The Stringness of Heavy Ion Collisions

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PEOPLE

Hot QCD

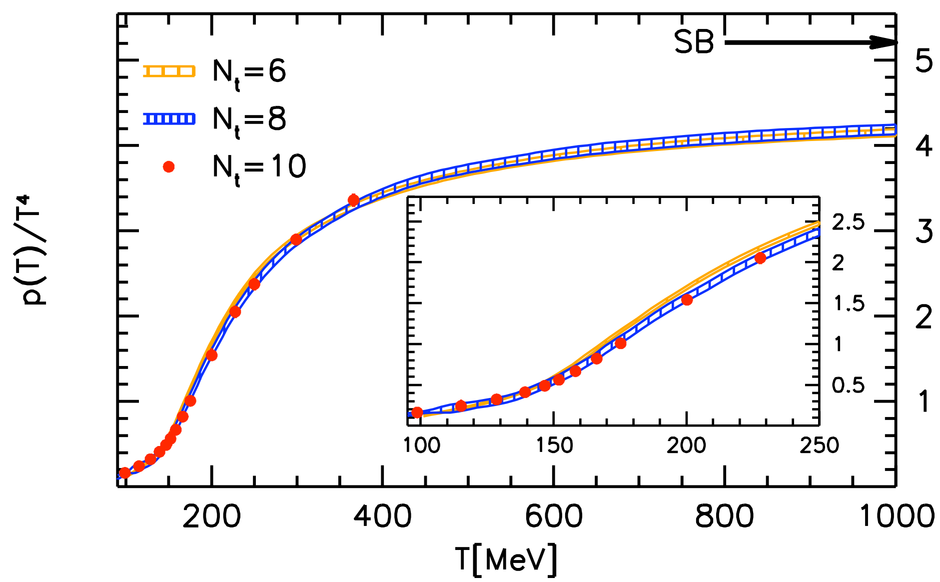
$T \ll \Lambda_{QCD}$

Confined color d. o. f

A gas of hadrons

$T \sim \Lambda_{QCD}$

Wuppertal-Budapest Col. arXiv: 1007.2580



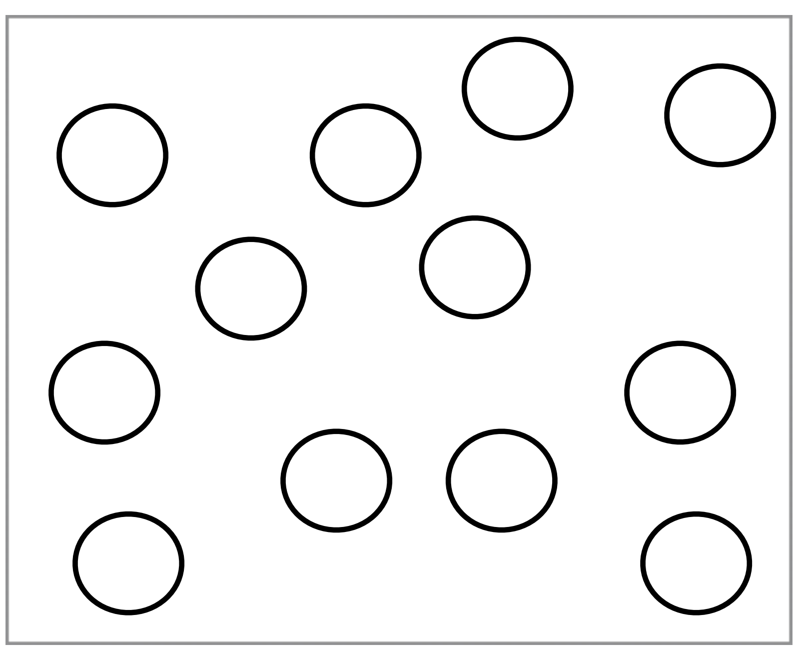
$T \gg \Lambda_{QCD}$

color is liberated

Plasma of quarks and gluons

An almost free gas

$T \sim 10^6$ GeV



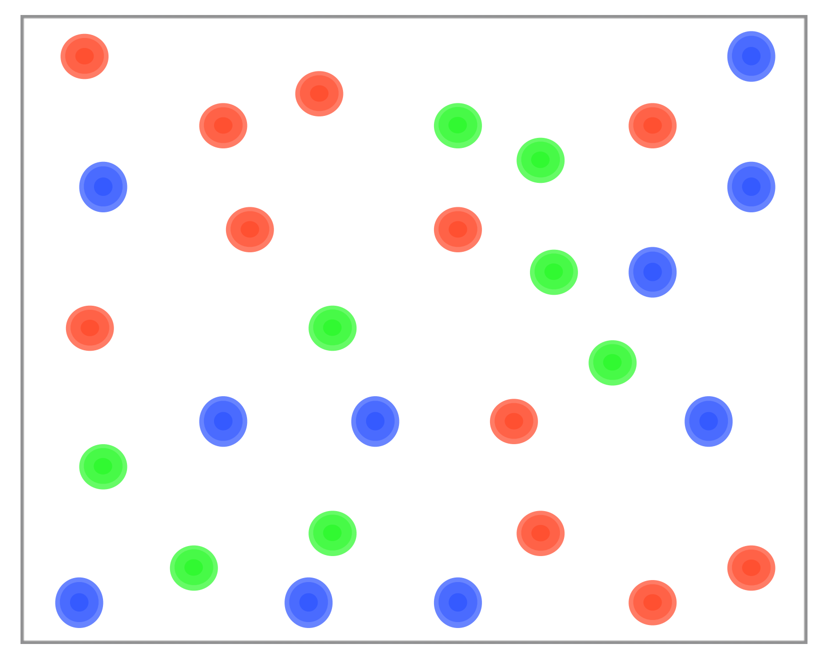
$1/T$

$\ggg$

$1/g^2T$

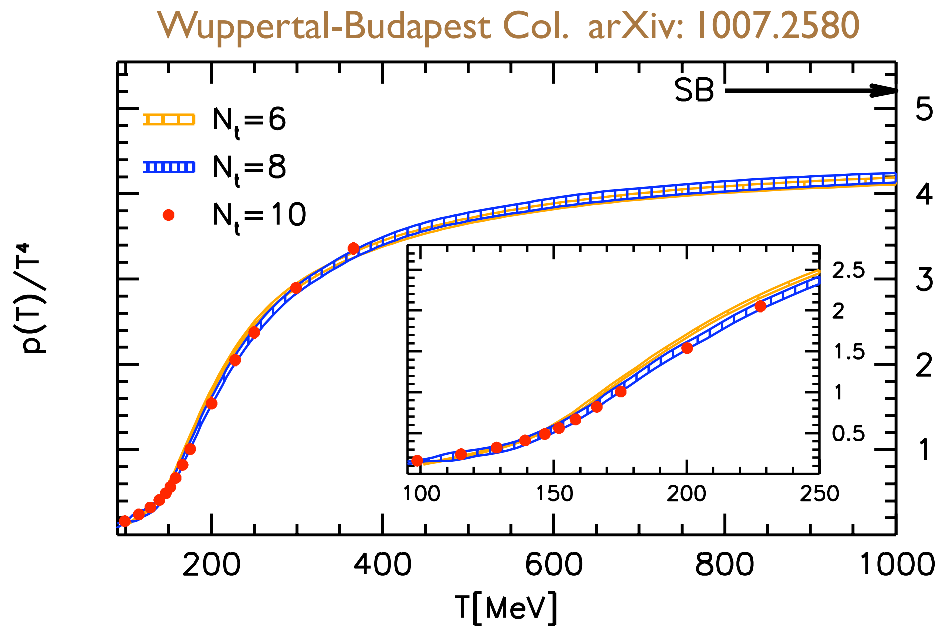
$\ggg$

$1/g^4T$



Hot QCD

T~Λ_{QCD}



- From (lattice) QCD we know:
  - ➤ equation of state
  - ➤ screening masses
  - ➤ euclidean correlators
  - ➤ ...

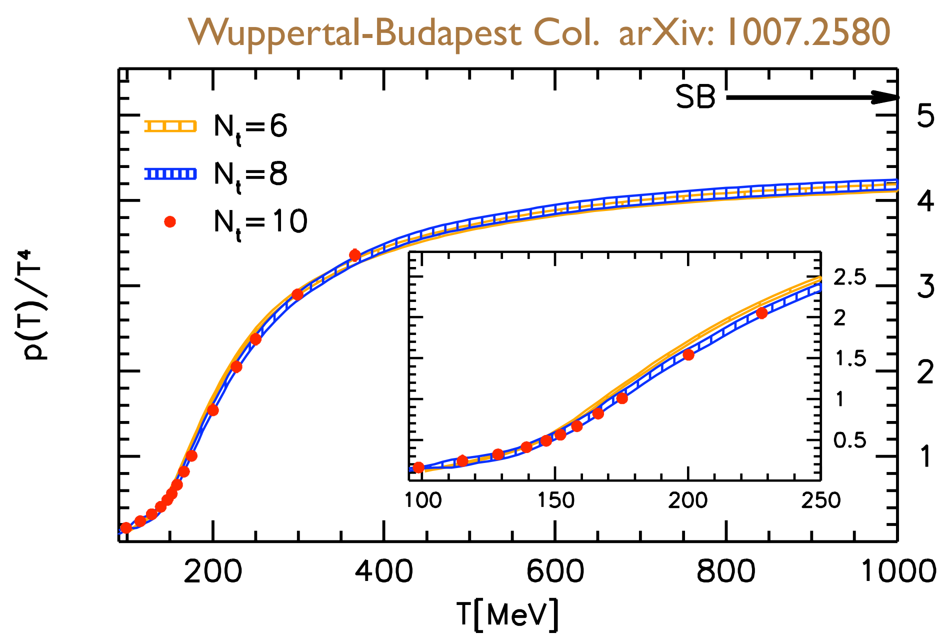
static properties

not too sensitive to the degrees of freedom

- Dynamical properties: hard for lattice
  - ➤ η/s
  - ➤ thermalization
  - ➤ opacity

A picture of the plasma

$T \sim \Lambda_{QCD}$



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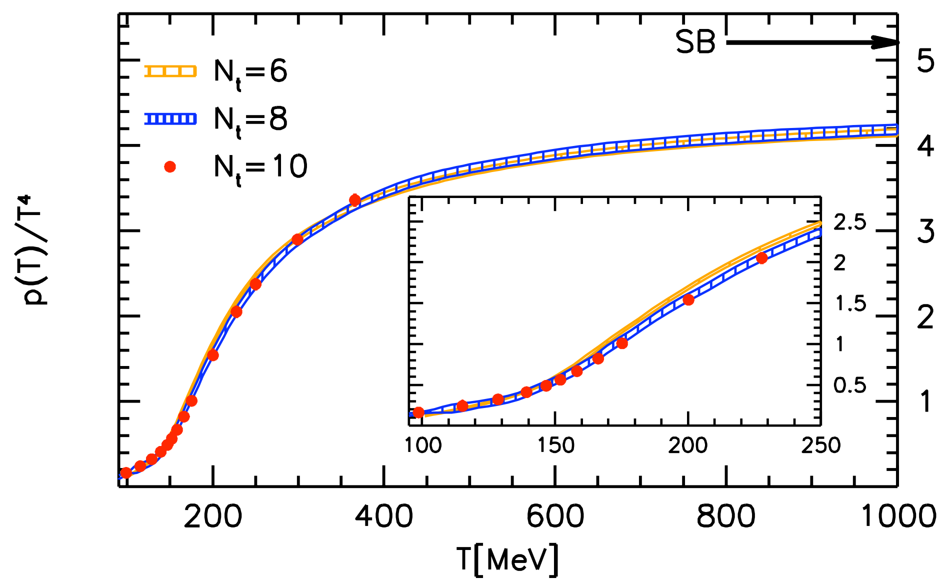

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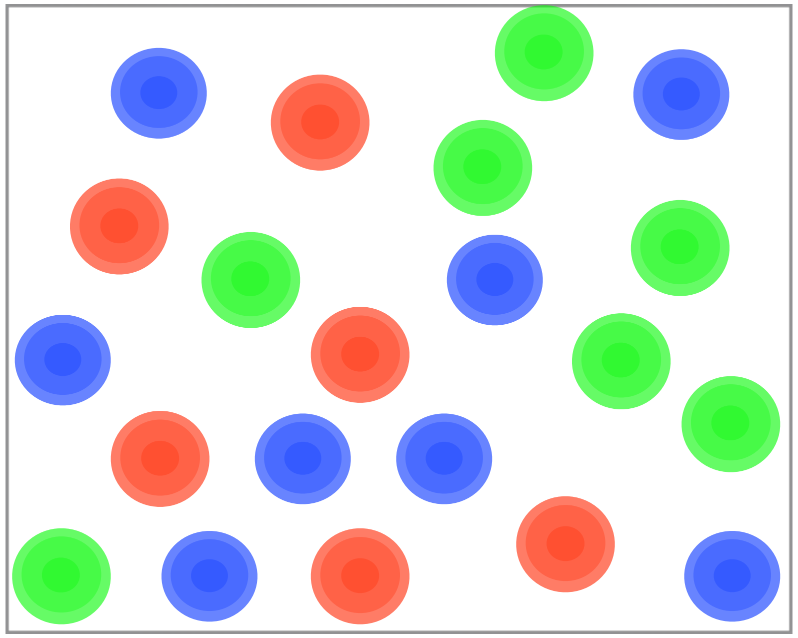

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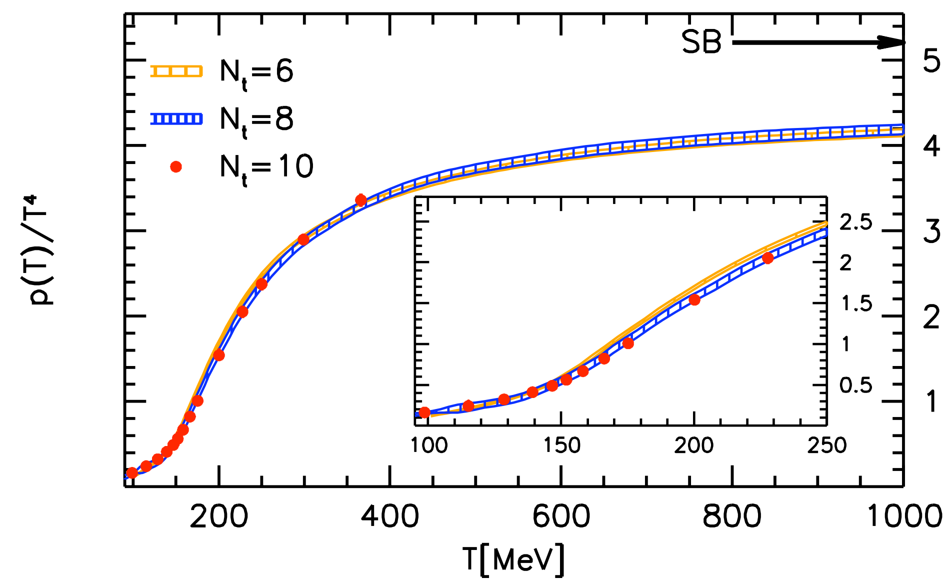

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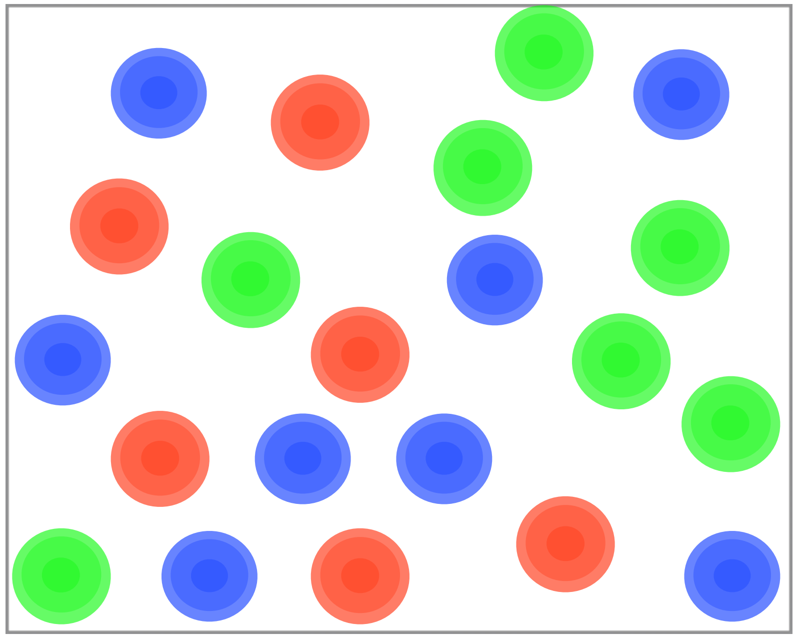
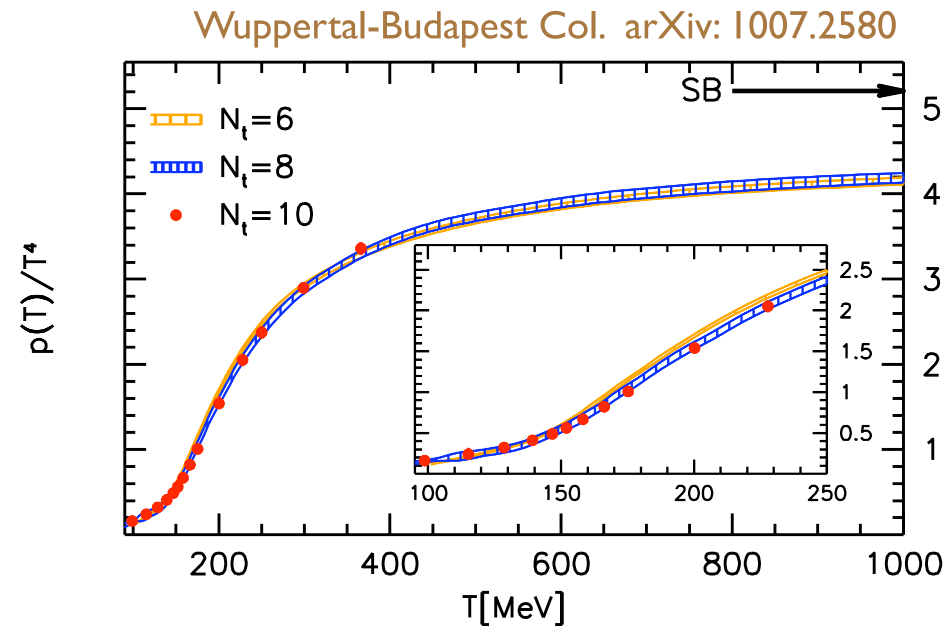


$$\alpha_s = 0.3 \Longrightarrow g = 2$$

A picture of the plasma

$T \sim \Lambda_{QCD}$



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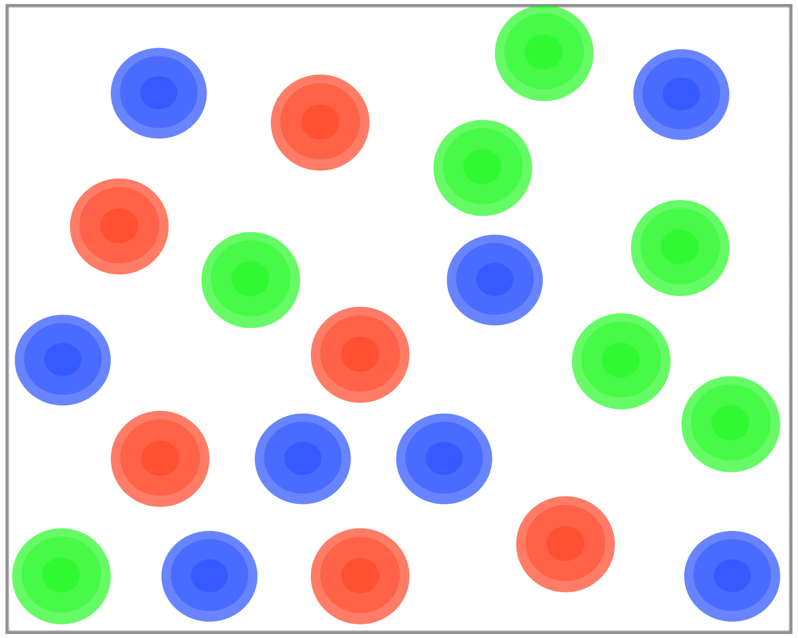

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$$T \sim g^2 T \sim g^4 T$$

A picture of the plasma

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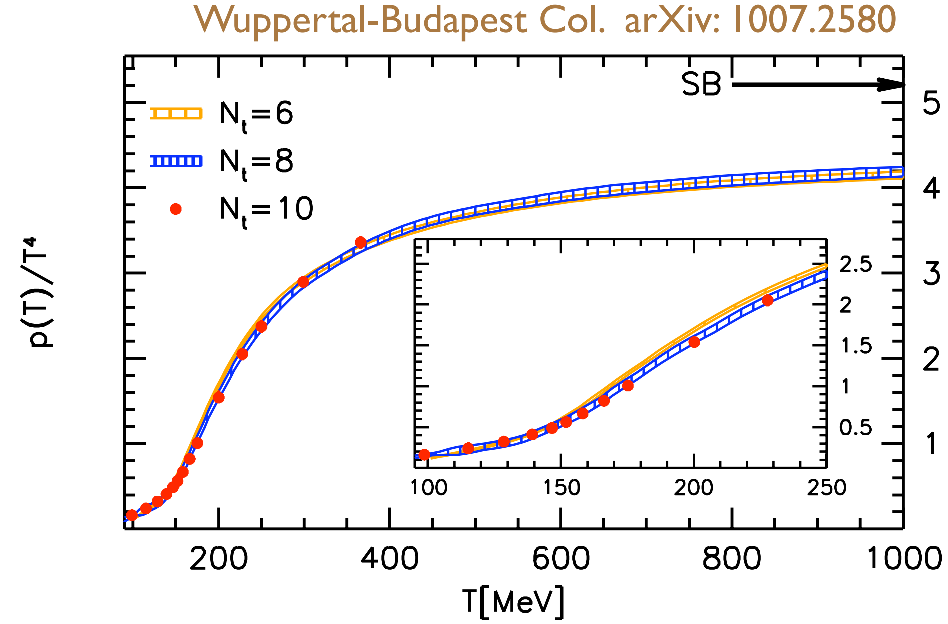
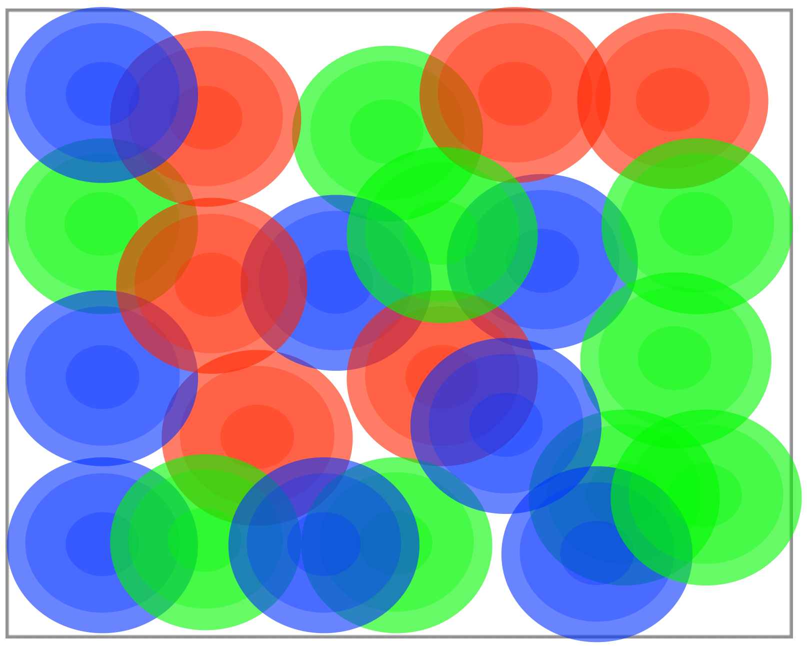


A strongly coupled goo?



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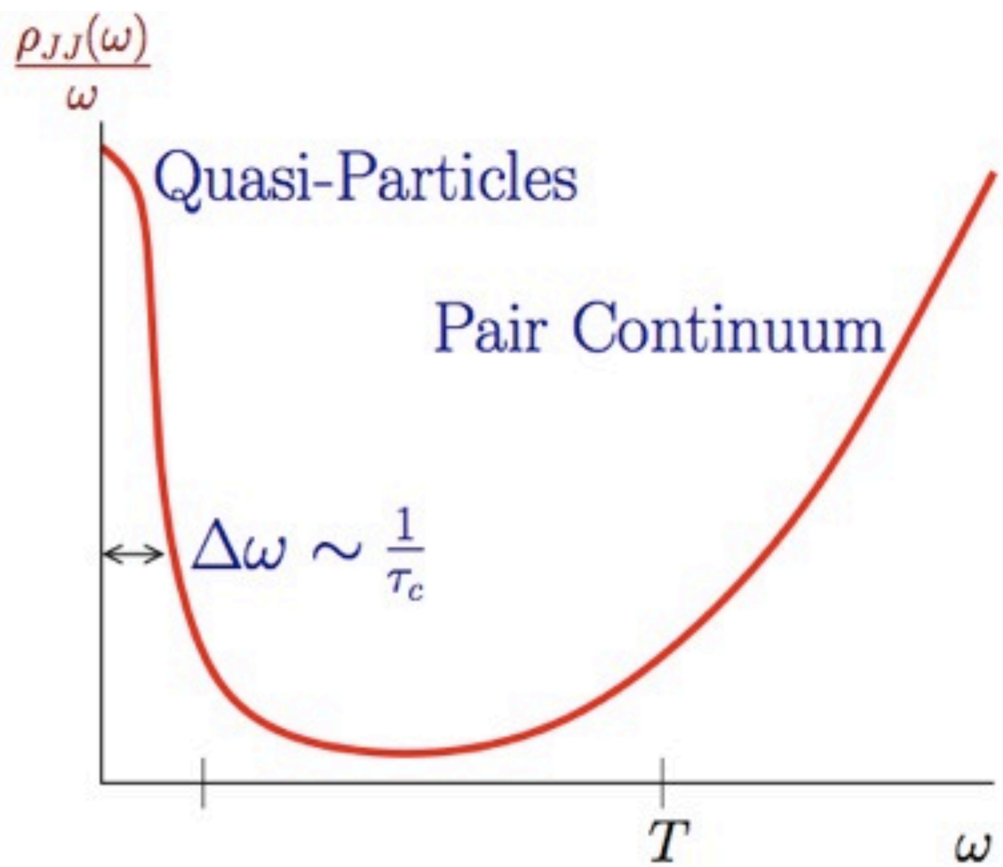
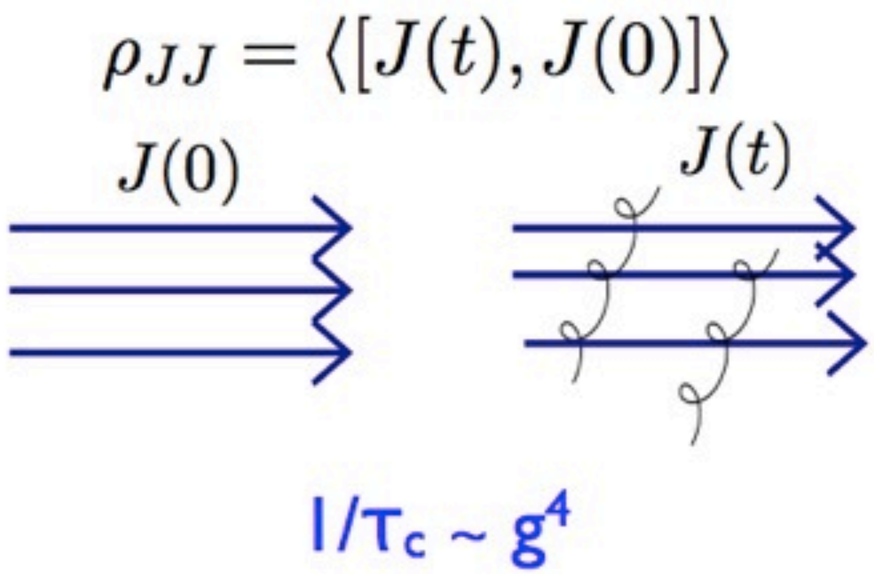
$T \sim g^2 T \sim g^4 T$

Quasi Particles

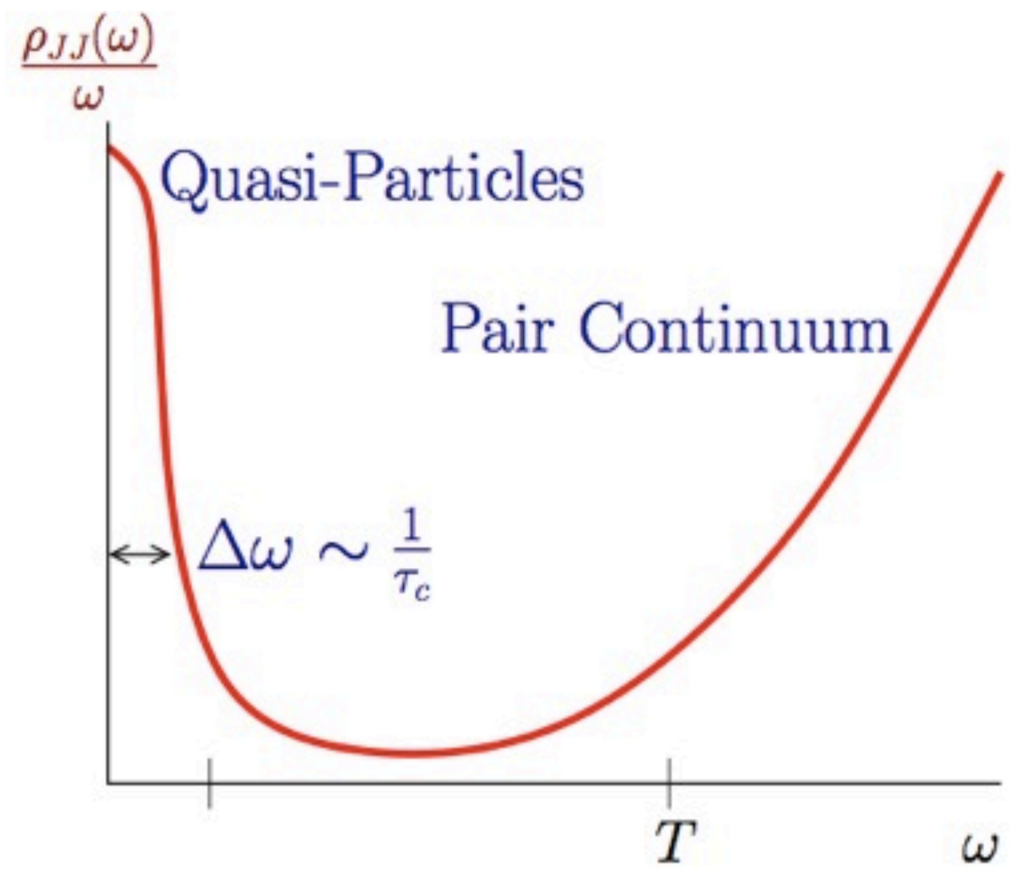


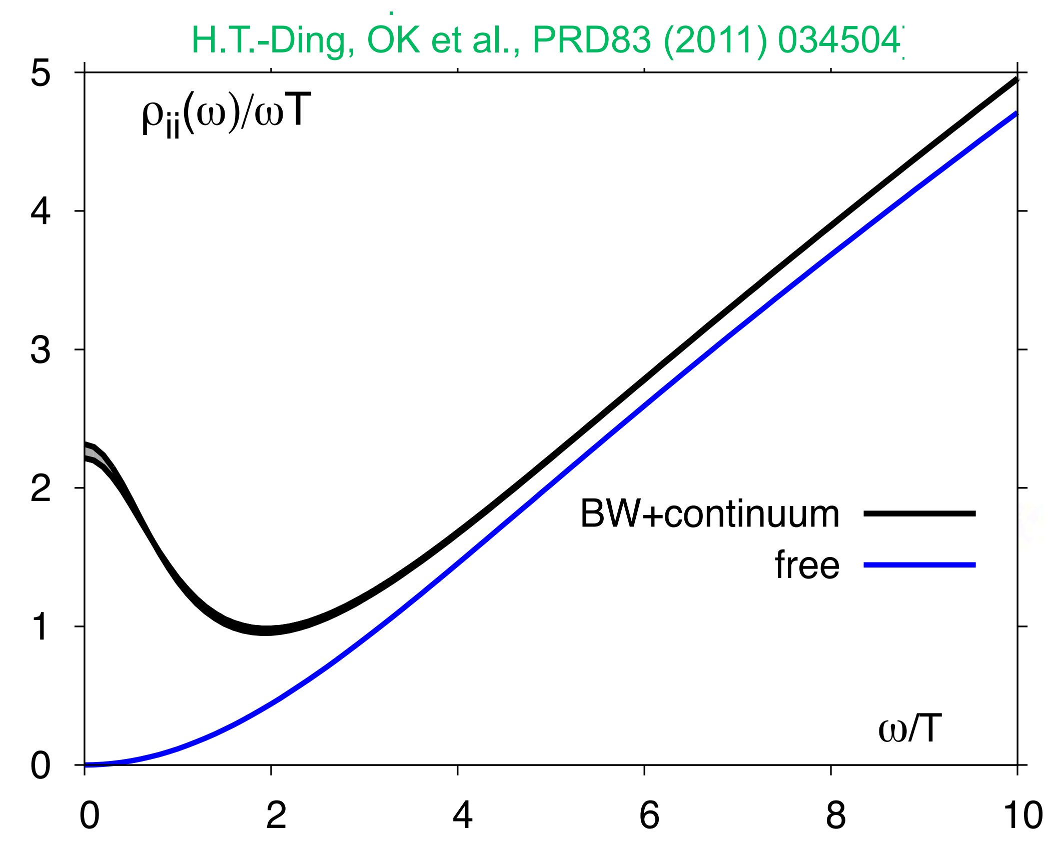


- Fishing for quasi-particles: conserved current correlator

narrow structures?

Quasi Particles



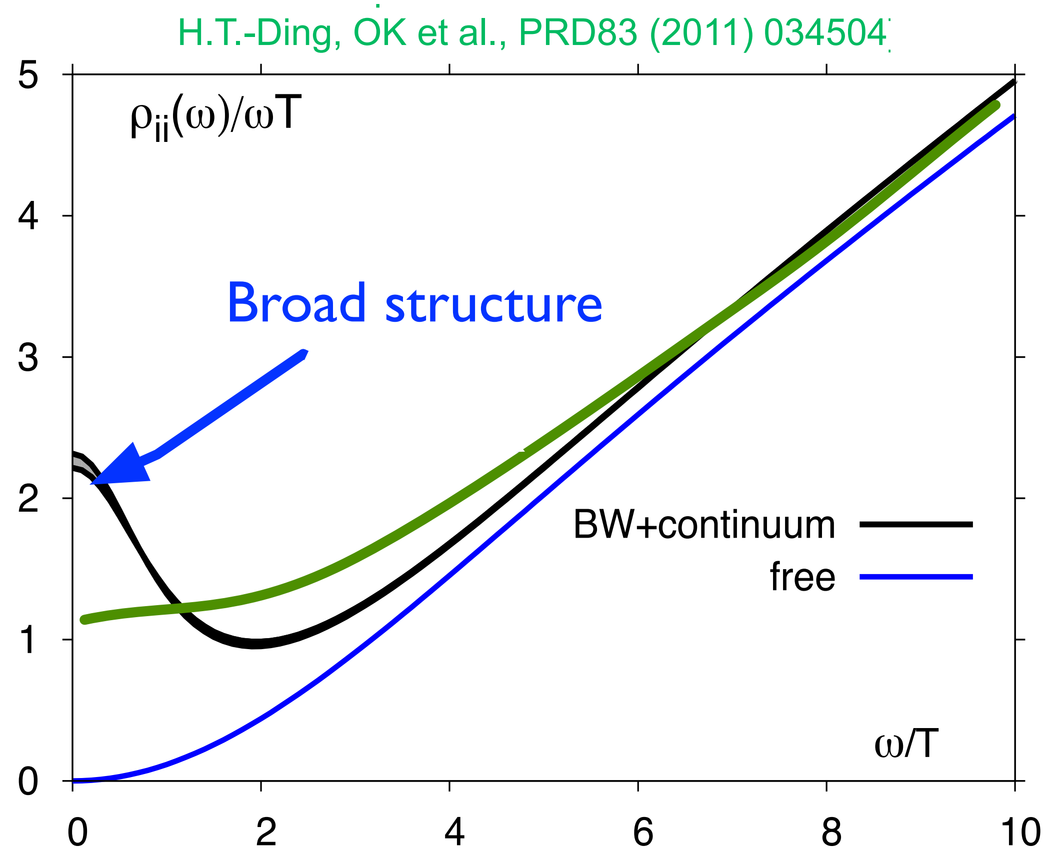


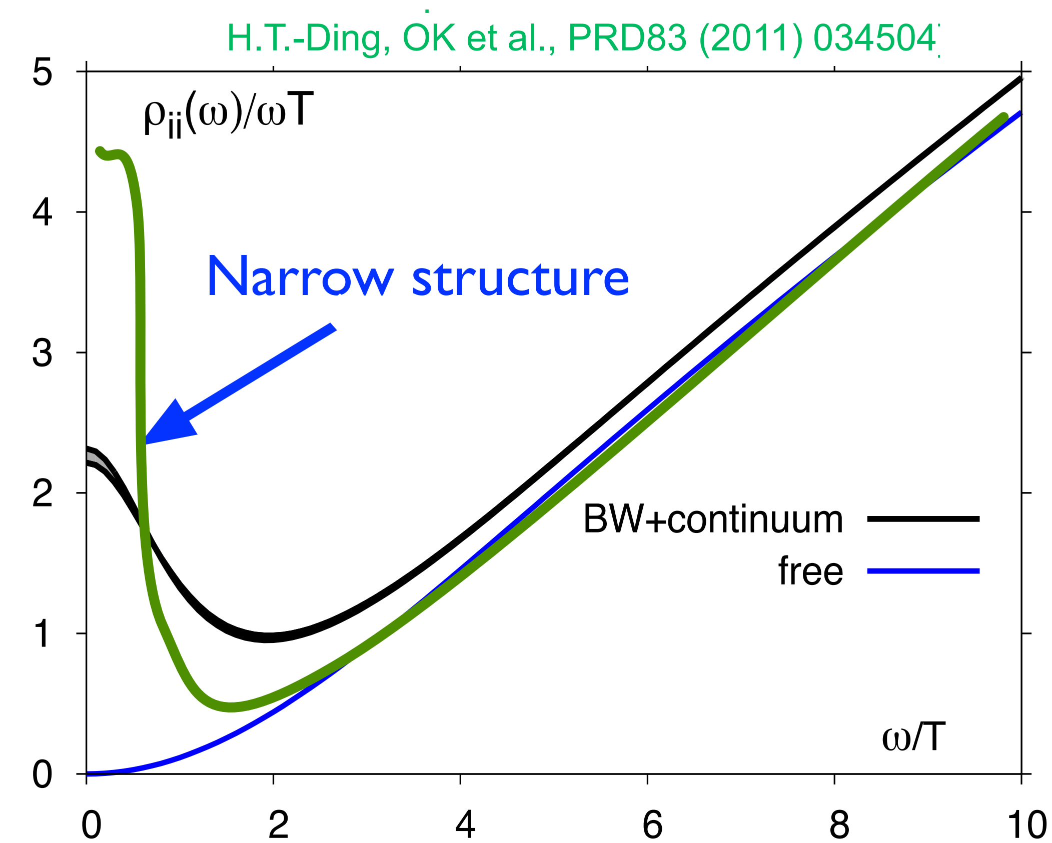
- Fishing for quasi-particles: conserved current correlator

  narrow structures?

- Lattice results (hard)

Quasi Particles vs no-Quasi Particles





- 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

What to do?

- Give up and move to something else
- Keep on doing/improving perturbation theory. Hope for the best
- Change the problem: look for a simpler example. Hope for the best
- Look at both extremes and try to understand the physics in both.

Holography

- Gauge-gravity duality

$\lambda = g^2 N_c \to \infty$

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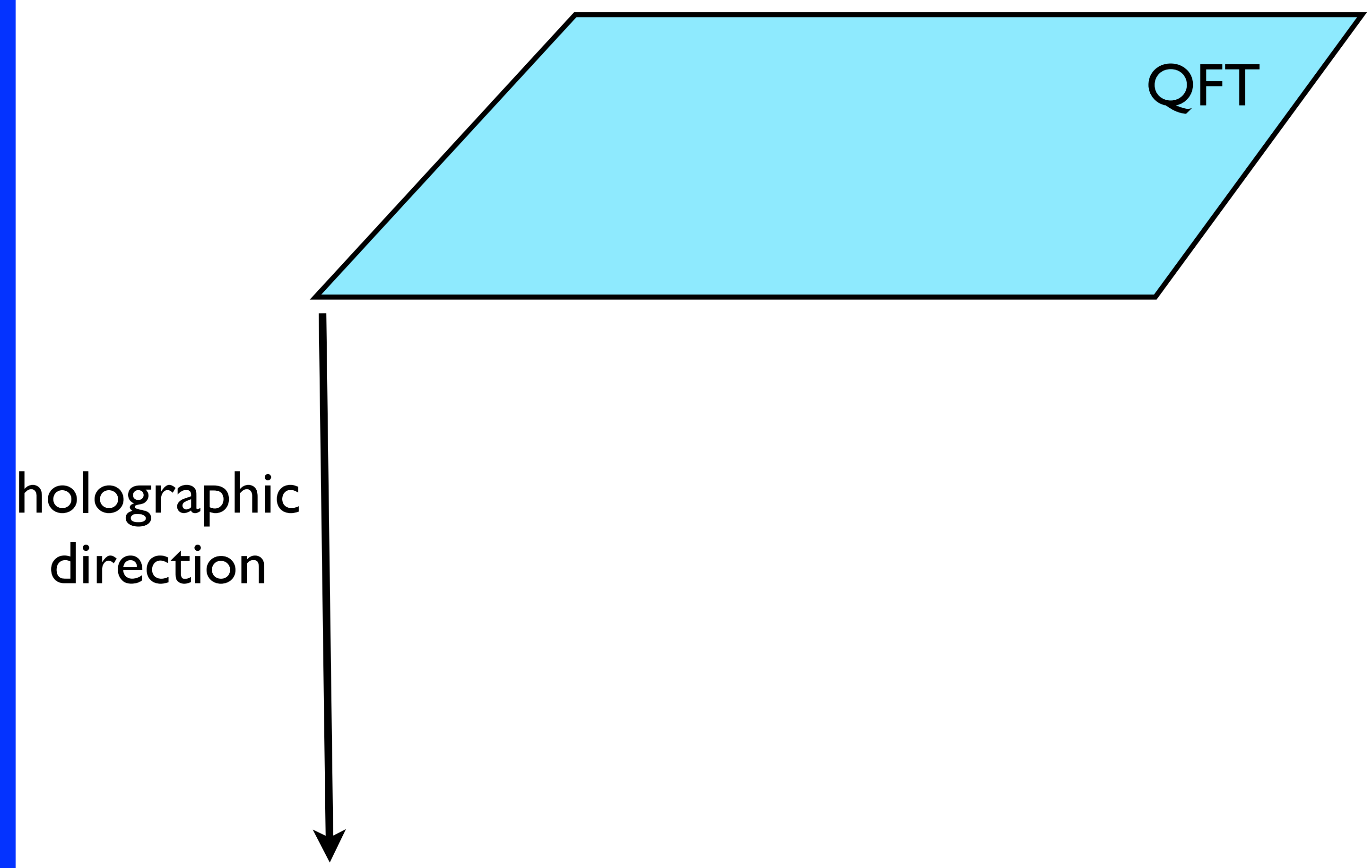

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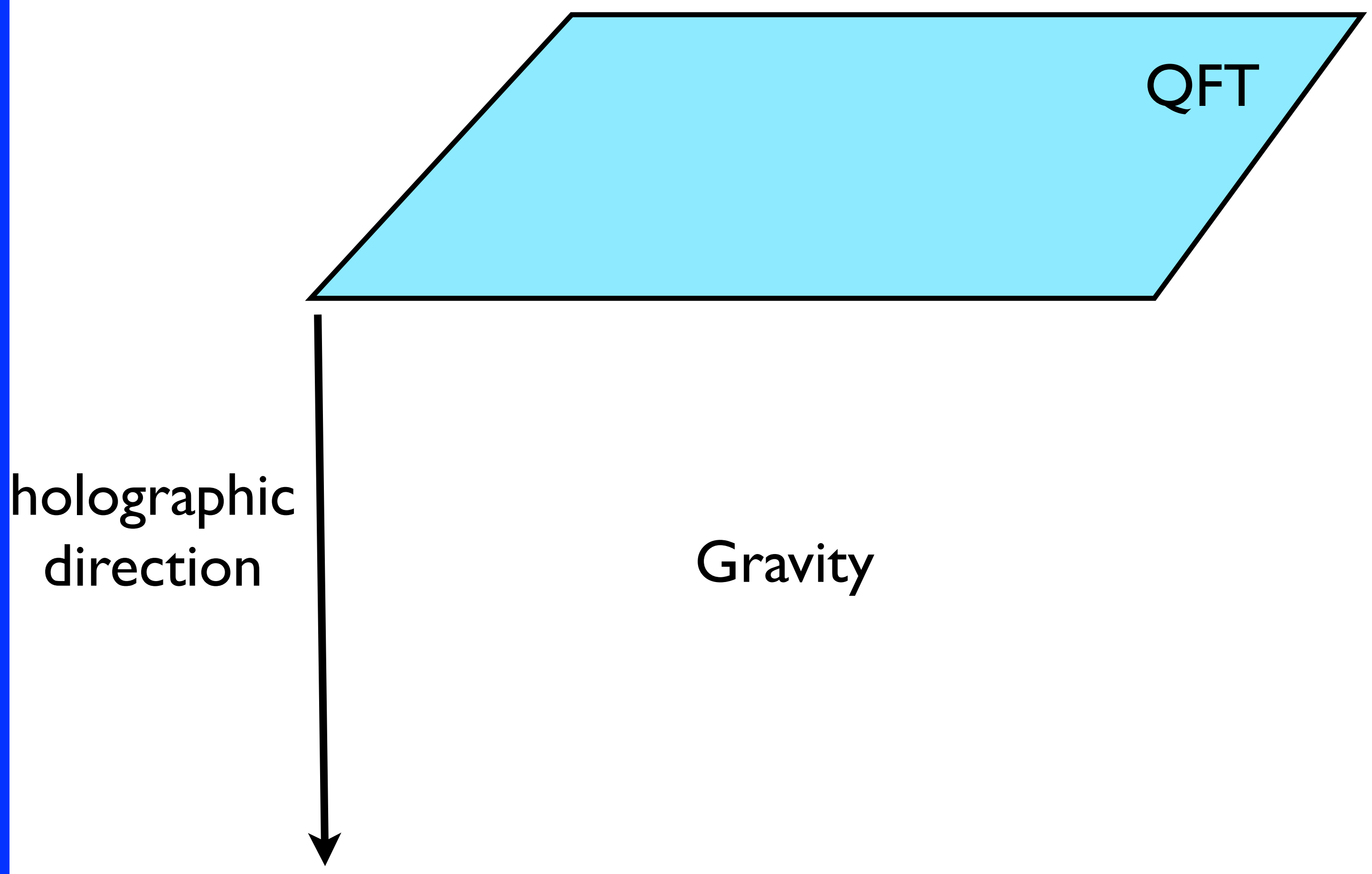

Holography

- Gauge-gravity duality

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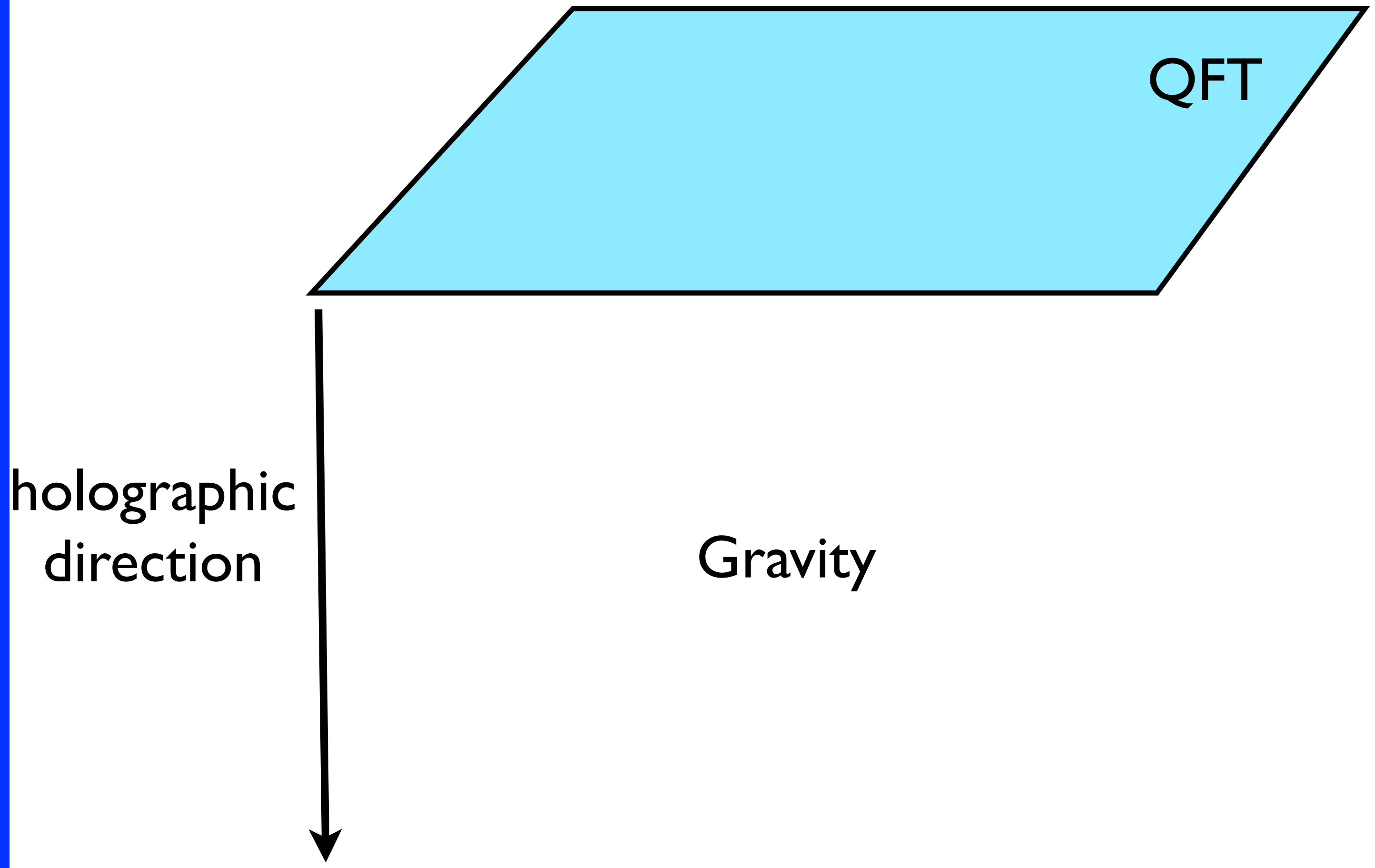
Dictionary



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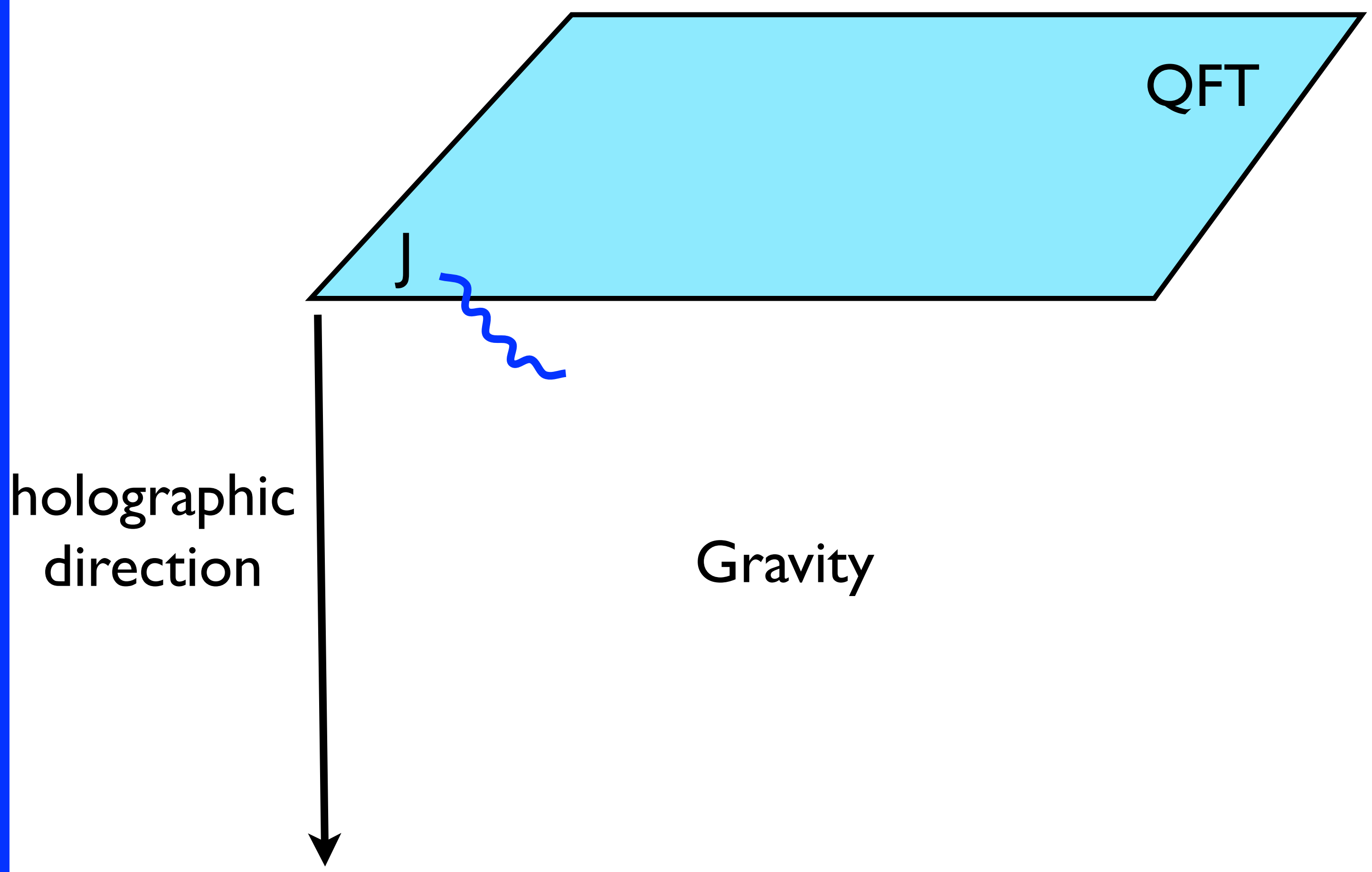

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$J_\mu \leftrightarrow A_\mu$

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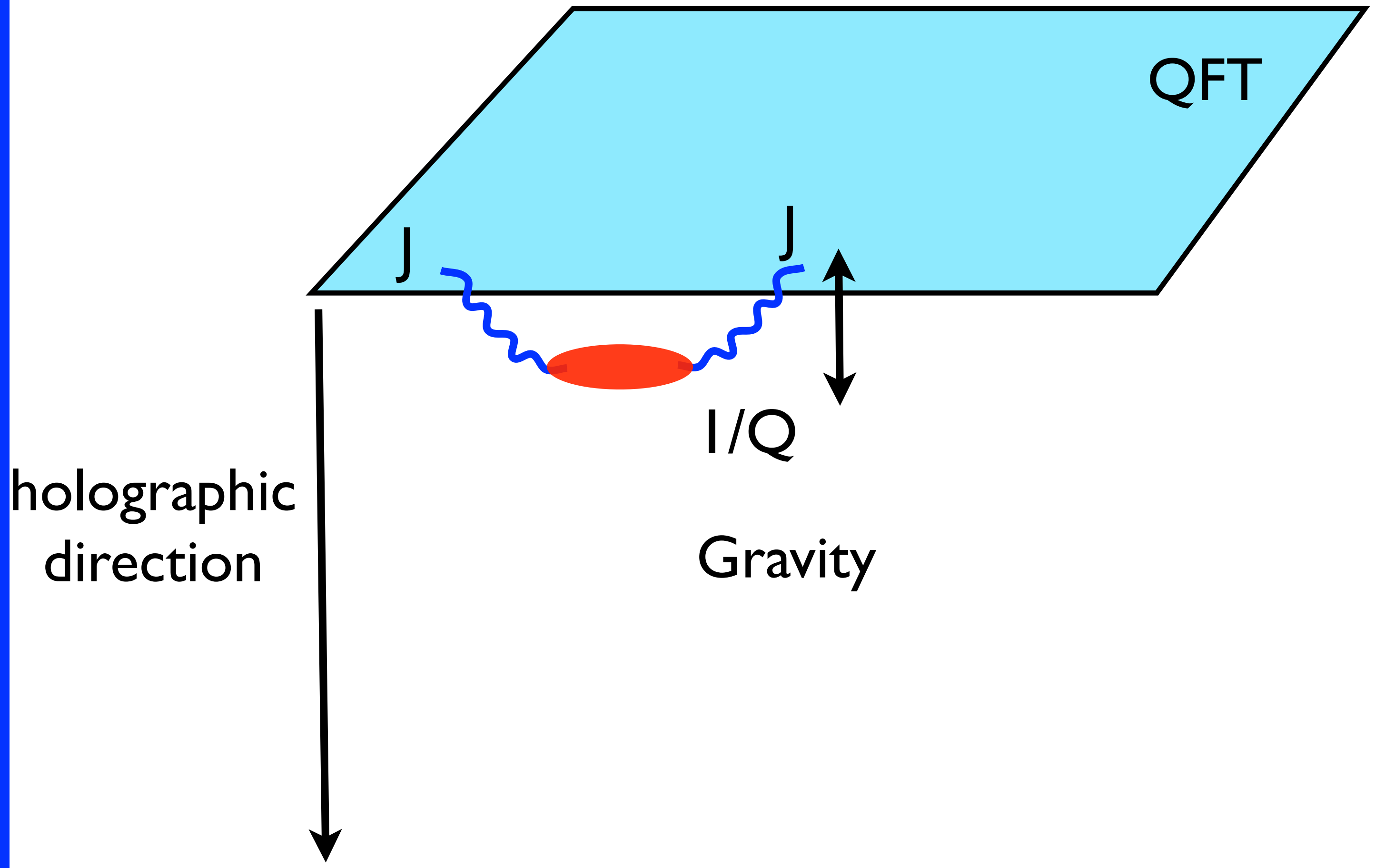

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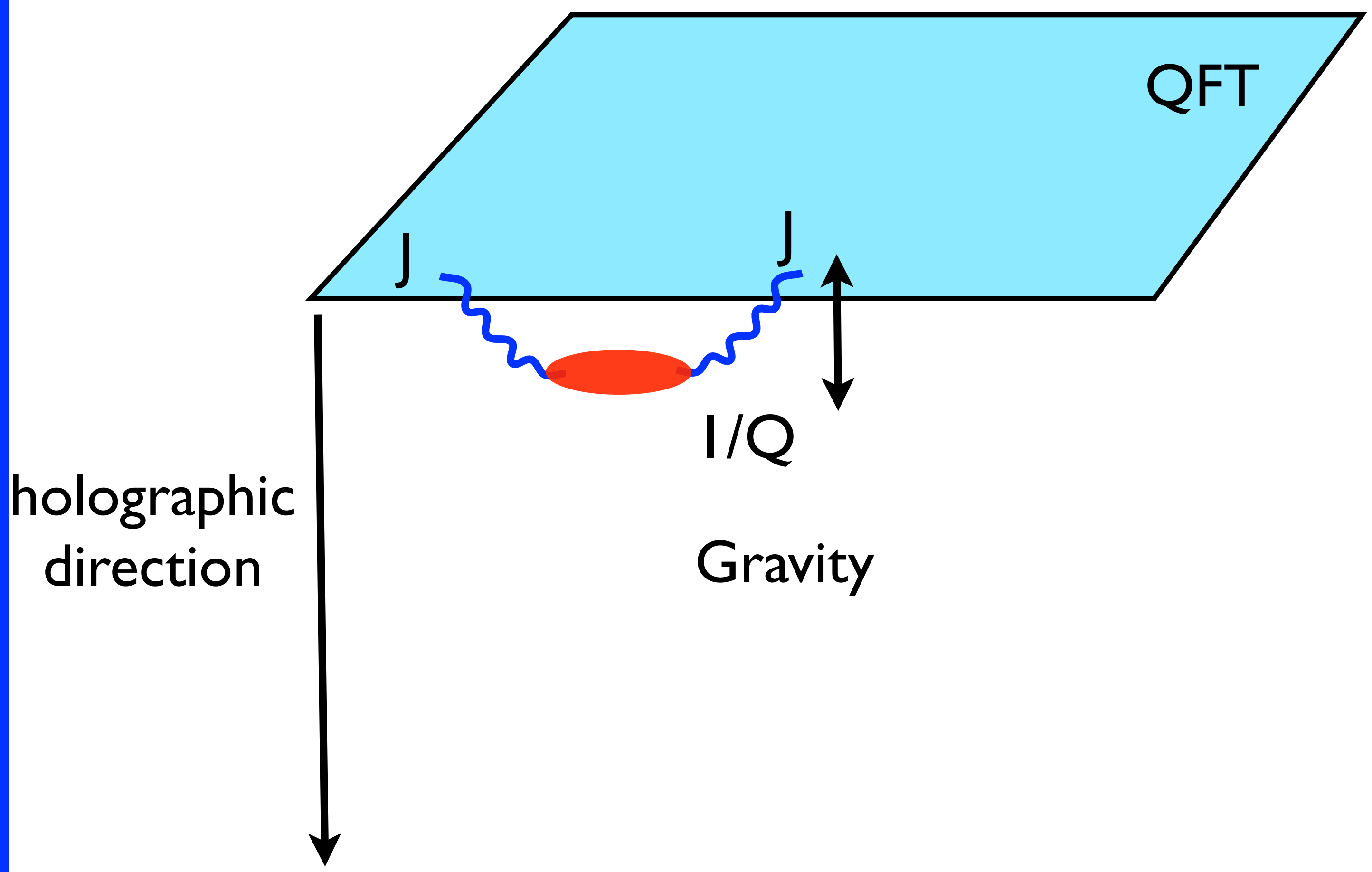

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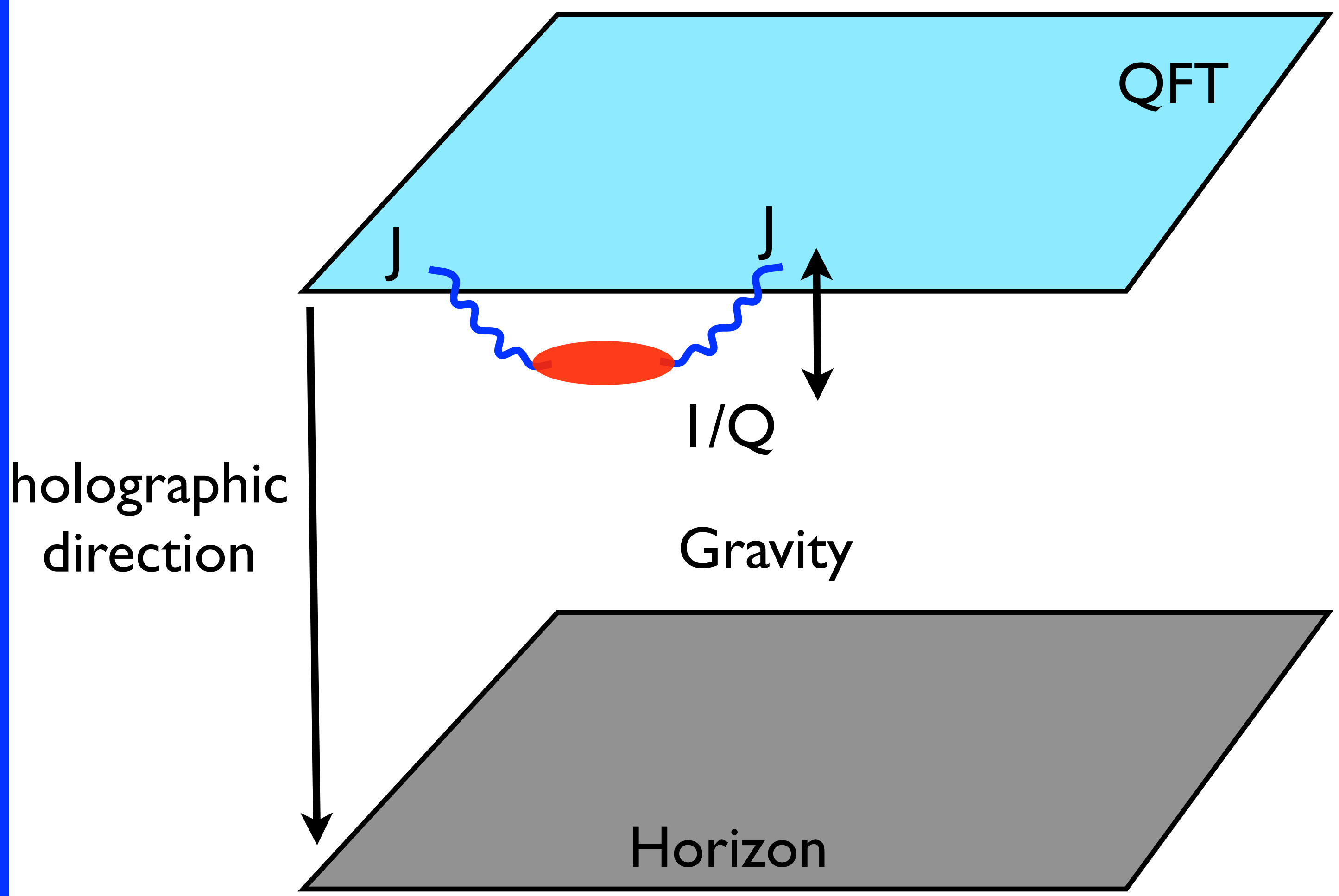

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$T \leftrightarrow$ *black hole*

Holography

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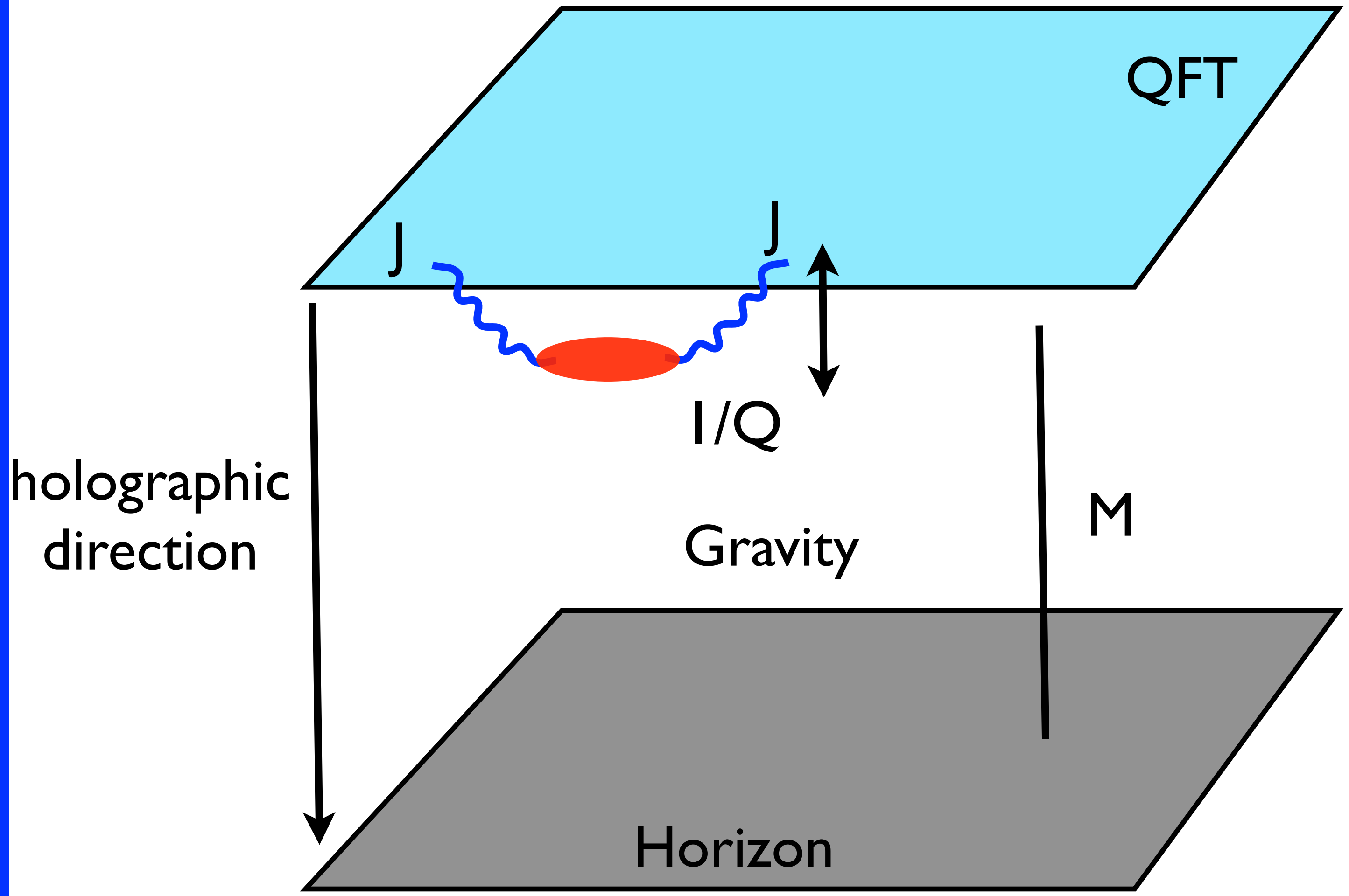

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$J_\mu \leftrightarrow A_\mu$

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T ↔ *black hole*

heavy quark ↔ *string*

What holography is not

- It is not a controlled approximation to QCD
  - ➤ conformal (most models)
    - ➤ no asymptotic freedom
  - ➤ supersymmetric
    - ➤ broken at finite temperature
    - ➤ different number of degrees of freedom
    - ➤ presence of scalars
  - ➤ Large number of colors
- It is hard to be quantitative

What holography can do

- Provide complete answers to complicated problems
- Correct (naive) expectations from pertubation theory
- Teach us new phenomena
- Even some quantitative predictions

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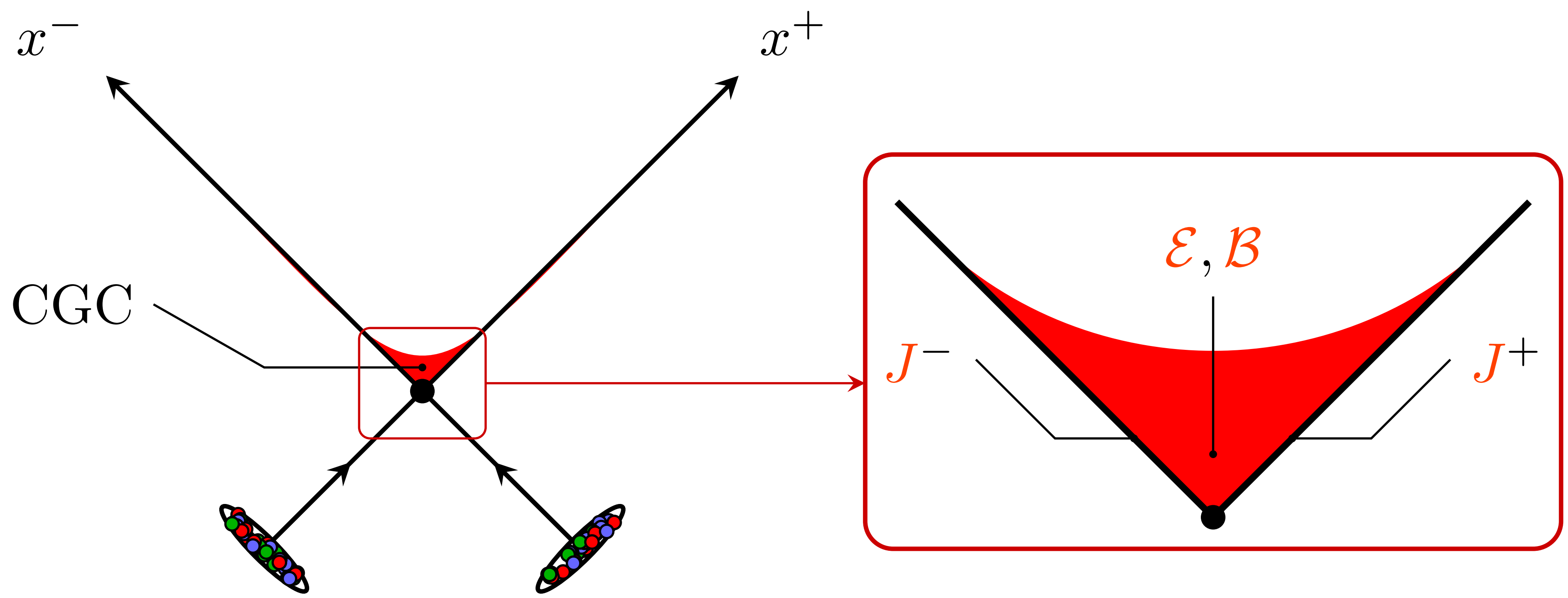
$\eta/s = 1/4\pi$ (universal for all gravity duals)

But connecting these computations to observables is a bit of an art

Collisions of Shocks

- Classic set-up for studying thermalization at weak coupling

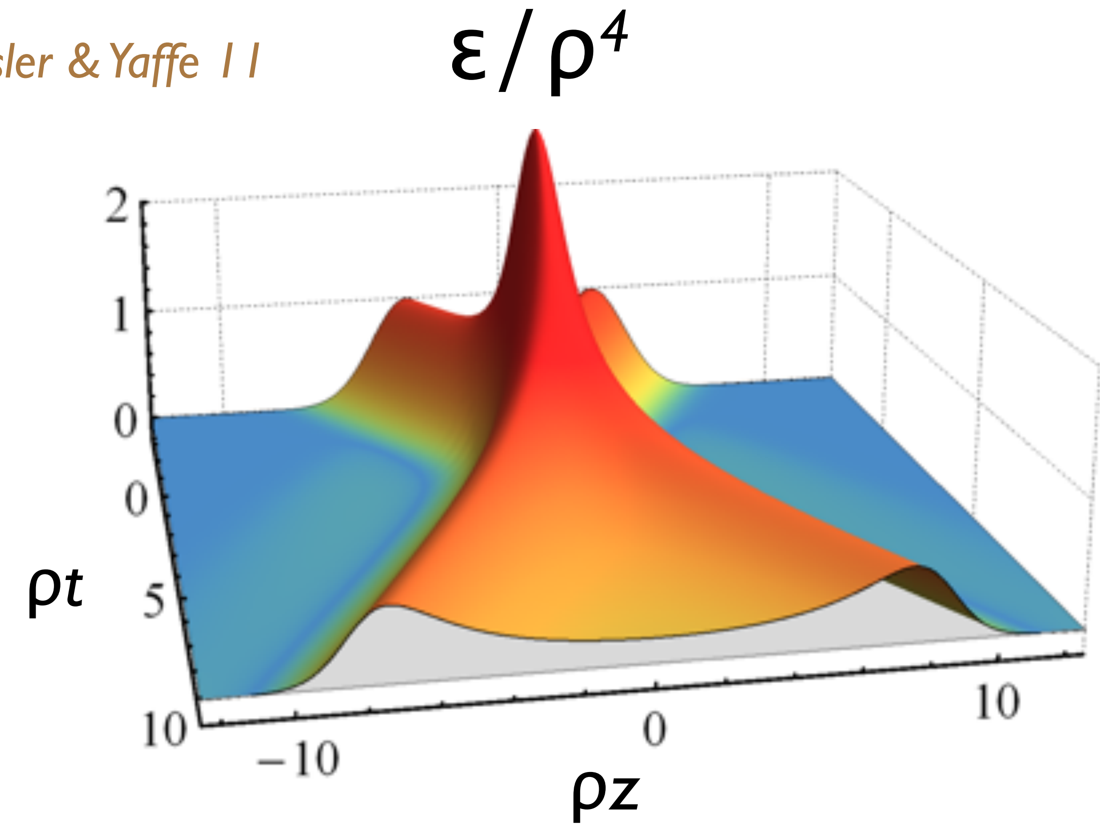


(nucleus modeled as strong classical current)

- Strong coupling "equivalent": collide energy lumps

Holography Shocks

Chesler & Yaffe 11



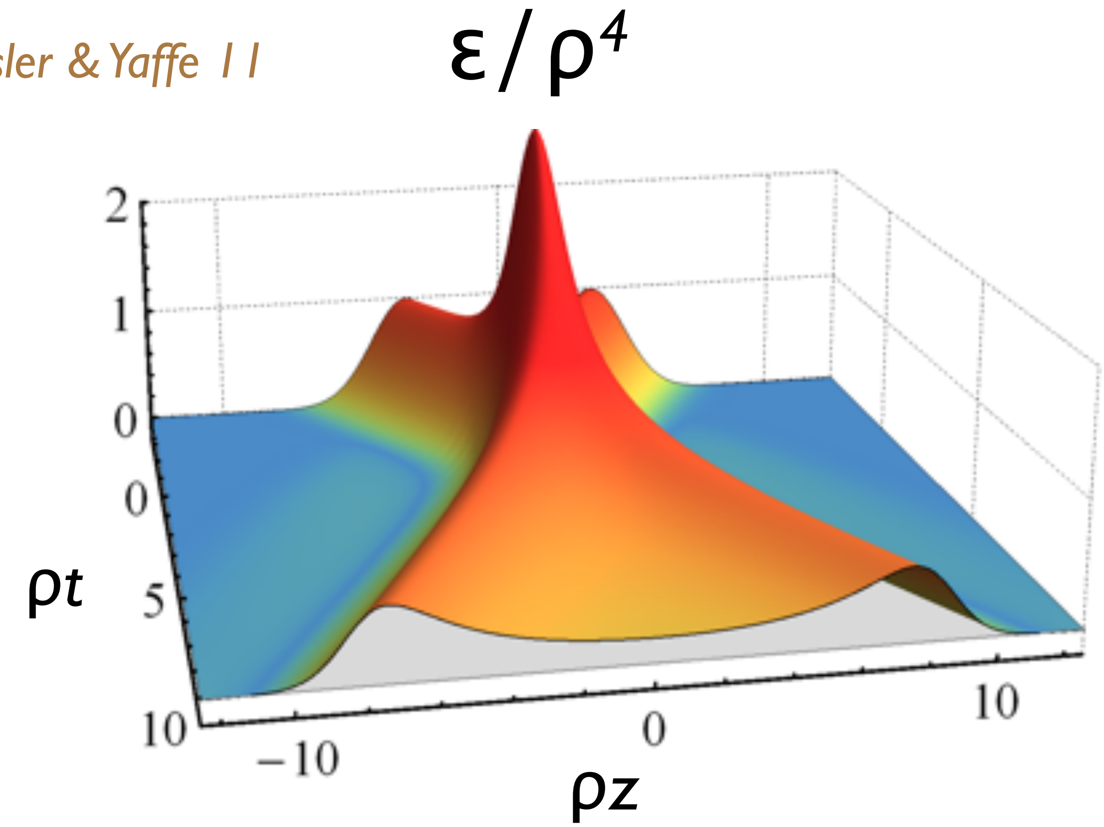
How well hydro works?

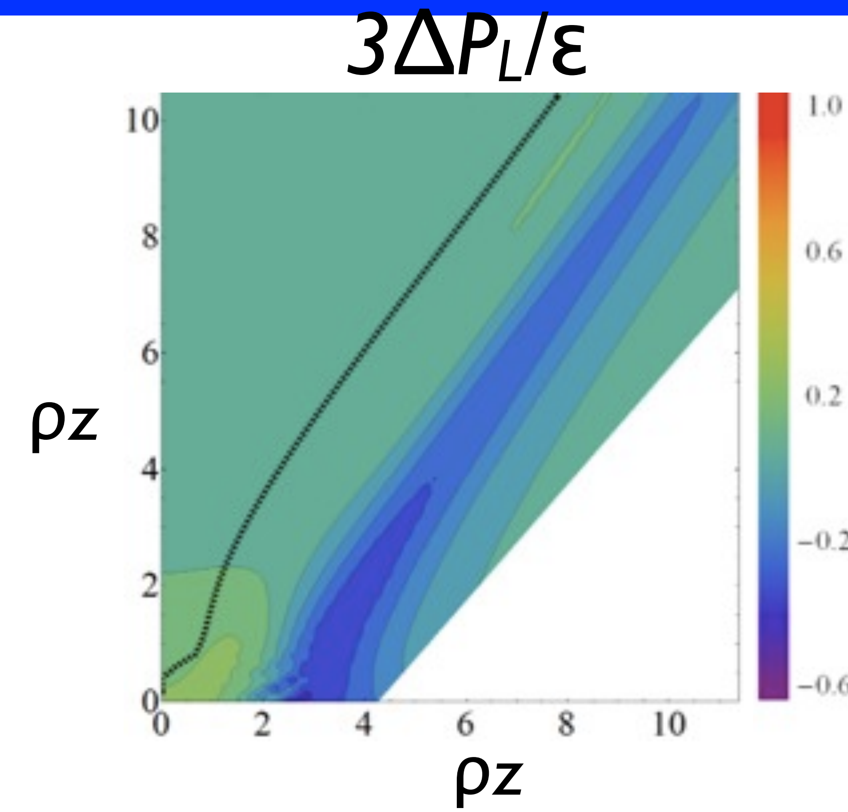
When does it start working?

$$T^{\mu\nu} \longrightarrow T^{\mu\nu}u_\nu \equiv \epsilon u^\mu \longrightarrow T^{\mu\nu}_{\text{rest frame}} = \text{diagonal}\{\epsilon, P_L, P_T\}$$

Holography Shocks

Chesler & Yaffe 11





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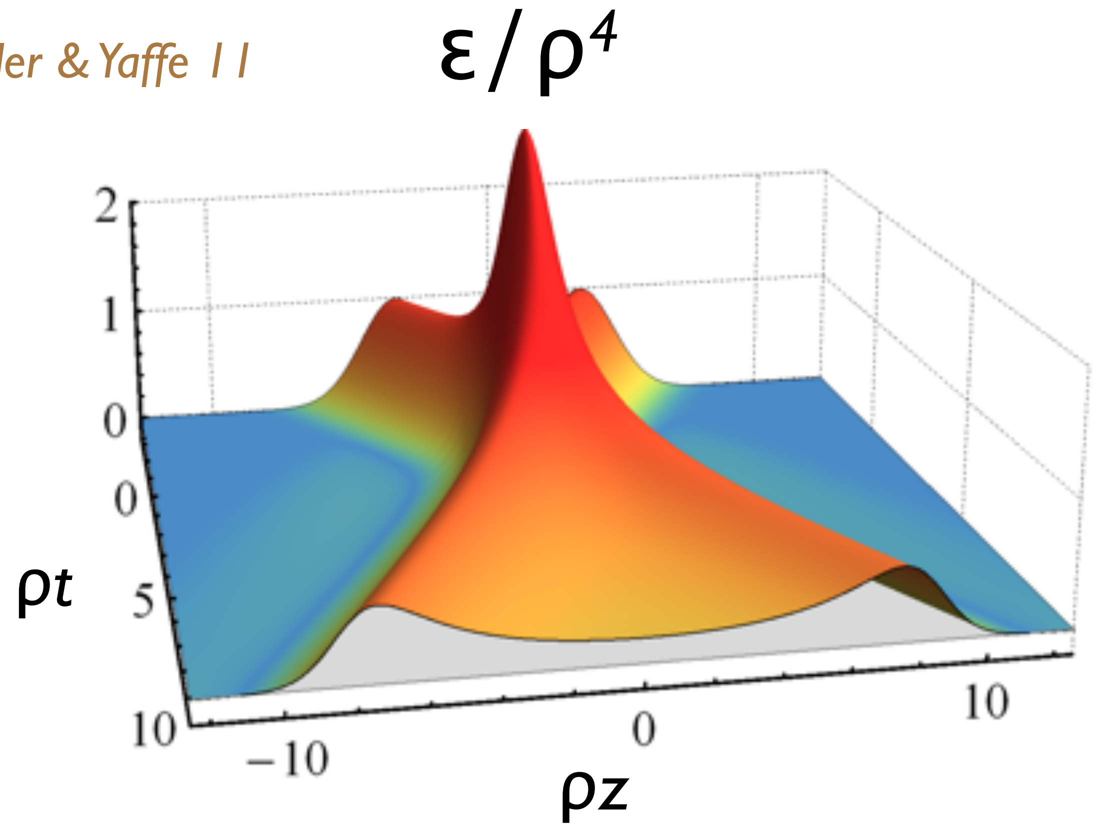
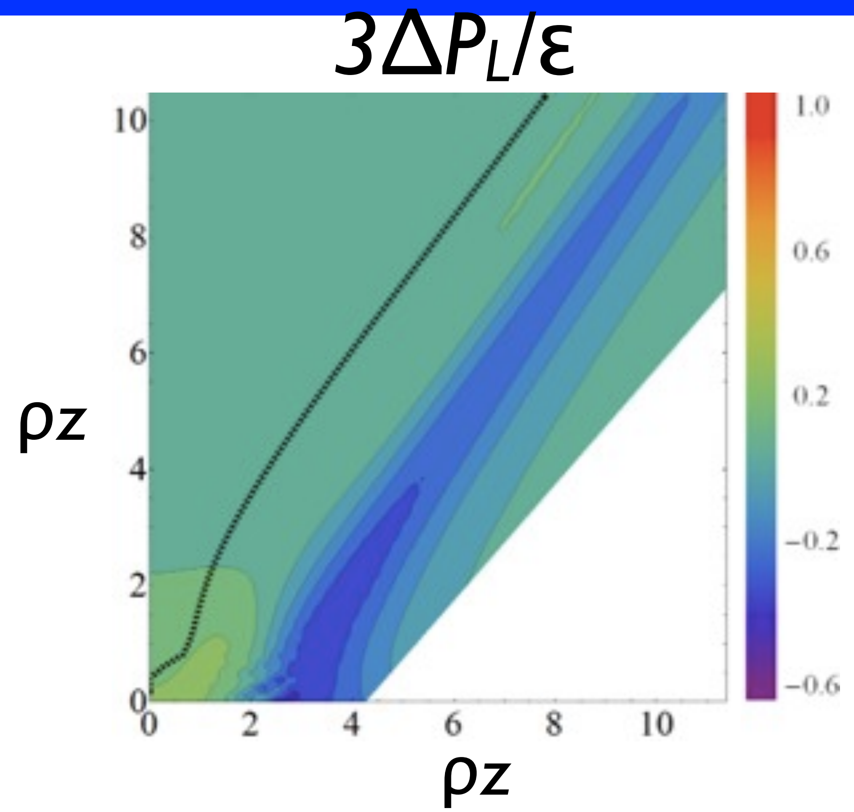
$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + \eta\sigma^{\mu\nu} \;?$$

Holography Shocks

Chesler & Yaffe 11

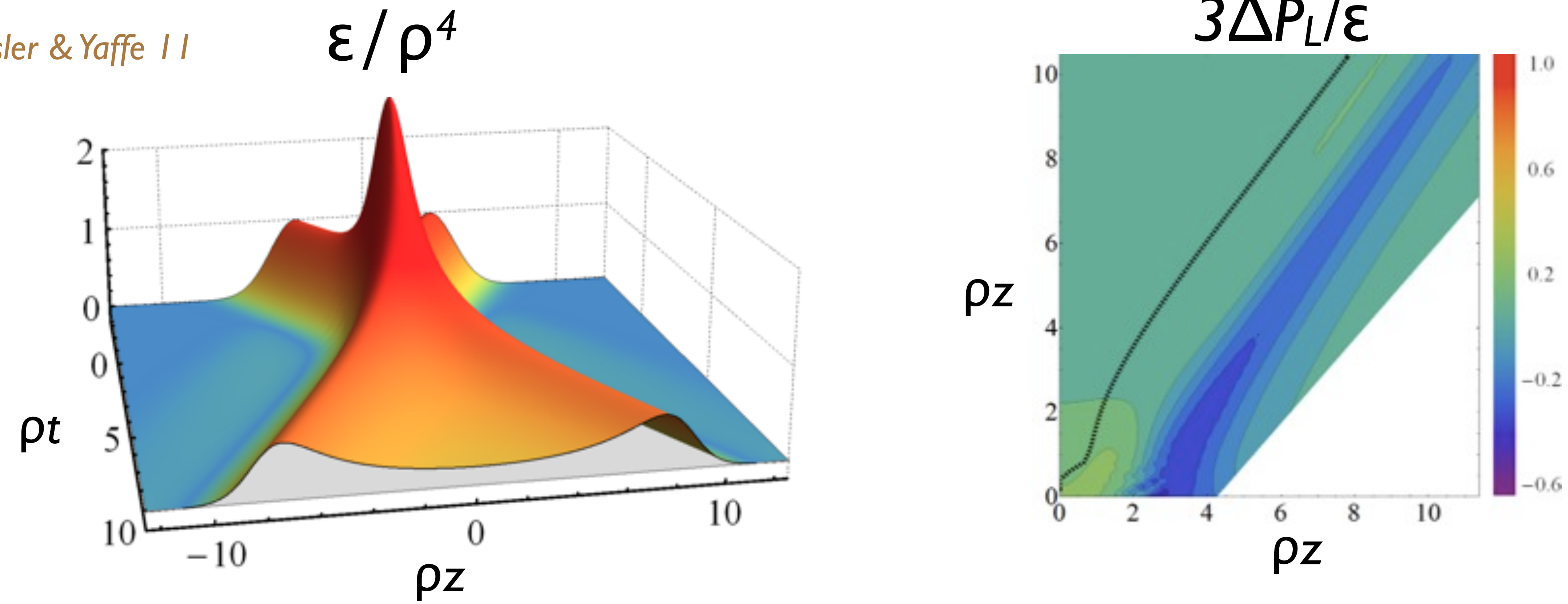




- Very early hydrodynamic behavior
- Realization of Landau model

Holography Shocks

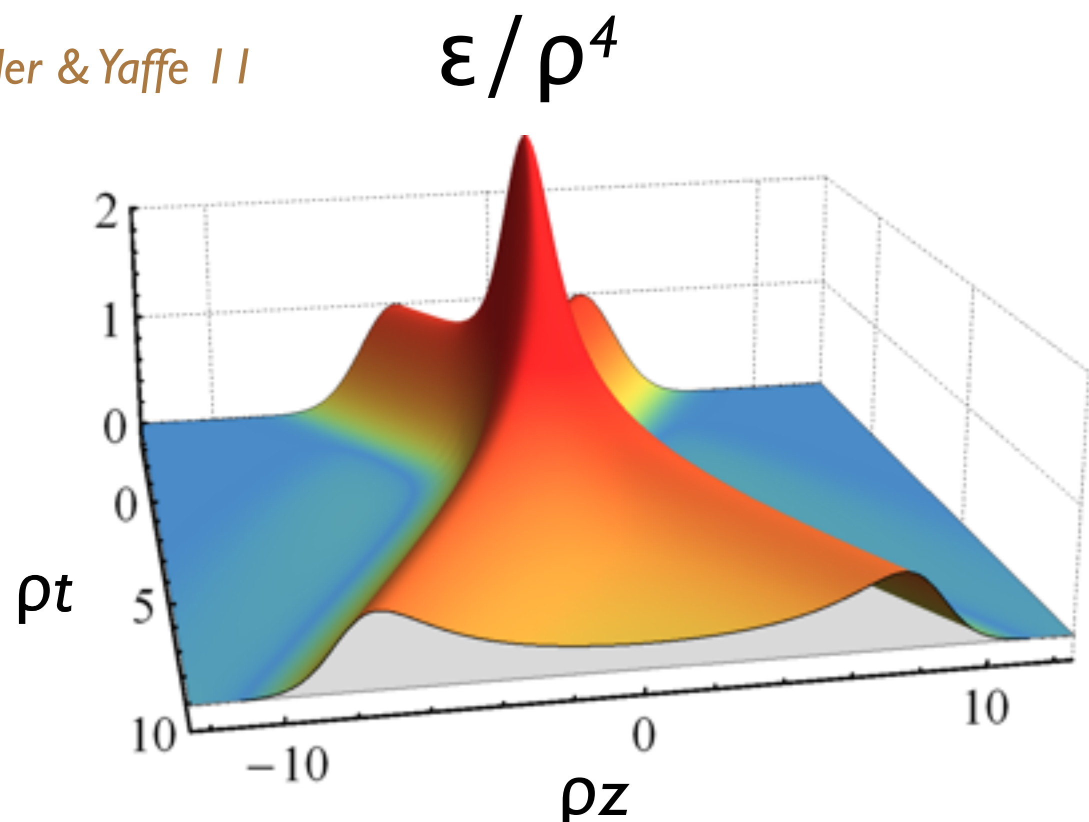
Chesler & Yaffe 11

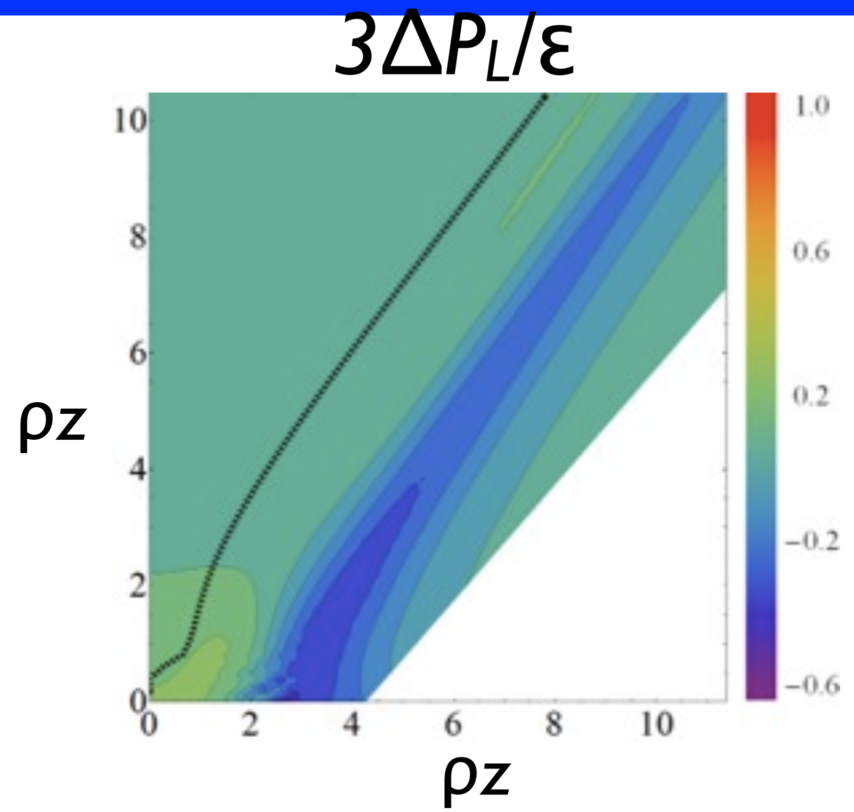


- Very early hydrodynamic behavior
- Realization of Landau model
- What happens at higher energies?

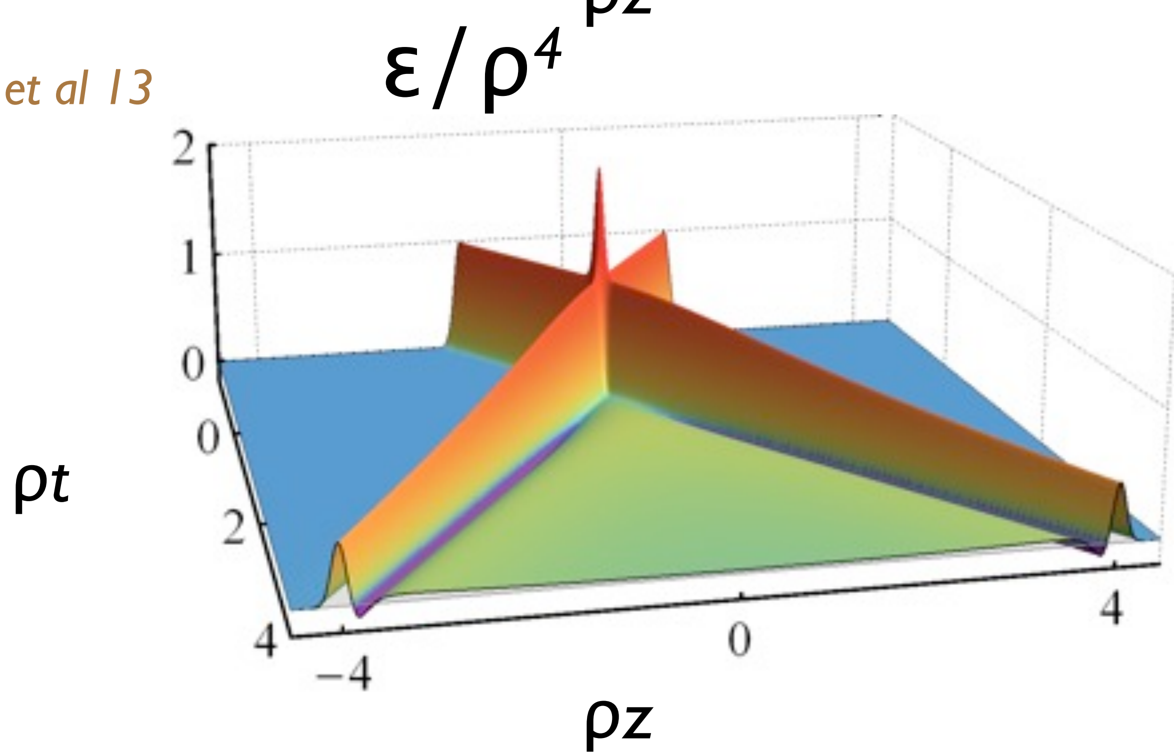
Holography Shocks

Chesler & Yaffe 11





JCS et al 13



Holography Shocks

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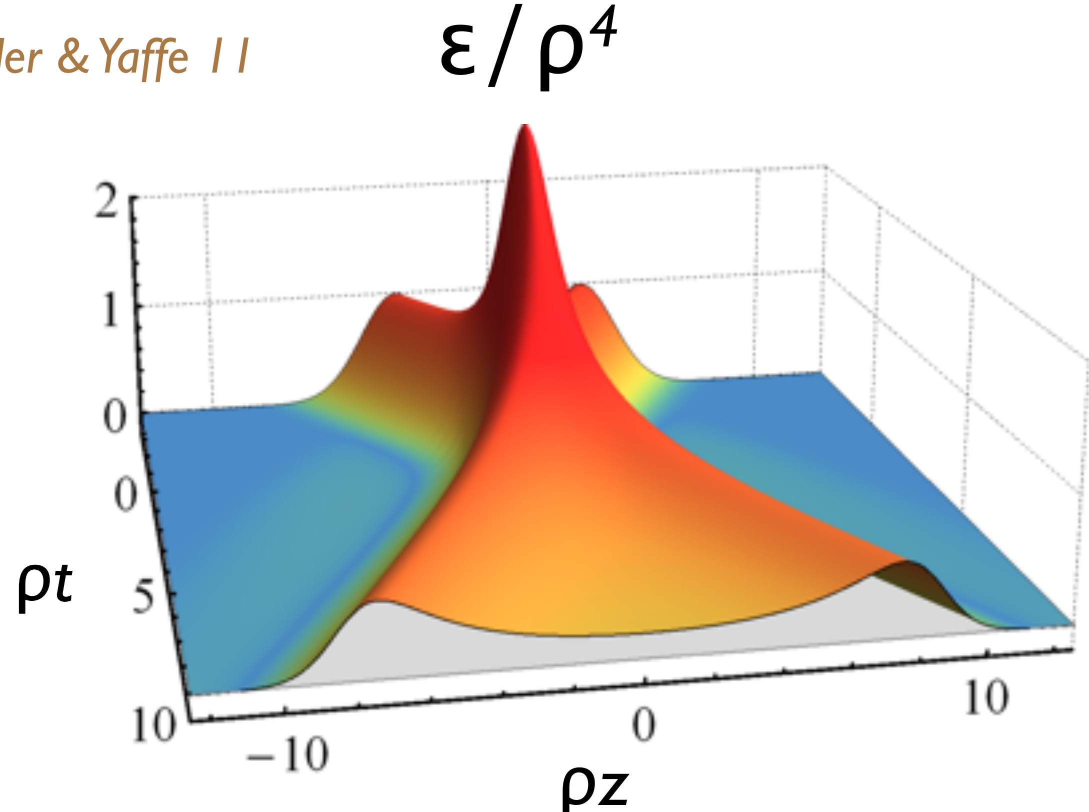

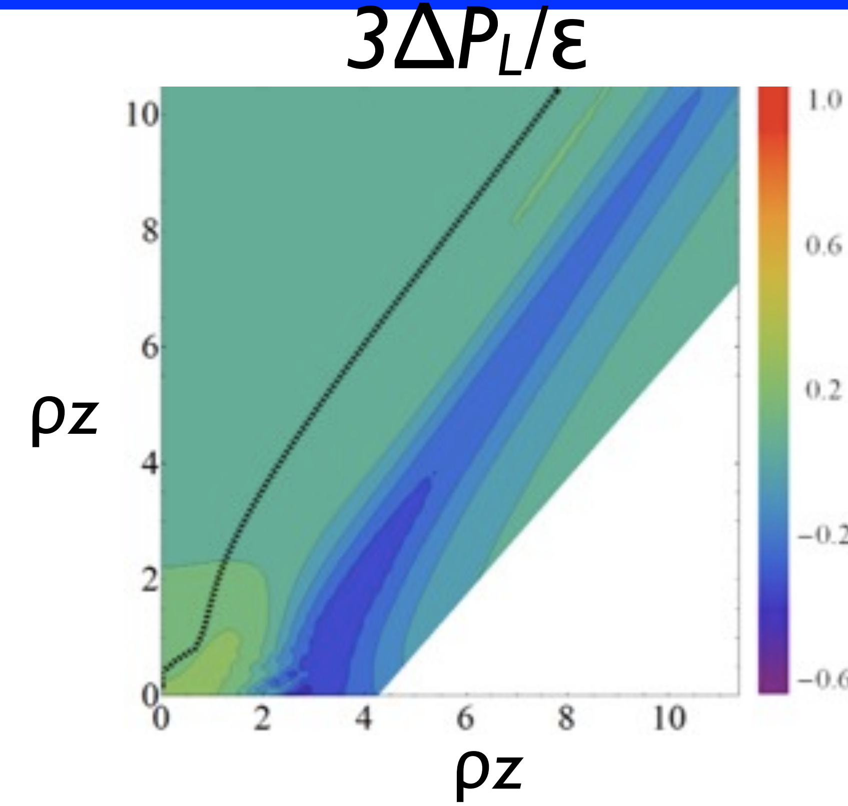

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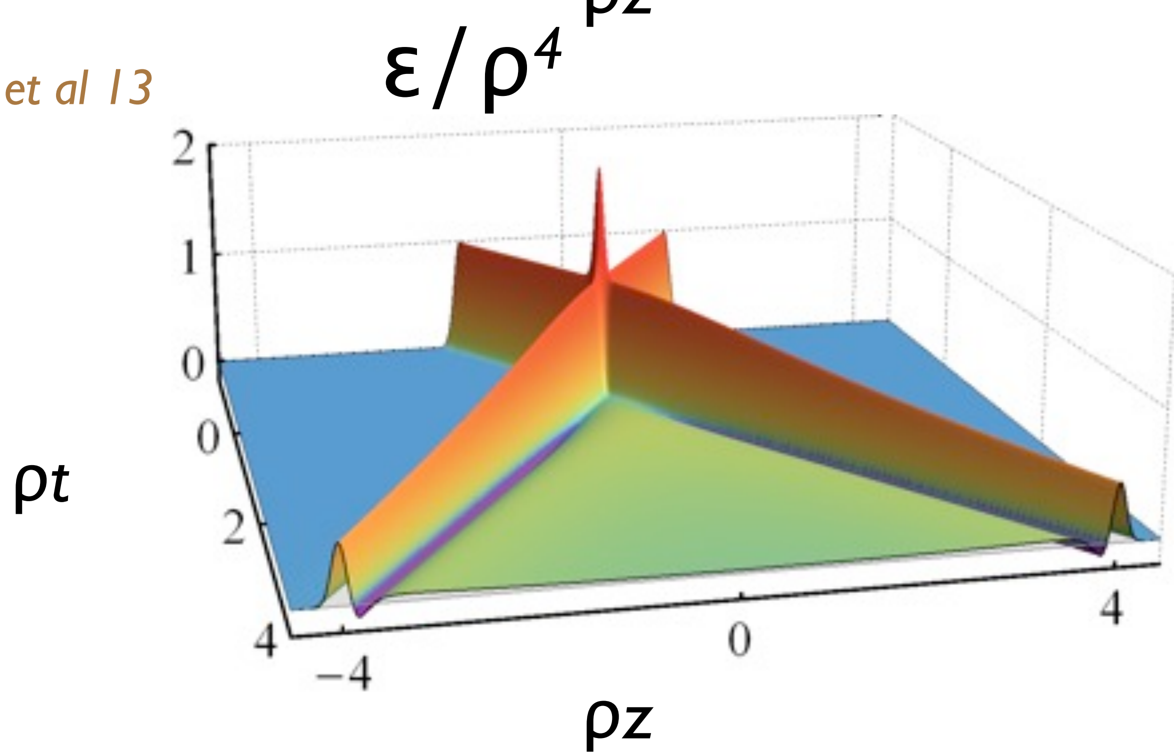

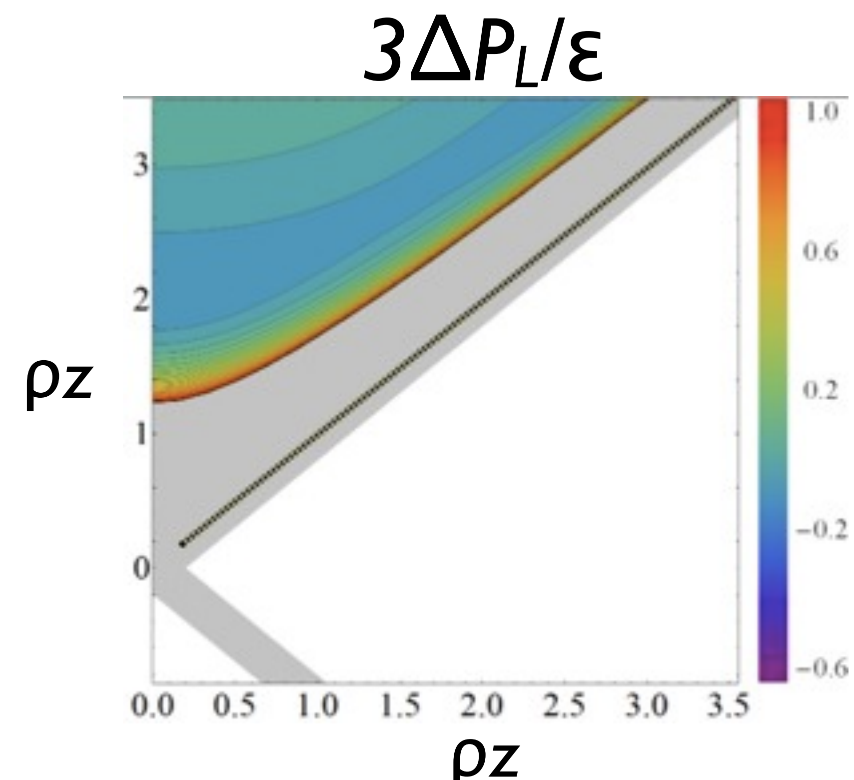

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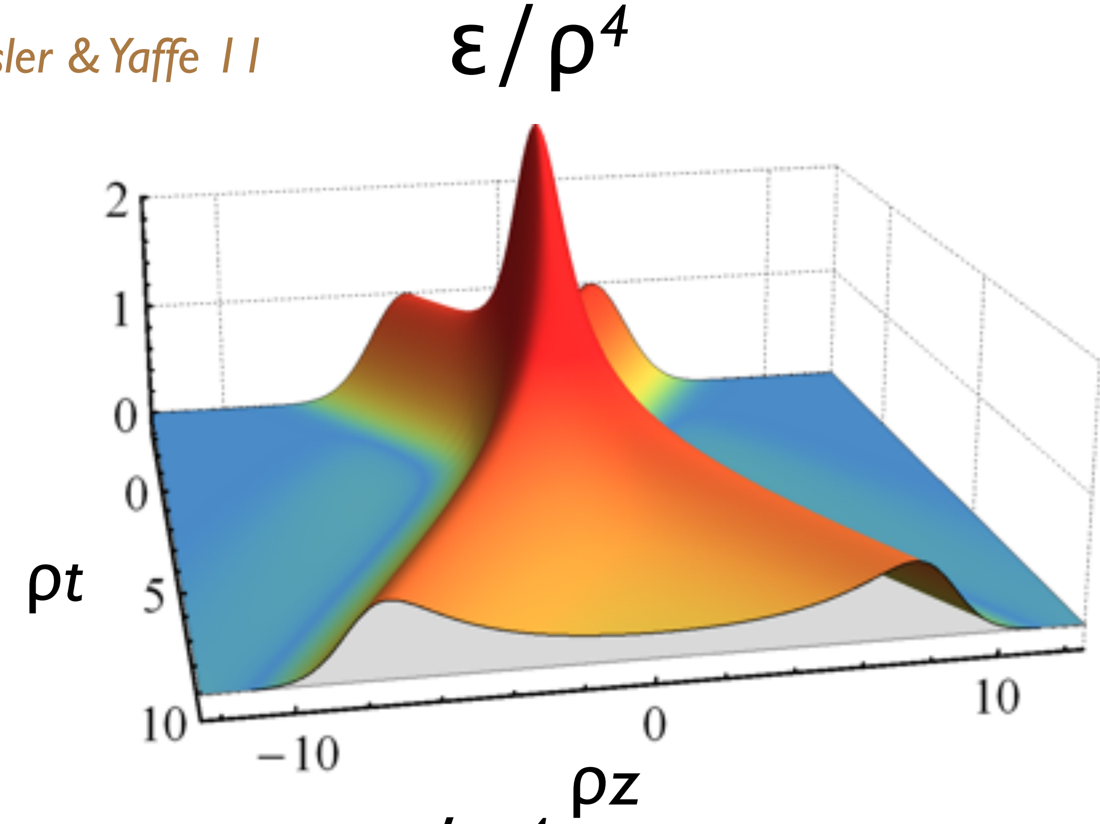

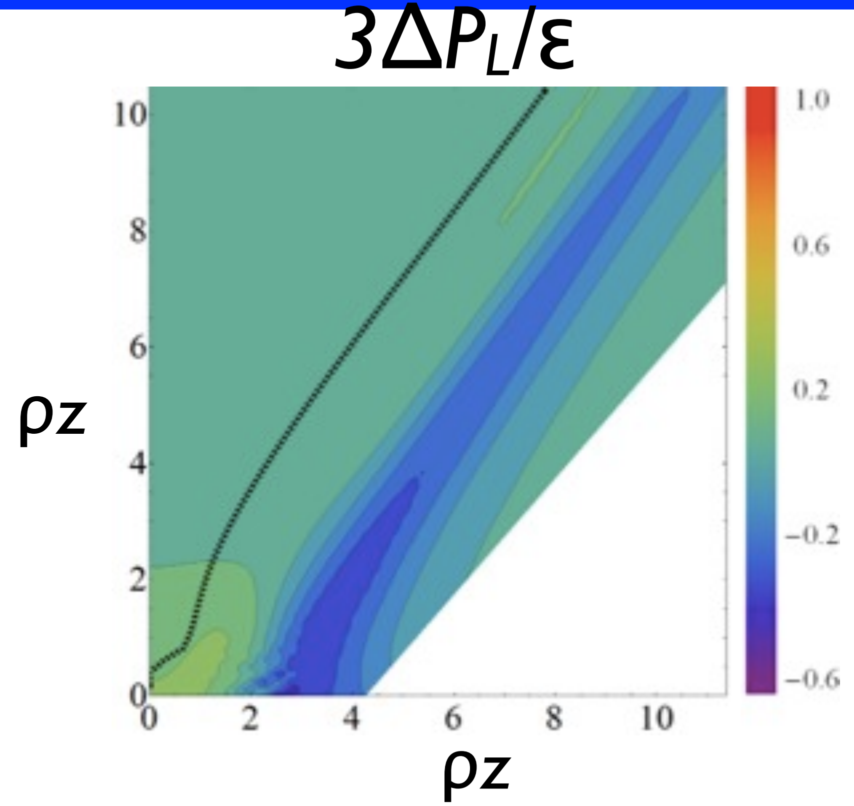

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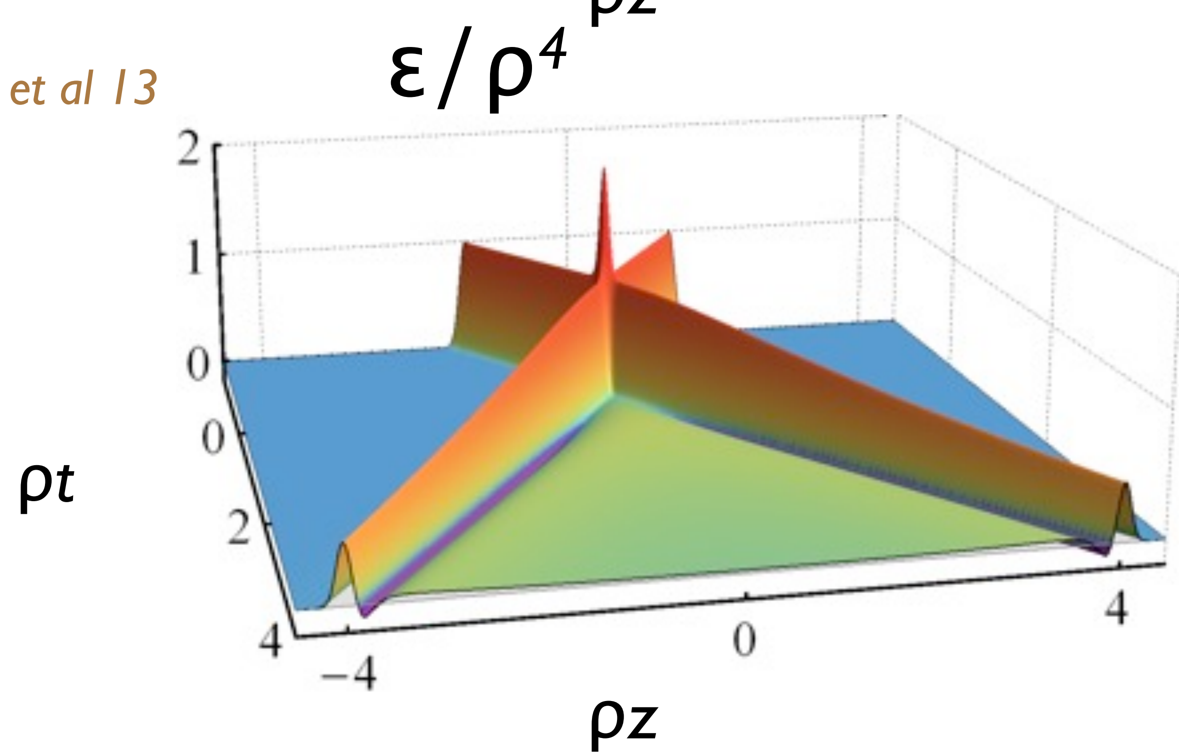
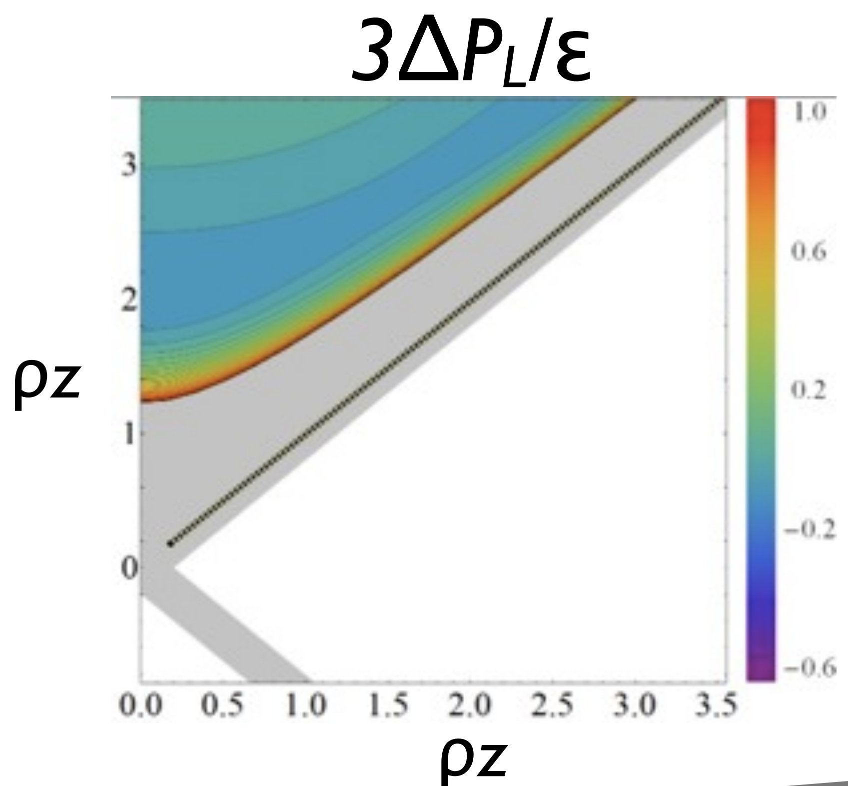
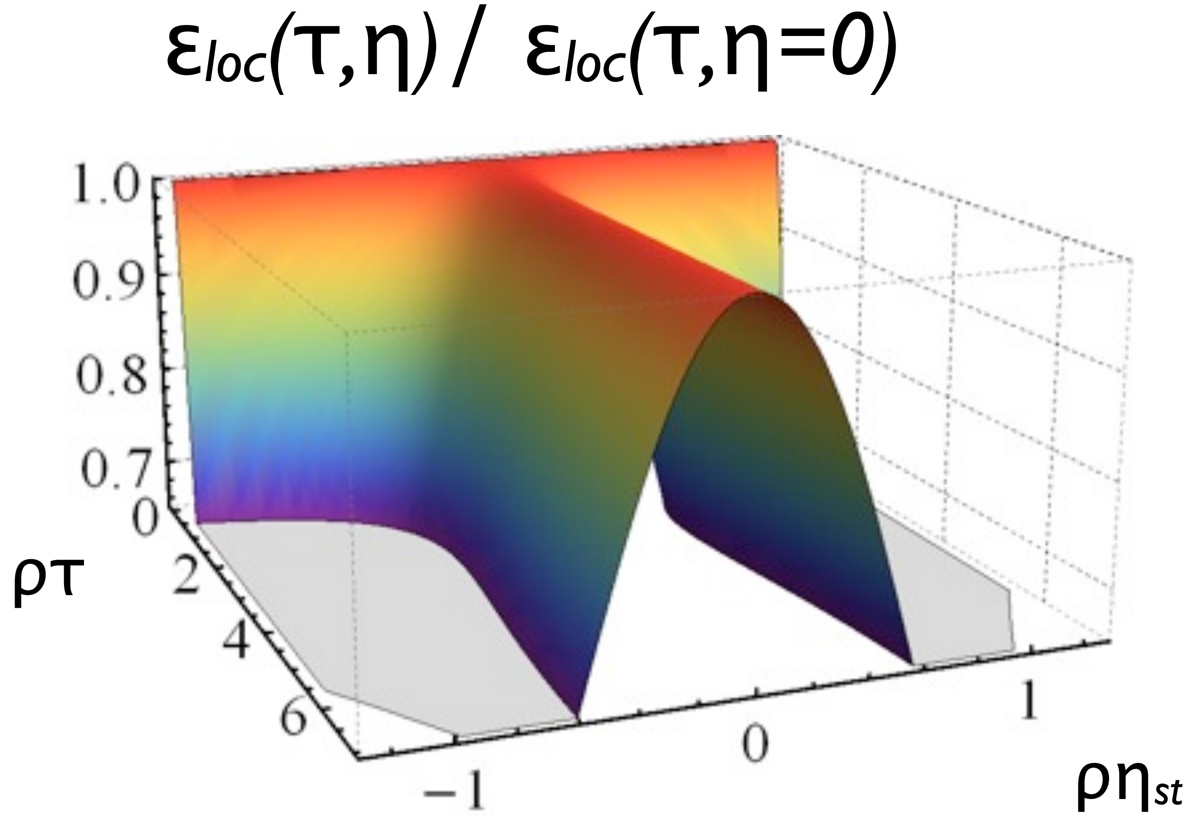
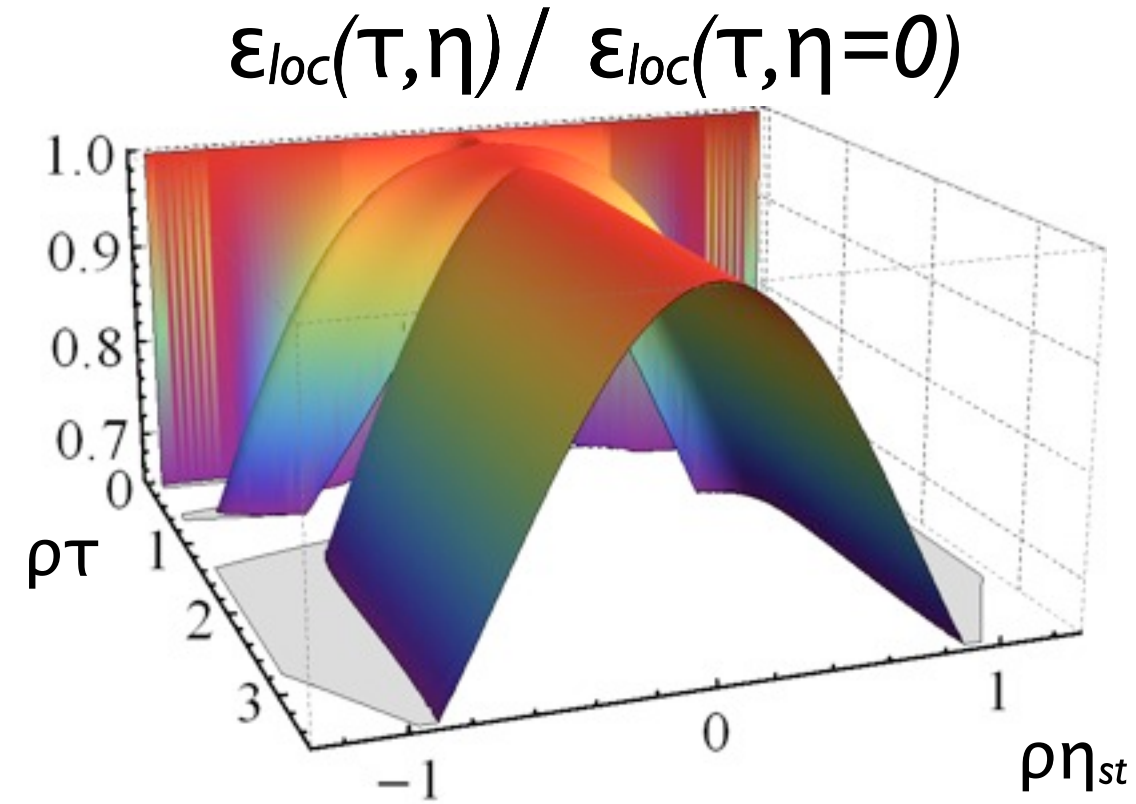




(Albacete, Kovchegov and Taliotis 08, Grumiller & Romatschke 08)

Non-Boost Invariant Initial Conditions





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

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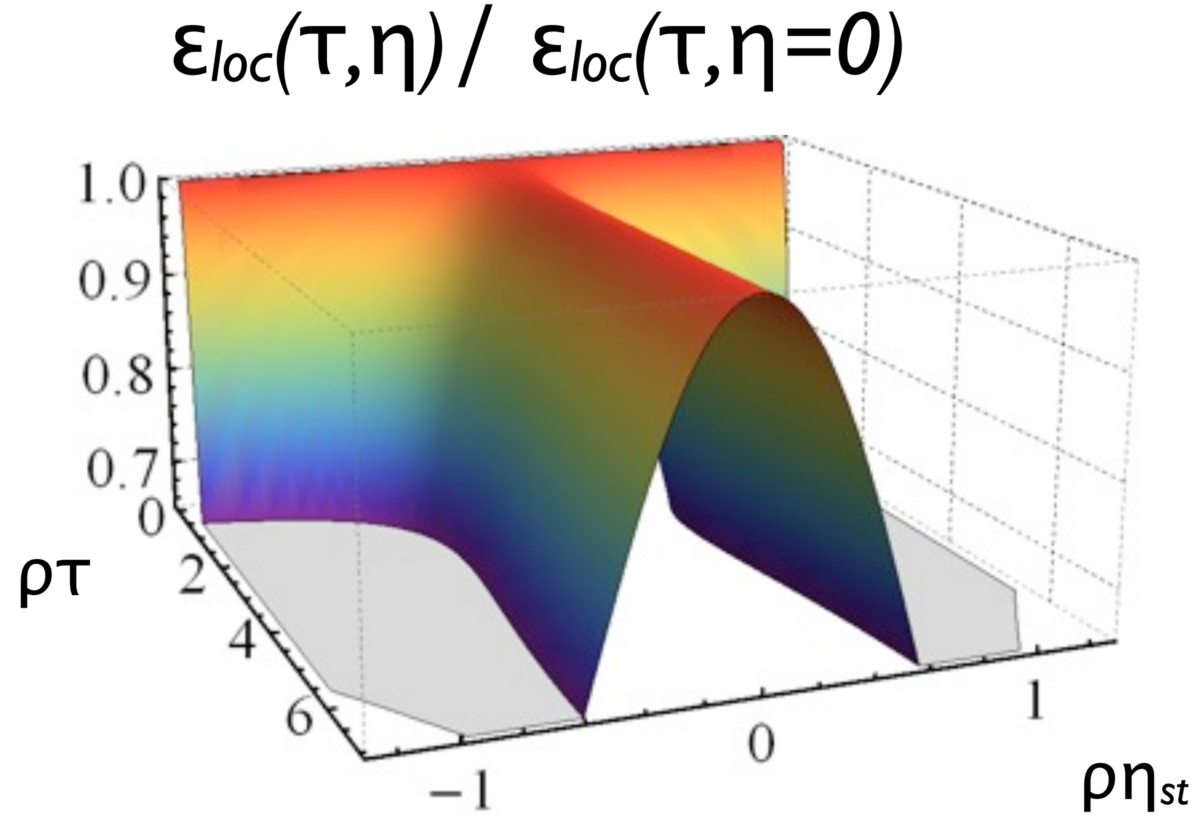

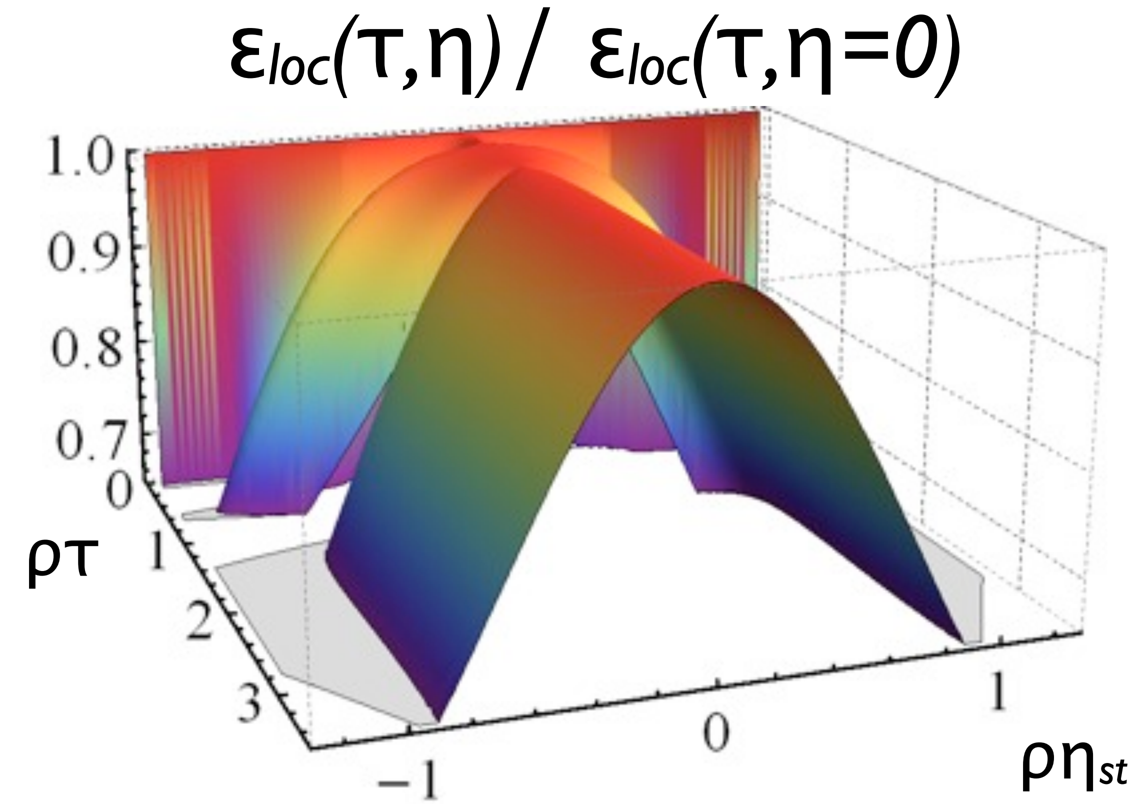

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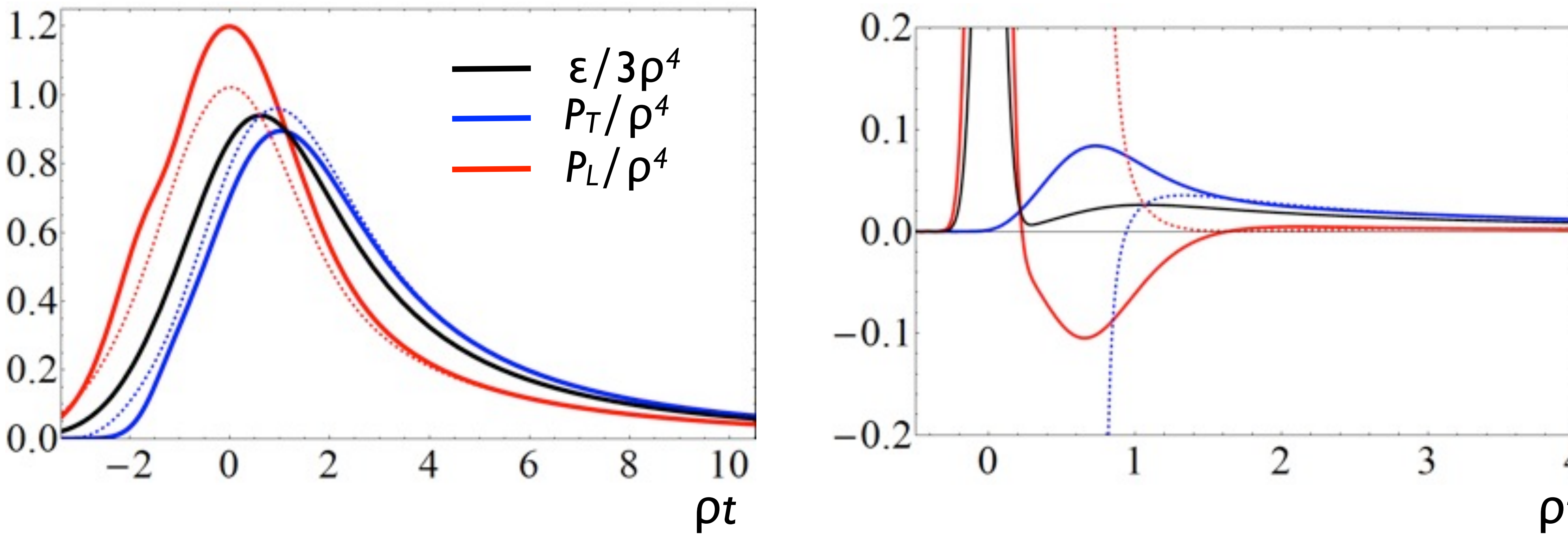
(subsequent time evolution well described by Bjorken like flow)

Chesler & Yaffe 13

Surprisingly Hydrodynamic



- ➤ Good hydrodynamic behavior from very early on
- ➤ Energetic shocks: Plasma develops after $t_{hyd}=1/\pi T_{hyd}$
- ➤ 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

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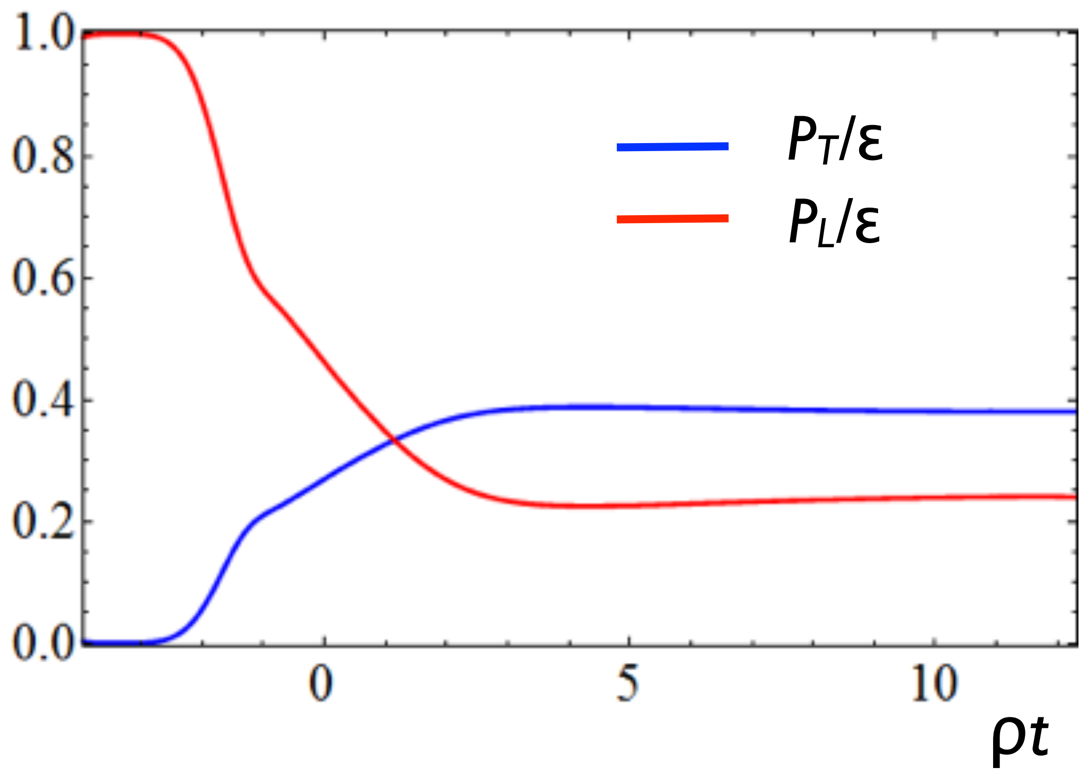

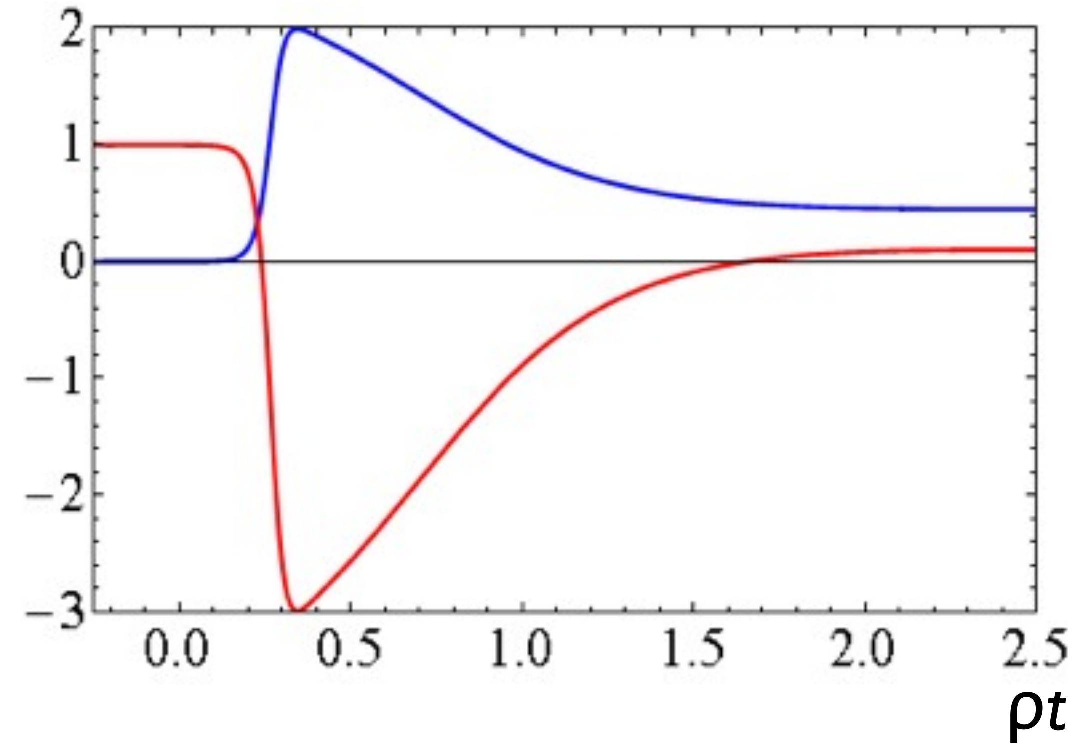

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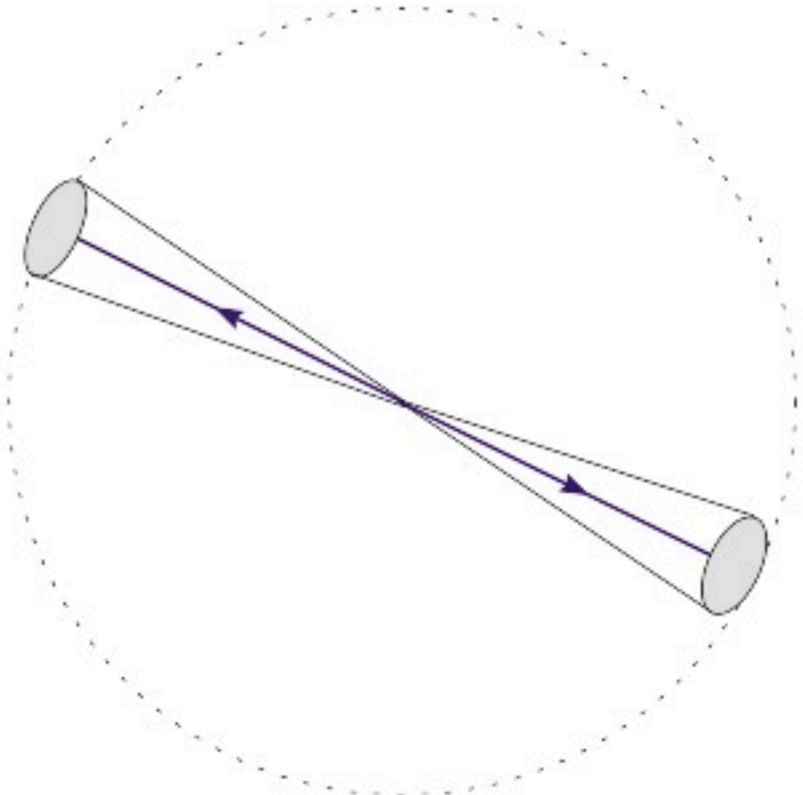
Hard Probes

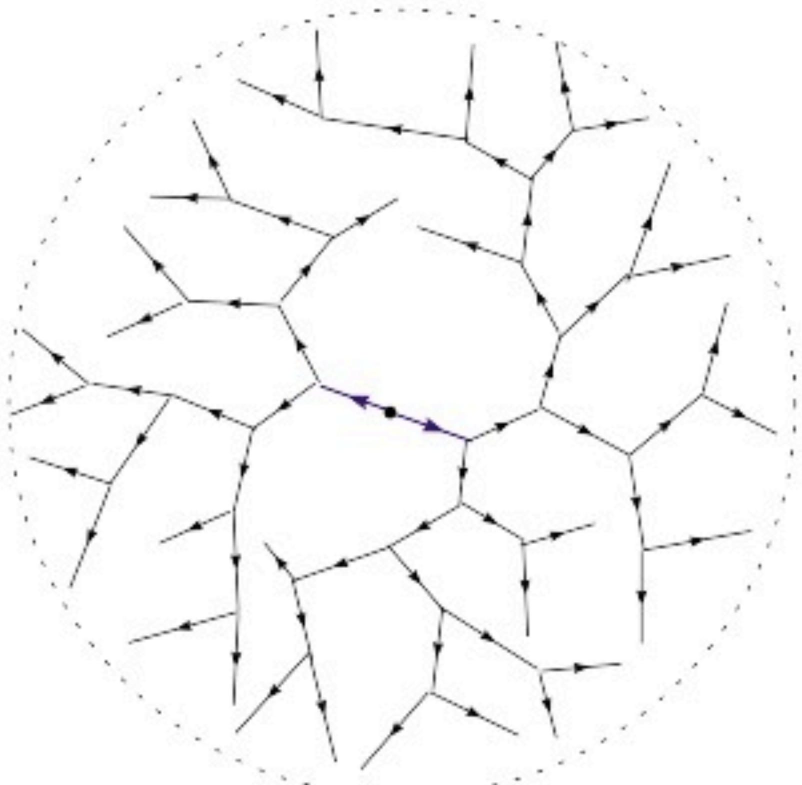
String theory vs Probes

- No jets at strong in N=4 at strong coupling!

Hofman and Maldacena 08
Iancu, Mueller, Hatta 08



weak coupling e+e- decay



strong coupling e+e- decay

- No asymptotic freedom.

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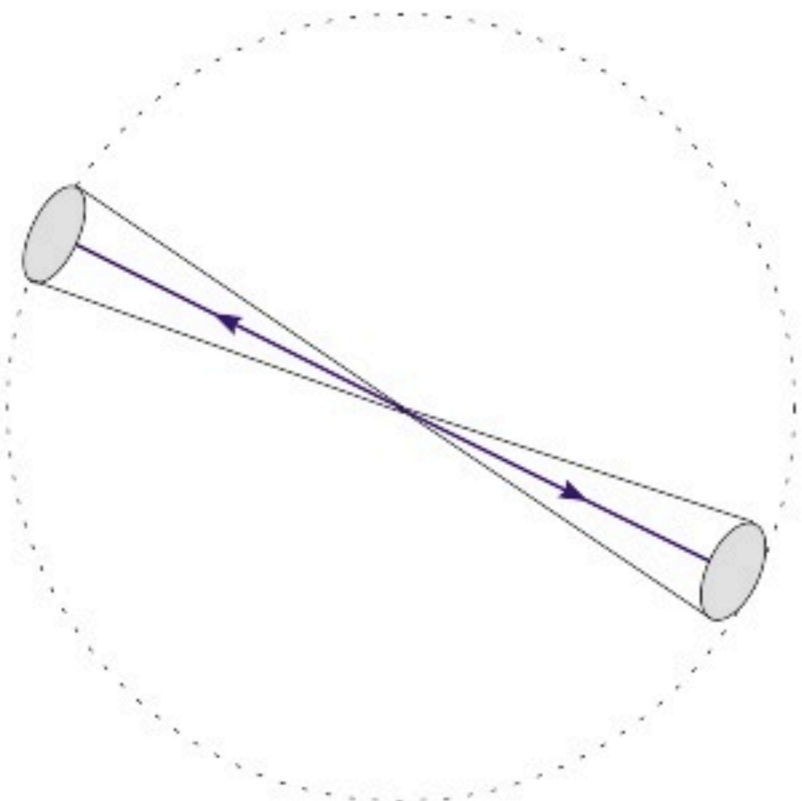
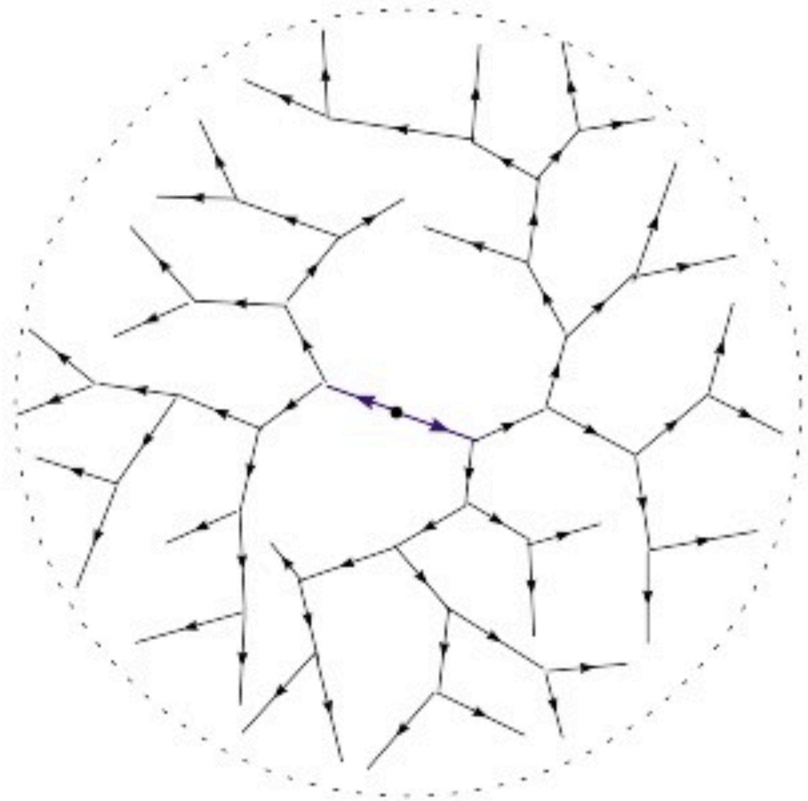


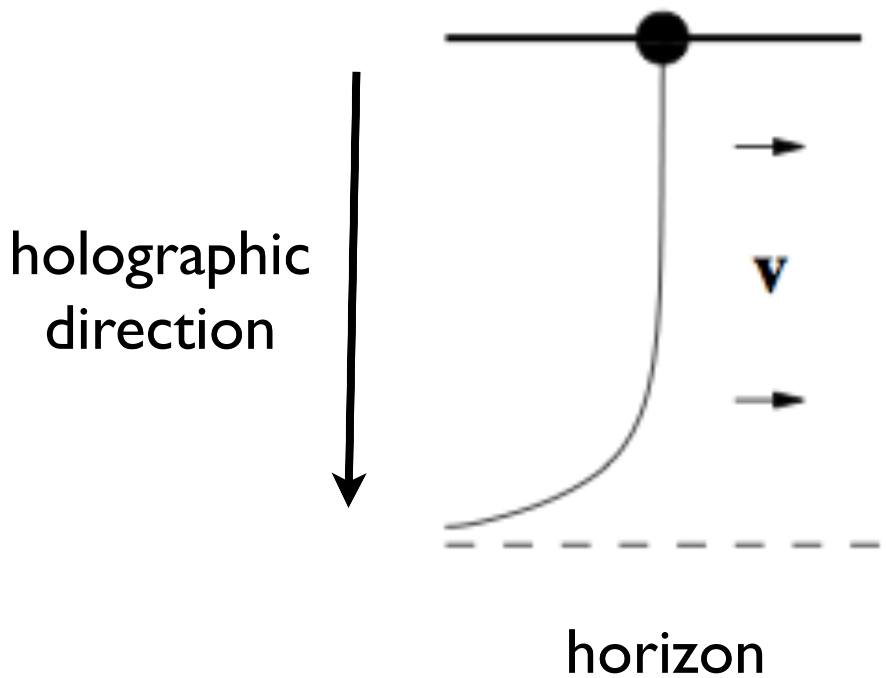
weak coupling e+e- decay



strong coupling e+e- decay

- No asymptotic freedom.
- A serious problem for hard probes

Drag Force



$$\frac{dp}{dt} = -\frac{\pi\sqrt{\lambda}T^2}{2M}p$$

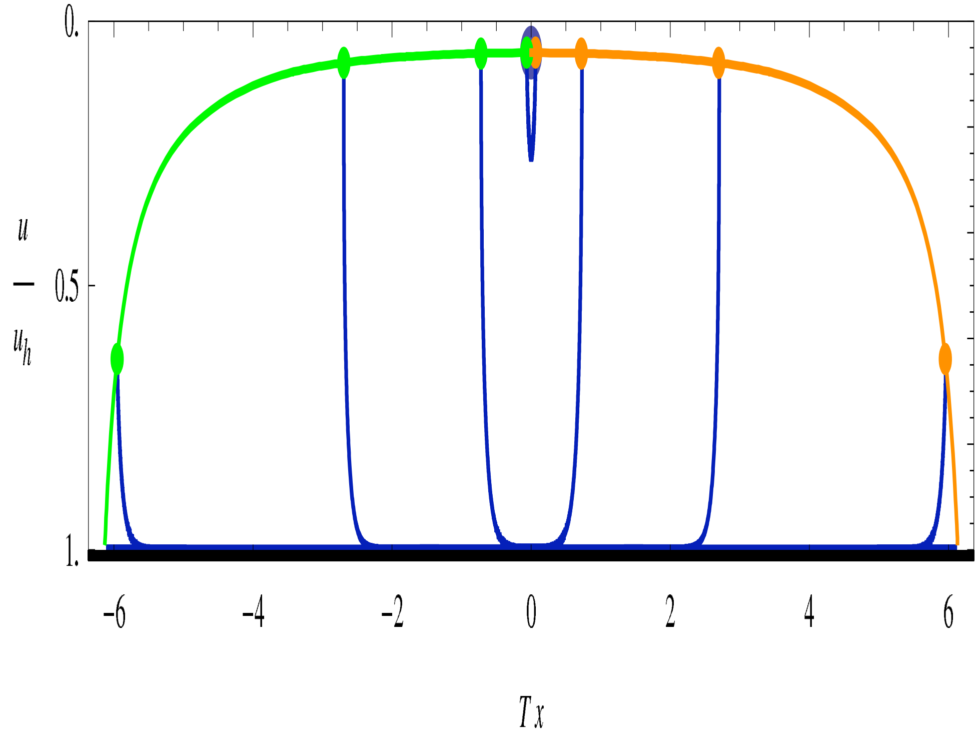
JCS an Teaney 06
Herzog et al. 06
Gubser 06

- ➤ Drag-like formula even for relativistic heavy quarks
- ➤ Sensitive to all scales

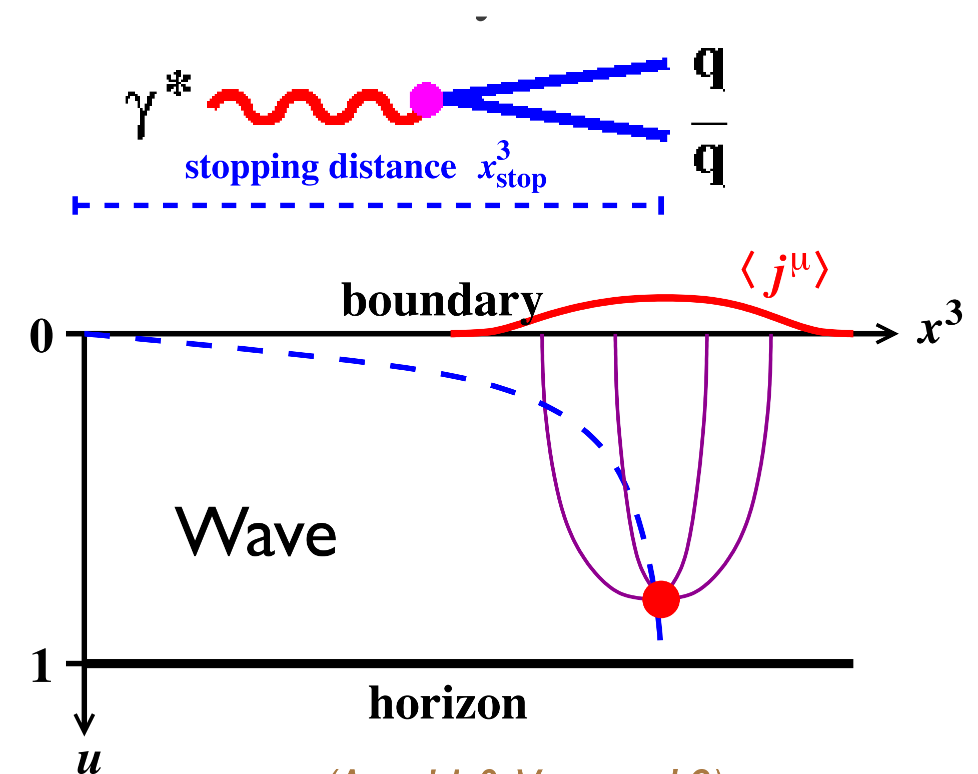
Light quark E-loss

Q-Qbar pair: string

(Chesler, Jensen, Karch, Yaffe 08)



Boosted virtual photon



(Arnold & Vaman 10)

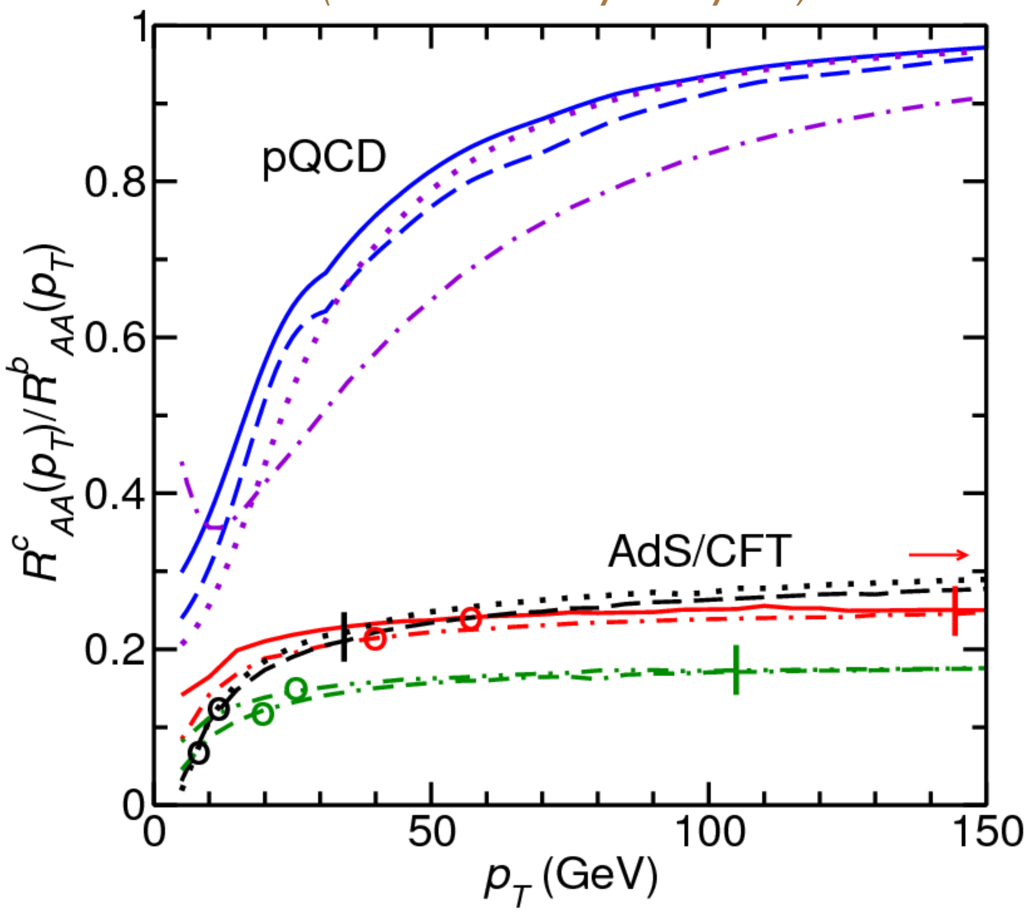
$$x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}}\,\frac{E_{\rm in}^{1/3}}{T^{4/3}}$$

$$\kappa_{\rm sc} \;=\; 1.05\,\lambda^{1/6},$$

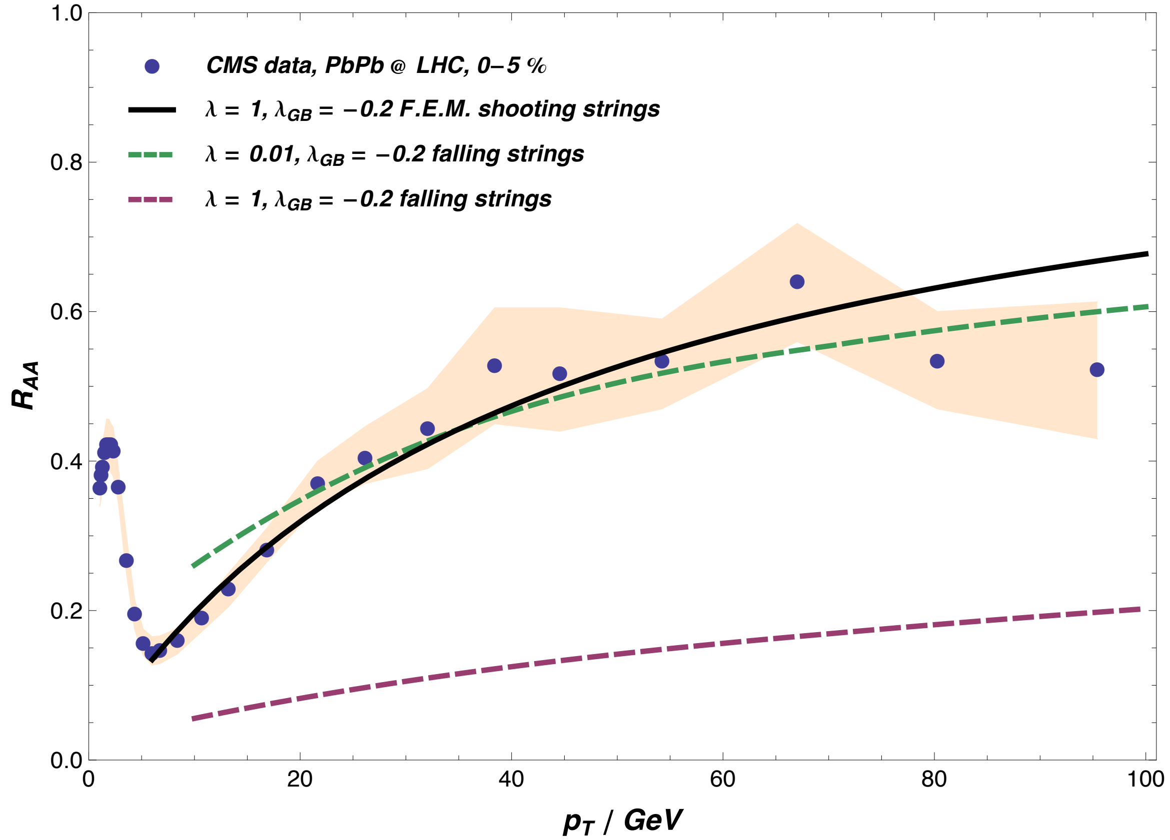
$$\kappa_{\rm SC} \propto \lambda^0$$

Straight - Forward approaches

(Horowitz & Gylassy 07)



(Ficnar, Gubser & Gylassy 13)



➤ Strong mass dependence of quenching (recently disproved by cms)

➤ Direct fits demand small values of λ (string computations)

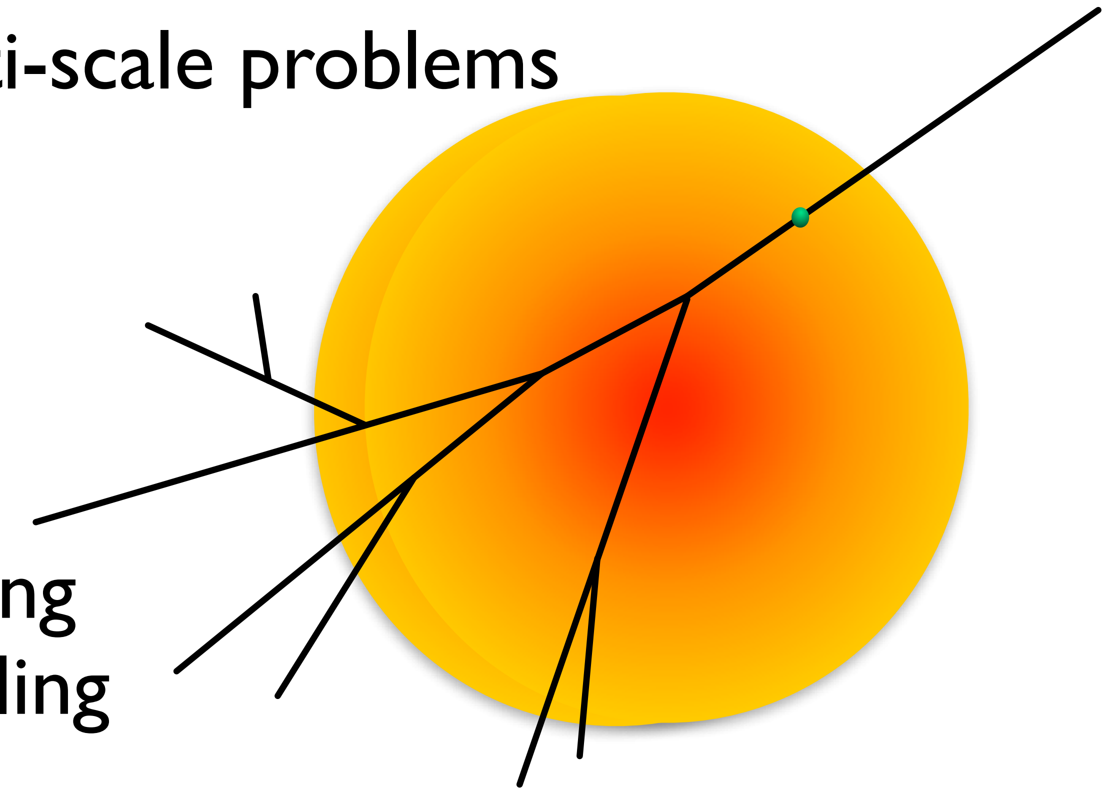
fixed by more complicated construction

➤ Contaminated from not asymptotic freedom at high scales

Towards a Hybrid model

- Jet interaction with medium is a multi-scale problems
  - ➤ Hard production (perturbative)
  - ➤ Hard evolutions (perturbative)
  - ➤ Exchanges at medium scale
  - ➤ Soft jet fragments

} strong coupling



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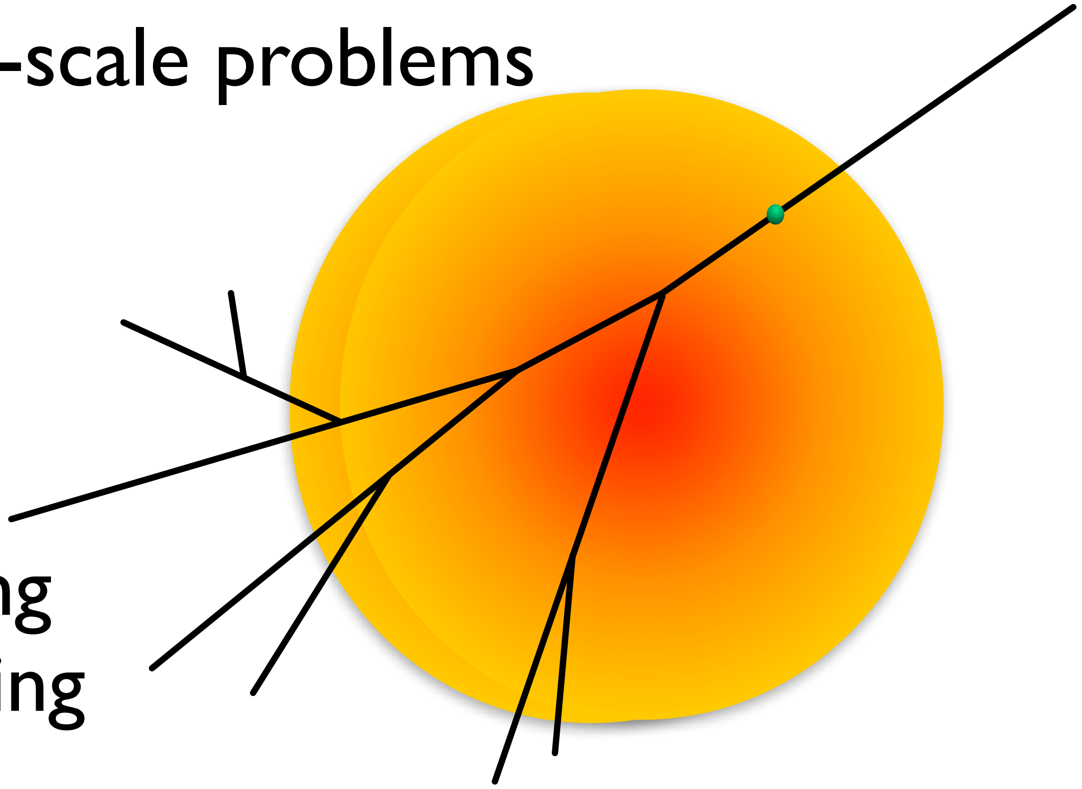

JCS, Gulhan, Milhano, Pablos and Rajagopal 2014

- Simple (and phenomenological) approach
  - ➤ Leave jet evolution unmodified (Q>>T)
  - ➤ Each in-medium parton losses energy (not necessarily perturbative)
  - ➤ Neglect in-medium radiation (first approximation)

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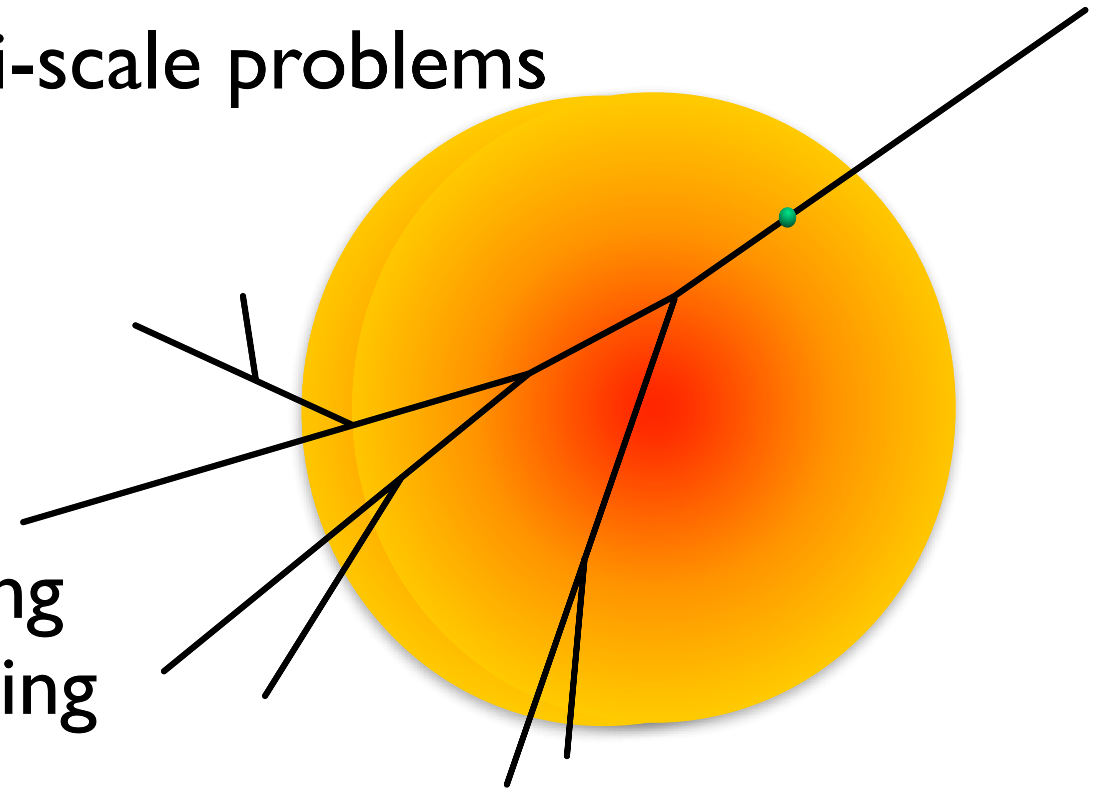


JCS, Gulhan, Milhano, Pablos and Rajagopal 2014

- Simple (and phenomenological) approach
  - ➤ Leave jet evolution unmodified (Q>>T)
  - ➤ Each in-medium parton losses energy (not necessarily perturbative)
  - ➤ Neglect in-medium radiation (first approximation)
- Not the only hybrid prescription:
  - ➤ Modify medium induced radiation $L^2 \to L^3$ (ASW-AdS/CFT)

Renk & Marquet 09

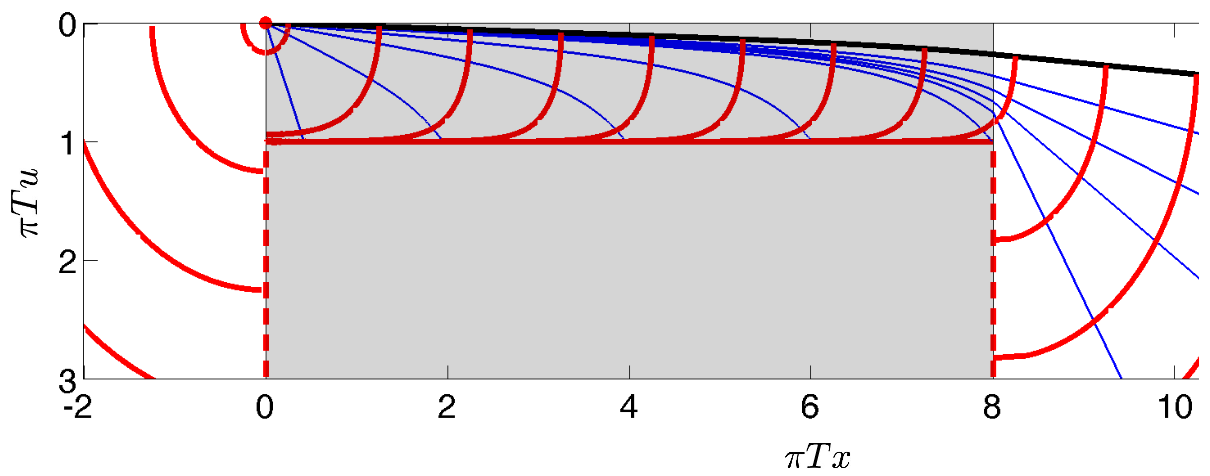
Energy Loss

- Energy loss of light quarks crossing a slab of plasma

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{\rm stop}^2}\frac{1}{\sqrt{x_{\rm stop}^2 - x^2}}$$

$$x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}}\frac{E_{\rm in}^{1/3}}{T^{4/3}}\,,$$

Chesler and Rajagopal ArXiv:14026746

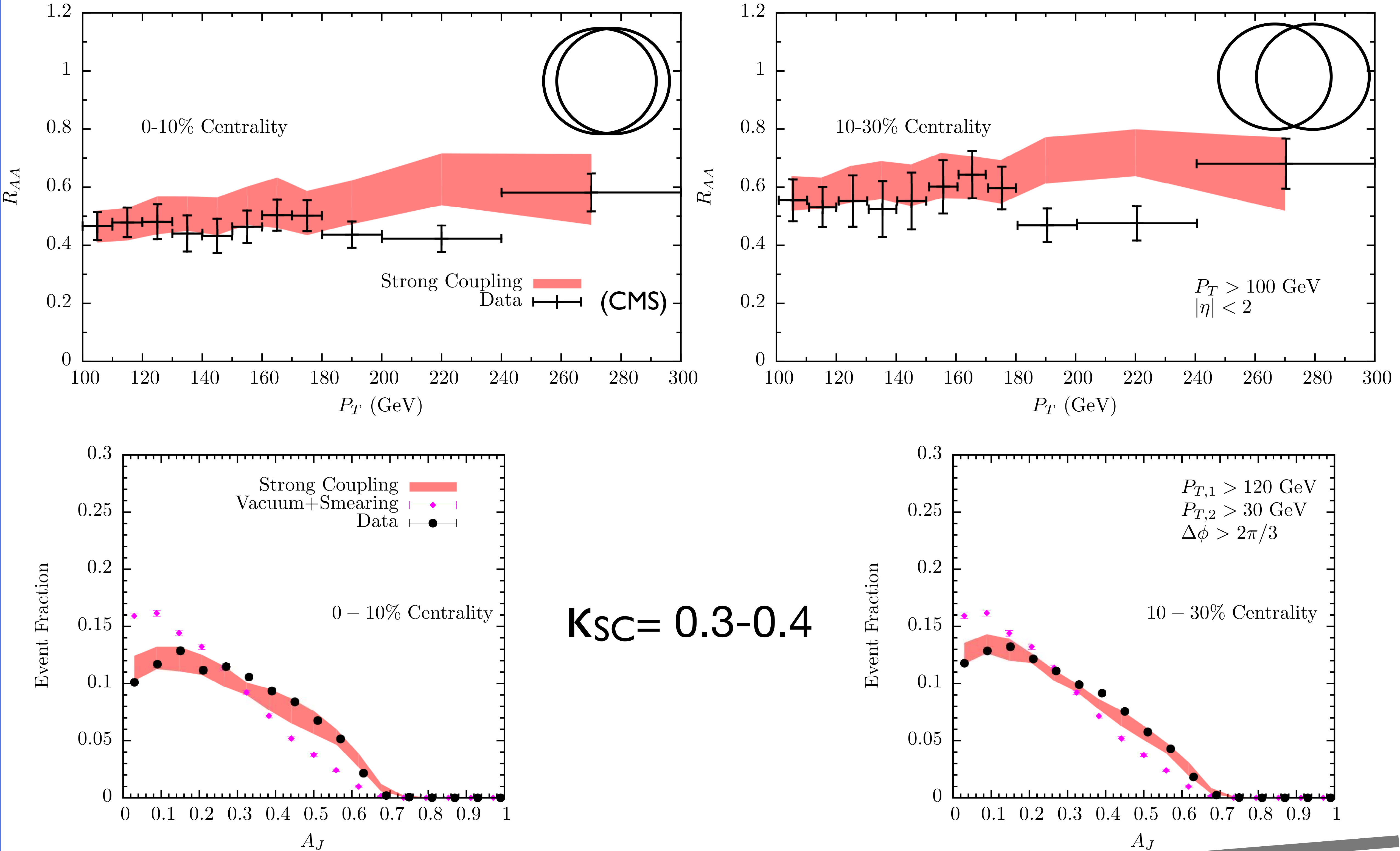


- κ_{SC} is not robust
  - ➤ $\kappa_{SC}\sim\lambda^{1/6}$ ($\lambda\sim g^2 N_c$) in string computations
    Gubser et al 08, Chesler et al. 08, Ficnar and Gubser 13, Chesler & Rajagopal 14
  - ➤ $\kappa_{SC}\sim\lambda^{0}$ ($\lambda\sim g^2 N_c$) in U(1) field decays
    Hatta, Iancu and Mueller 08, Arnold & Vaman 10

} order one (λ ~ 10)

- We use κ_{SC} as a fitting parameter

Confronting data

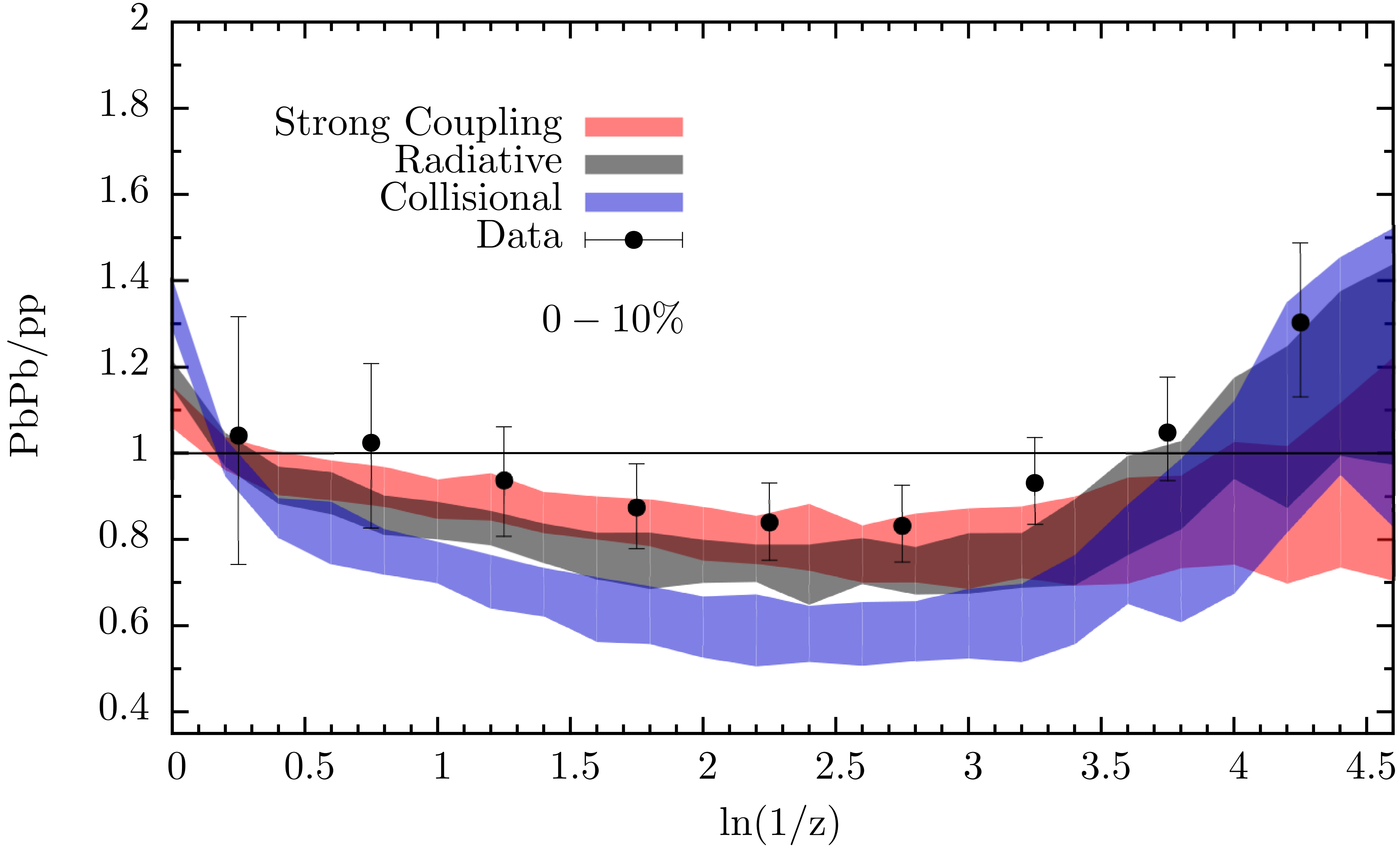


K_{SC}= 0.3-0.4

JCS, Gulhan, Milhano, Pablos and Rajagopal 2014

FF

JCS, Gulhan, Milhano, Pablos and Rajagopal
2014



Radiative $\frac{dE}{dx} \propto L$

Simplified control models

Collisional $\frac{dE}{dx} \propto L^0$

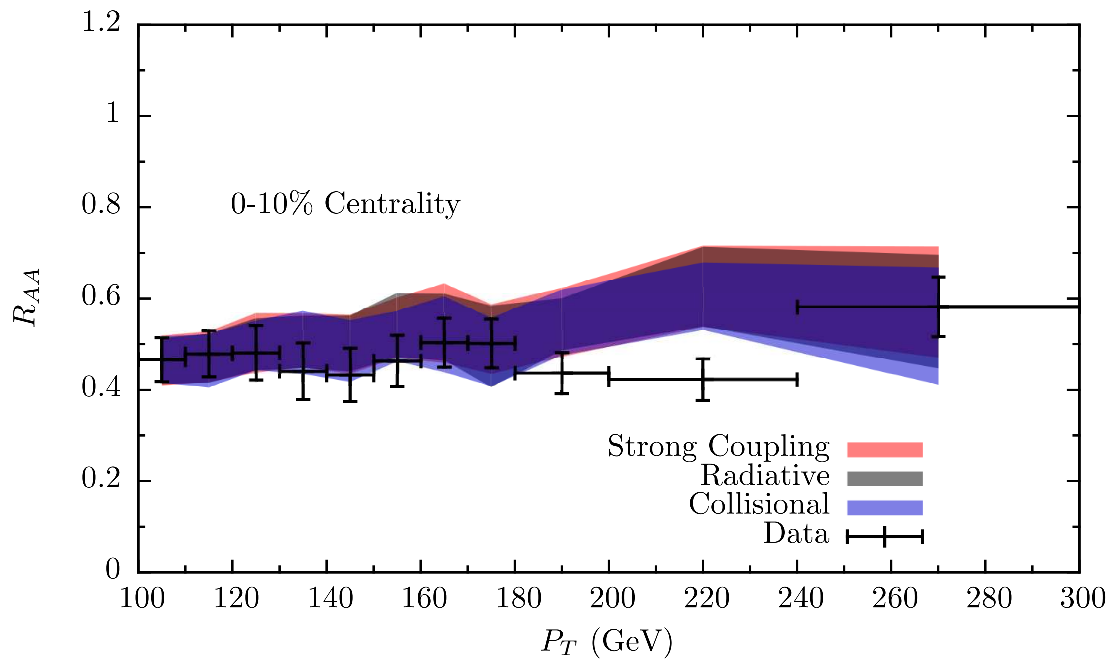
Conclussions

- Gauge/gravity duality provides a theoretical laboratory

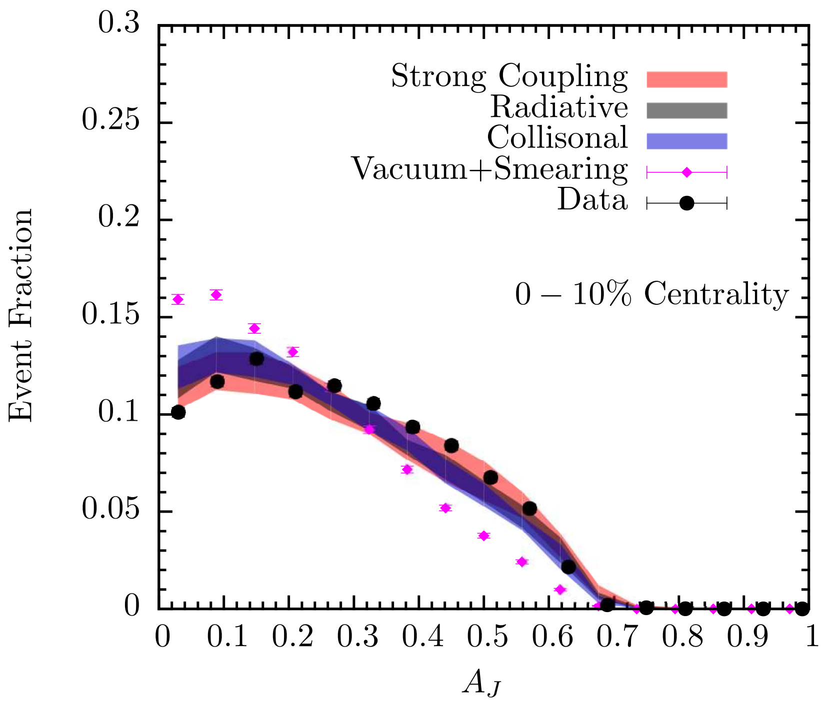
  How does a plasma with no quasiparticles behave?

- It gives us information of physics at scale T
  - ➤ Transport coefficients
  - ➤ Hydrodynamization
- Connection with hard probes is complicated
  - ➤ Some promising results
  - ➤ We need to search direct signals of quasi-particle (absence)

Back-up

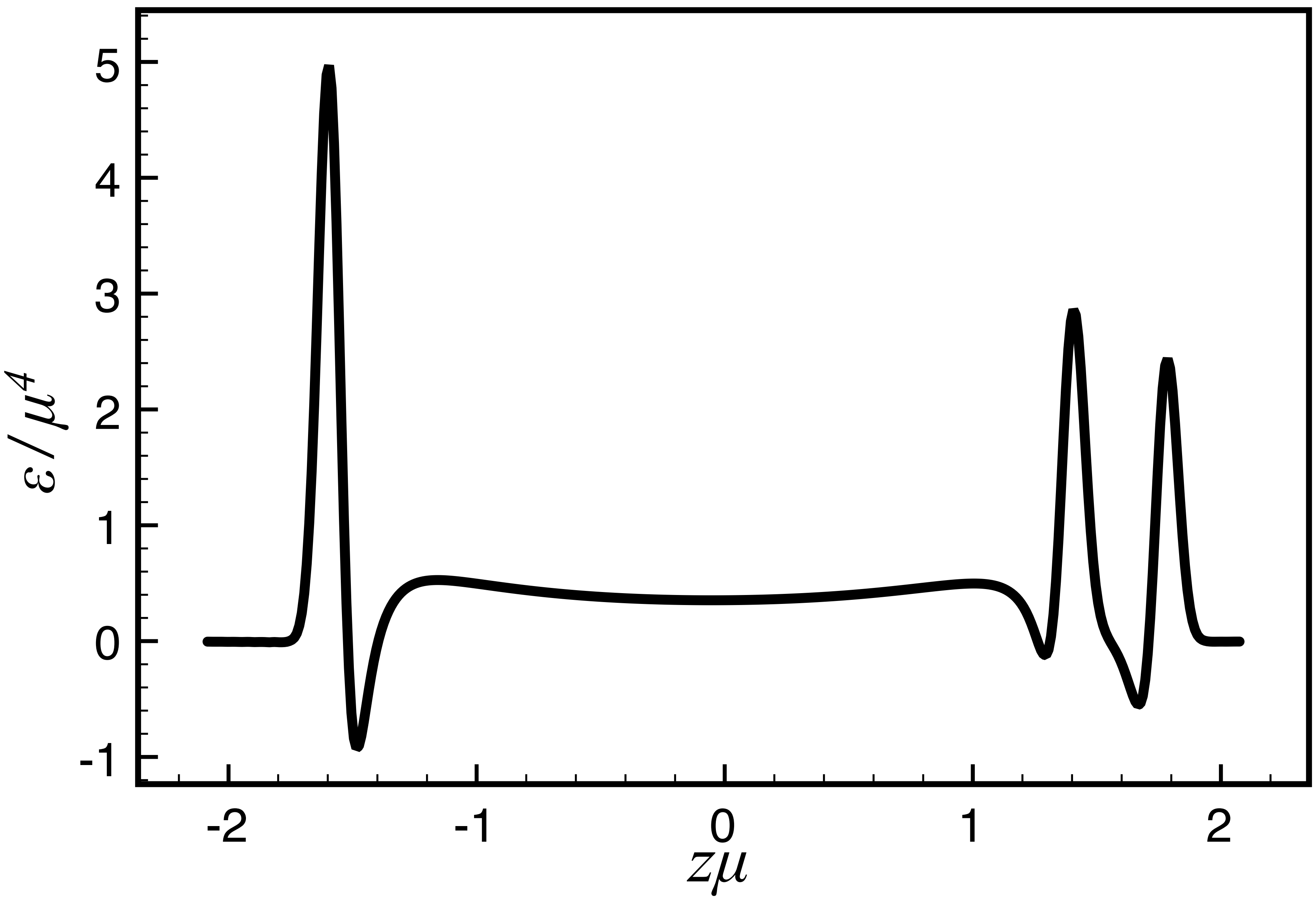


0-10% Centrality
Strong Coupling
Radiative
Collisional
Data
R_{AA}
P_T (GeV)



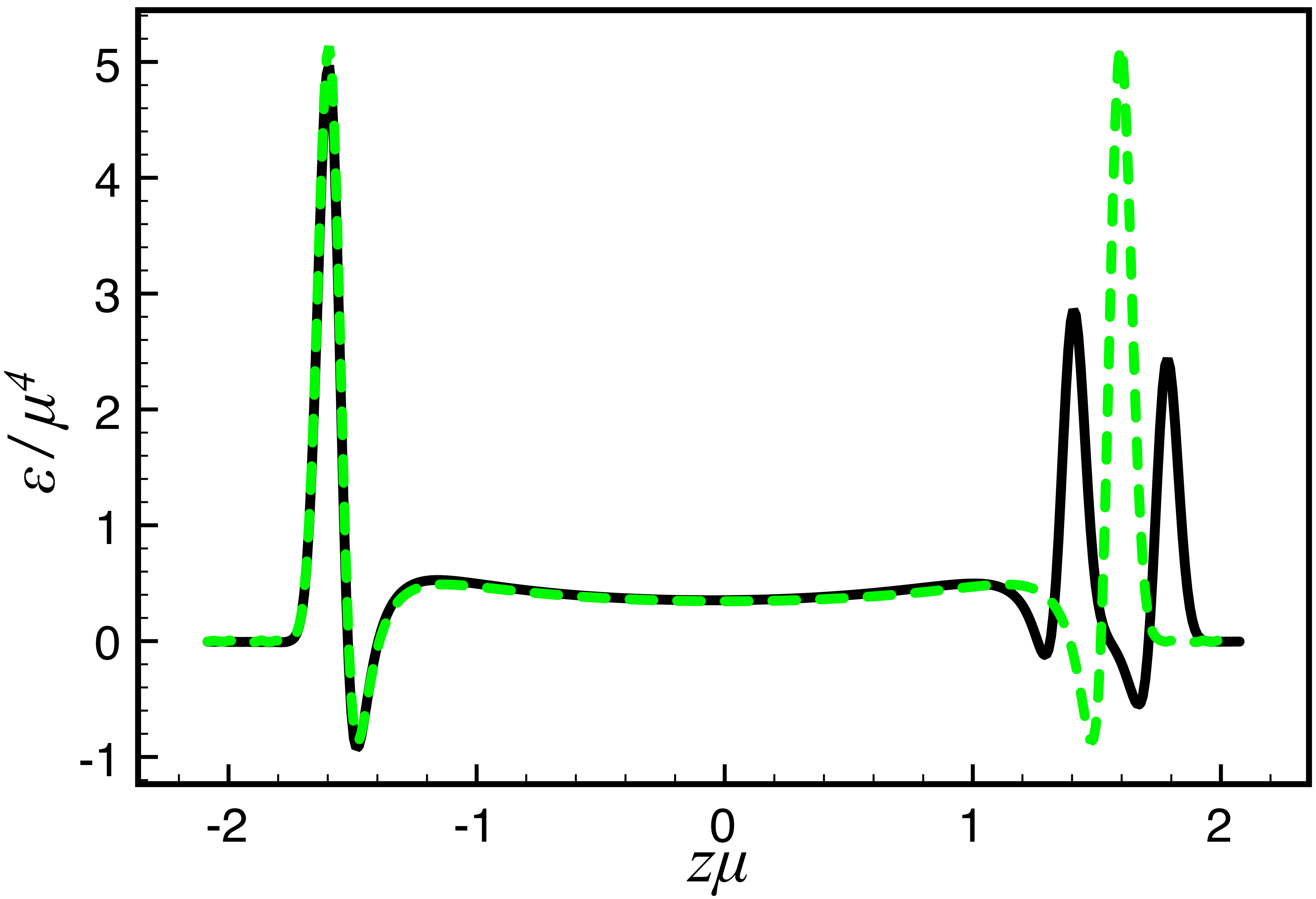
Strong Coupling
Radiative
Collisonal
Vacuum+Smearing
Data
0 – 10% Centrality
Event Fraction
A_J

Towards p-A: Longitudinal Coherence



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

Towards p-A: Longitudinal Coherence



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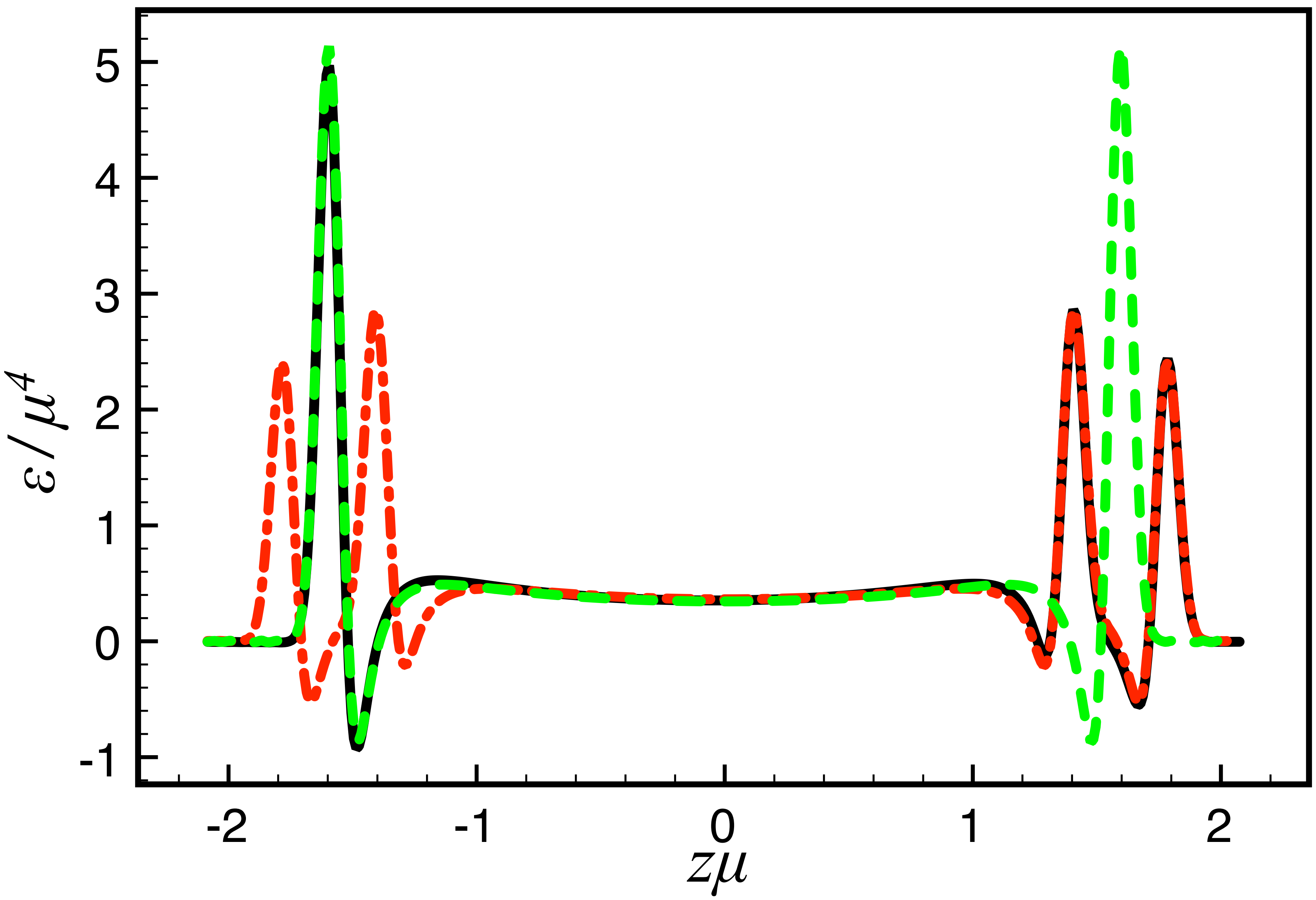

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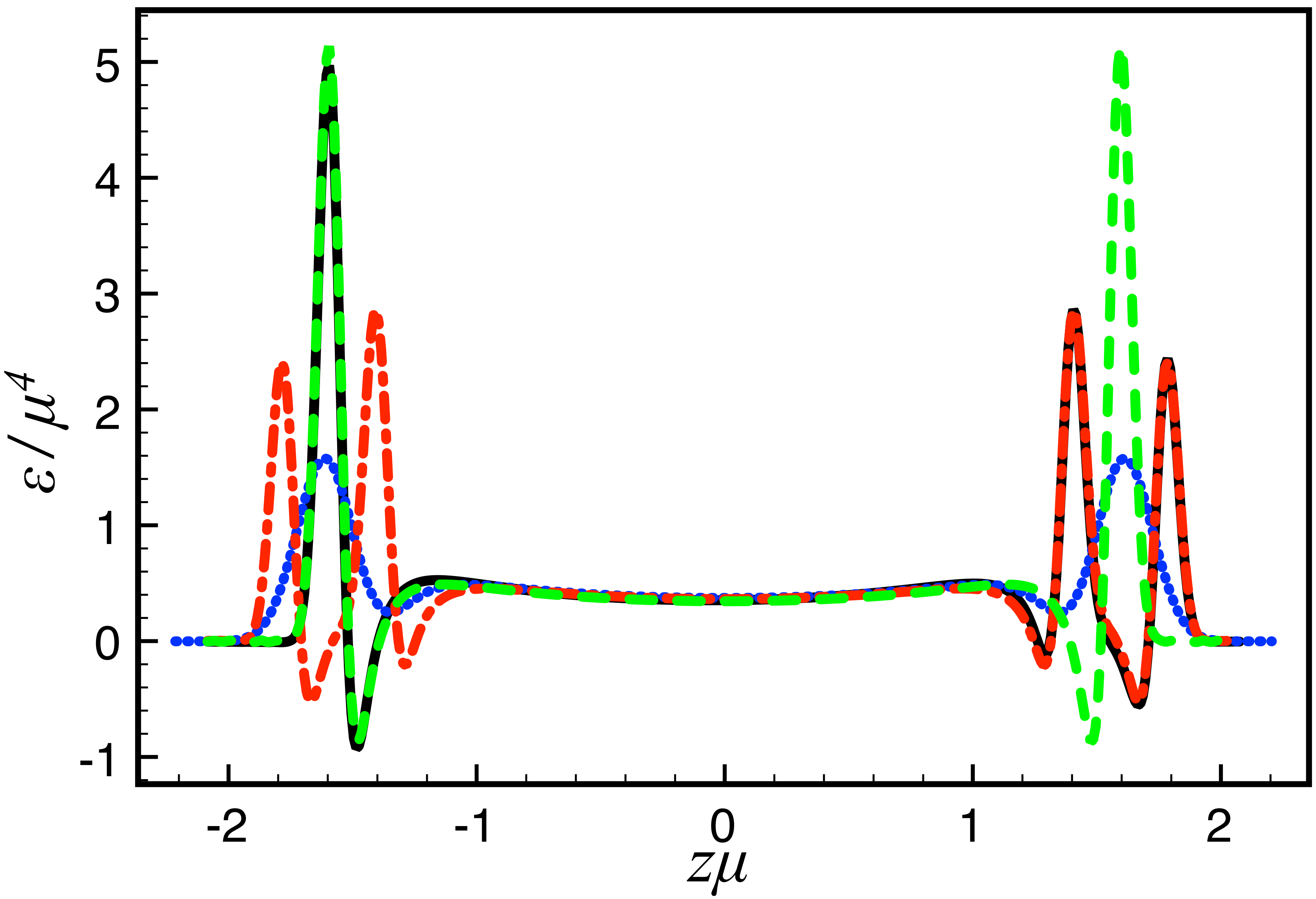
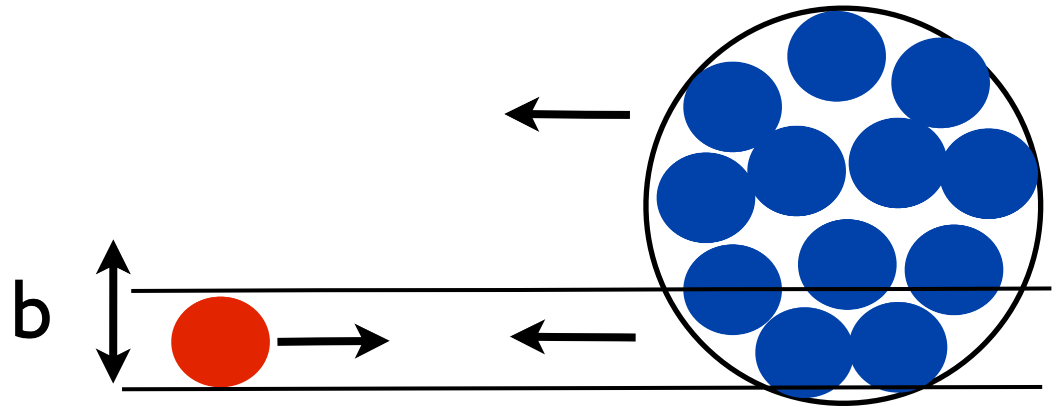
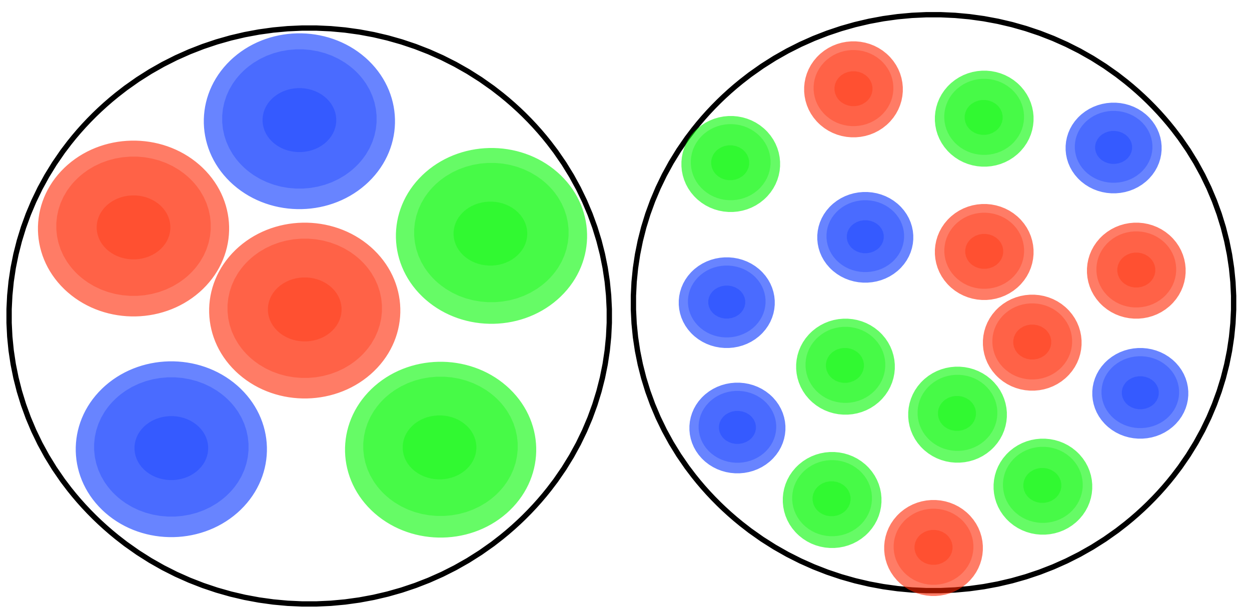


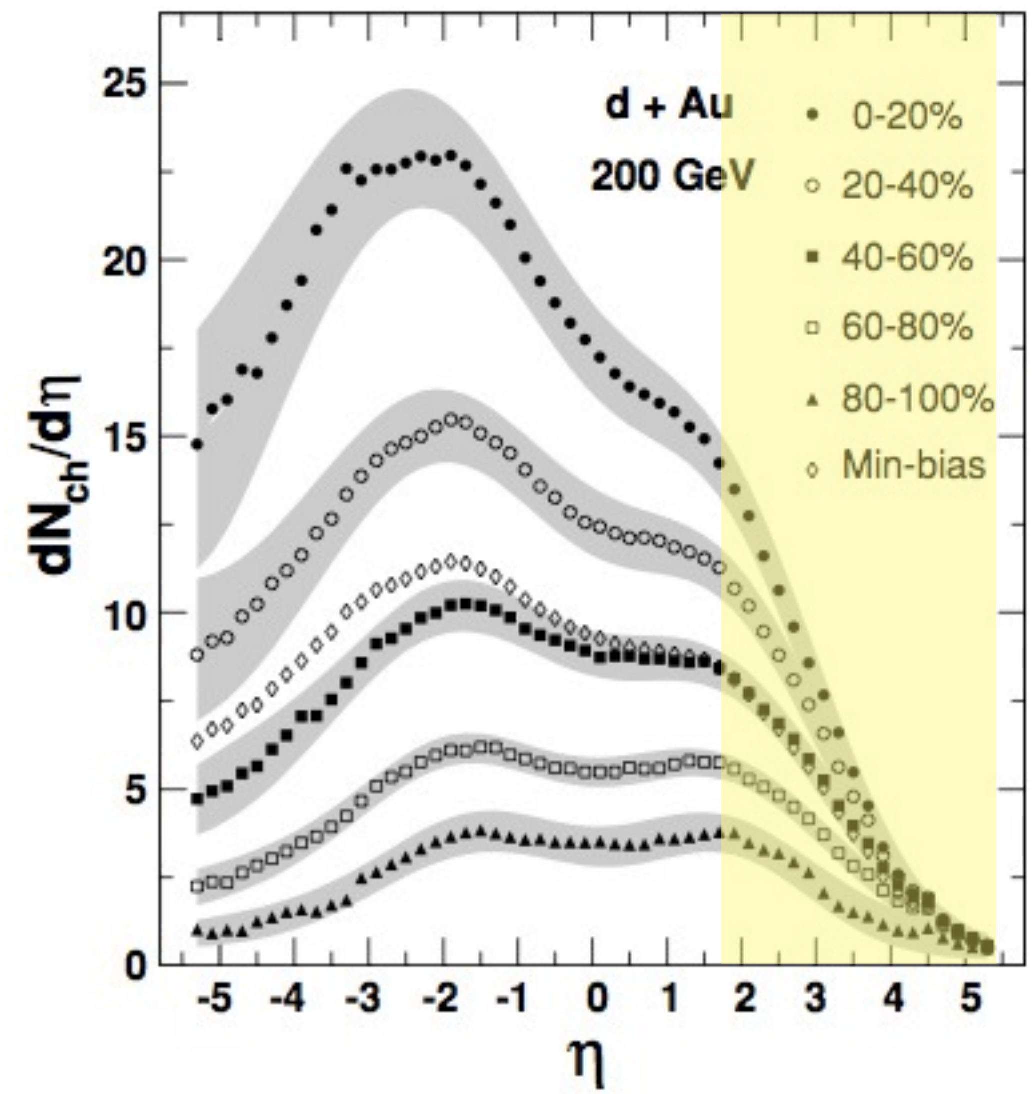
- In the center of mass of the "nucleus-nucleon" collision
  - Midd rapidity region independent of collision system
  - Maximum at y=0 and symmetric w.r.t center of mass

The Weak Coupling Picture



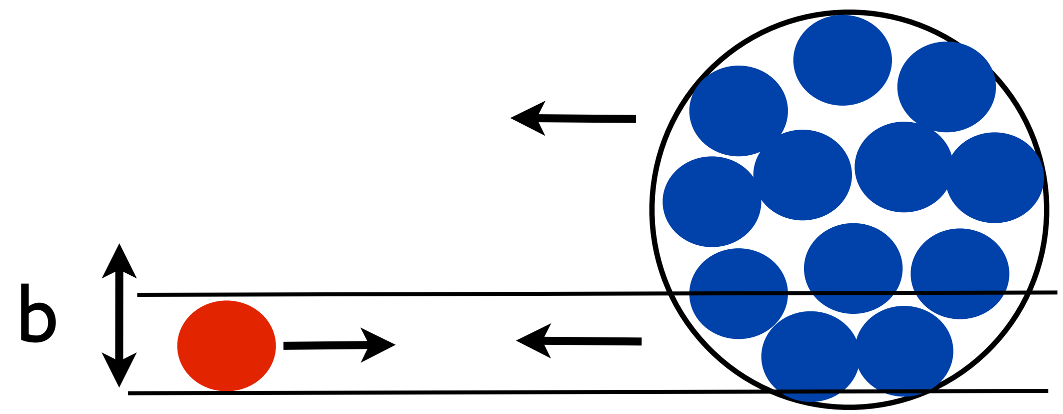


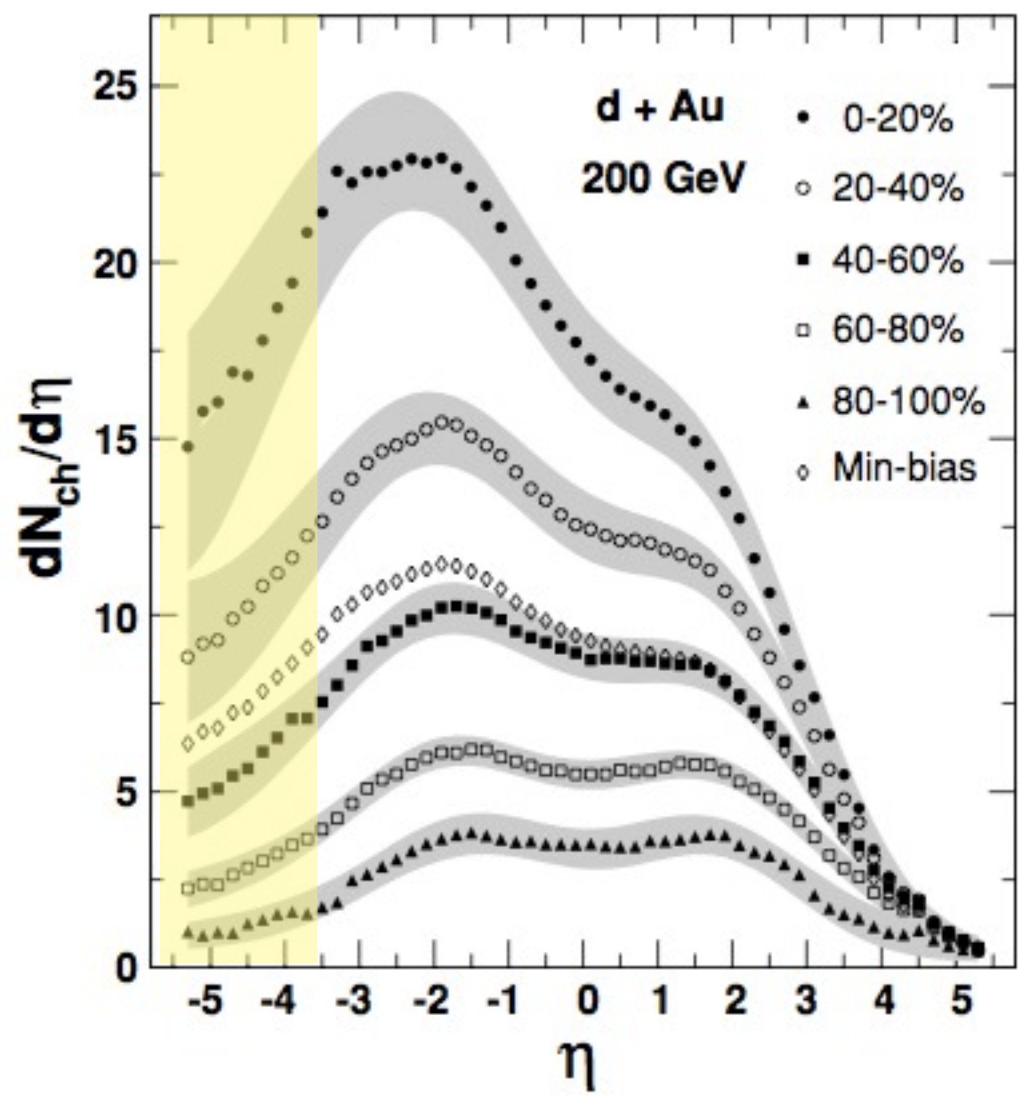
$Q^2_s(A)$ $\quad$ $Q^2_s(B)$

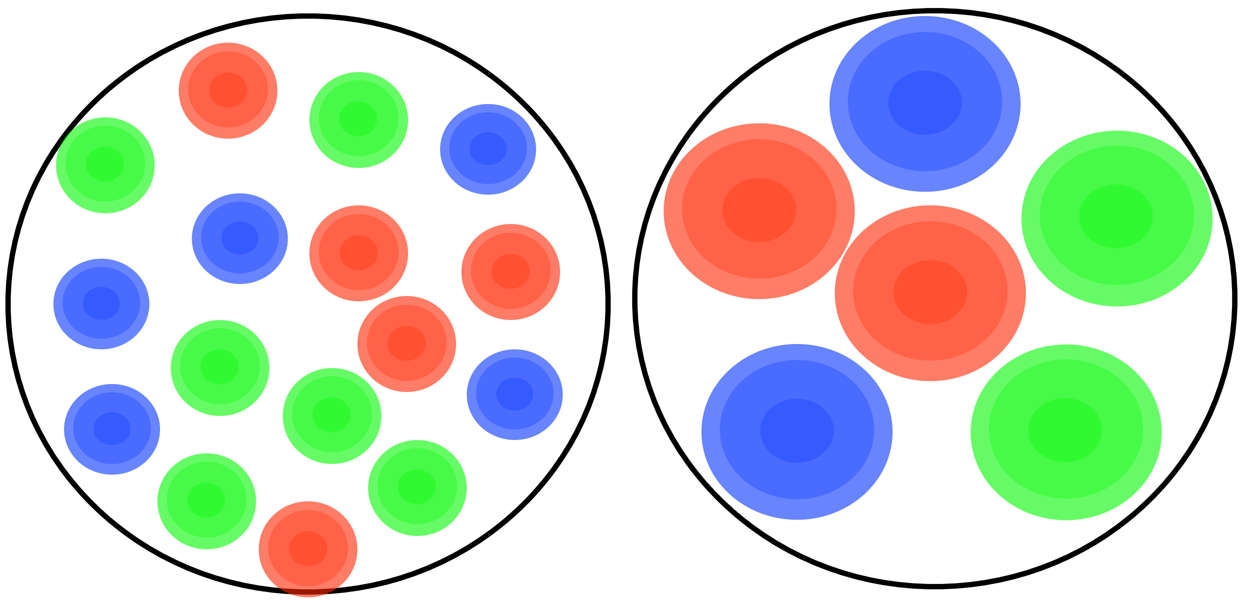


$$\frac{dN}{dy} \propto \pi R^2\, Q^2_s(A)$$

The Weak Coupling Picture







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

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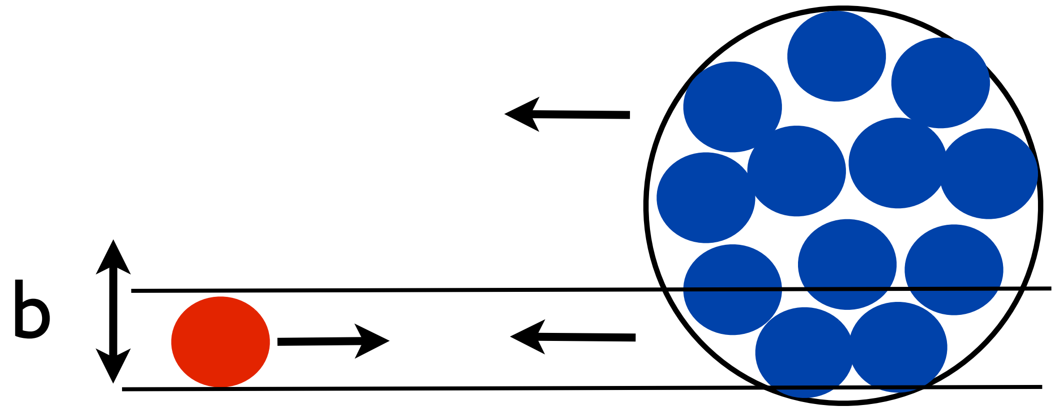
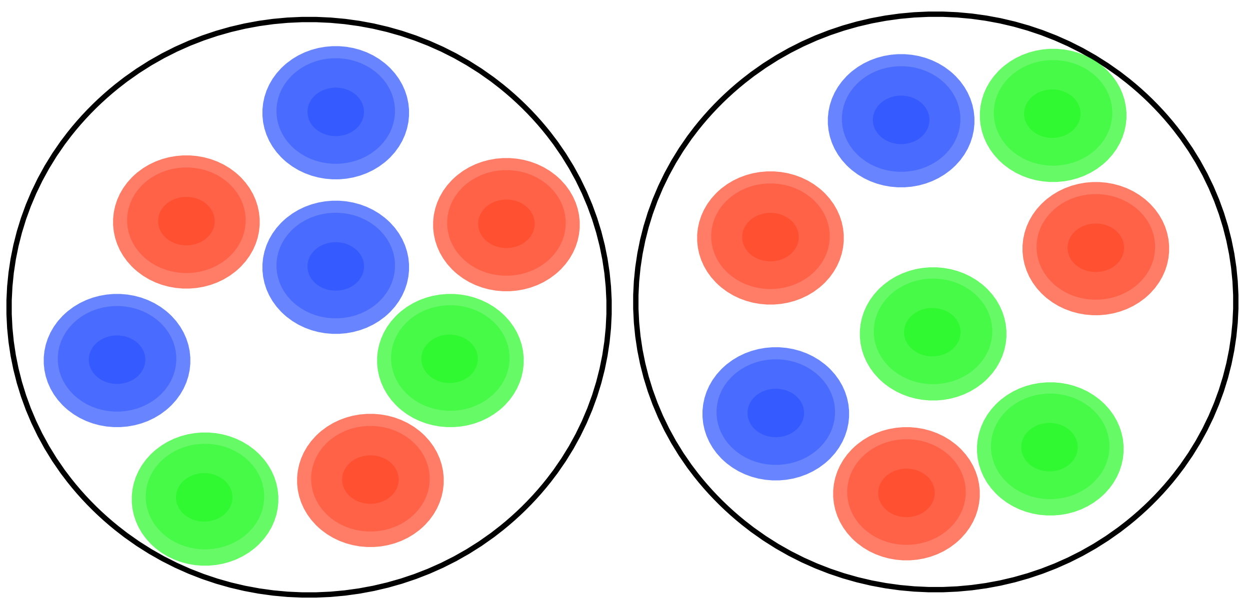
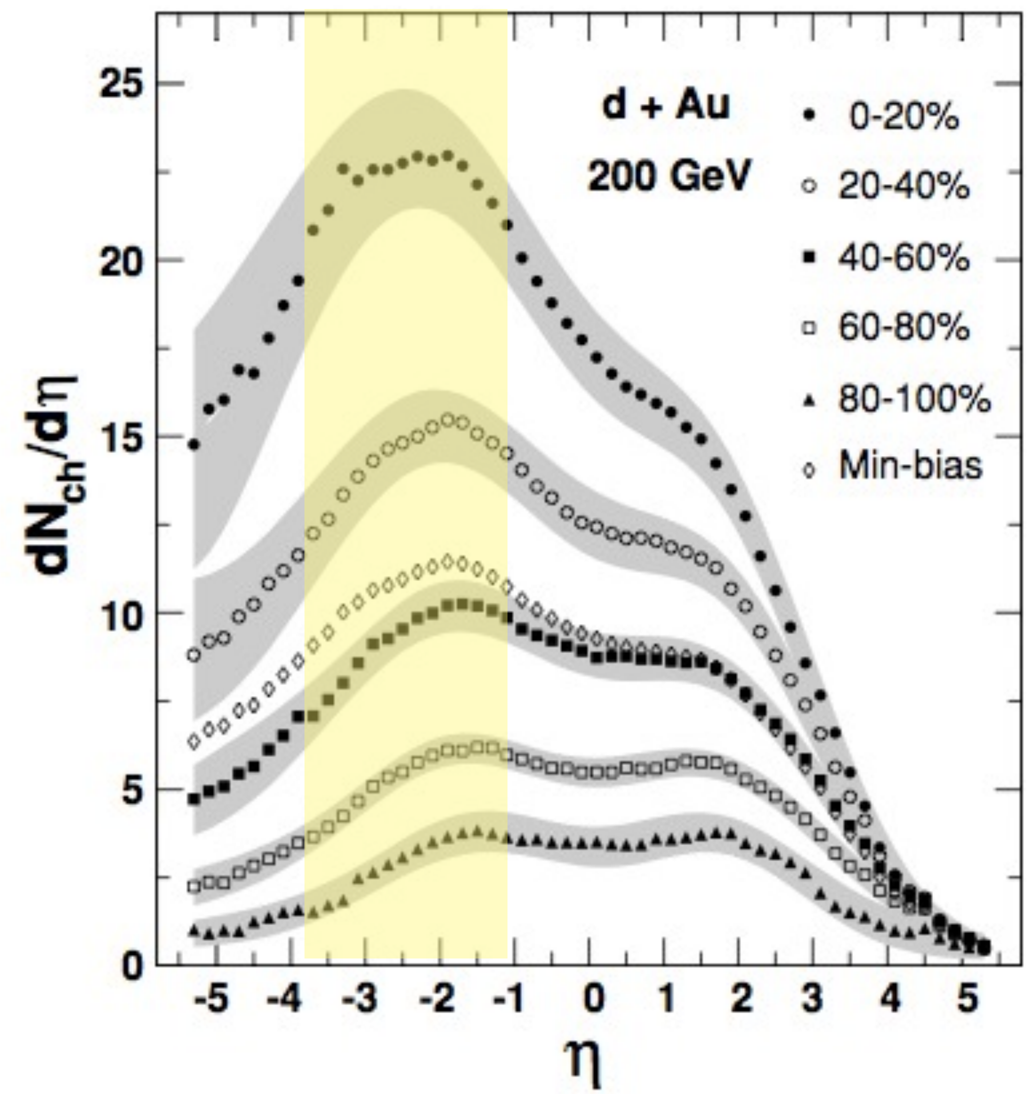






$$Q^2_s(A) = Q^2_s(B)$$

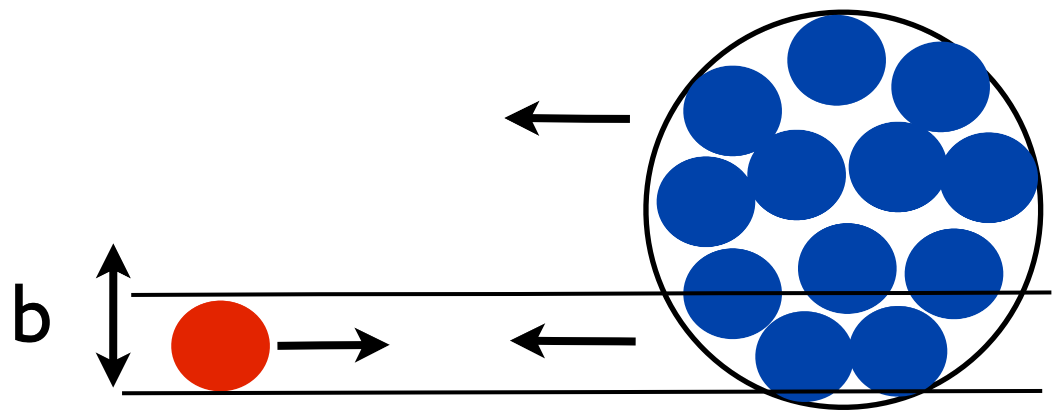
$$Q^2_s(A) = Q^2_0\, A\, e^{\lambda(Ya-y)}$$

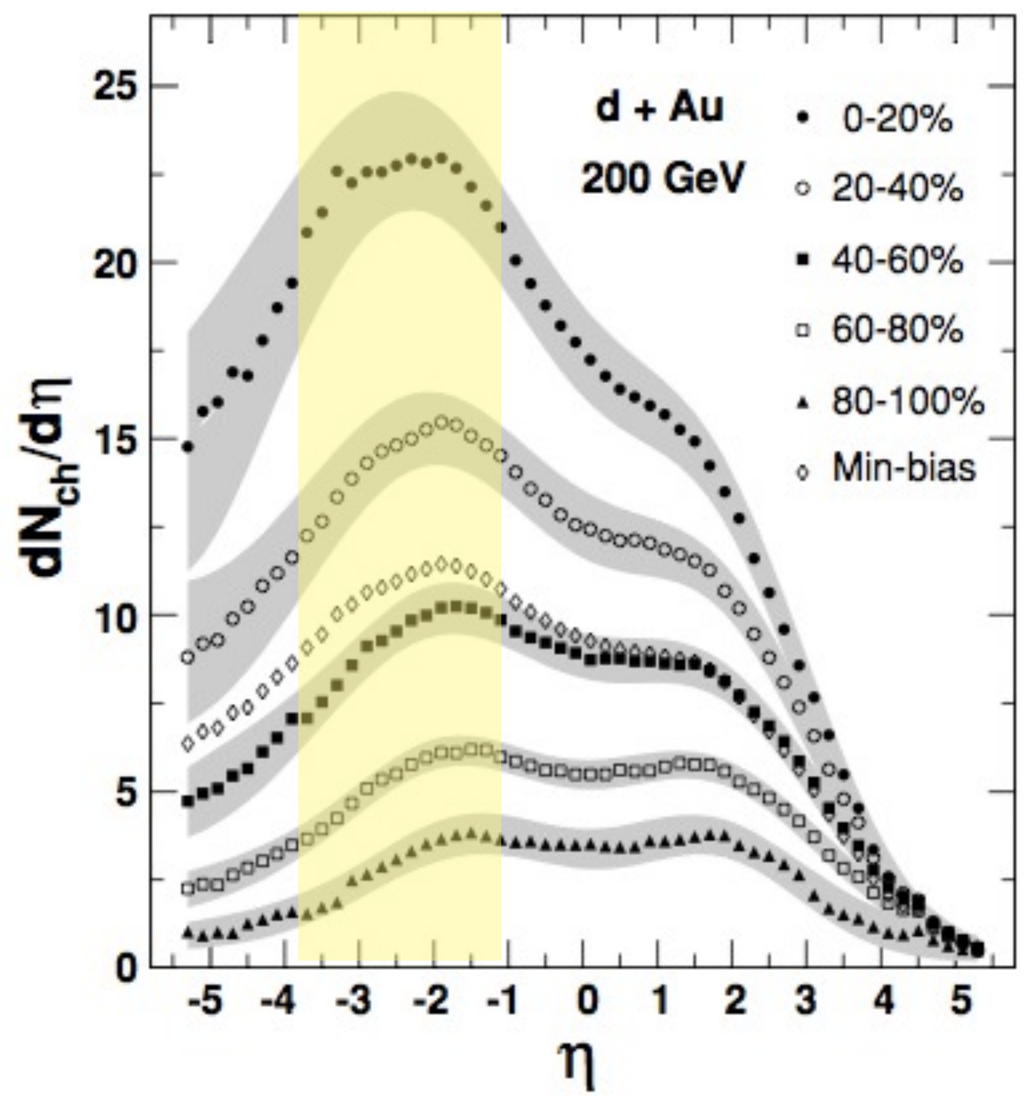
$$Q^2_s(B) = Q^2_0\, B\, e^{\lambda(Yb-y)}$$

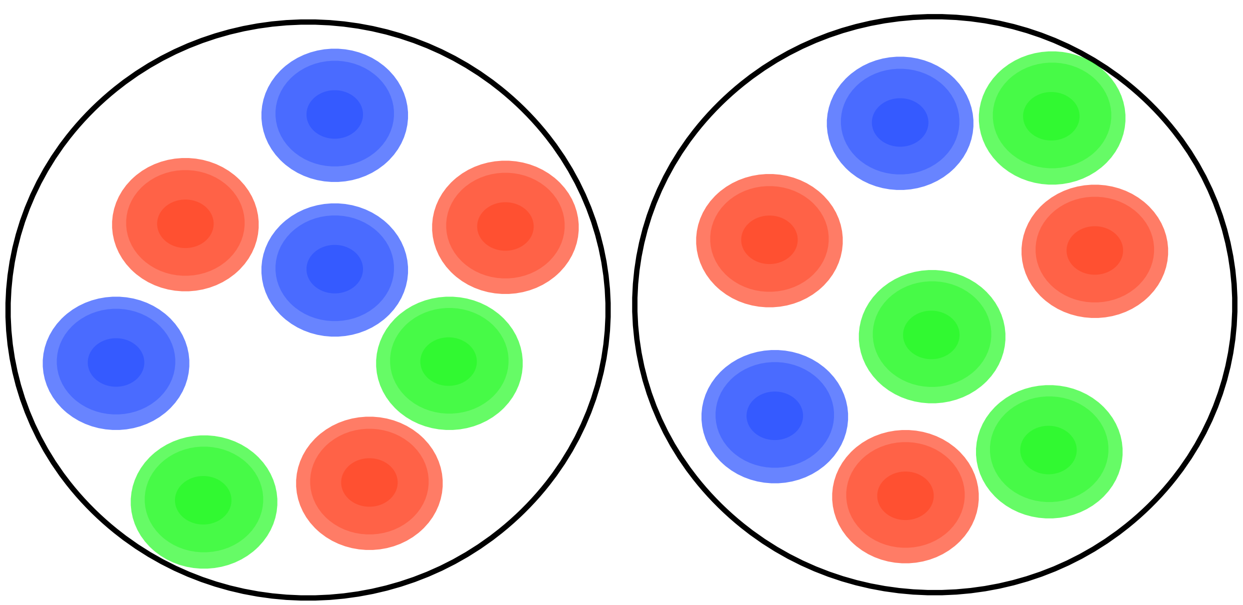
Choosing $y_{lab}=(Yb-Ya)/2$

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

The Weak Coupling Picture







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