Bjorken)

Landau vs Bjorken



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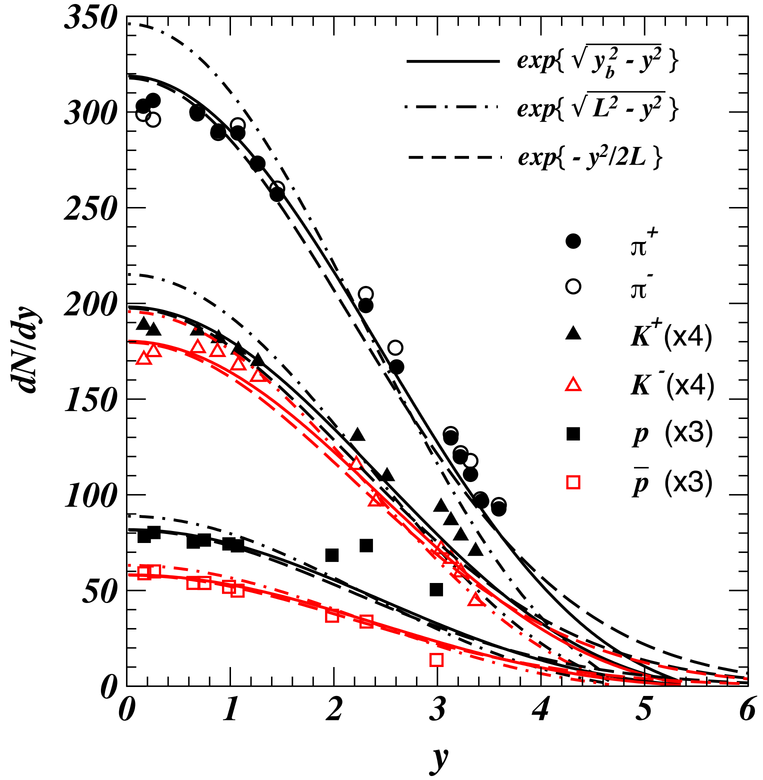
(Bjorken)

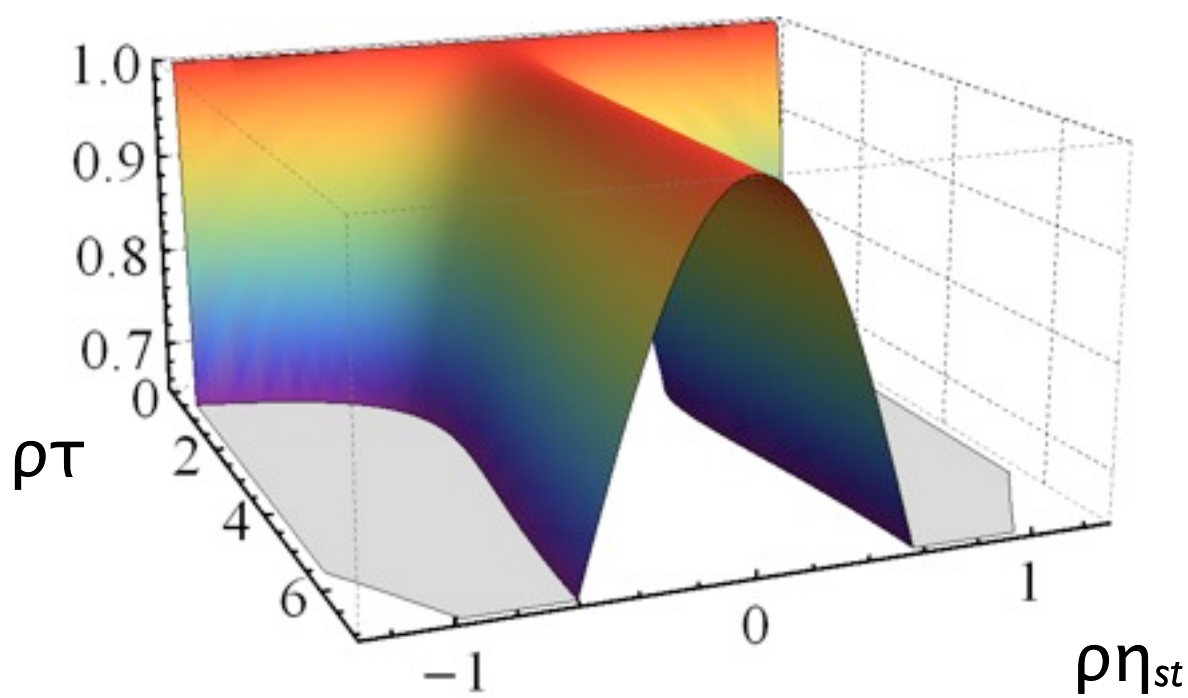
(C-Y Wong 09)



Gaussian profile in rapidity
(Landau)

Non-Boost Invariant Initial Conditions

$\varepsilon_{loc}(\tau,\eta) / \varepsilon_{loc}(\tau,\eta=0)$



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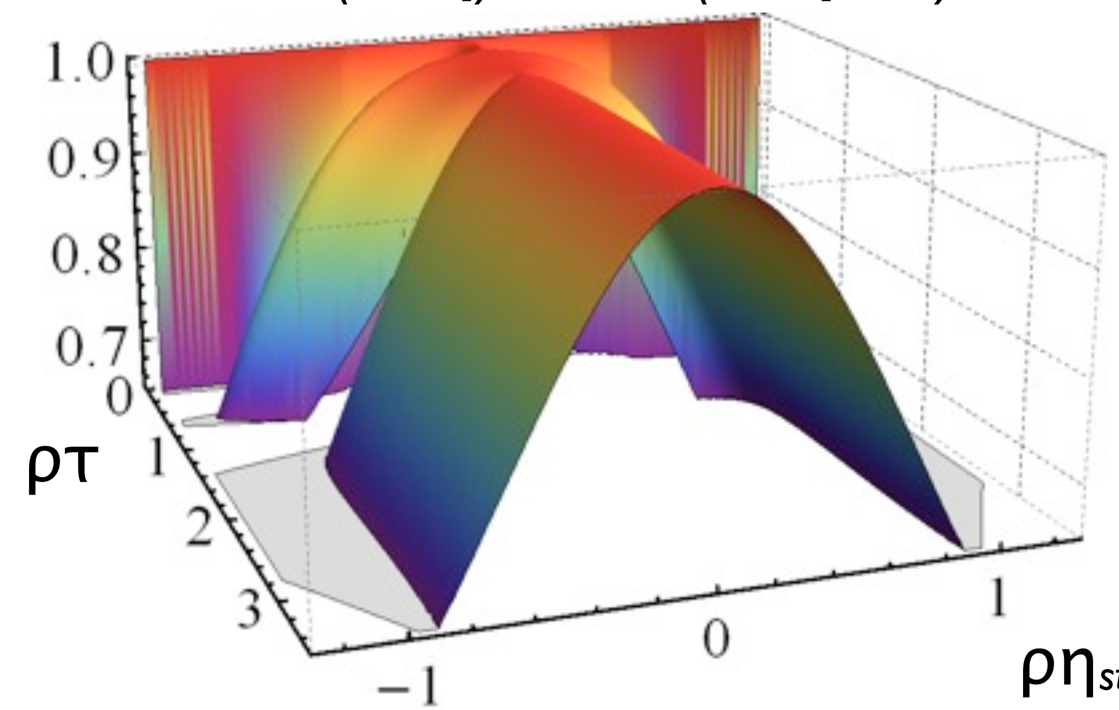
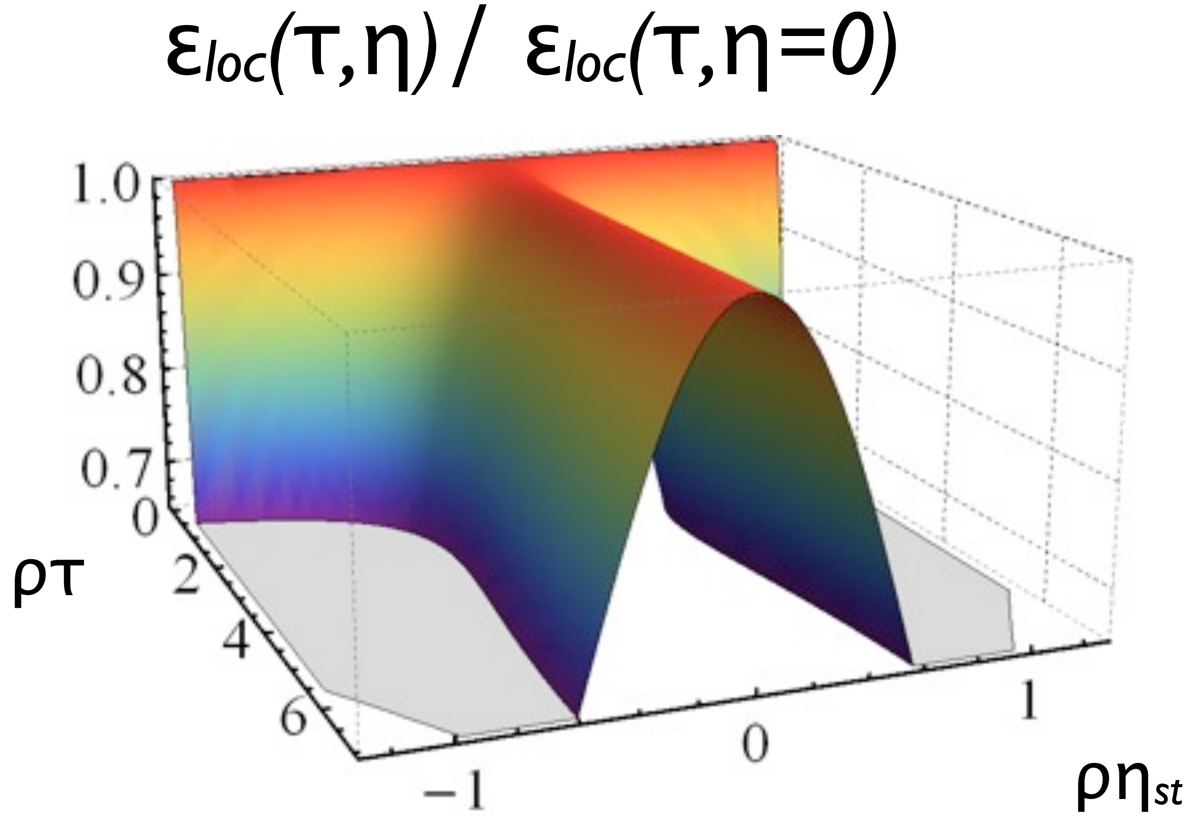
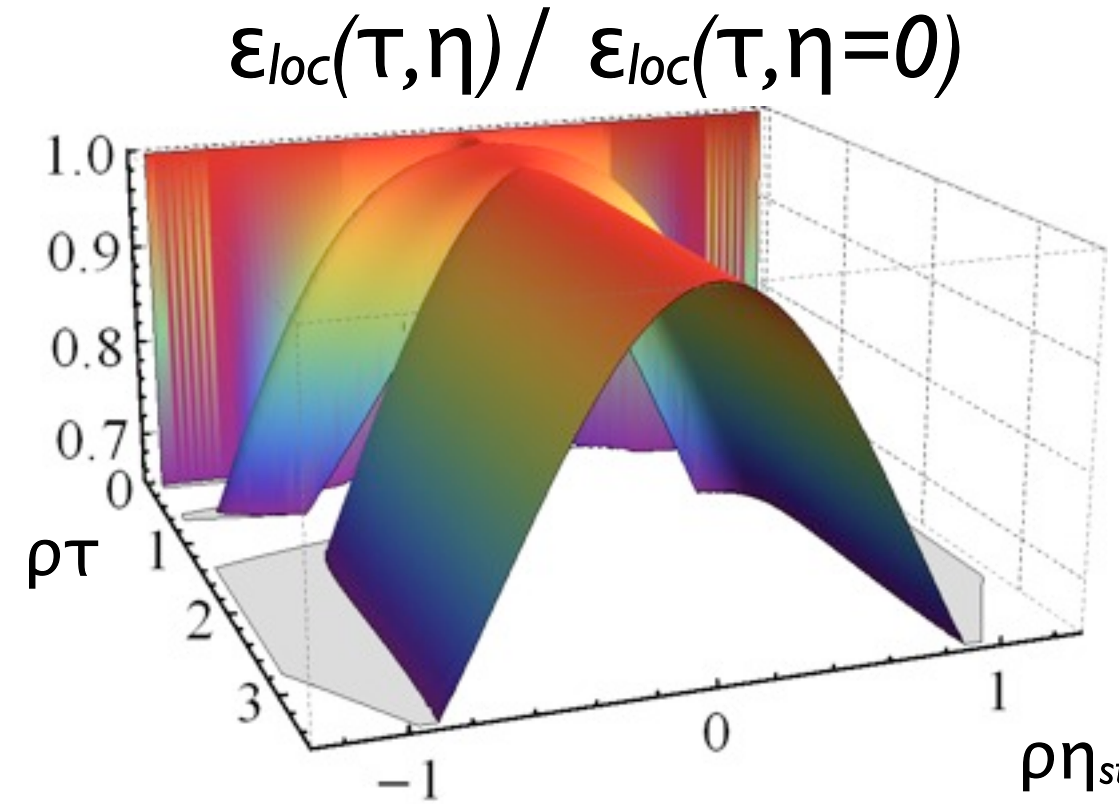


- Gaussian rapidity profile
  - Low energies: expected from Landau hydrodynamics
  - High energies: relatively mild increase of width

Non-Boost Invariant Initial Conditions





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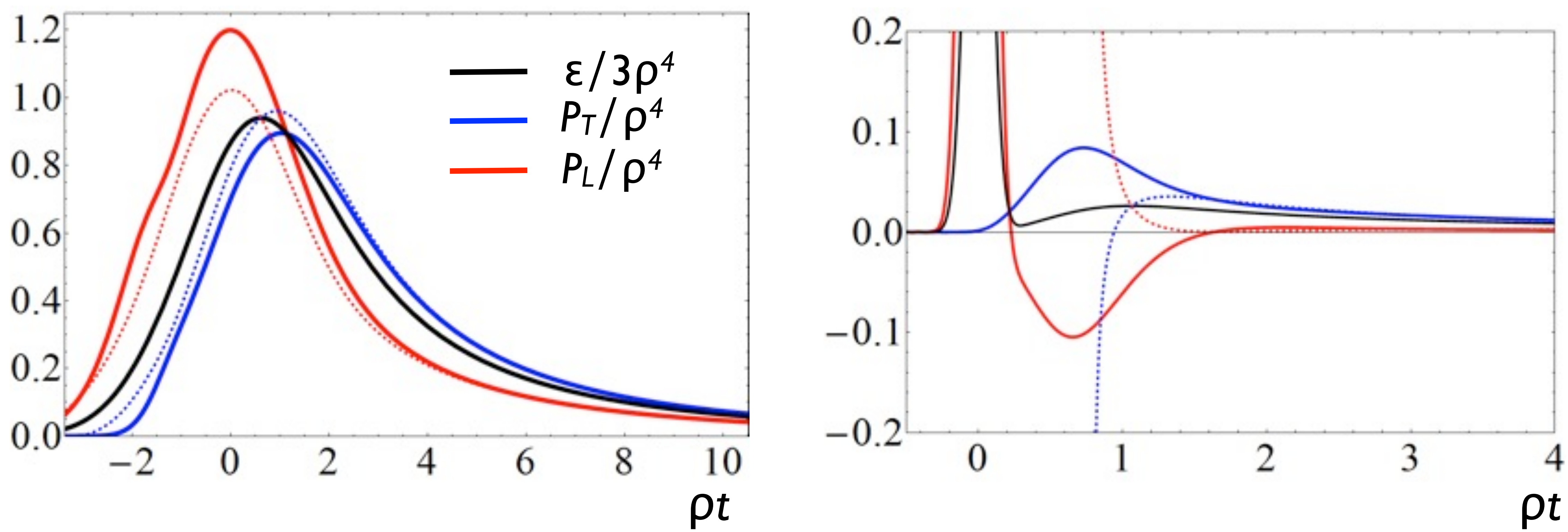
(subsequent time evolution well described by Bjorken like flow)

Chesler & Yaffe 13

Surprisingly Hydrodynamic

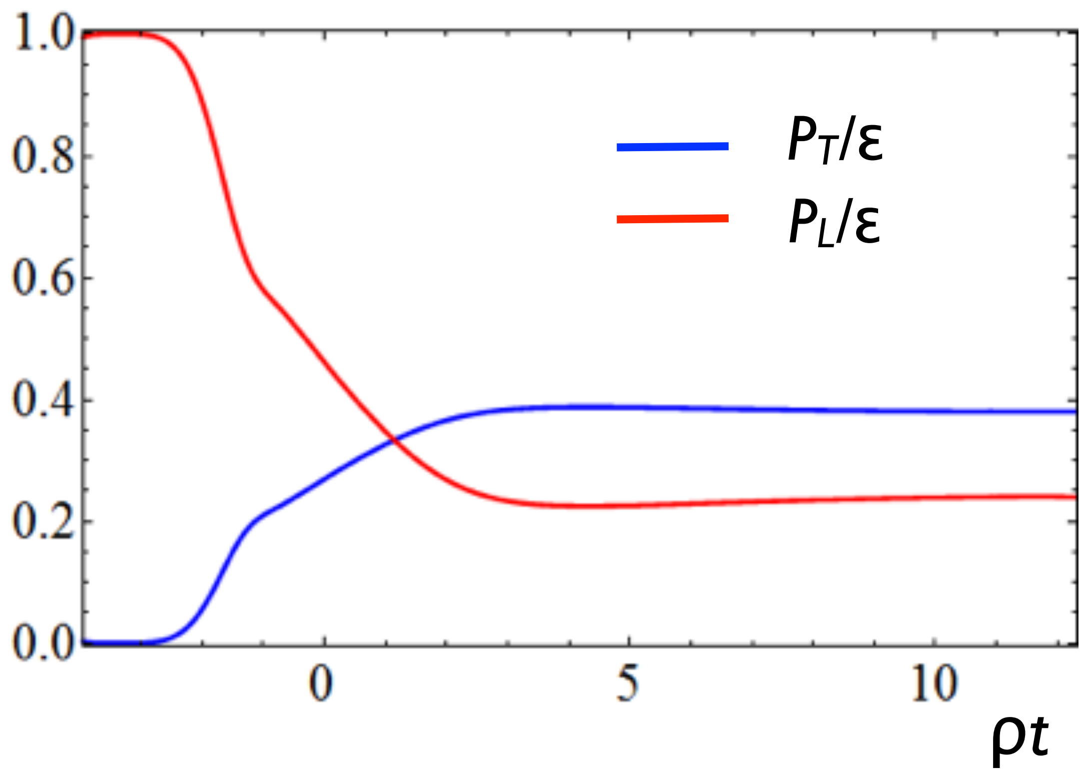


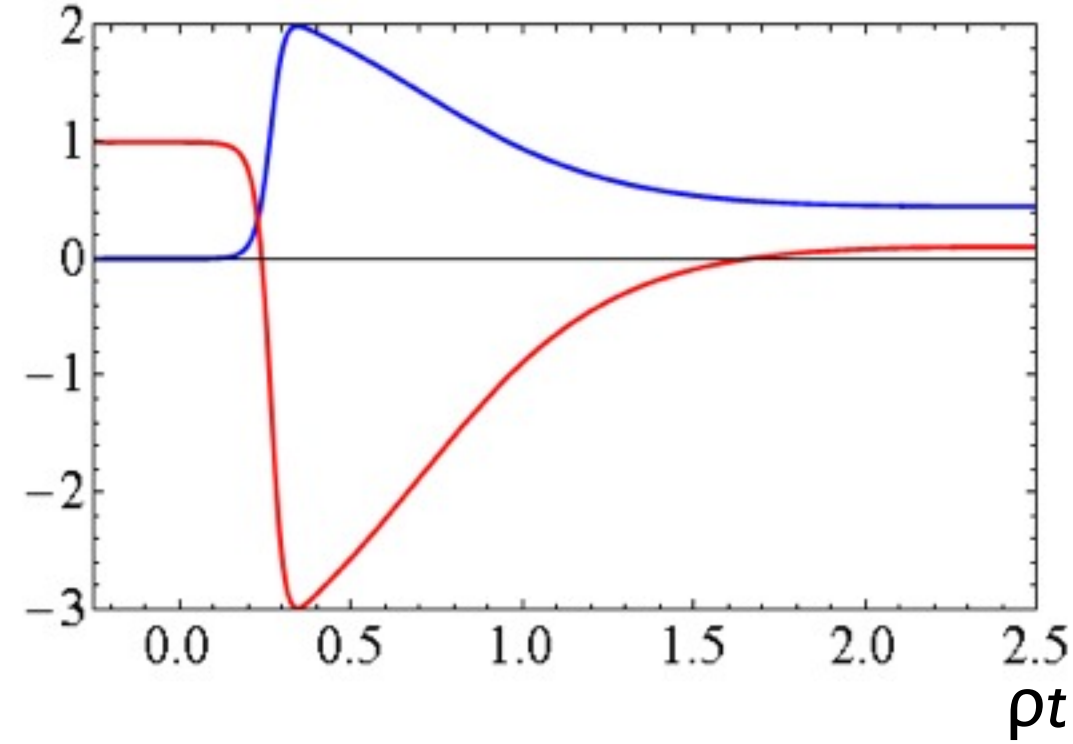
- Good hydrodynamic behavior from very early on
- Energetic shocks: Plasma develops after $t_{hyd}=1/\pi T_{hyd}=0.87/\mu$
- Very large viscous corrections! *Hydrodynamization*

Chesler & Yaffe, Wu & Romatschke, Heller, Janik & Witaszczyk,
Heller, Mateos, van der Schee, Trancanelli

- Early behavior of pressures due to vanishing initial ε

Surprisingly Hydrodynamic





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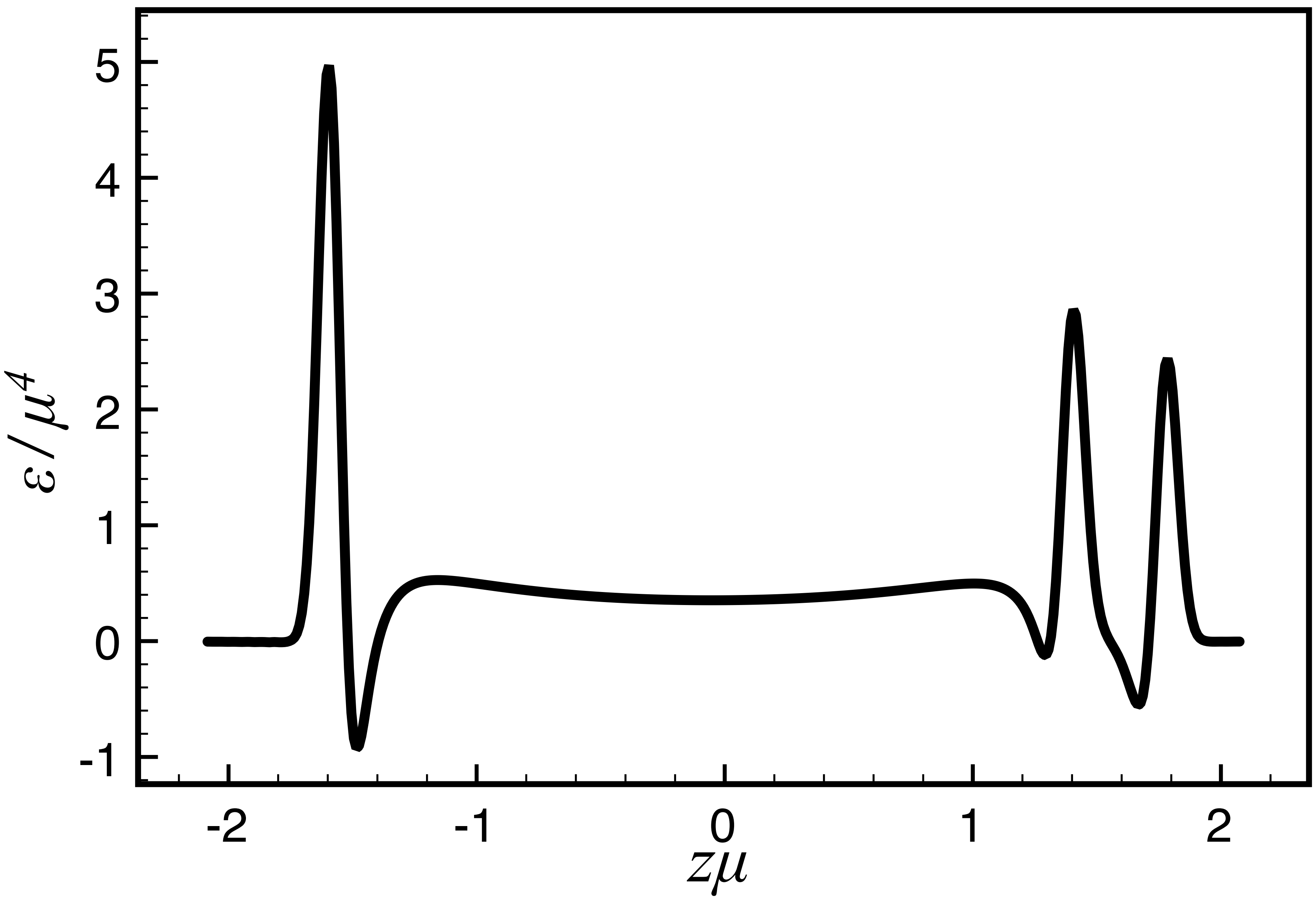
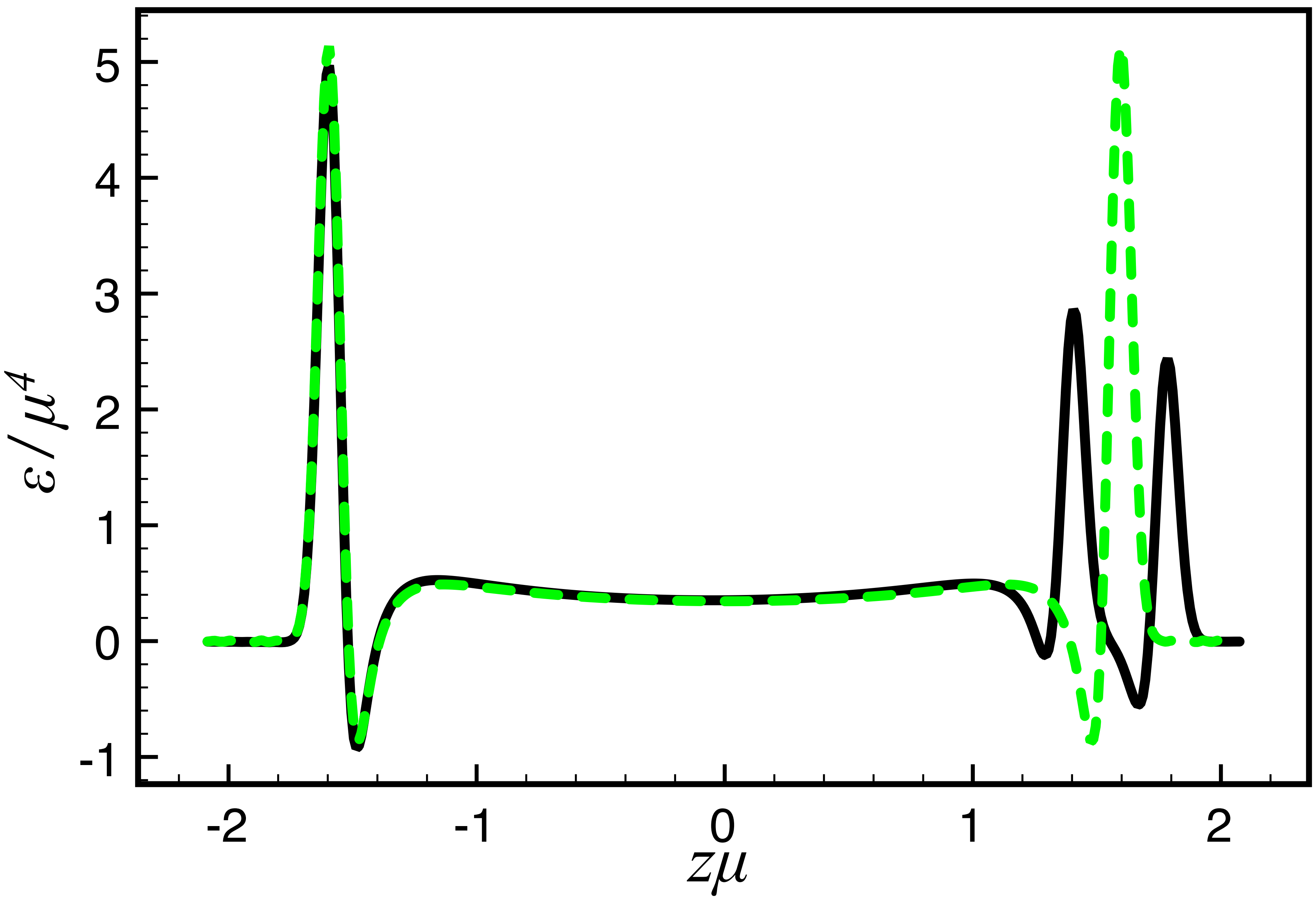
Towards p-A: Longitudinal Coherence



➤ In the center of mass of the "nucleus-nucleon" collision

Towards p-A: Longitudinal Coherence



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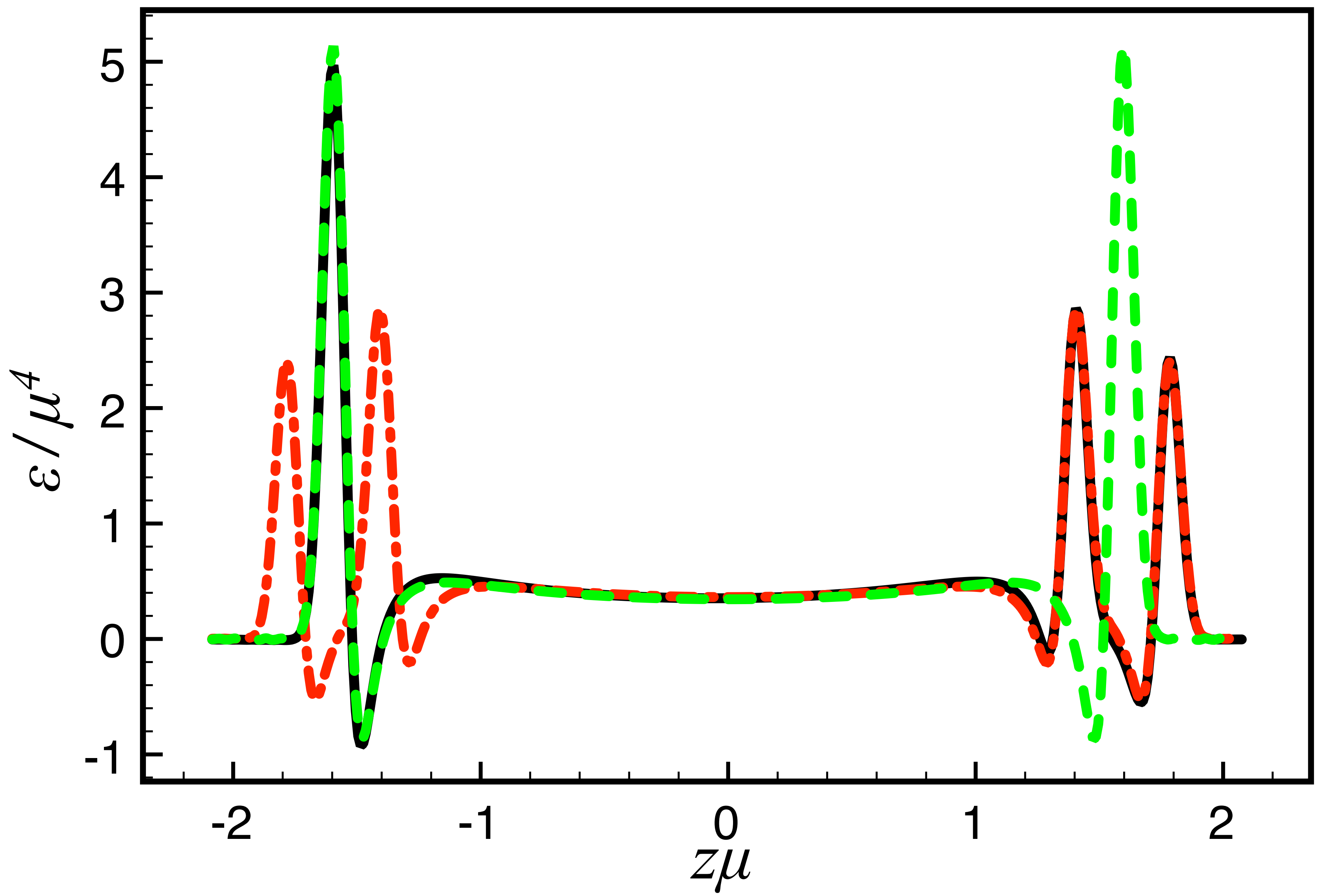

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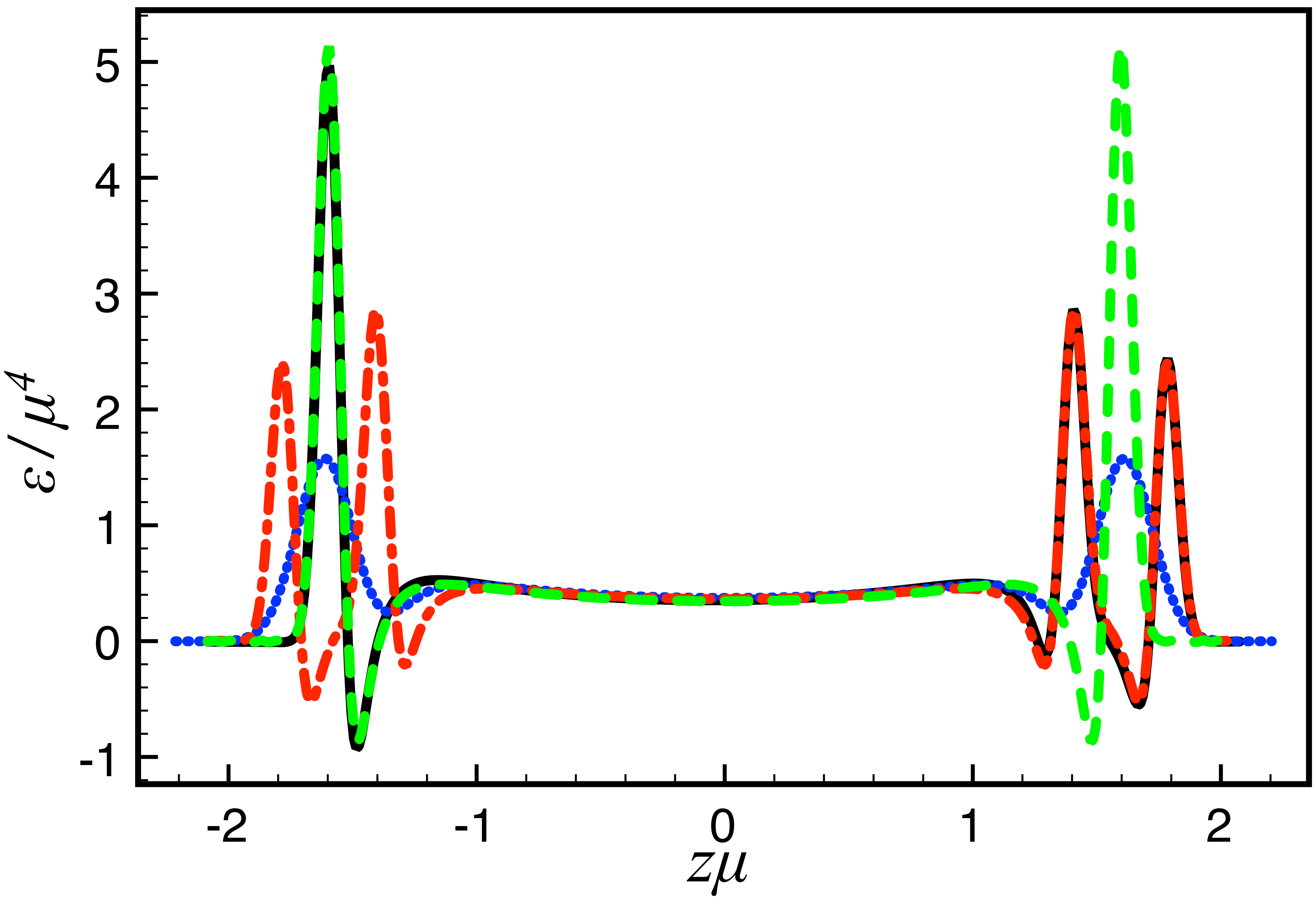
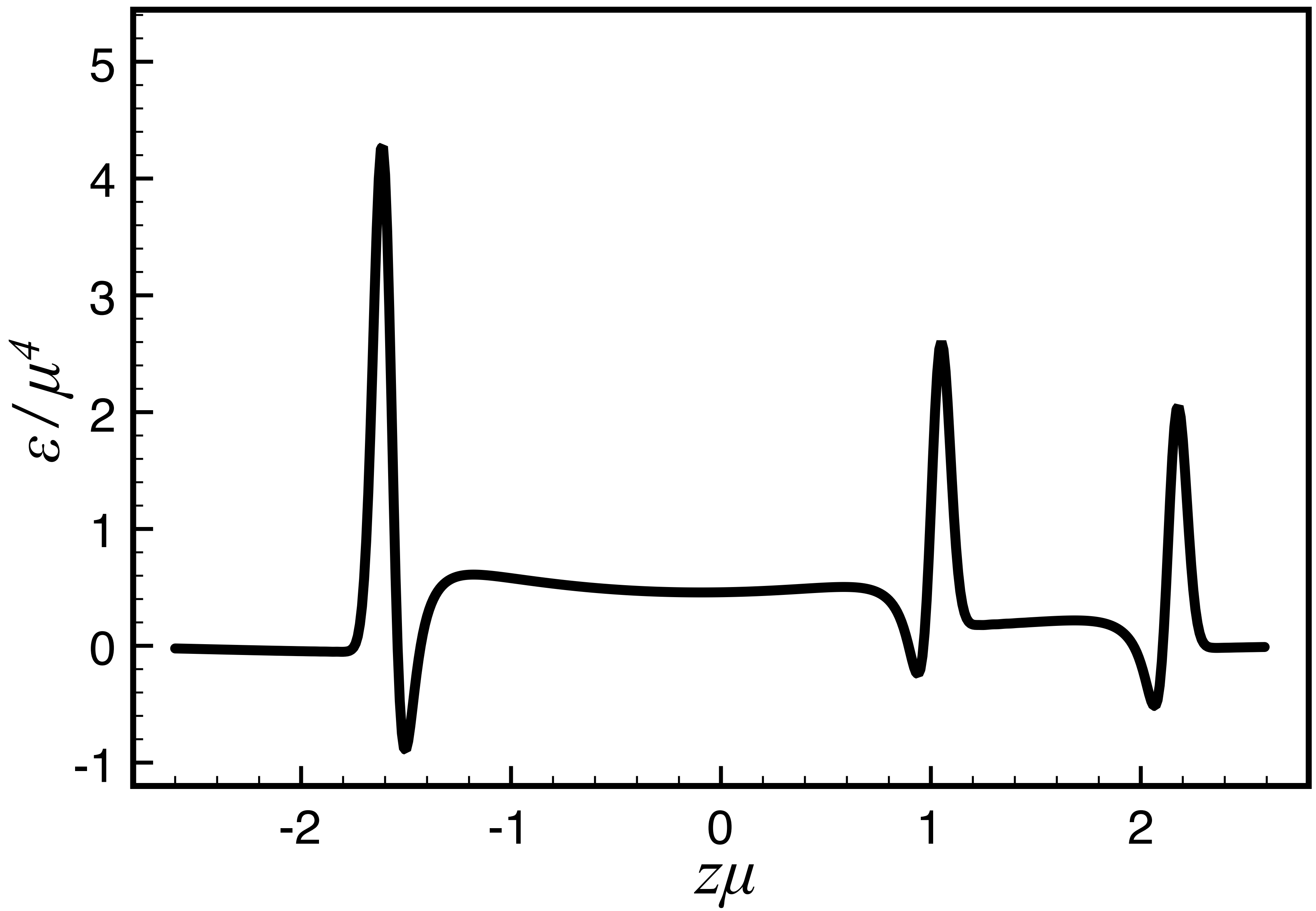


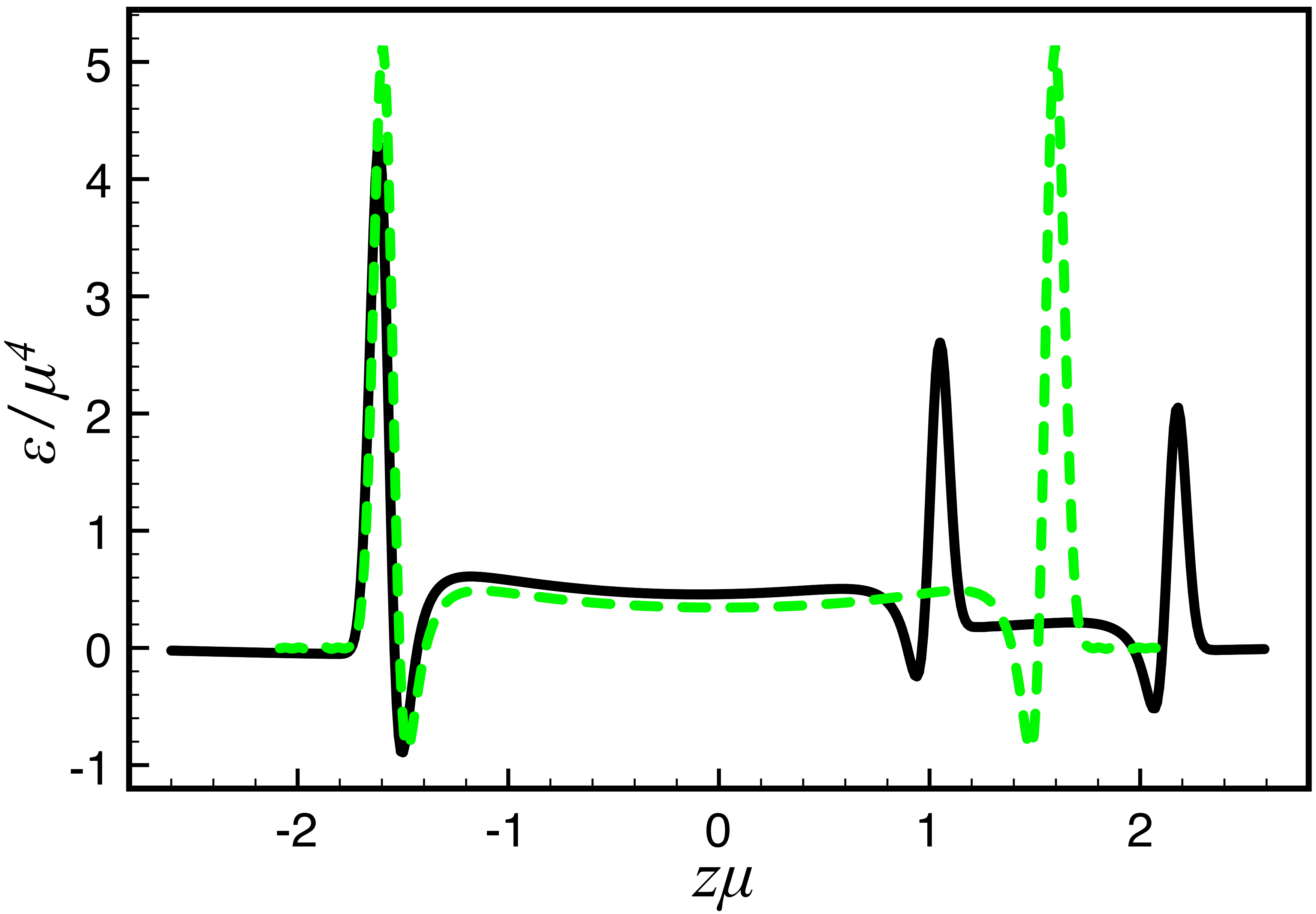
- In the center of mass of the "nucleus-nucleon" collision
  - Midd rapidity region independent of collision system
  - Maximum at y=0 and symmetric w.r.t center of mass

Absence of Longitudinal Coherence



➤ Larger longitudinal structures

Absence of Longitudinal Coherence



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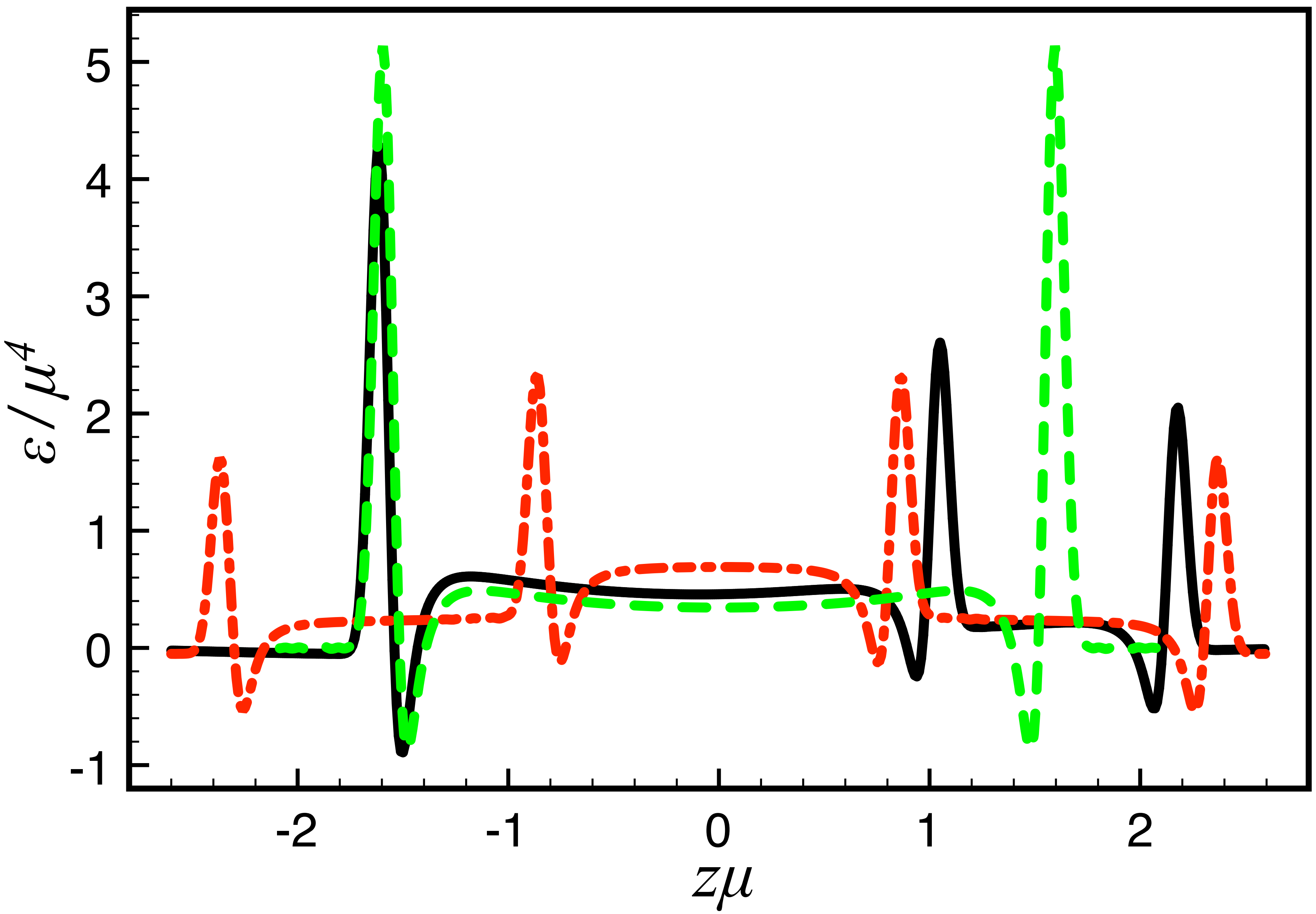

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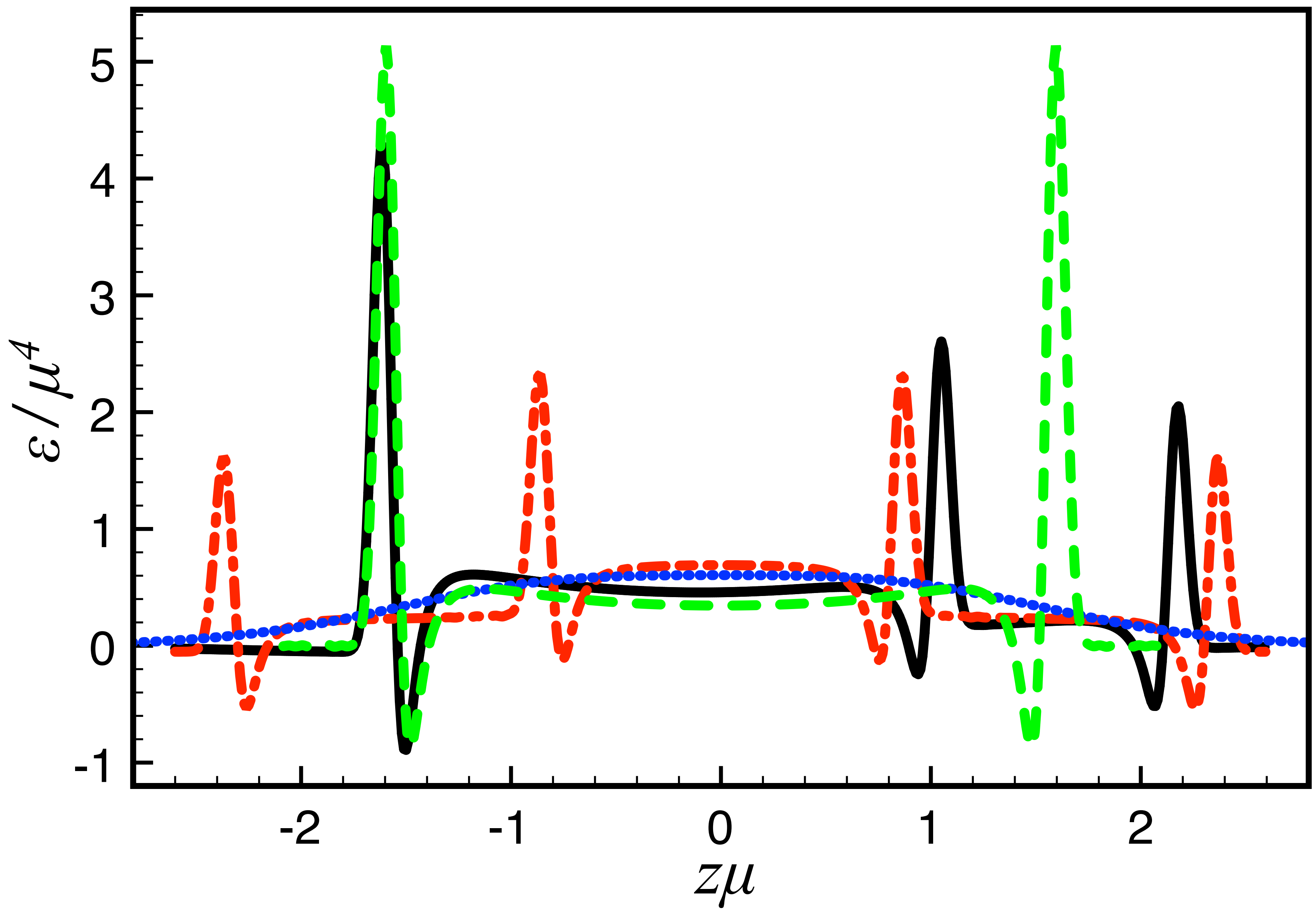
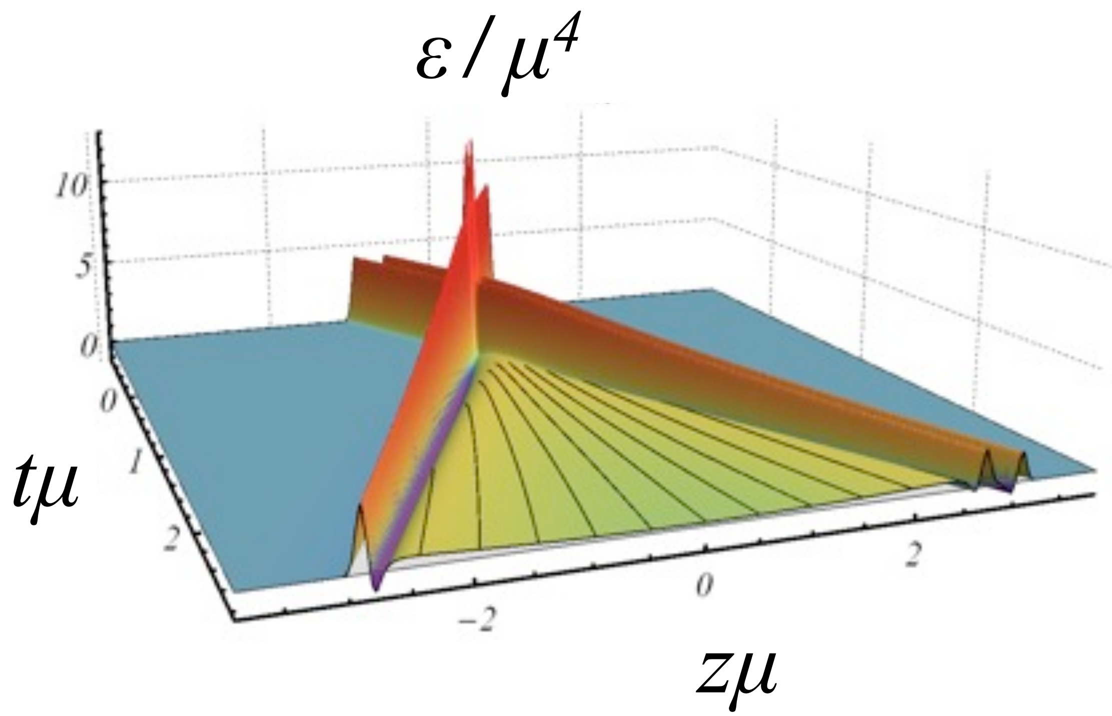
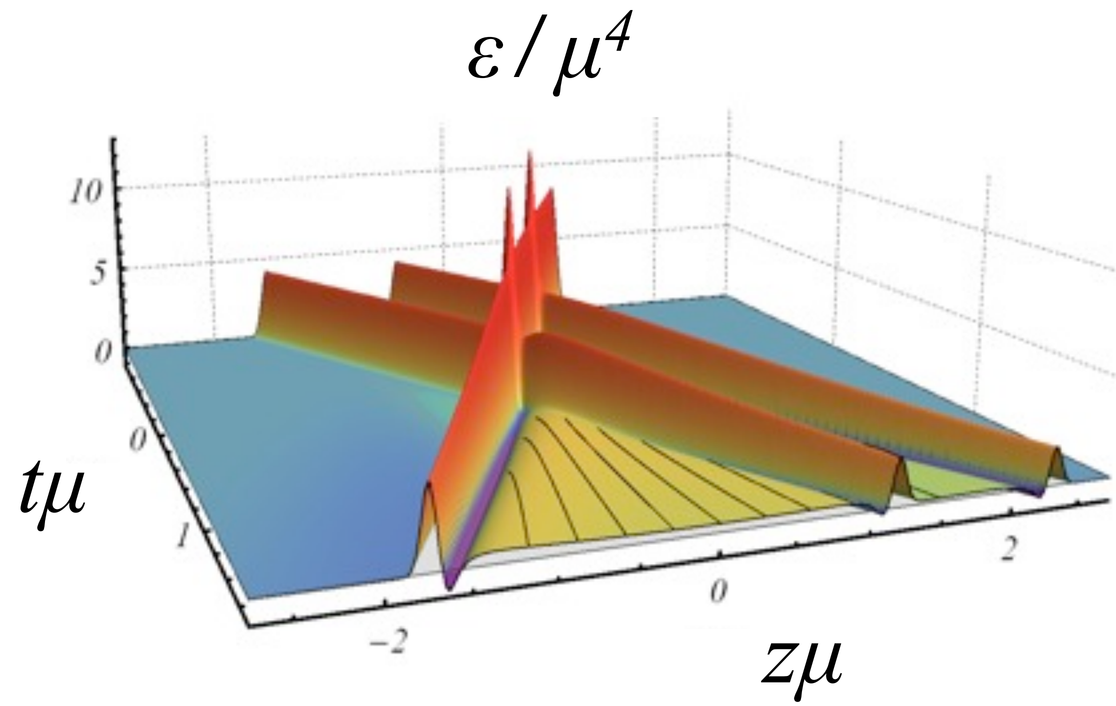


- Larger longitudinal structures
  - Sensitivity to the colliding system
  - Asymmetric distribution for asymmetric systems

Holography and Physics at T-Scale



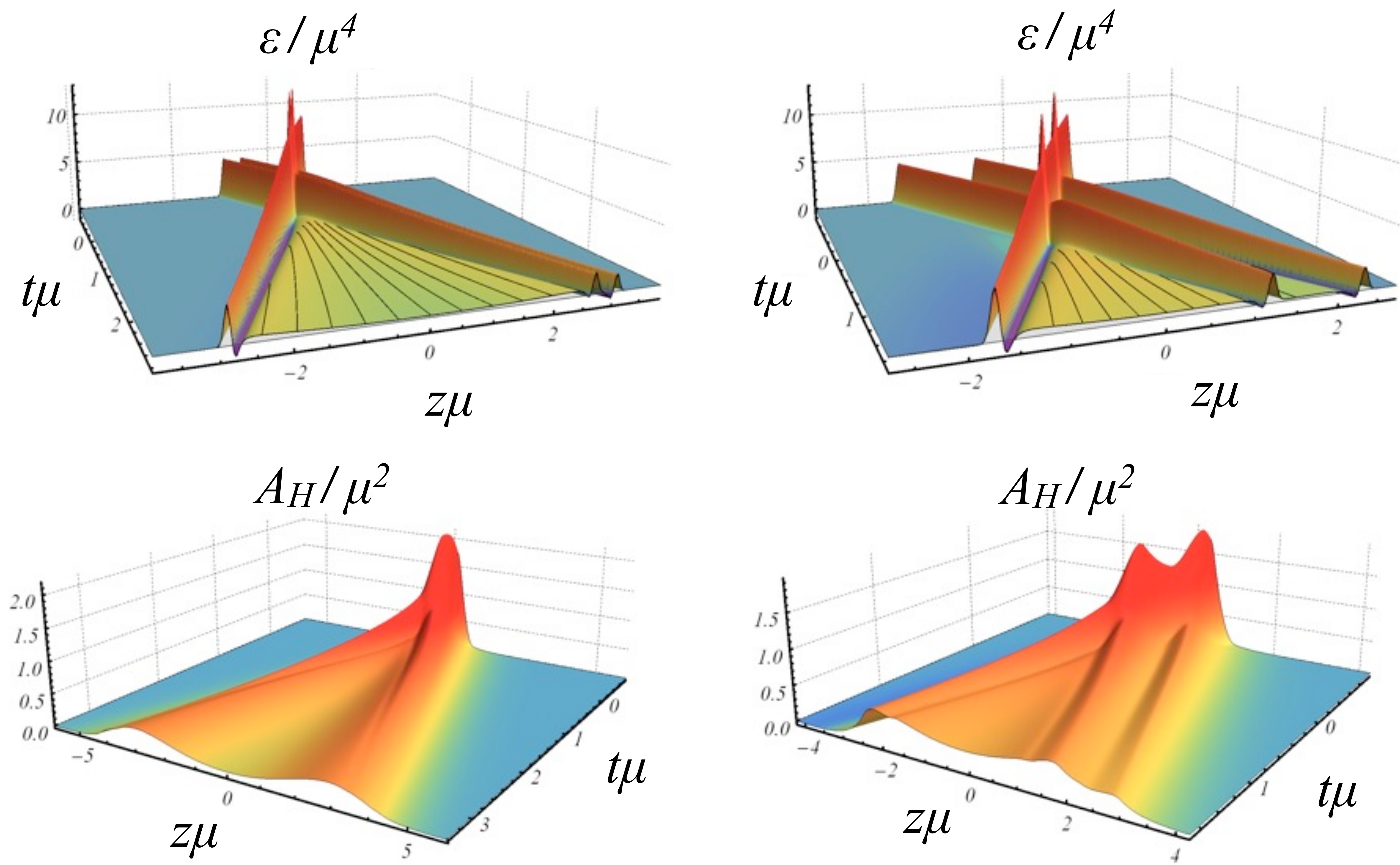


➤ Coherent response depends on longitudinal structure

➤ Structures of size < 1/ πT_{hyd} are not resolved by the collision dynamics

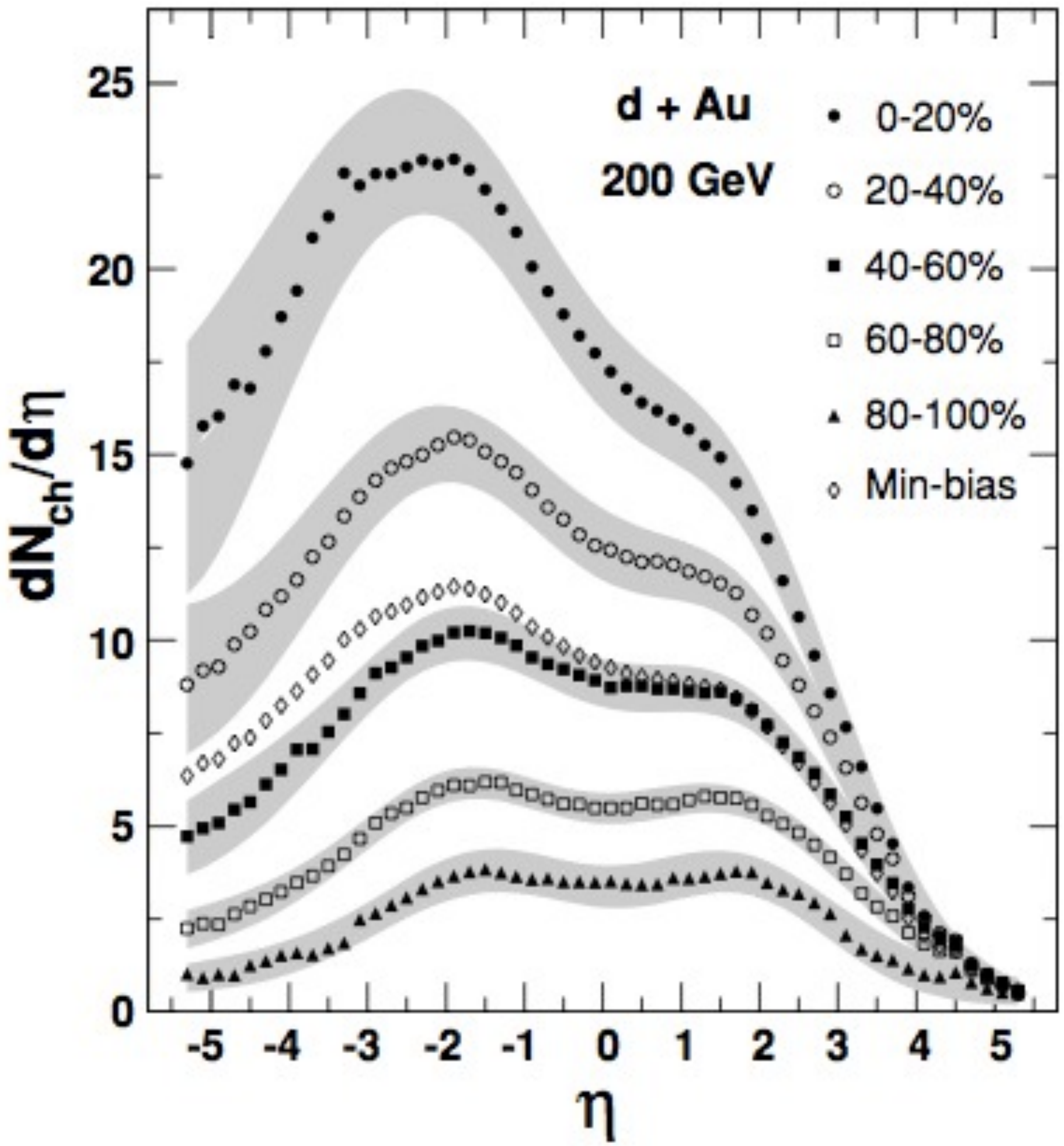
➤ Structures of size < 1/ πT_{hyd} act incoherently

Holography and Physics at T-Scale



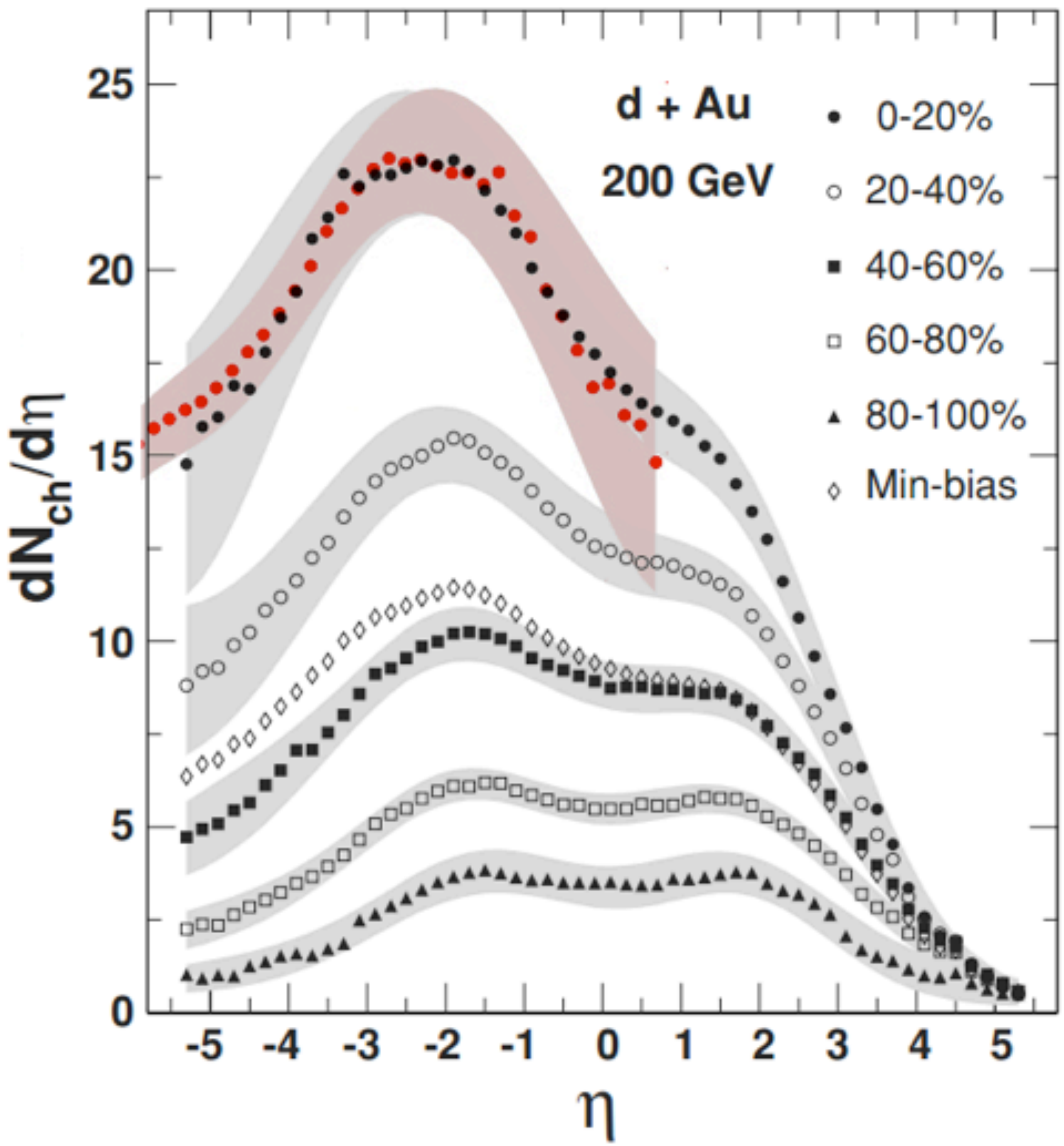
➤ Holography provides a simple picture!

Qualitative Expectation



(Steinberg 07)

Qualitative Expectation



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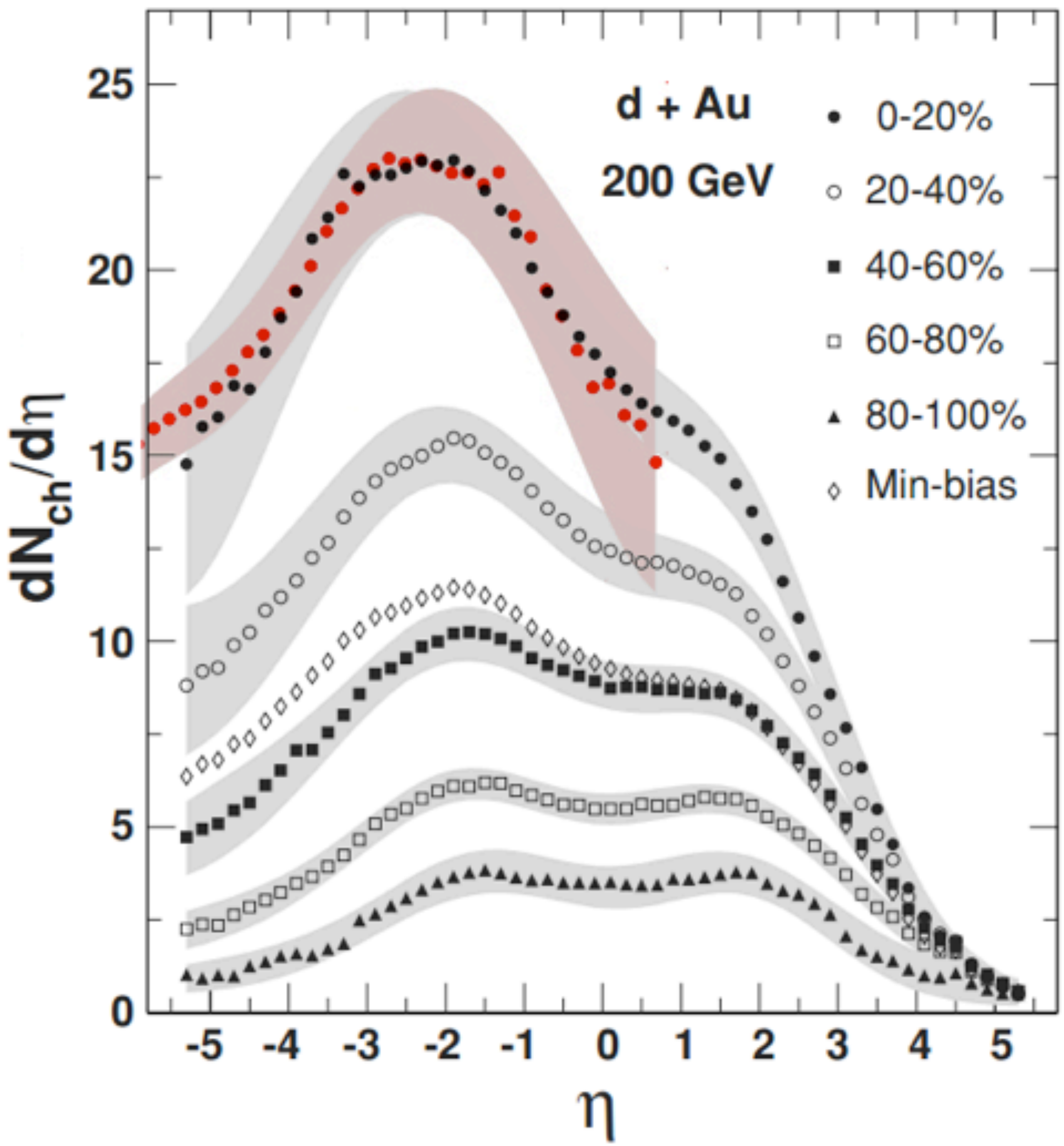


- Unfair comparison:

pseudo-rapidity

$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L}\right)$$

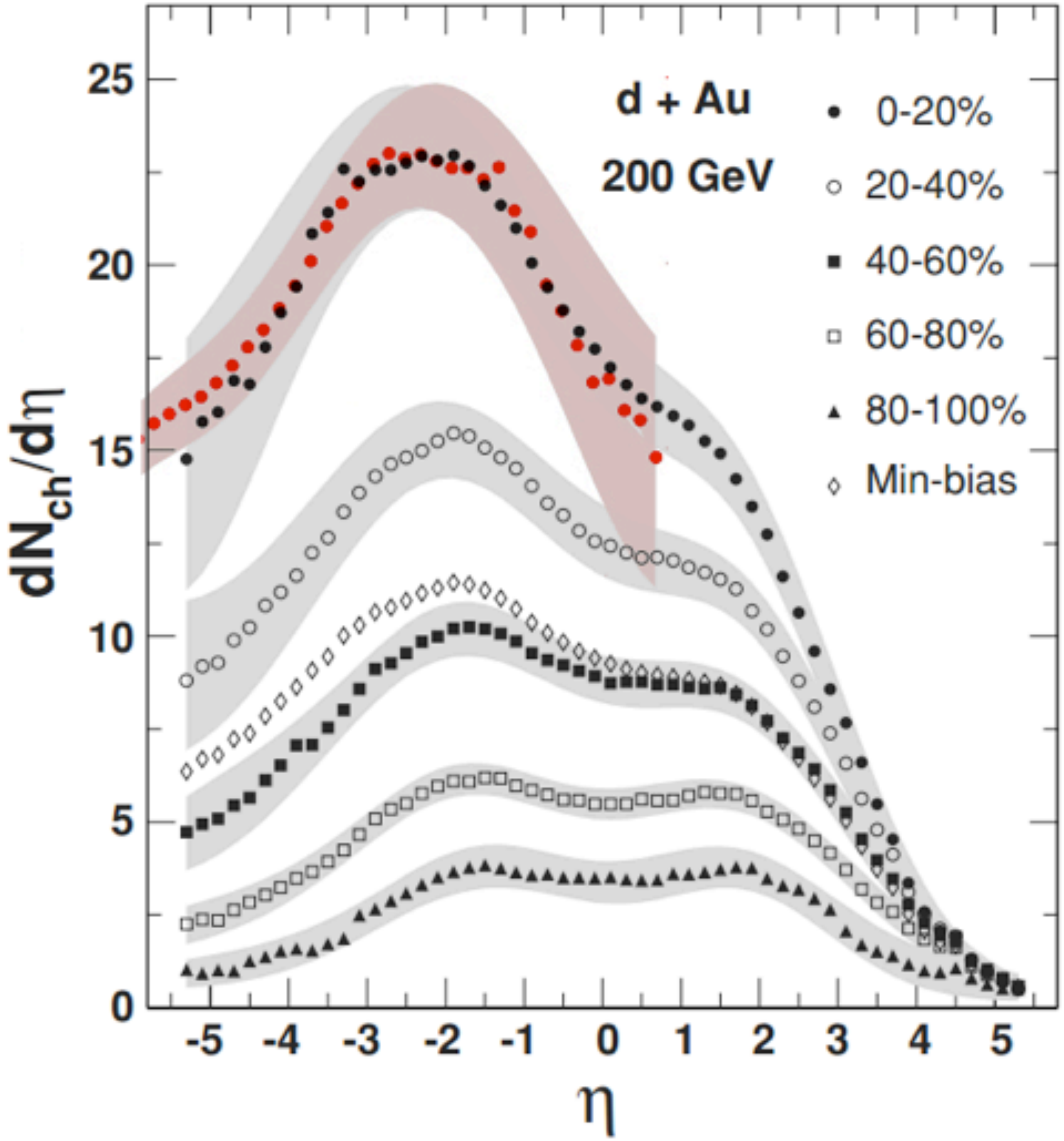
rapidity

$$y = \frac{1}{2}\ln\left(\frac{E + p_L}{E - p_L}\right)$$

most non-trivial structure due to the transverse mass

(Steinberg 07)

Qualitative Expectation



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rapidity

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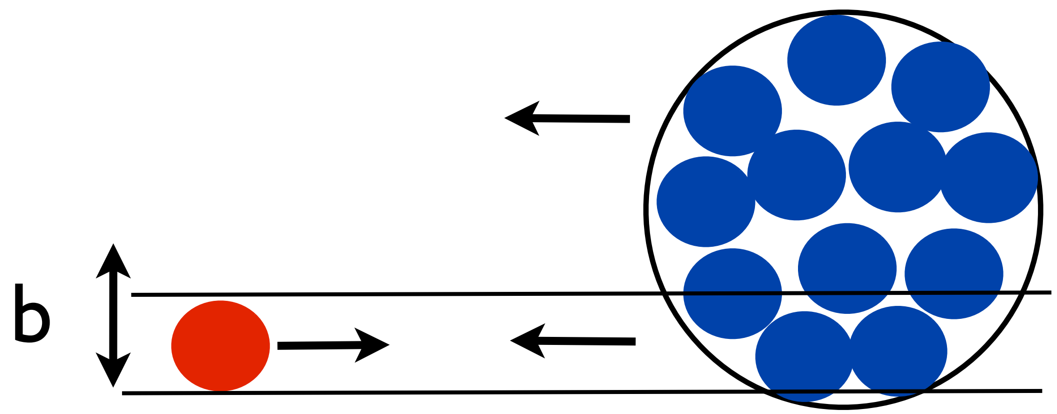
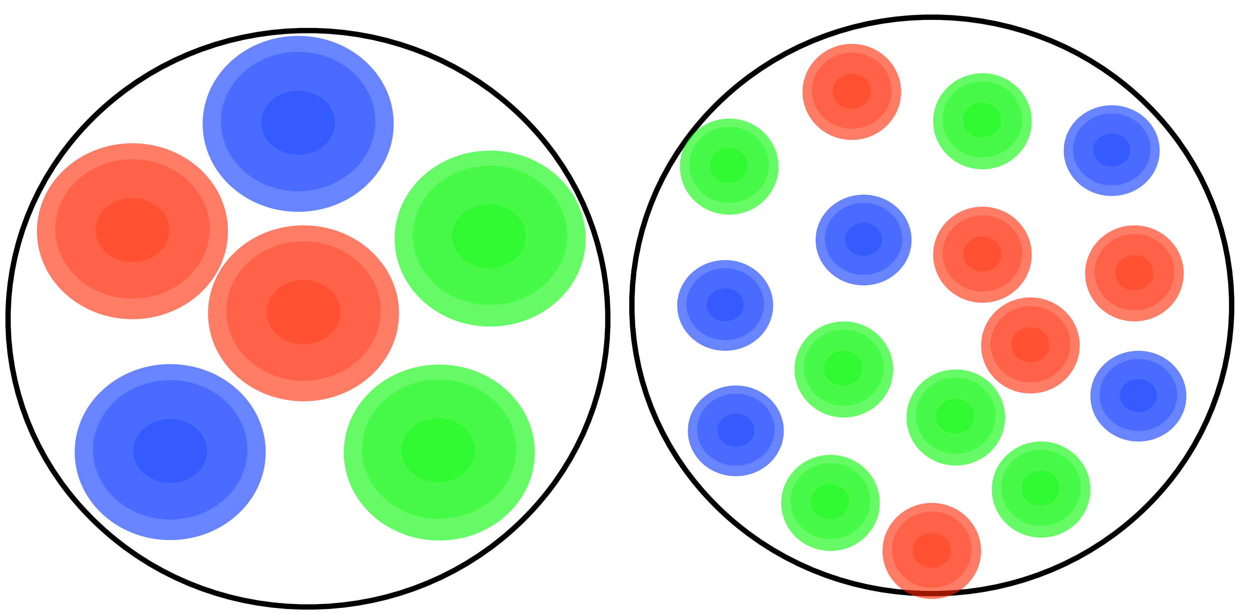
most non-trivial structure due to the transverse mass

Careful analysis of LE data: consistent with a rapidity shift

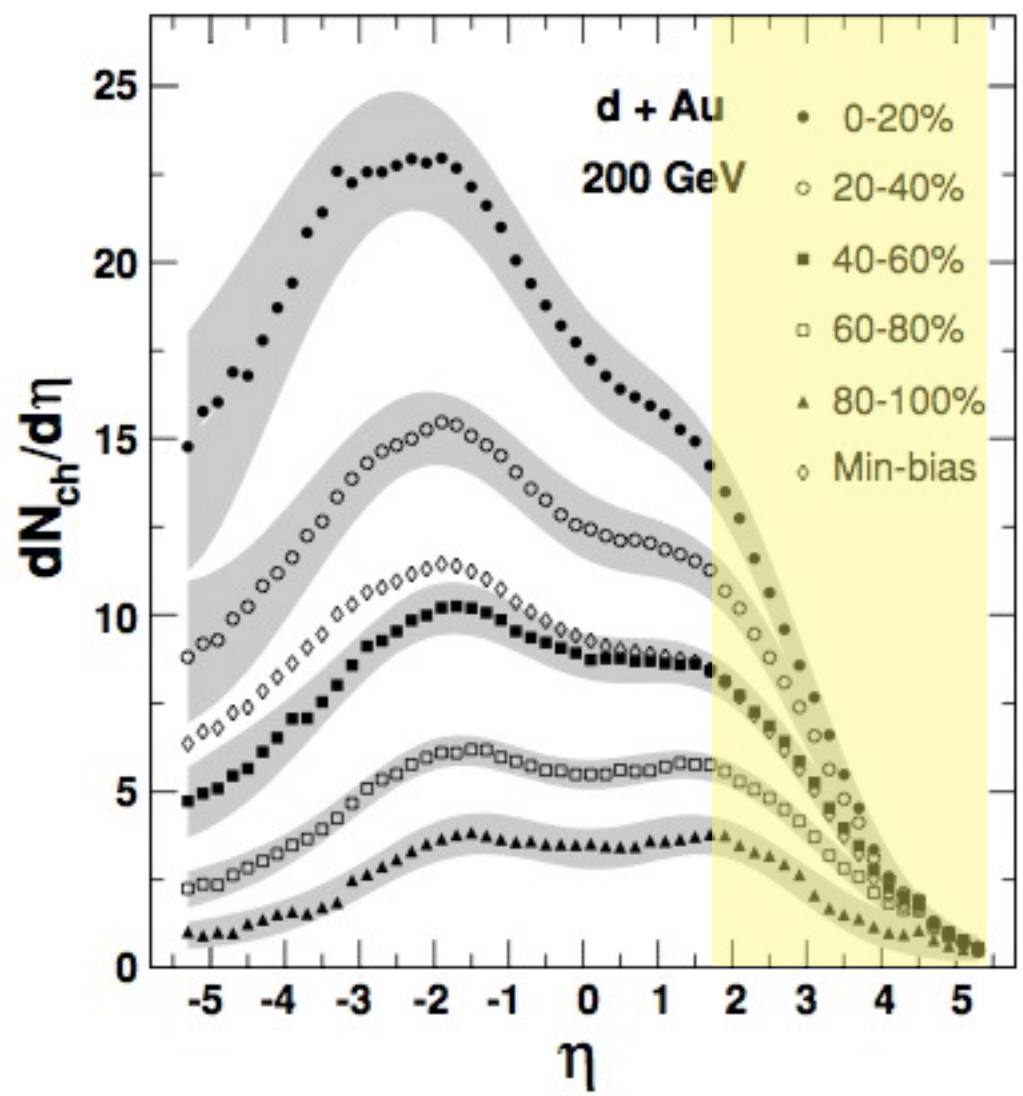
$y_s = y_{c.o.m} + 0.3$ *(Steinberg 07)*

The Weak Coupling Picture



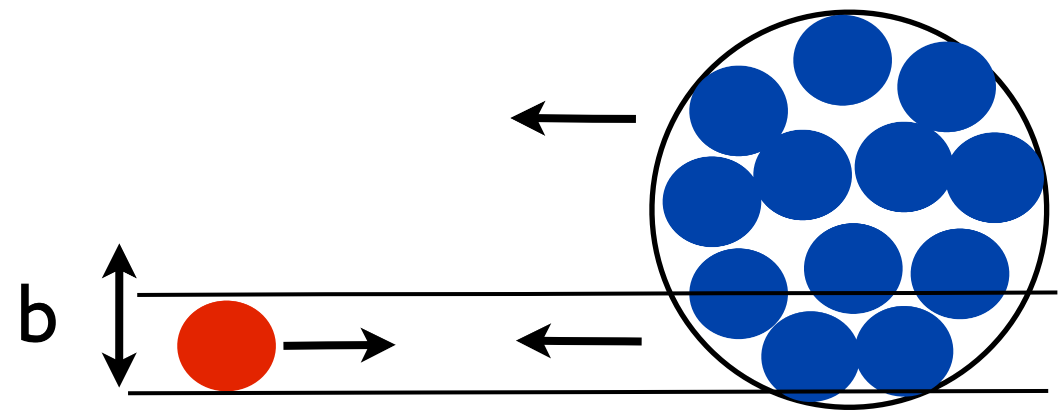


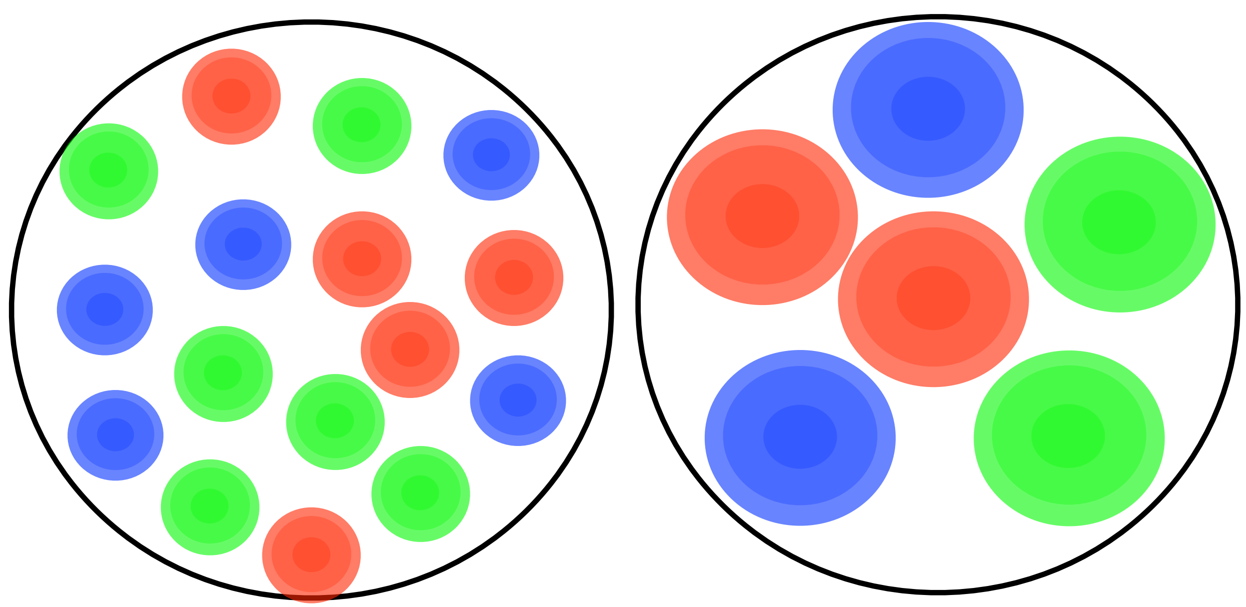
$Q^2_s(A)$ $Q^2_s(B)$



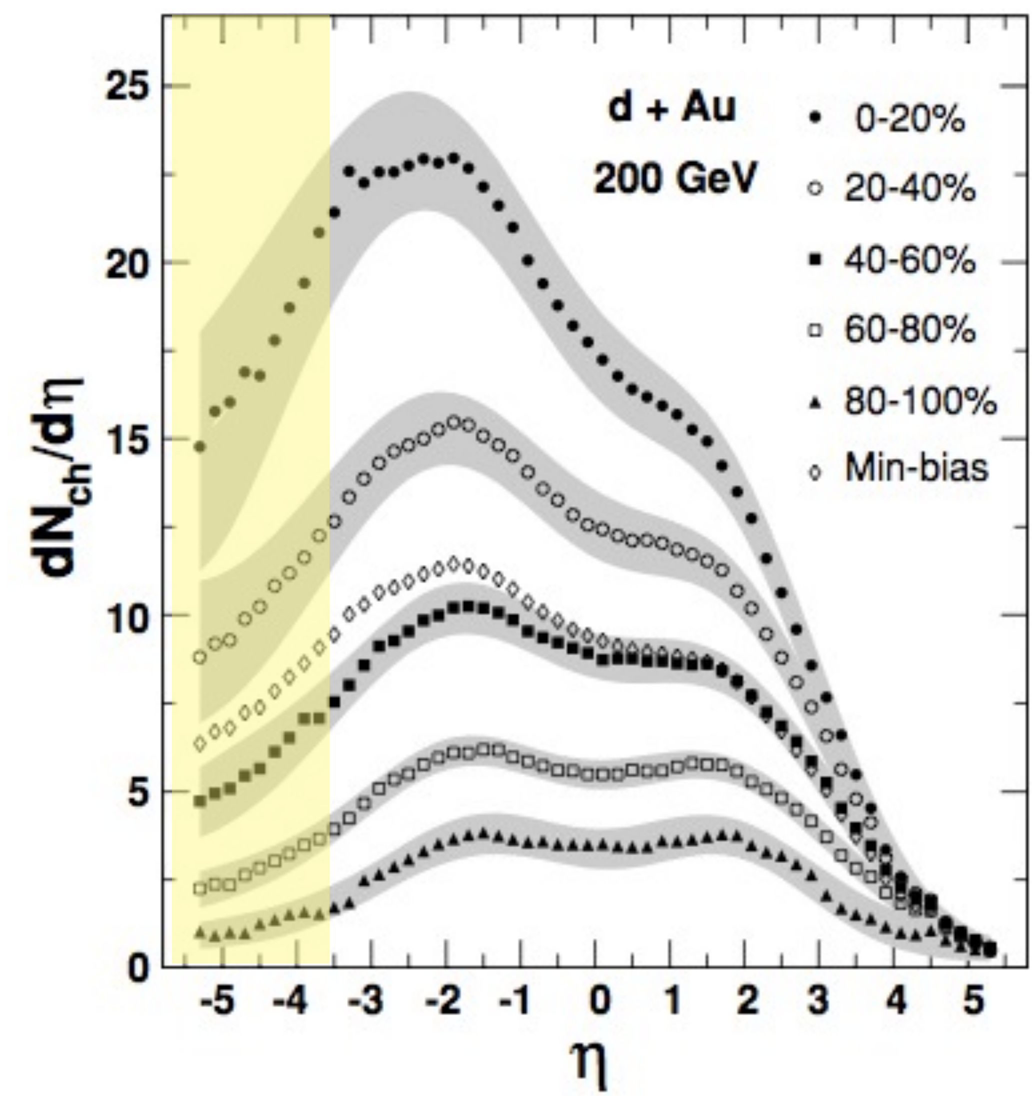
$$\frac{dN}{dy} \propto \pi R^2\, Q^2_s(A)$$

The Weak Coupling Picture



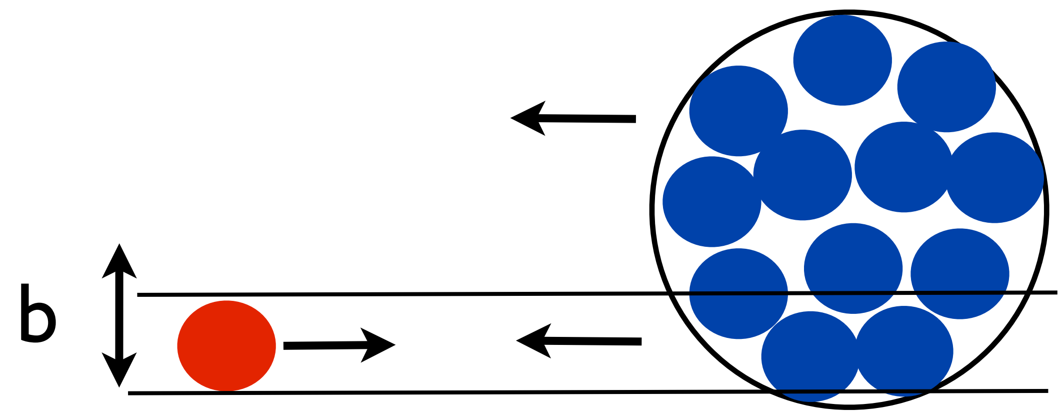


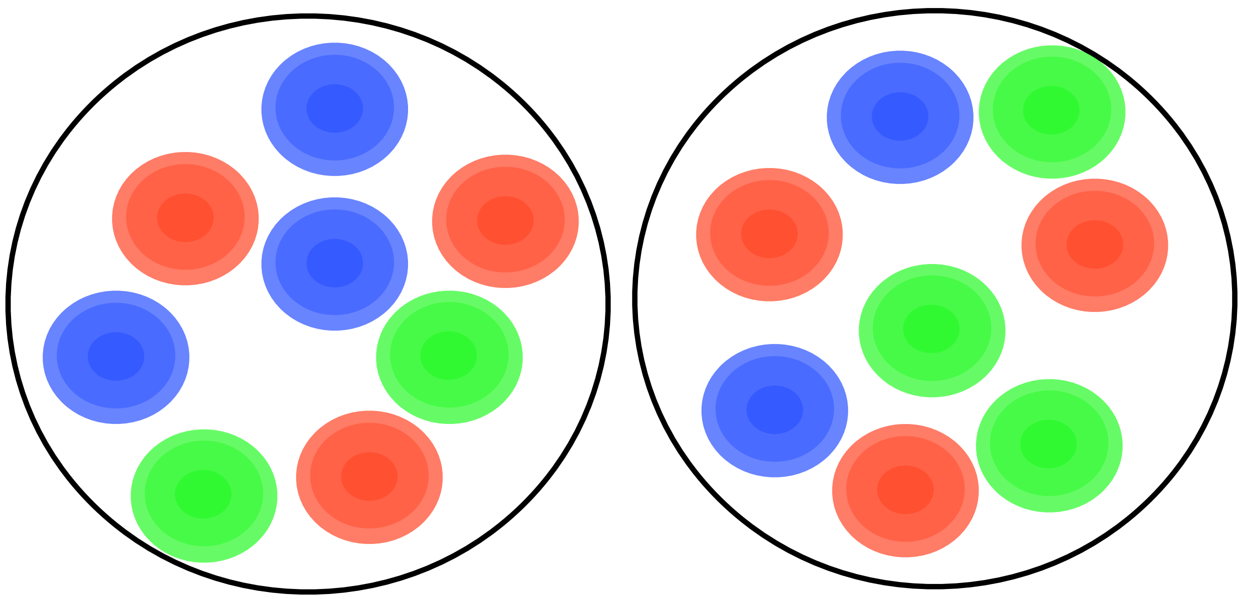
$Q^2_s(A)$ $Q^2_s(B)$

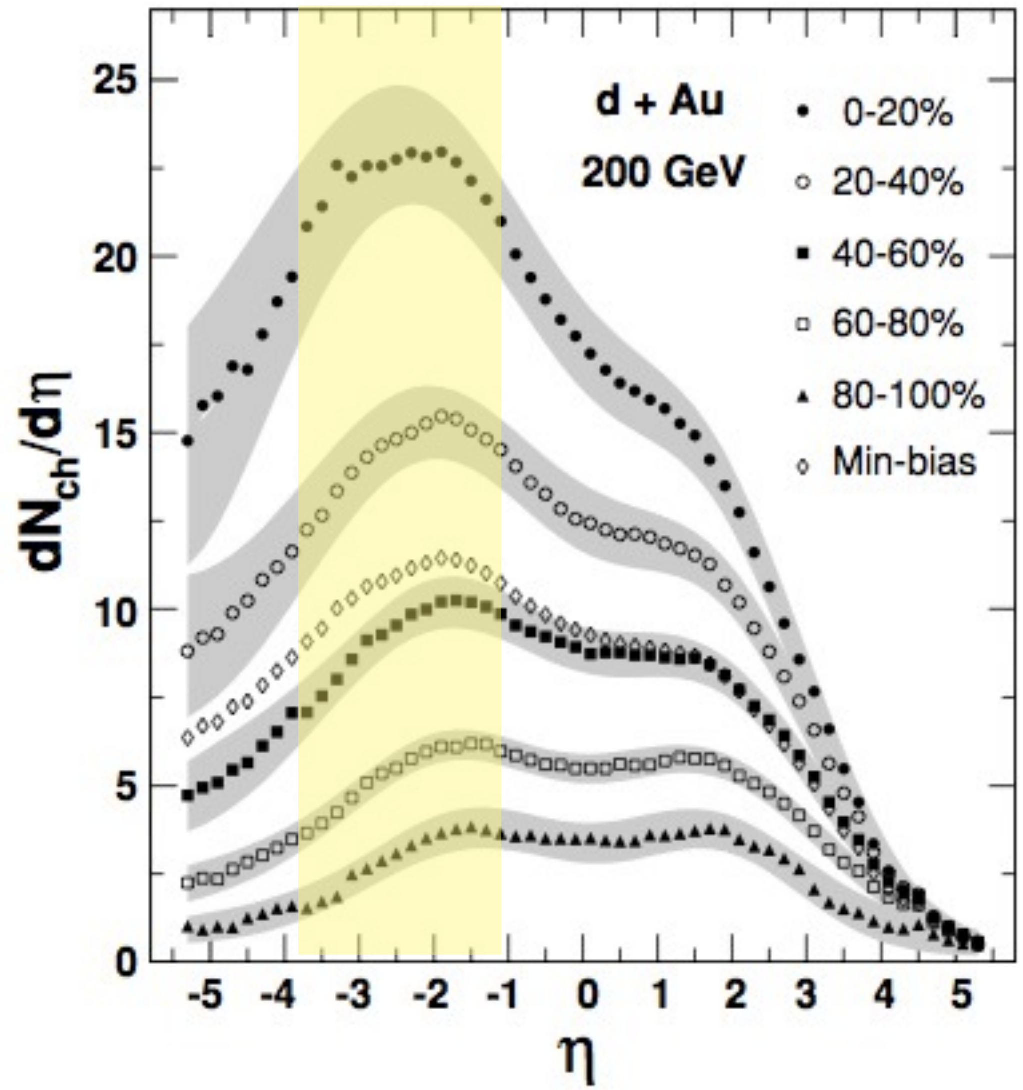


$$\frac{dN}{dy} \propto \pi R^2 \, Q^2_s(B)$$

The Weak Coupling Picture







$Q^2_s(A) = Q^2_s(B)$

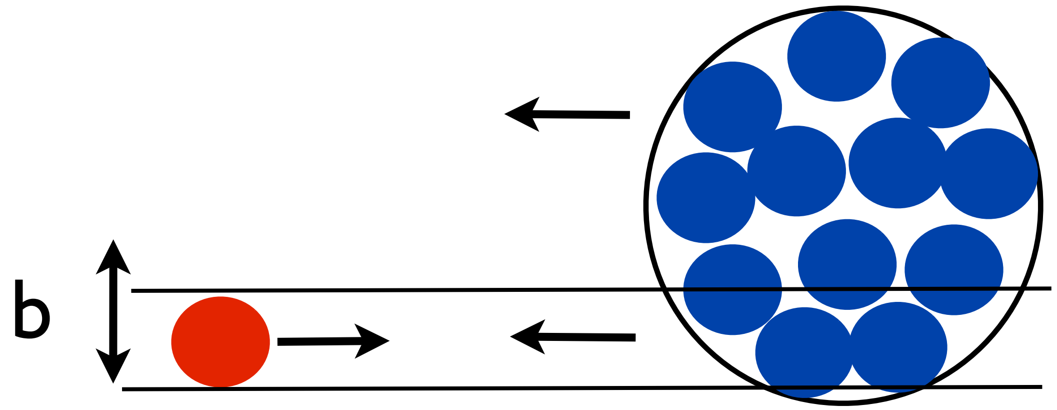
$Q^2_s(A) = Q^2_0\, A\, e^{\lambda(Y_a - y)}$

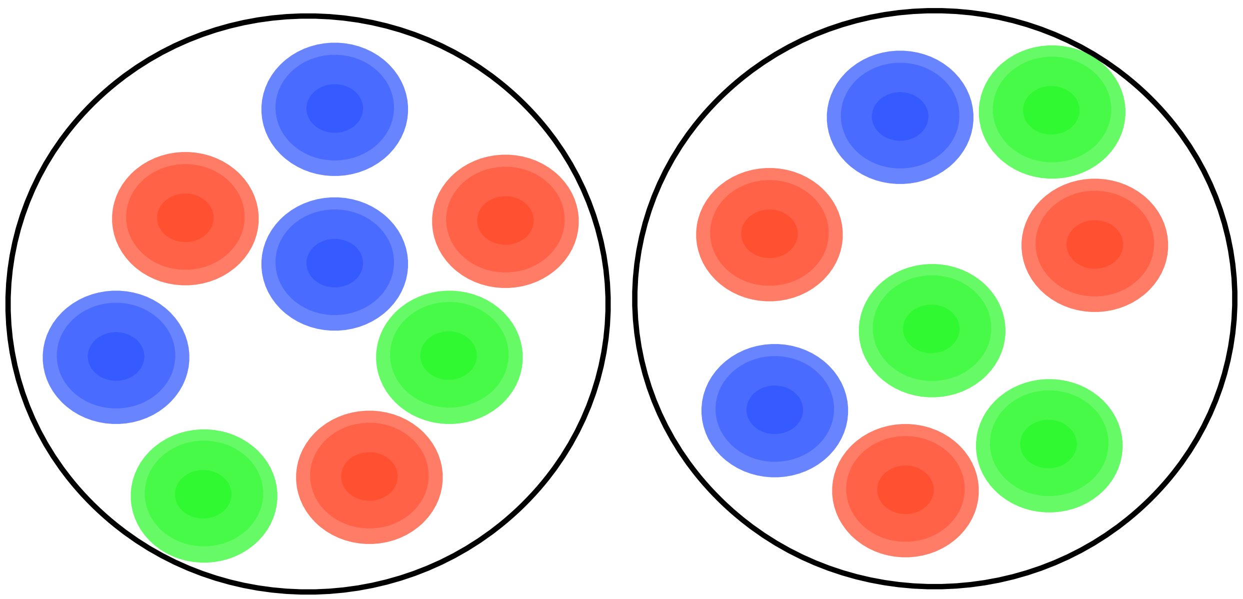
$Q^2_s(B) = Q^2_0\, B\, e^{\lambda(Y_b - y)}$

Choosing $y_{lab} = (Y_b - Y_a)/2$

$y_{max} = \frac{y_{c.o.m}}{\lambda}$ $\lambda \approx 0.5$

The Weak Coupling Picture

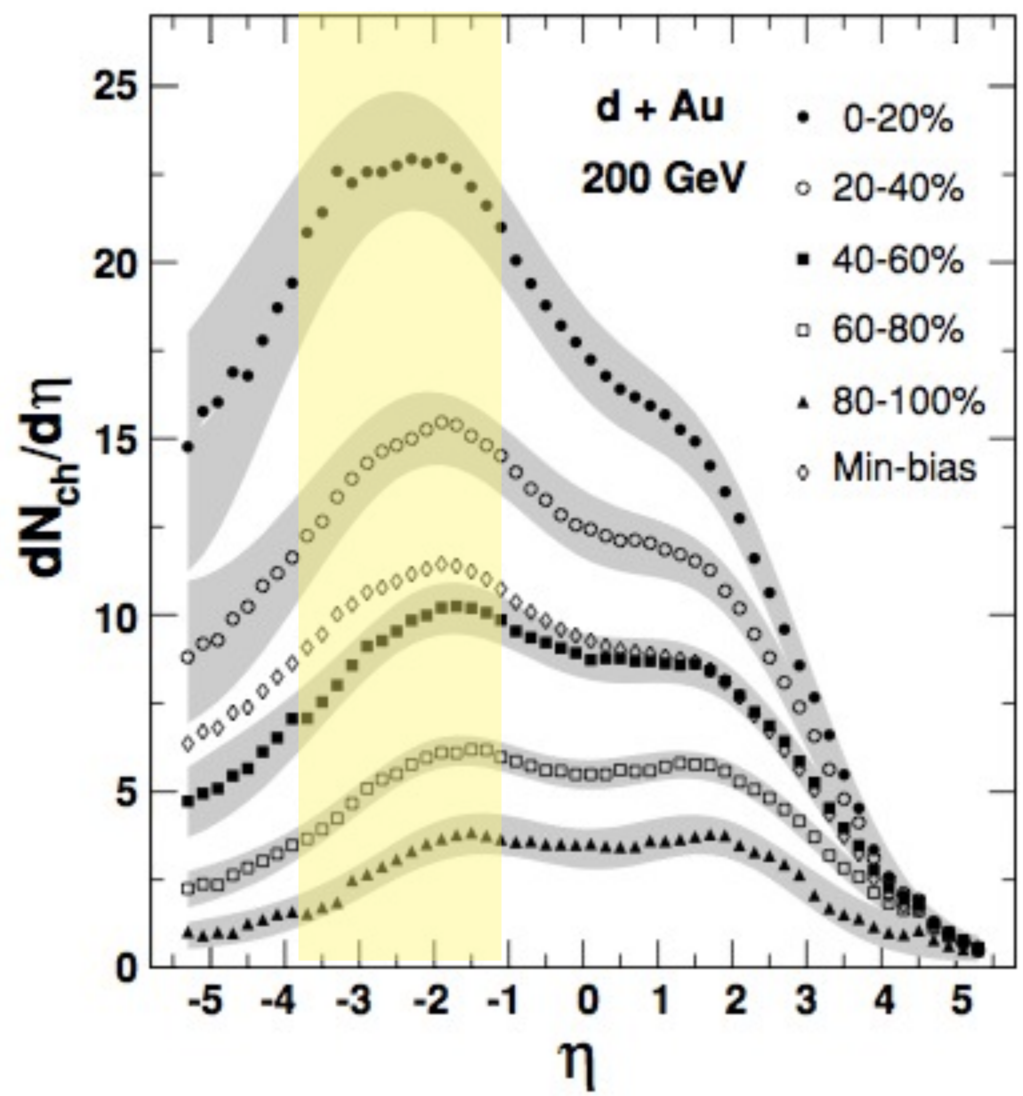




$Q^2_s(A) = Q^2_s(B)$

$Q^2_s(A) = Q^2_0\, A\, e^{\lambda(Ya-y)}$

$Q^2_s(B) = Q^2_0\, B\, e^{\lambda(Yb-y)}$



Choosing $y_{lab}=(Yb-Ya)/2$

$y_{max} = \frac{y_{c.o.m}}{\lambda}$ $\lambda \approx 0.5$

LHC most central pPB $y_{c.o.m}=1.7$

Conclusions

- Shock wave collisions exhibit a dynamical cross over
  - Low energy: full stopping ⇒ Landau hydrodyanamics
  - High energy:

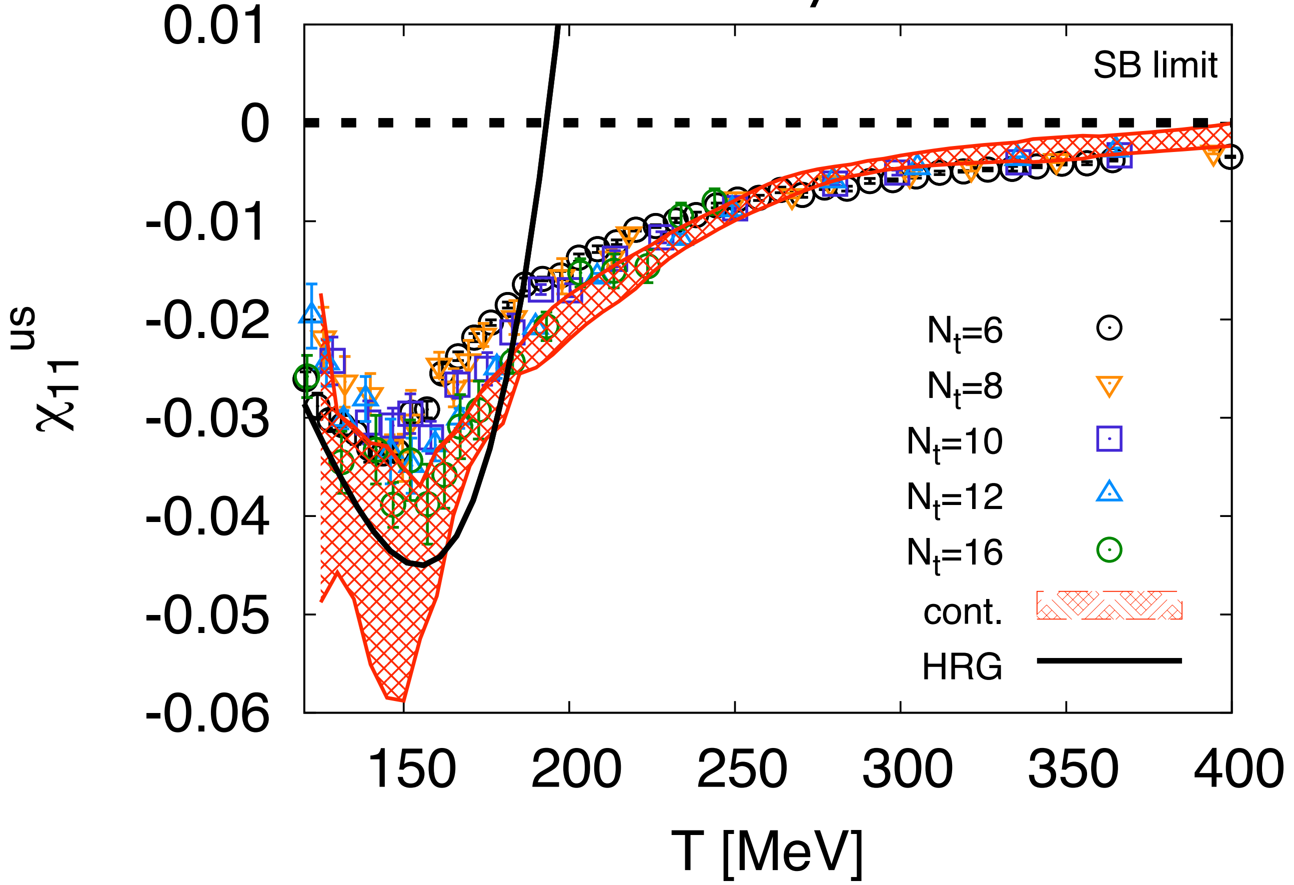
    Transparency: energy propagation in the lightcone

    Not-boost invariant initial conditions
- Longitudinal coherence on shock components
  - Fluid c.o.m = collision c.o.m.
  - Reflexion symmetric matter around the collision point

    (near mid rapidity)

Correlations

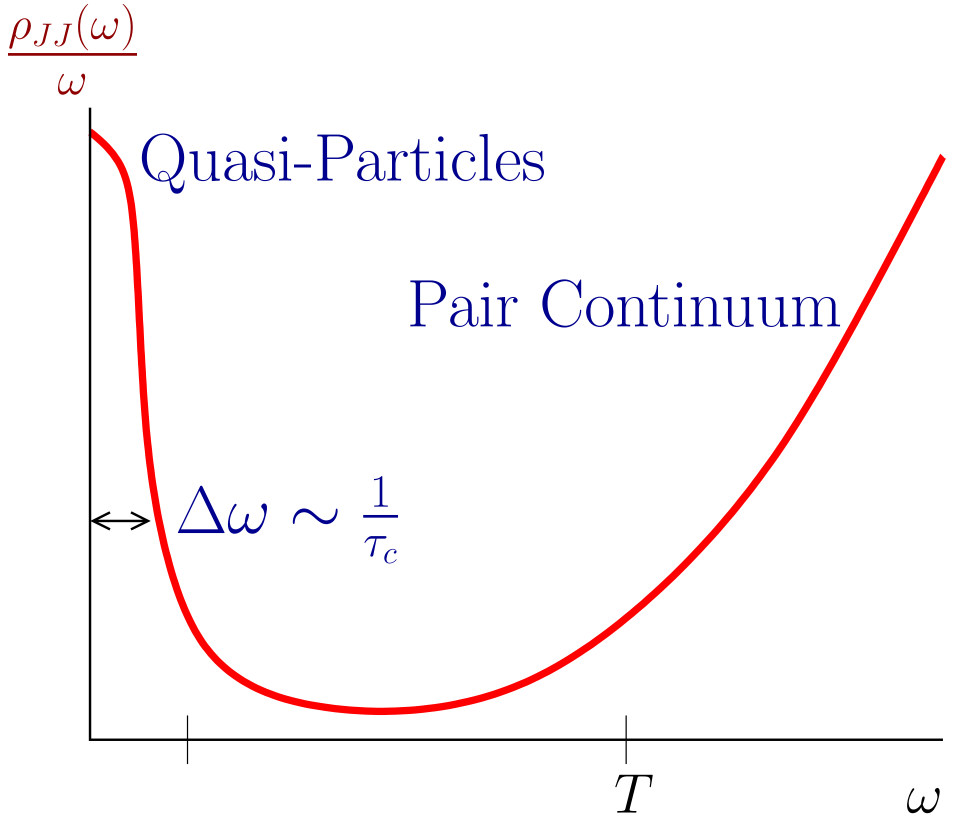
Borsanyi et al. 1112.4416



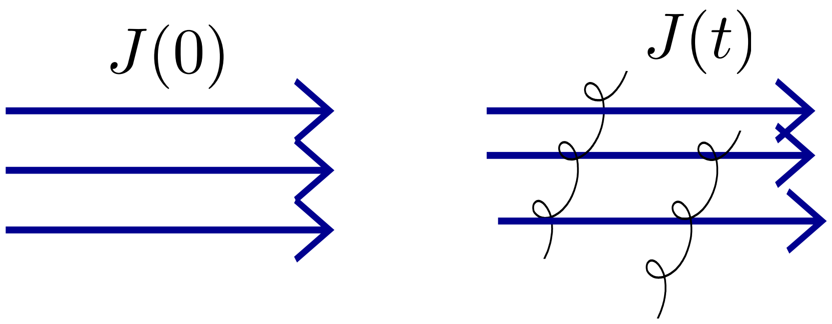
$$\chi_{11}^{us} \propto \langle n_u n_s \rangle$$

- Most thermodynamic properties are insensitive to the nature of the degrees of freedom
- However: strong correlations among flavor
  - ➤ not compatible with an almost free gas of quarks and gluons
  - ➤ consistent with strongly correlated flavor (JCS and D. Mateos 12)

Quasi-Particles



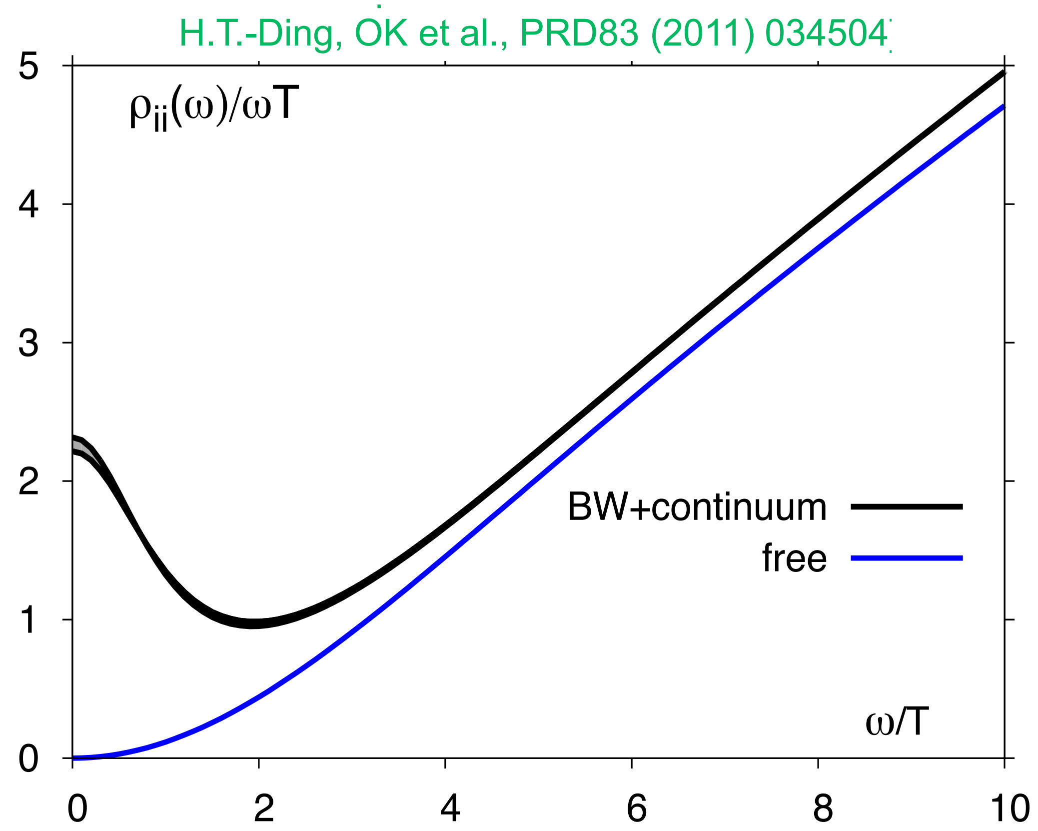
$$\rho_{JJ} = \langle [J(t), J(0)] \rangle$$



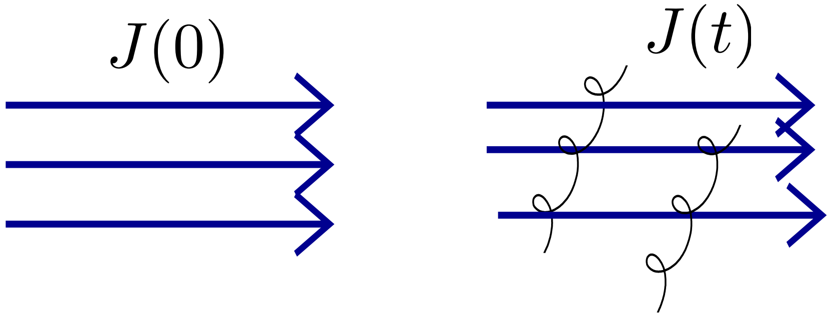
$1/\tau_c \sim g^4$

- Fishing for quasi-particles: conserved current correlator narrow structures?

Quasi-Particles



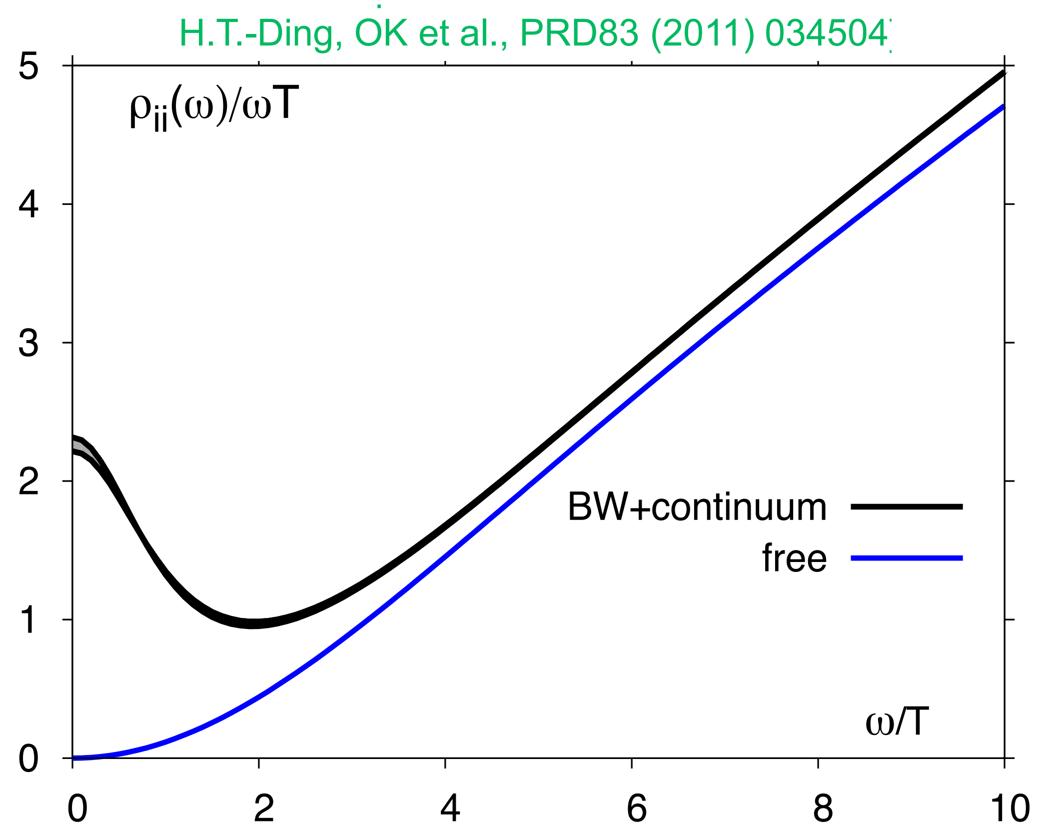
$$\rho_{JJ} = \langle [J(t), J(0)] \rangle$$

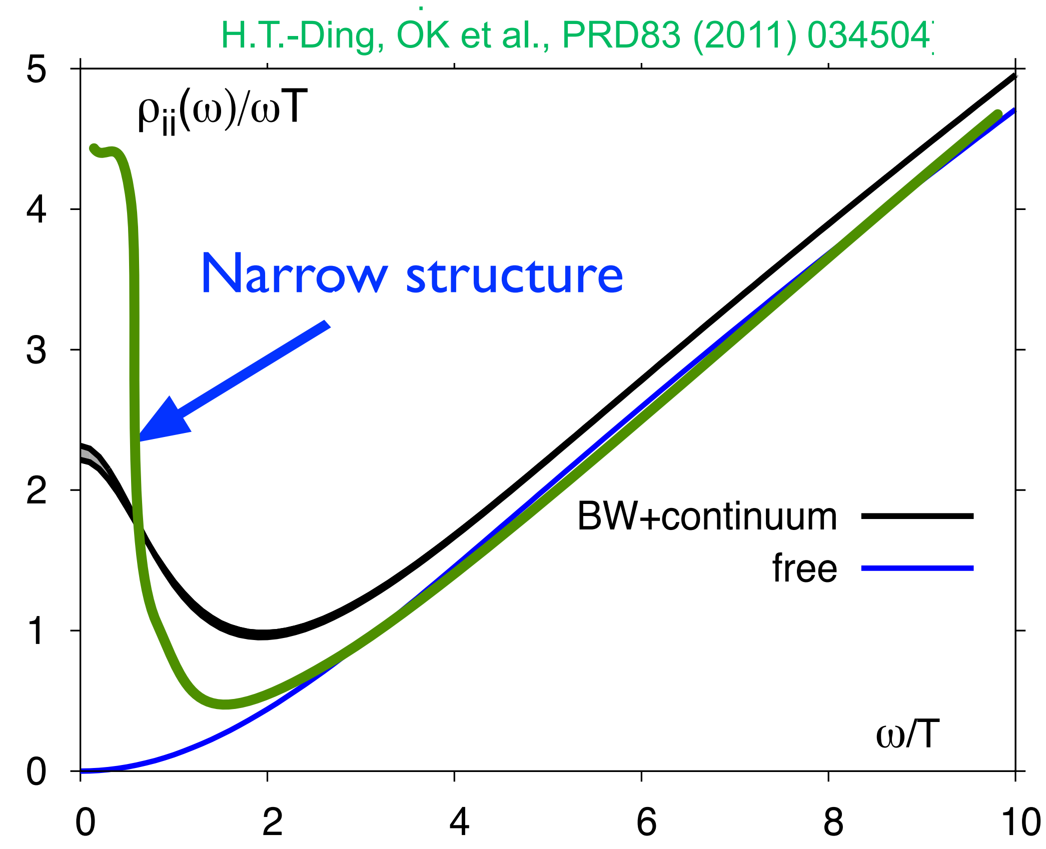


$1/\tau_c \sim g^4$

- Fishing for quasi-particles: conserved current correlator narrow structures?
- Lattice results (hard)

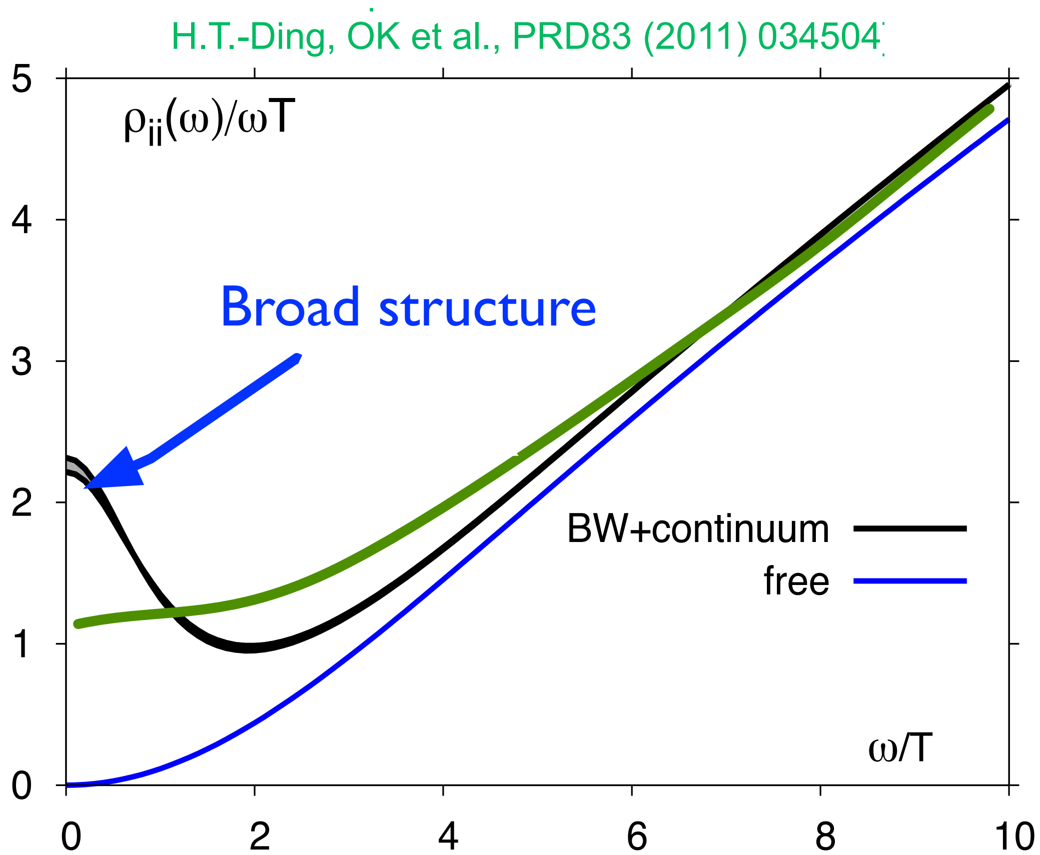
Quasi-Particles

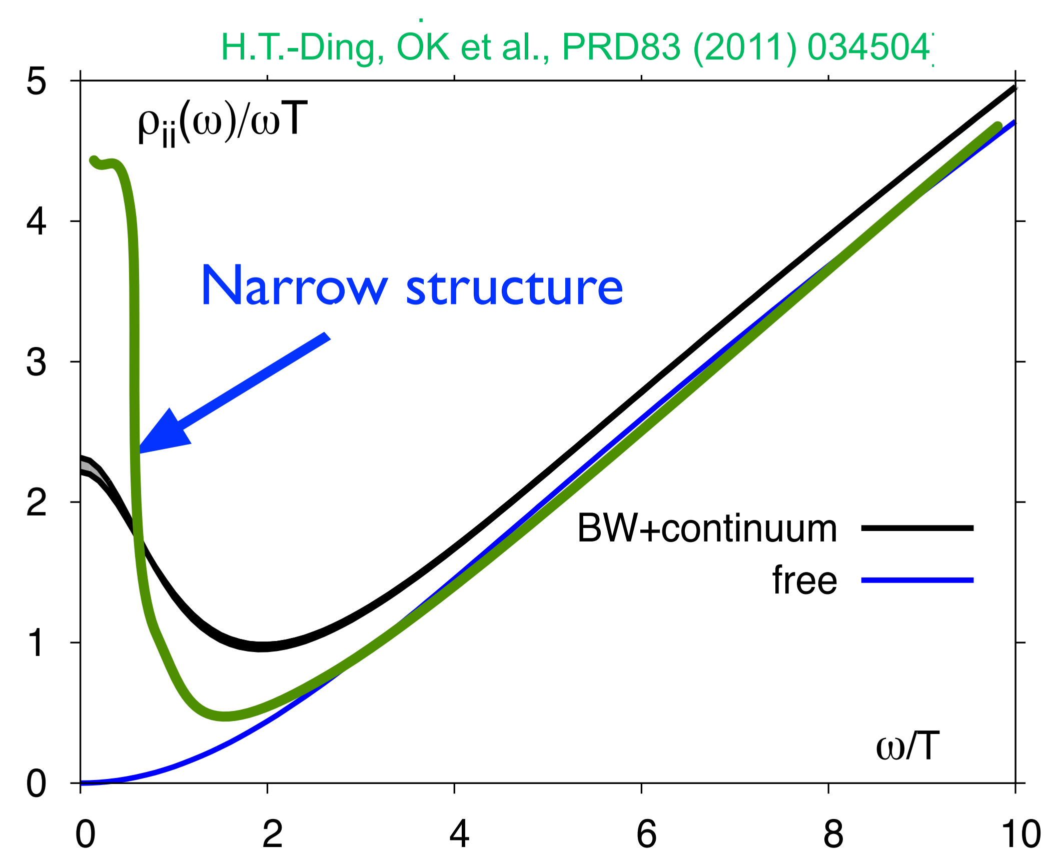




- Fishing for quasi-particles: conserved current correlator narrow structures?
- Lattice results (hard)
  - ➤ no clear quasi-particle peak (unlike pQCD)

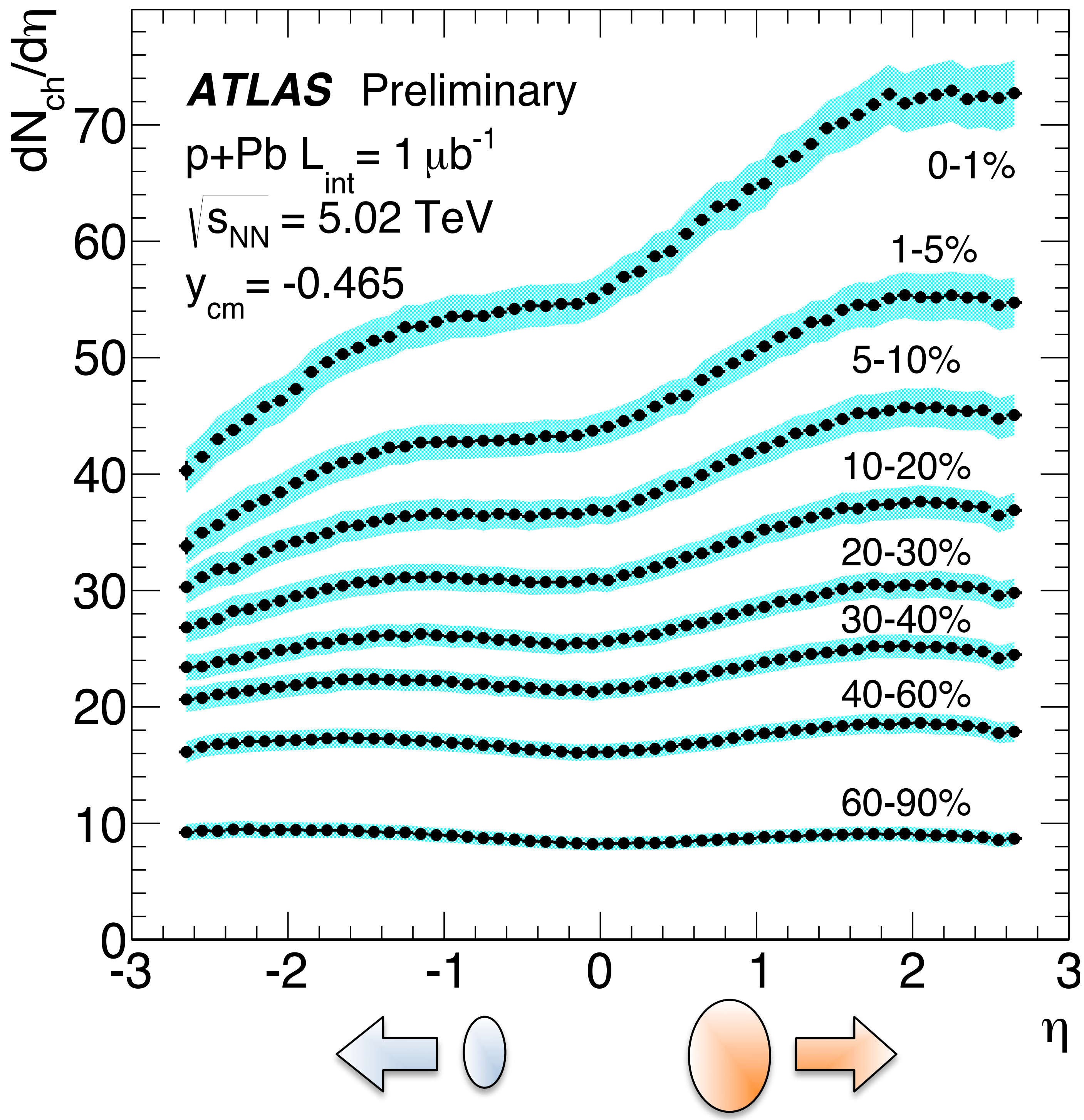
Quasi-Particles





- Fishing for quasi-particles: conserved current correlator narrow structures?
- Lattice results (hard)
  - ➤ no clear quasi-particle peak (unlike pQCD)
  - ➤ some broad structure remains comparable to $N_c g^2 \to \infty$ for SYM via AdS/CFT

Teaney 06


ATLAS Preliminary
p+Pb L_int = 1 μb^-1
√s_NN = 5.02 TeV
y_cm = -0.465
dN_ch/dη
η
0-1%
1-5%
5-10%
10-20%
20-30%
30-40%
40-60%
60-90%
0
10
20
30
40
50
60
70
-3
-2
-1
0
1
2
3