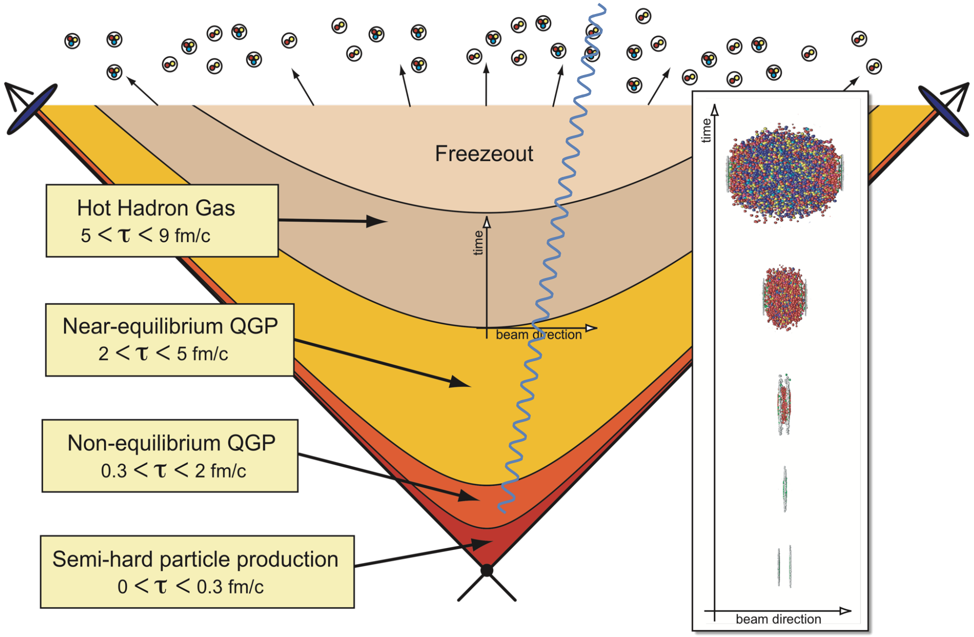
Electromagnetic observables of pre-equilibrium

Michael Strickland
Kent State University
Kent, OH USA

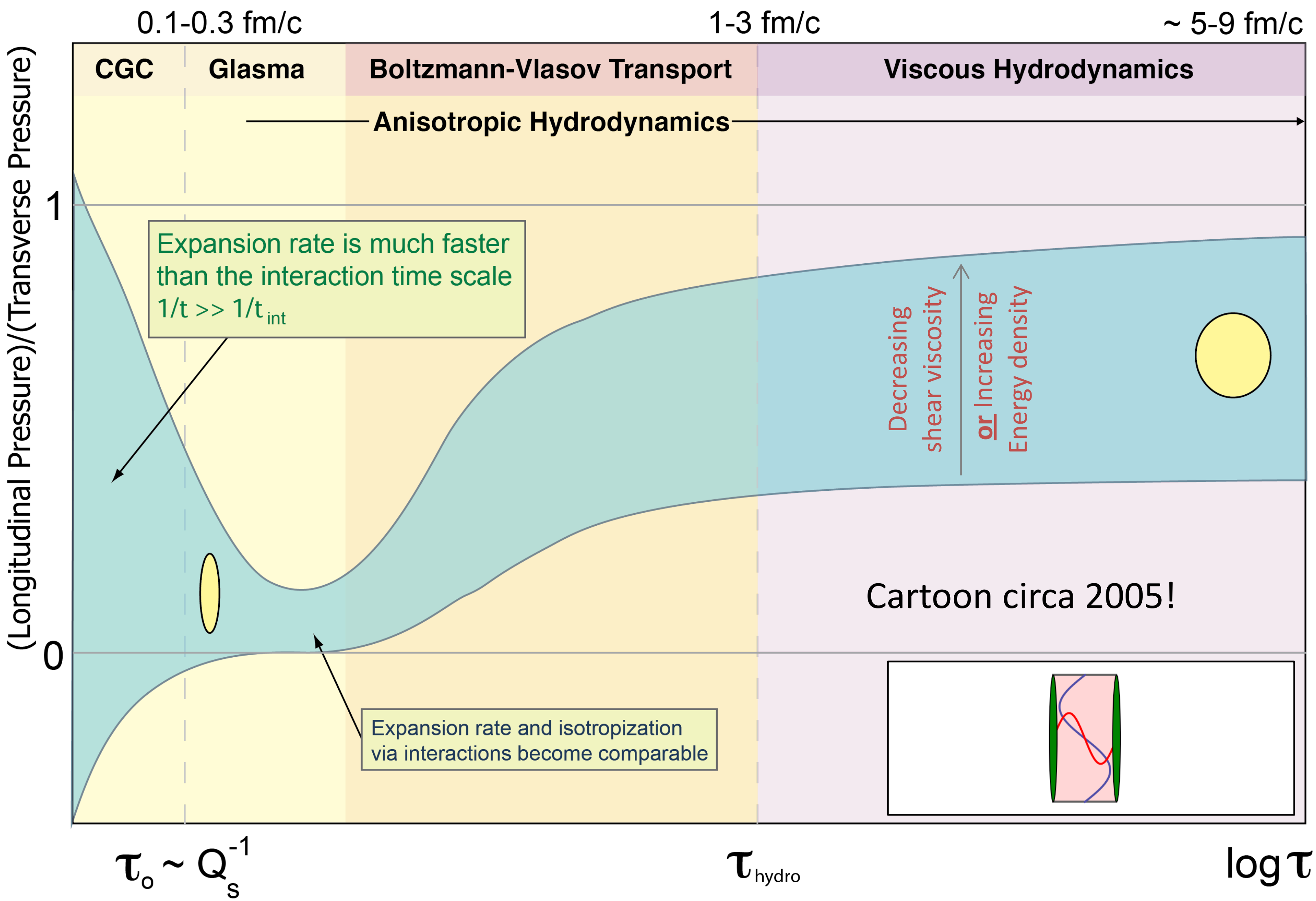
From initial gluons to hydrodynamics:
Gluons inside hadrons and their thermalization,
Institut Pascal, Orsay
Oct 25, 2022

Electromagnetic Probes

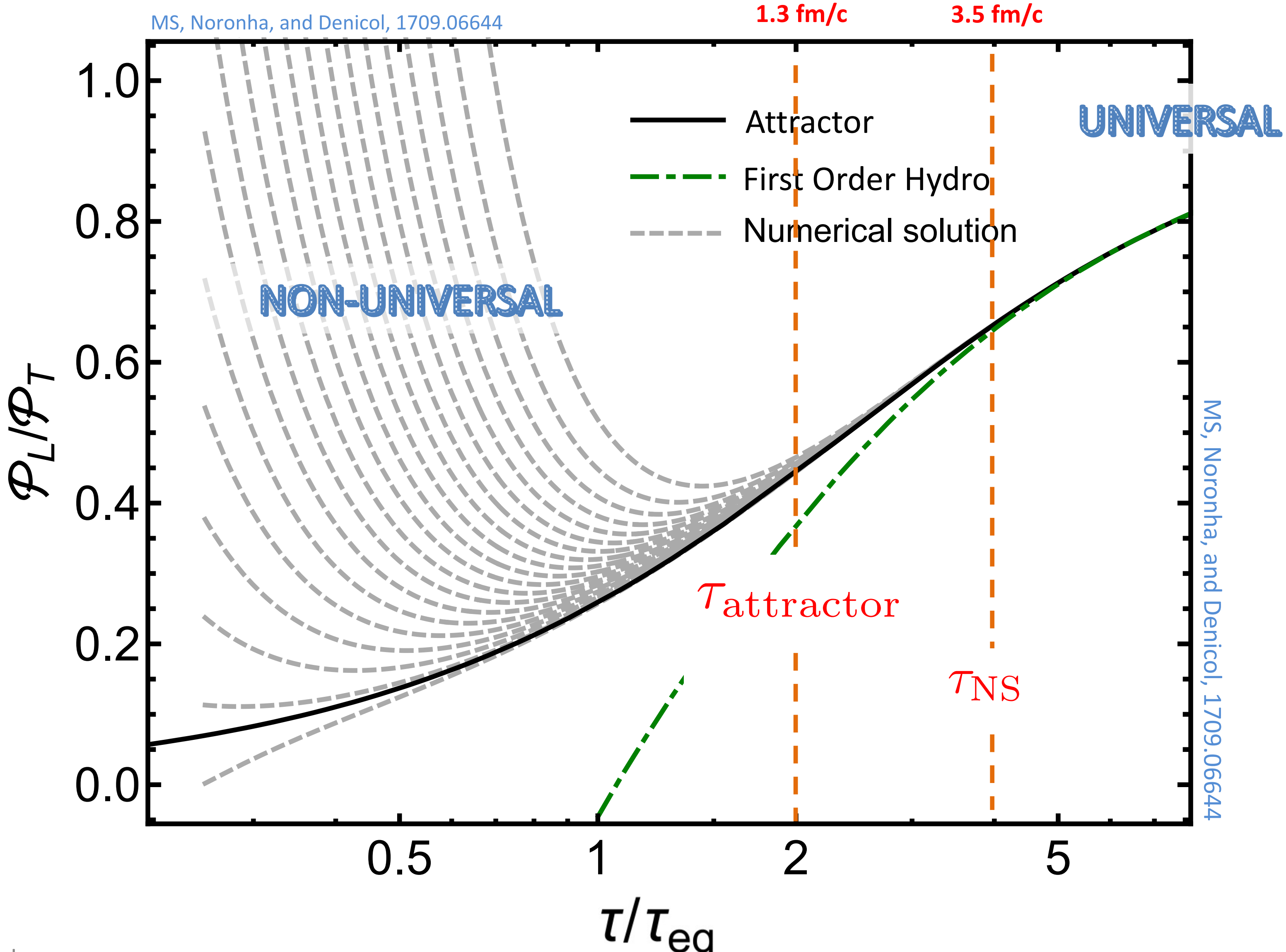


- Real and virtual photon production; latter maps to dilepton production.
- **Weakly interacting**, $\alpha_s \gg \alpha$
- Produced at all times, including the initial stages
- Higher momentum/ invariant mass emissions are predominately produced early in the QGP lifetime, allowing us to experimentally access this time scale
- We hope to learn information about the initial state from high momentum/invariant mass E&M emissions.

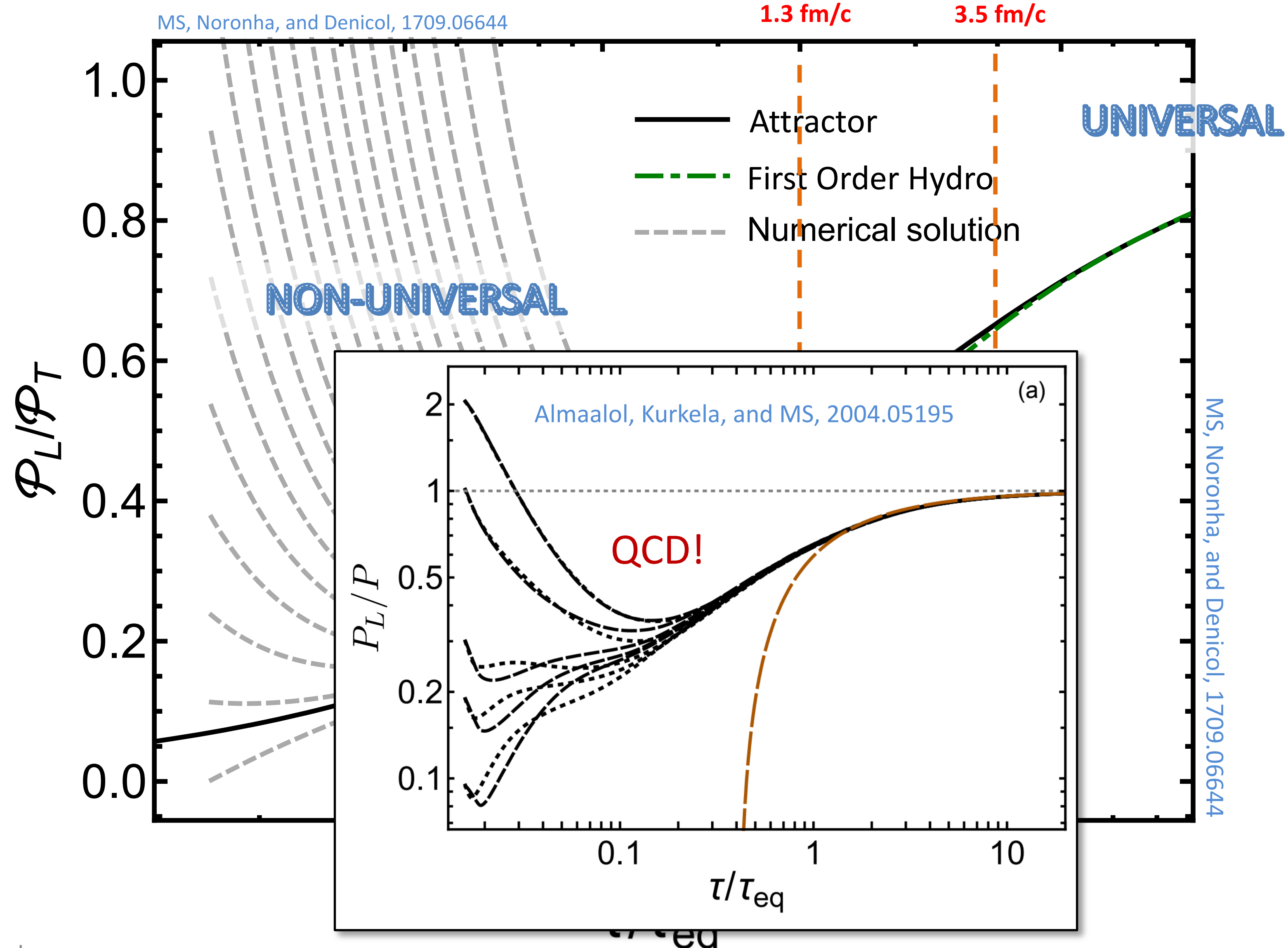
QGP momentum anisotropy cartoon



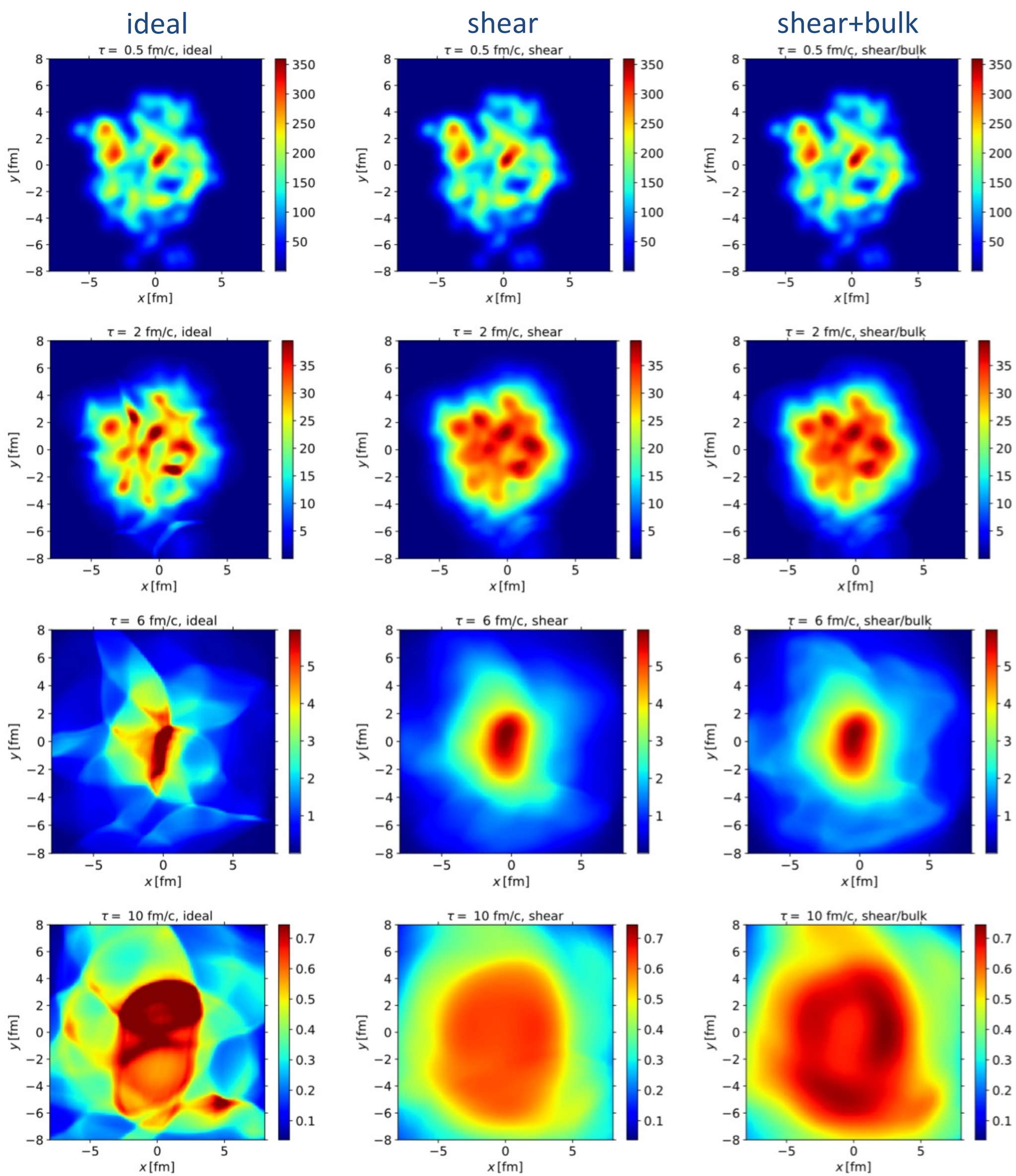
The attractor concept



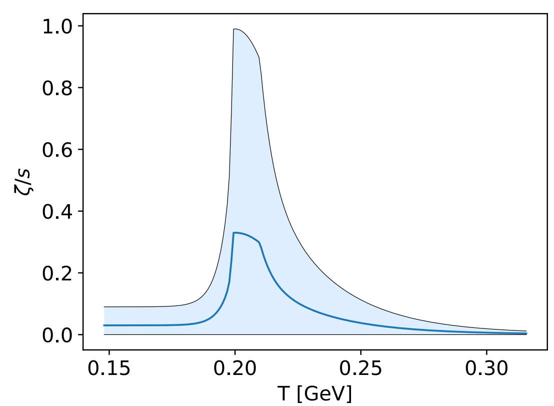
The attractor concept



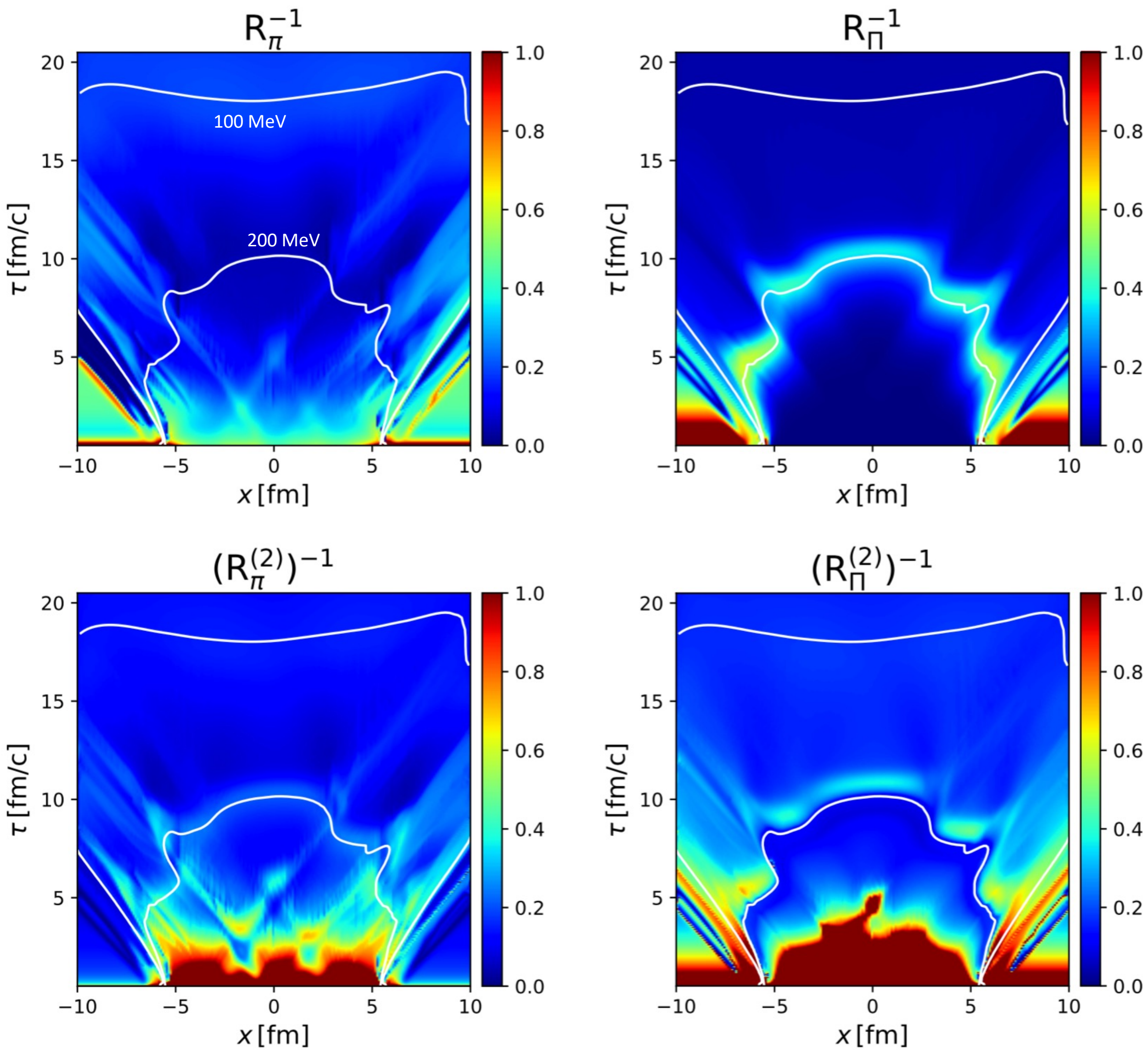
Some pretty pictures from 3d viscous hydro



- Left panels show output from a Ohio State/Kent State GPU-based viscous hydro code
  Bazow, Heinz, and MS, 1608.06577
- Solves the non-conformal DNMR (Denicol, Niemi, Molnar, Rischke) equations with a realistic EoS
- Parameterized ζ/s (plot below)
- $\eta/s = 0.2$
- $T_0 = 600$ MeV @ $t_0 = 0.5$ fm/c



Quantifying the departure from equilibrium

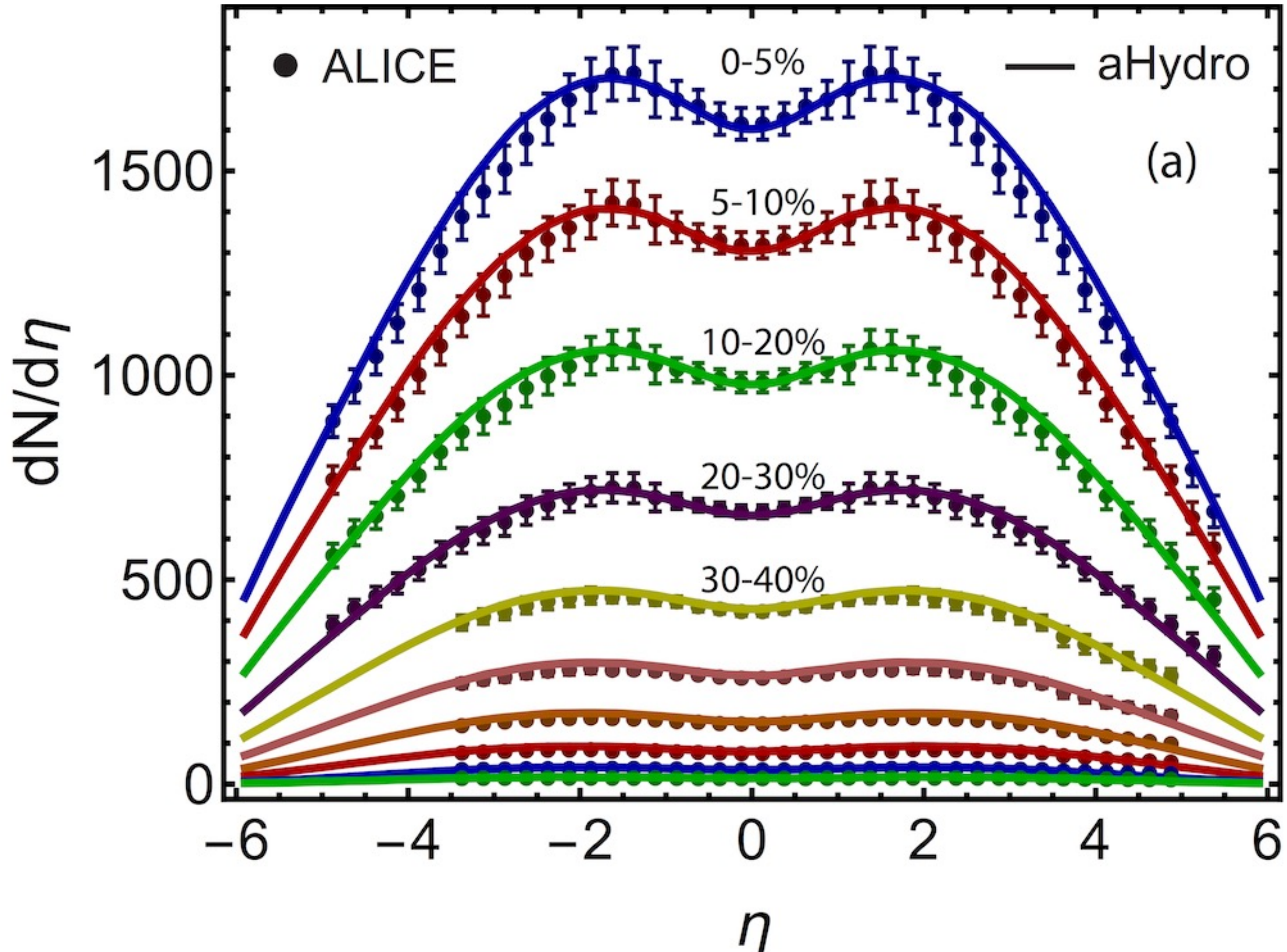


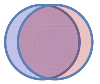
$$\mathrm{R}_\pi^{-1} \equiv \frac{\sqrt{\pi^{\mu\nu}\pi_{\mu\nu}}}{\mathscr{P}_0}, \quad \mathrm{R}_\Pi^{-1} \equiv \frac{|\Pi|}{\mathscr{P}_0}.$$

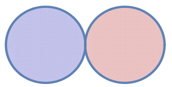
$$(\mathrm{R}_\pi^{(2)})^{-1} \equiv \frac{\sqrt{\mathscr{J}^{\mu\nu}\mathscr{J}_{\mu\nu}}}{2\eta\sqrt{\sigma^{\mu\nu}\sigma_{\mu\nu}}}, \quad (\mathrm{R}_\Pi^{(2)})^{-1} \equiv \frac{|\mathscr{J}|}{\zeta|\theta|}.$$

Charged particle multiplicity

Alqahtani, Nopoush, Ryblewski, MS, 1703.05808; 1705.10191

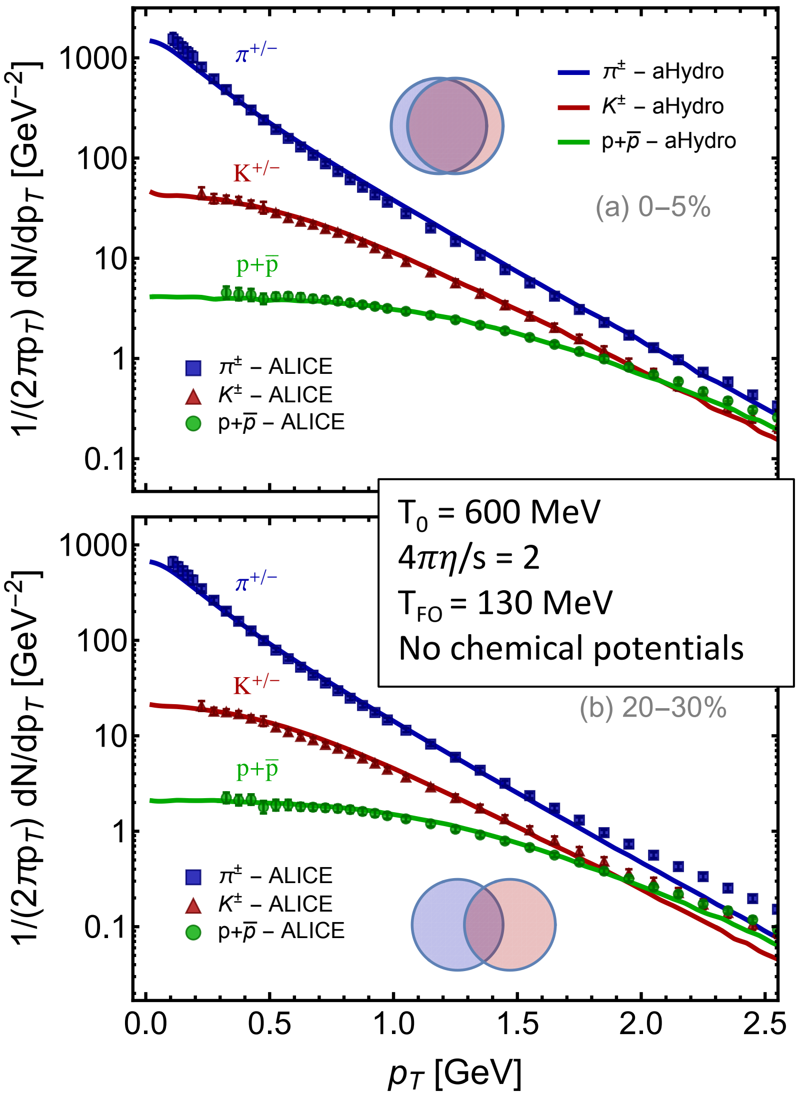


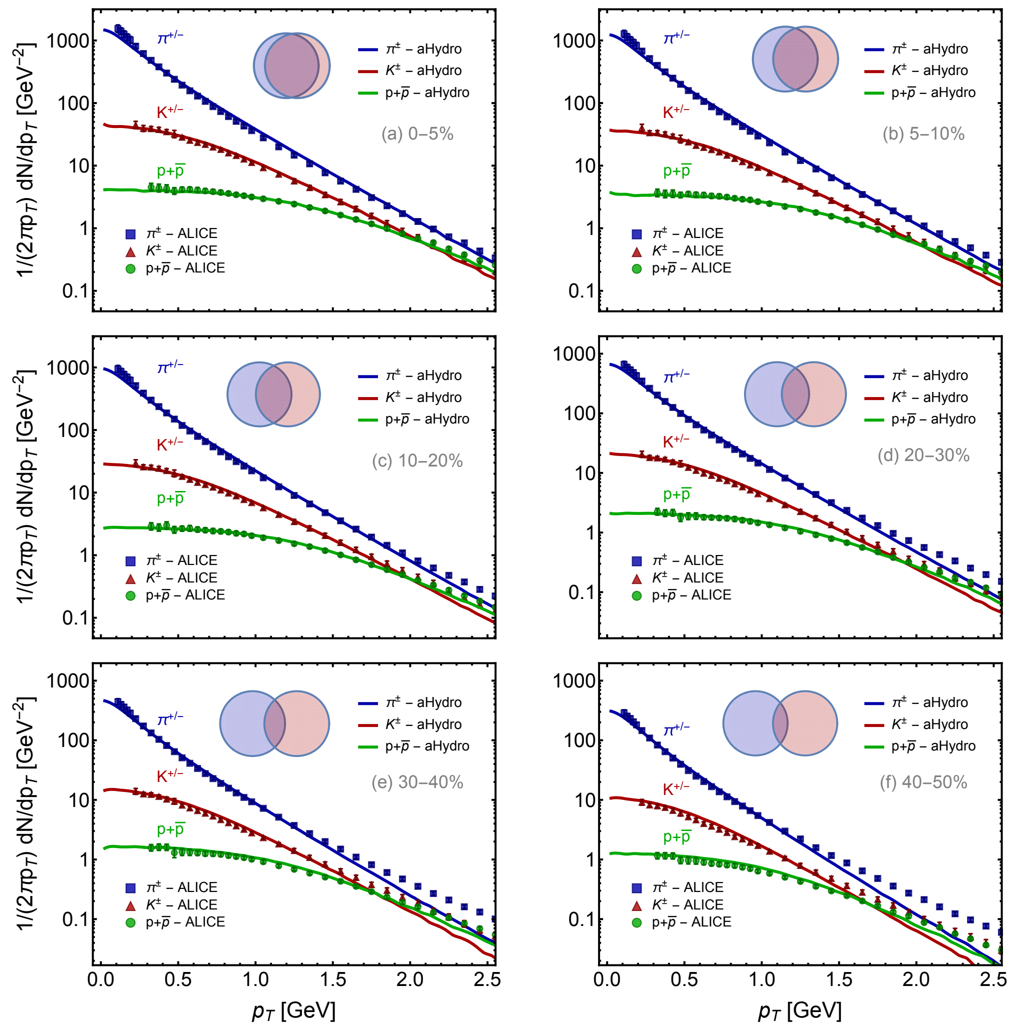




Identified particle spectra

Alqahtani, Nopoush, Ryblewski, MS, 1703.05808; 1705.10191

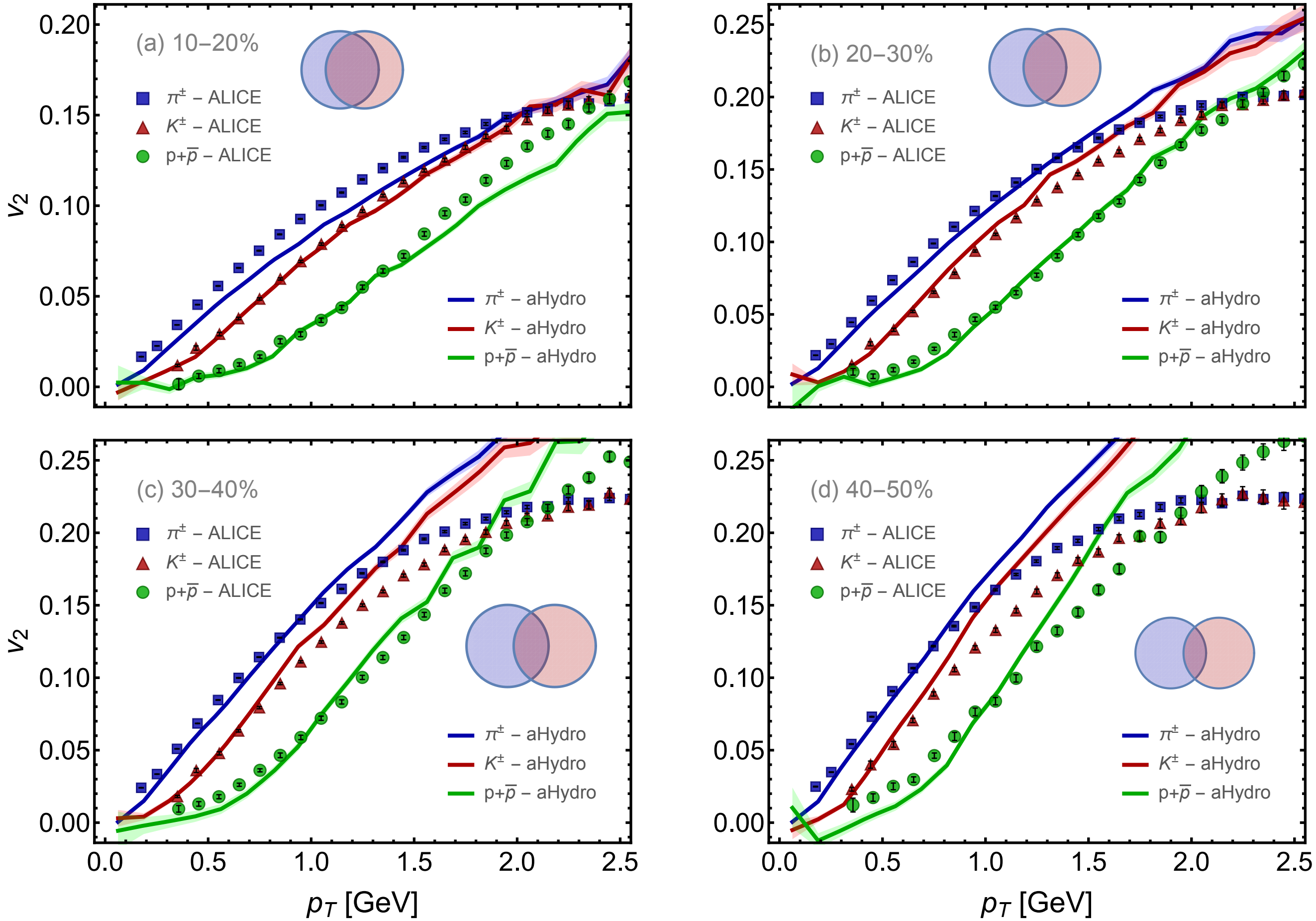




Data are from the ALICE collaboration data for **Pb-Pb collisions @ 2.76 TeV/nucleon**

Elliptic flow

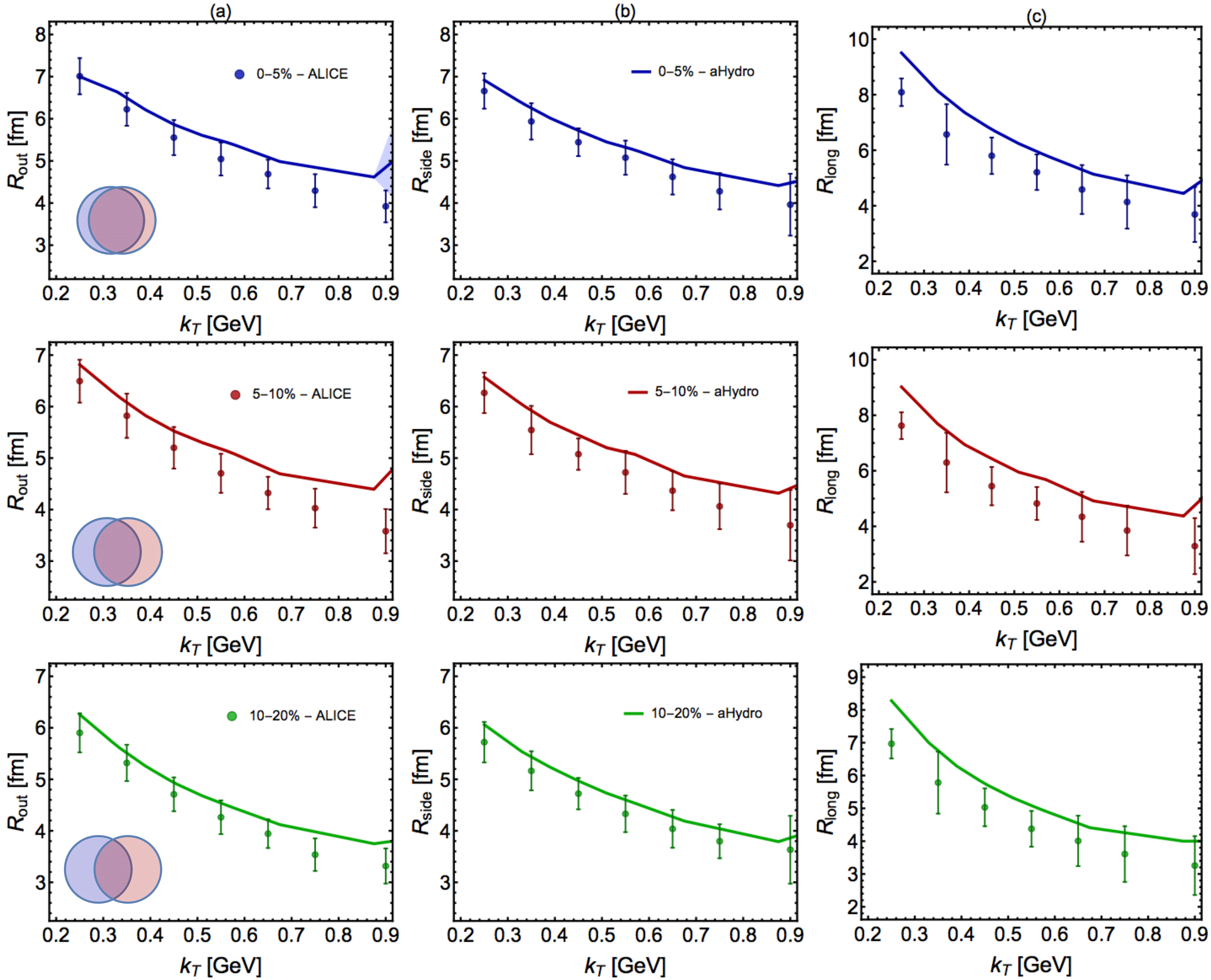
- Quite good description of identified particle elliptic flow as well
- Central collisions → need to include fluctuating init. Conditions!



Alqahtani, Nopoush, Ryblewski, MS, 1703.05808 (PRL); 1705.10191

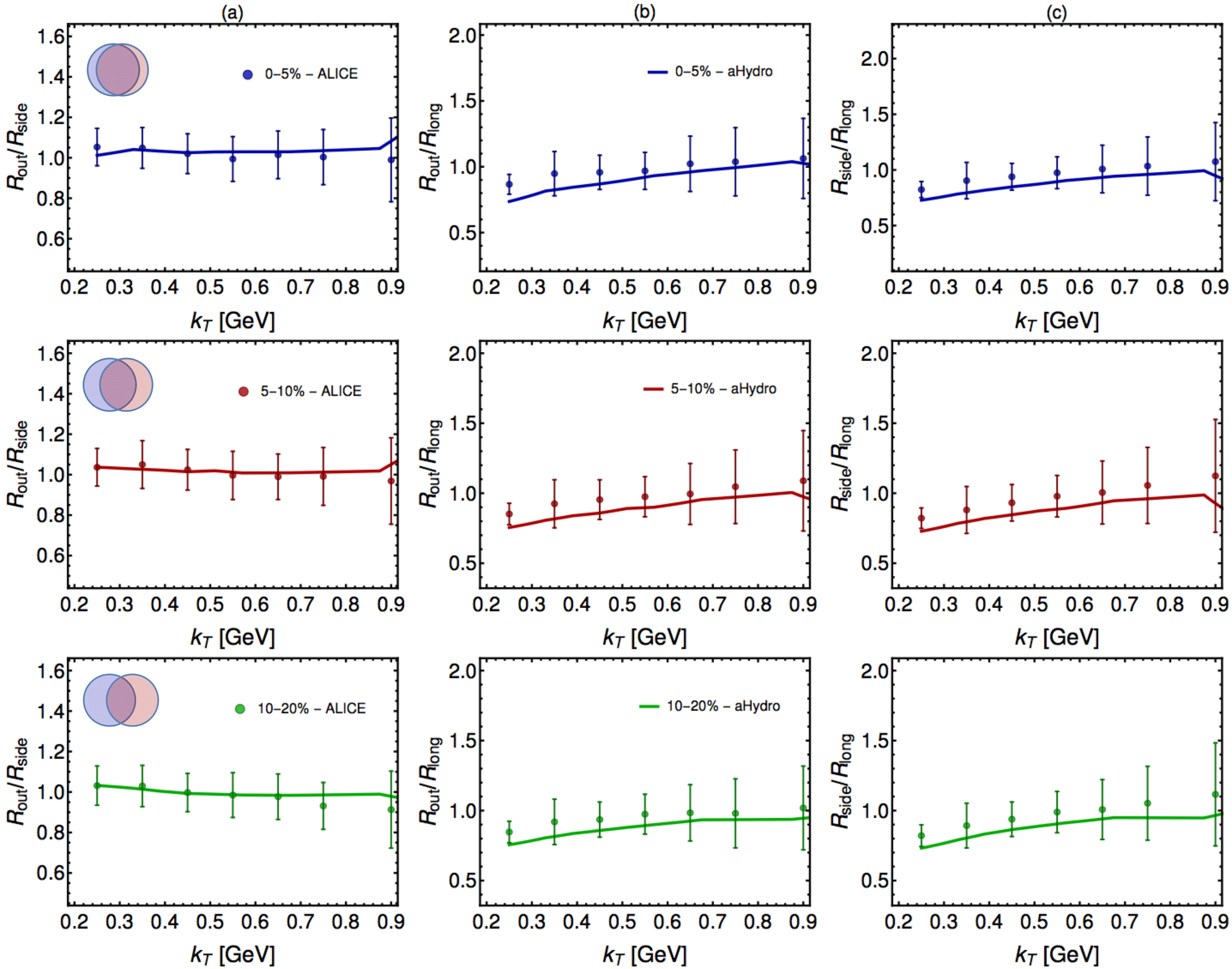
HBT Radii

Alqahtani, Nopoush, Ryblewski, MS, 1705.10191



HBT Radii Ratios

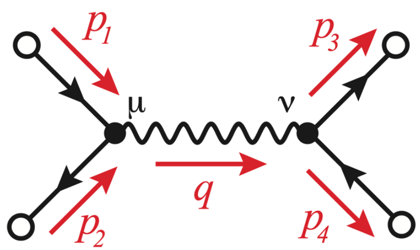
Alqahtani, Nopoush, Ryblewski, MS, 1705.10191



Using E&M emissions to probe the initial state

- Dilepton pairs with p_T and invariant masses in the range 2 - 6 GeV and photons with $p_T > 2$ GeV can, in principle, provide much needed information about **QGP initial conditions**.
- In the past, high-energy dileptons coming from the QGP were difficult to extract due to large open **heavy-flavor decay backgrounds**, but with ALICE's new tracking capabilities, it may be **possible to isolate this contribution** to dilepton production and subtract it.
- Dilepton production in this energy range is dominated by early-time production when the QGP is hottest ($t < 1$ fm/c)
- All dynamical models (e.g. hydro, kinetic theory, and AdS/CFT) predict the existence of **large early-time momentum-space anisotropies** in the LRF energy-momentum tensor; would be nice to have experimental verification/constraints concerning this feature.
- In addition, it is expected that at early times the QGP is **gluon dominated, and quark production is delayed**. This can be described as a time-dependent fugacity.

LO dilepton production from the QGP



$$\mathcal{O}(\alpha^2)$$

$$\frac{dR^{l^+l^-}}{d^4P} = \int \frac{d^3\mathbf{p}_1}{(2\pi)^3}\frac{d^3\mathbf{p}_2}{(2\pi)^3}\, f_q(\mathbf{p}_1)\, f_{\bar{q}}(\mathbf{p}_2)\, v_{q\bar{q}}\, \sigma^{l^+l^-}_{q\bar{q}}\ \delta^{(4)}(P^\mu - p_1^\mu - p_2^\mu)\,,$$

$$v_{q\bar{q}} = \frac{\sqrt{(p_1\cdot p_2)^2 - m_q^4}}{E_1 E_2} \qquad \sigma^{l^+l^-}_{q\bar{q}} = \frac{4\pi}{3}\frac{\alpha^2}{M^2}\left(1+\frac{2m_l^2}{M^2}\right)\left(1-\frac{4m_l^2}{M^2}\right)^{1/2}$$

Note: This is the rate in the local rest frame. Transverse flow causes a boost which results in anisotropic dilepton production, aka "flow"

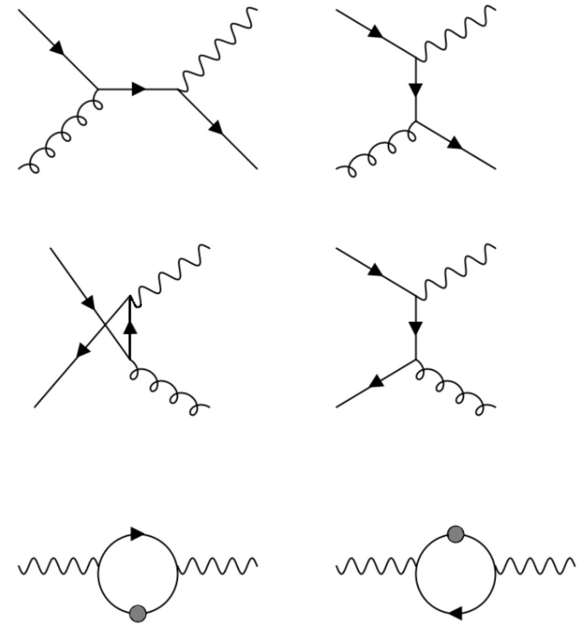
- Leading-order process is Drell-Yan with the incoming quark/anti-quark distribution functions taken to have a particular (non-)equilibrium form.
- One can include effects of finite fugacity and momentum-anisotropy by modeling the form of f_q. However, in that case we also need to specify the dynamics of f_q → need dynamical model.
- In traditional viscous hydro approaches f_q is linearized around equilibrium; this is important for self-consistency, but care needs to be taken.

LO photon production from the QGP

$$q\frac{dR^{\gamma}_{\rm Com}}{d^3q} = -128\pi^3\alpha_s\alpha_{\rm em}\sum_{j\in\{u,d\}} e_j^2 \int_{\mathbf{k_1}} \frac{f_q(\mathbf{k_1})}{k_1}\int_{\mathbf{k_2}} \frac{f_g(\mathbf{k_2})}{k_2}\int_{\mathbf{k_3}} \frac{1-f_q(\mathbf{k_3})}{k_3} \times\delta^4\left(K_1-K_2-K_3-Q\right)\left[\frac{s}{t}+\frac{t}{s}\right],$$

$$q\frac{dR^{\gamma}_{\rm Ann}}{d^3q} = 64\pi^3\alpha_s\alpha_{\rm em}\sum_{j\in\{u,d\}} e_j^2 \int_{\mathbf{k_1}} \frac{f_q(\mathbf{k_1})}{k_1}\int_{\mathbf{k_2}} \frac{f_q(\mathbf{k_2})}{k_2}\int_{\mathbf{k_3}} \frac{1+f_g(\mathbf{k_3})}{k_3} \times\delta^4\left(K_1-K_2-K_3-Q\right)\left[\frac{u}{t}+\frac{t}{u}\right],$$

$$q\frac{dR^{\gamma}_{\rm Soft}}{d^3q} = \frac{i}{2(2\pi)^3}{\rm Tr}\Pi_{12}(Q),$$



- At leading order, we have Compton and annihilation processes. Both are **infrared divergent** and removing this IR divergence requires **hard thermal loop (HTL) resummation**.
- In a non-equilibrium setting this requires generalizing the HTL resummation to “hard-loop resummation”. This has been done in a series of papers:

P. Romatschke and M. Strickland, Phys. Rev. D 68, 036004 (2003) **[spheroidal]**
B. Schenke and M.Strickland, Phys. Rev. D76, 025023 (2007) **[spheroidal, quarks]**
B. Kasmaei, M. Nopoush, and M. Strickland, Phys. Rev. D 94, 125001 (2016) **[ellipsoidal, quarks]**
B. Kasmaei and M. Strickland, Phys. Rev. D 97, 054022 (2018) **[general, quarks and gluons]**

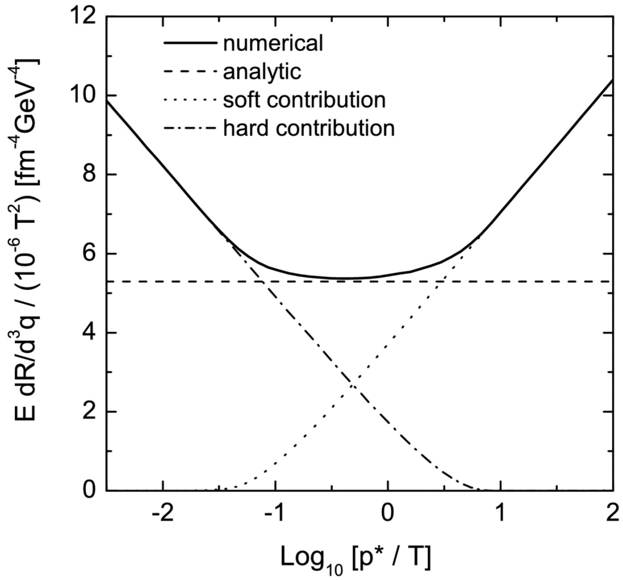
LO photon production from the QGP

$$q\frac{dR^{\gamma}_{\rm Com}}{d^3q} = -128\pi^3\alpha_s\alpha_{\rm em}\sum_{j\in\{u,d\}} e_j^2 \int_{\mathbf{k_1}} \frac{f_q(\mathbf{k_1})}{k_1}\int_{\mathbf{k_2}} \frac{f_g(\mathbf{k_2})}{k_2}\int_{\mathbf{k_3}} \frac{1-f_q(\mathbf{k_3})}{k_3} \times\delta^4\left(K_1-K_2-K_3-Q\right)\left[\frac{s}{t}+\frac{t}{s}\right],$$

$$q\frac{dR^{\gamma}_{\rm Ann}}{d^3q} = 64\pi^3\alpha_s\alpha_{\rm em}\sum_{j\in\{u,d\}} e_j^2 \int_{\mathbf{k_1}} \frac{f_q(\mathbf{k_1})}{k_1}\int_{\mathbf{k_2}} \frac{f_q(\mathbf{k_2})}{k_2}\int_{\mathbf{k_3}} \frac{1+f_g(\mathbf{k_3})}{k_3} \times\delta^4\left(K_1-K_2-K_3-Q\right)\left[\frac{u}{t}+\frac{t}{u}\right],$$

$$q\frac{dR^{\gamma}_{\rm Soft}}{d^3q} = \frac{i}{2(2\pi)^3}{\rm Tr}\Pi_{12}(Q),$$

B. Schenke and M.Strickland, Phys. Rev. D76, 025023 (2007)



- At leading order, we have Compton and annihilation processes. Both are **infrared divergent** and removing this IR divergence requires **hard thermal loop (HTL) resummation**.
- In a non-equilibrium setting this requires generalizing the HTL resummation to “hard-loop resummation”. This has been done in a series of papers:

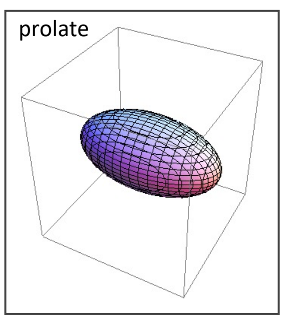
P. Romatschke and M. Strickland, Phys. Rev. D 68, 036004 (2003) **[spheroidal]**
B. Schenke and M.Strickland, Phys. Rev. D76, 025023 (2007) **[spheroidal, quarks]**
B. Kasmaei, M. Nopoush, and M. Strickland, Phys. Rev. D 94, 125001 (2016) **[ellipsoidal, quarks]**
B. Kasmaei and M. Strickland, Phys. Rev. D 97, 054022 (2018) **[general, quarks and gluons]**

Modeling the non-equilibrium distribution function

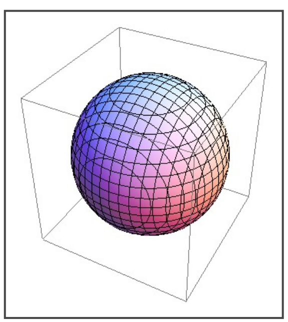
$$\frac{dR^{l^+l^-}}{d^4P} = \int \frac{d^3\mathbf{p}_1}{(2\pi)^3} \frac{d^3\mathbf{p}_2}{(2\pi)^3} f_q(\mathbf{p}_1)\, f_{\bar{q}}(\mathbf{p}_2)\, v_{q\bar{q}}\, \sigma_{q\bar{q}}^{l^+l^-}\, \delta^{(4)}(P^\mu - p_1^\mu - p_2^\mu)\,,$$

Can introduce a form for f that takes into account both momentum anisotropy (general) and chemical potential (related to fugacity)

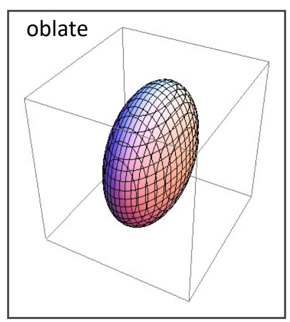
$$f_q(\mathbf{p}) = \frac{1}{e^x + 1} \qquad x \equiv \underbrace{\frac{1}{\Lambda}\sqrt{p_\mu \Xi^{\mu\nu} p_\nu}}_{\equiv \tilde{E}} - \underbrace{\frac{\mu}{\Lambda}}_{\equiv \tilde{\mu}}$$



$-1 < \xi < 0$



$\xi = 0$



$\xi > 0$

High-energy limit

$$\begin{aligned} f_q(\mathbf{p}) &= \frac{1}{e^{\tilde{E}-\tilde{\mu}} + 1} \\ &= \frac{\lambda_q}{e^{\tilde{E}} + \lambda_q} \qquad \lambda_q = \exp(\tilde{\mu}) \\ &= \sum_{k=1}^{\infty} (-1)^{k+1} \lambda_q^k e^{-k\tilde{E}} \\ &\sim \lambda_q e^{-\tilde{E}} + \cdots \end{aligned}$$

M. Strickland, Phys. Lett. B 331, 245 (1994)

Modeling the non-equilibrium distribution function

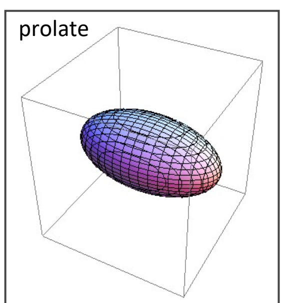
7 July 1994
PHYSICS LETTERS B
ELSEVIER
Physics Letters B 331 (1994) 245–250

Thermal photons and dileptons from non-equilibrium quark-gluon plasma

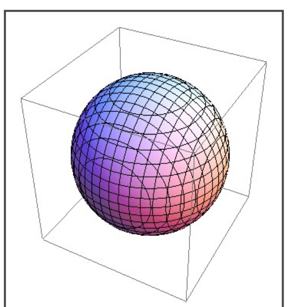
Michael Strickland
Department of Physics, Duke University, Durham, NC 27708-0305, USA

Received 1 April 1994
Editor: G.F. Bertsch

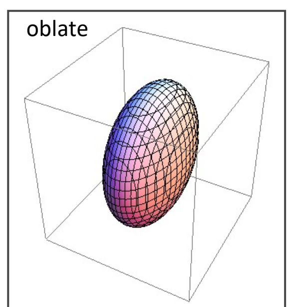
$$e^x + 1 \qquad \underbrace{\Lambda}_{\equiv \tilde{E}} \qquad \underbrace{\Lambda}_{\equiv \tilde{\mu}}$$



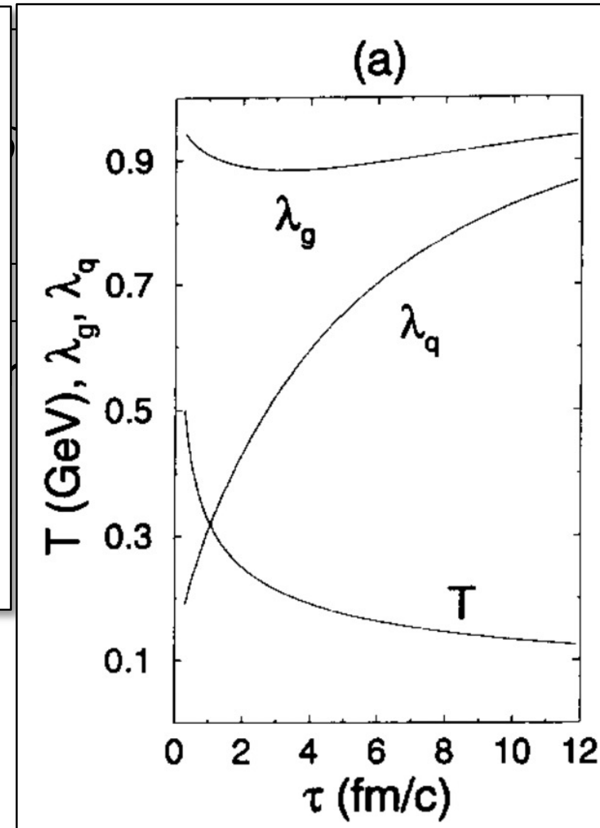
$-1 < \xi < 0$



$\xi = 0$



$\xi > 0$

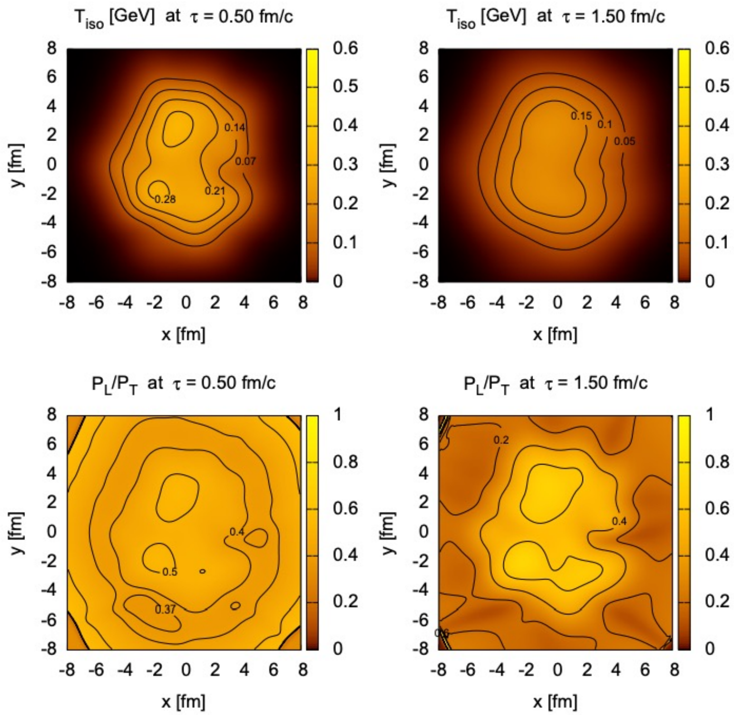


$$= \sum_{k=1} (-1) \quad \lambda_q e$$

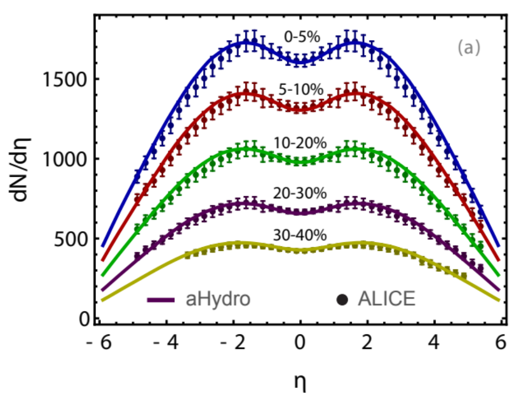
$$\sim \lambda_q e^{-\tilde{E}} + \cdots$$

M. Strickland, Phys. Lett. B 331, 245 (1994)

How can we use this information?



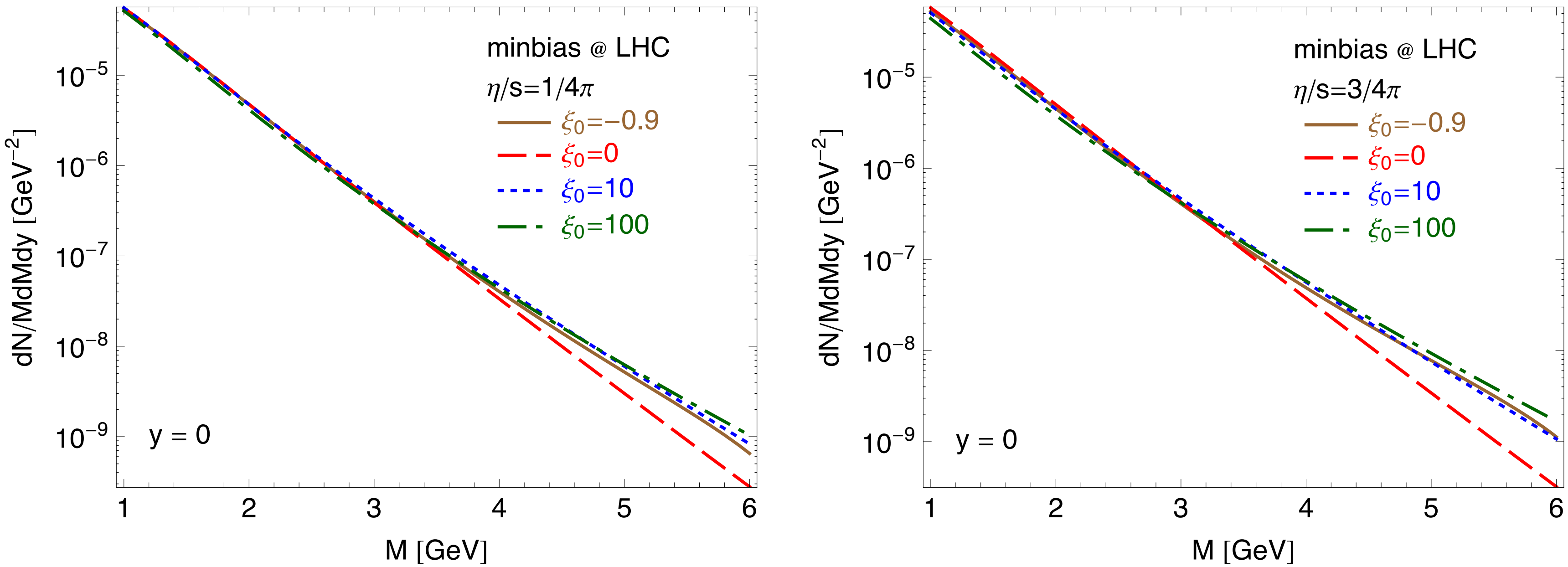
Alqahtani, Nopoush, Ryblewski, MS, 1705.10191



- In classical approximation, the rate is proportional to the quark fugacity squared → can have an important role to play; CGC implies low quark occupancy (see end of talk)?
- The anisotropic form used underlies anisotropic hydrodynamics → can read the anisotropy tensor $\Xi^{\mu\nu}$ etc. directly from 3+1D aHydro simulations than have been tuned to data.
- Unlike linearized approaches, the **non-equilibrium quark distribution function is positive ($\geq$ 0) at all points in phase space**.
- **I will focus on momentum-anisotropy effects today**, but one can envisage evolving the fugacity along with the standard hydro variables.

Dilepton results – Invariant mass

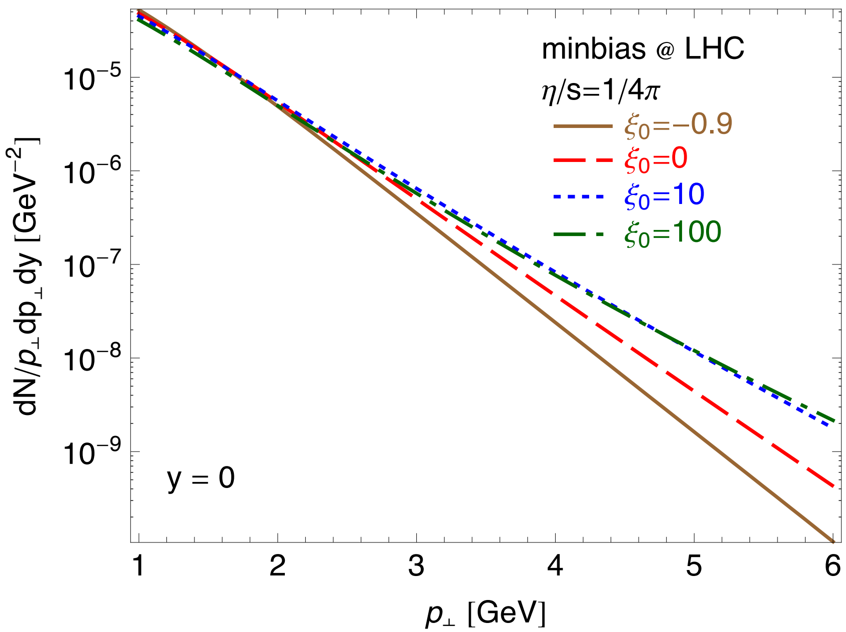
R. Ryblewski and M. Strickland, Phys. Rev. D 92, 025026 (2015)

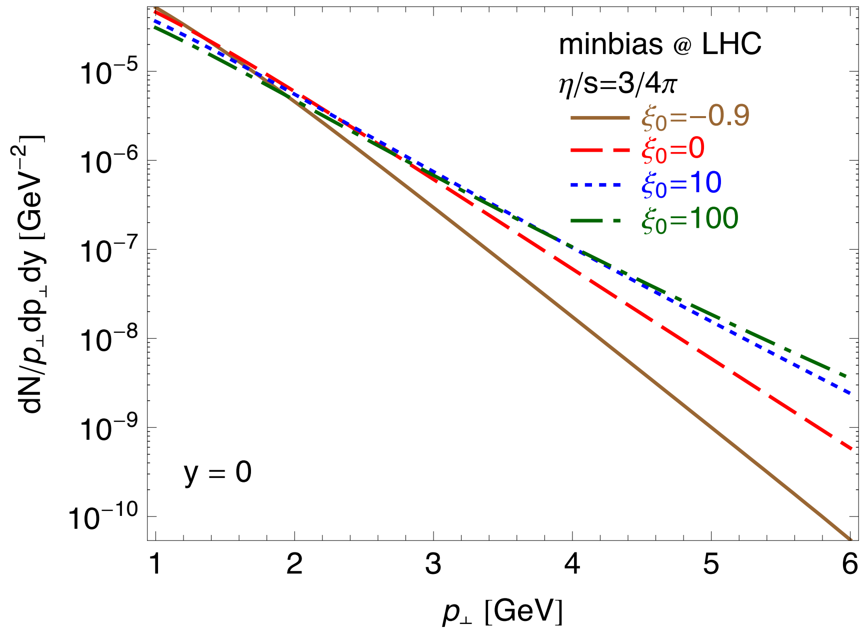


- Left and right panels show different values of the specific shear viscosity
- Different lines correspond to different assumed initial anisotropies, ranging from extremely prolate (-0.9) to extremely oblate (100)
- Small effects below 3 GeV, with magnitude increasing with assumed eta/s
- Isotropic different from anisotropic, but can't even tell prolate from oblate

Dilepton results – p_T spectrum

R. Ryblewski and M. Strickland, Phys. Rev. D 92, 025026 (2015)

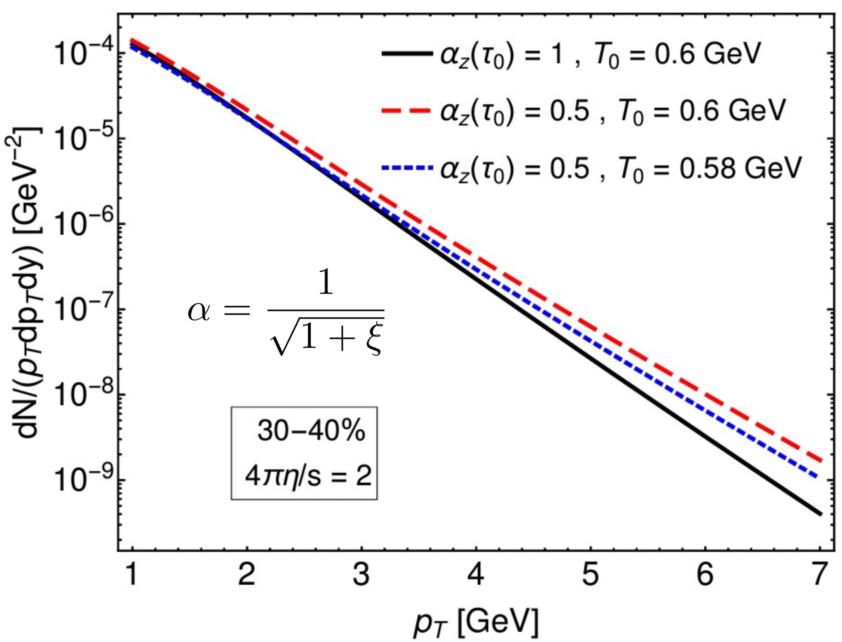


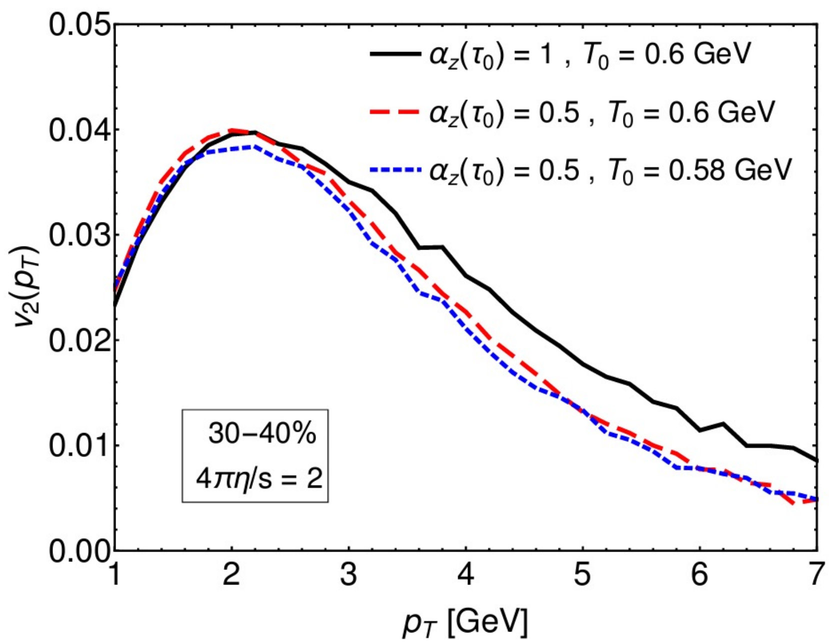


- Left and right panels show different values of the specific shear viscosity
- Different lines correspond to different assumed initial anisotropies, ranging from extremely prolate (-0.9) to extremely oblate (100)
- Larger effect, with magnitude increasing with assumed eta/s
- <u>Can distinguish prolate from oblate</u>

Dilepton results – Using 3+1D aHydro

B. Kasmaei and M. Strickland, Phys. Rev. D 99, 034015 (2019)

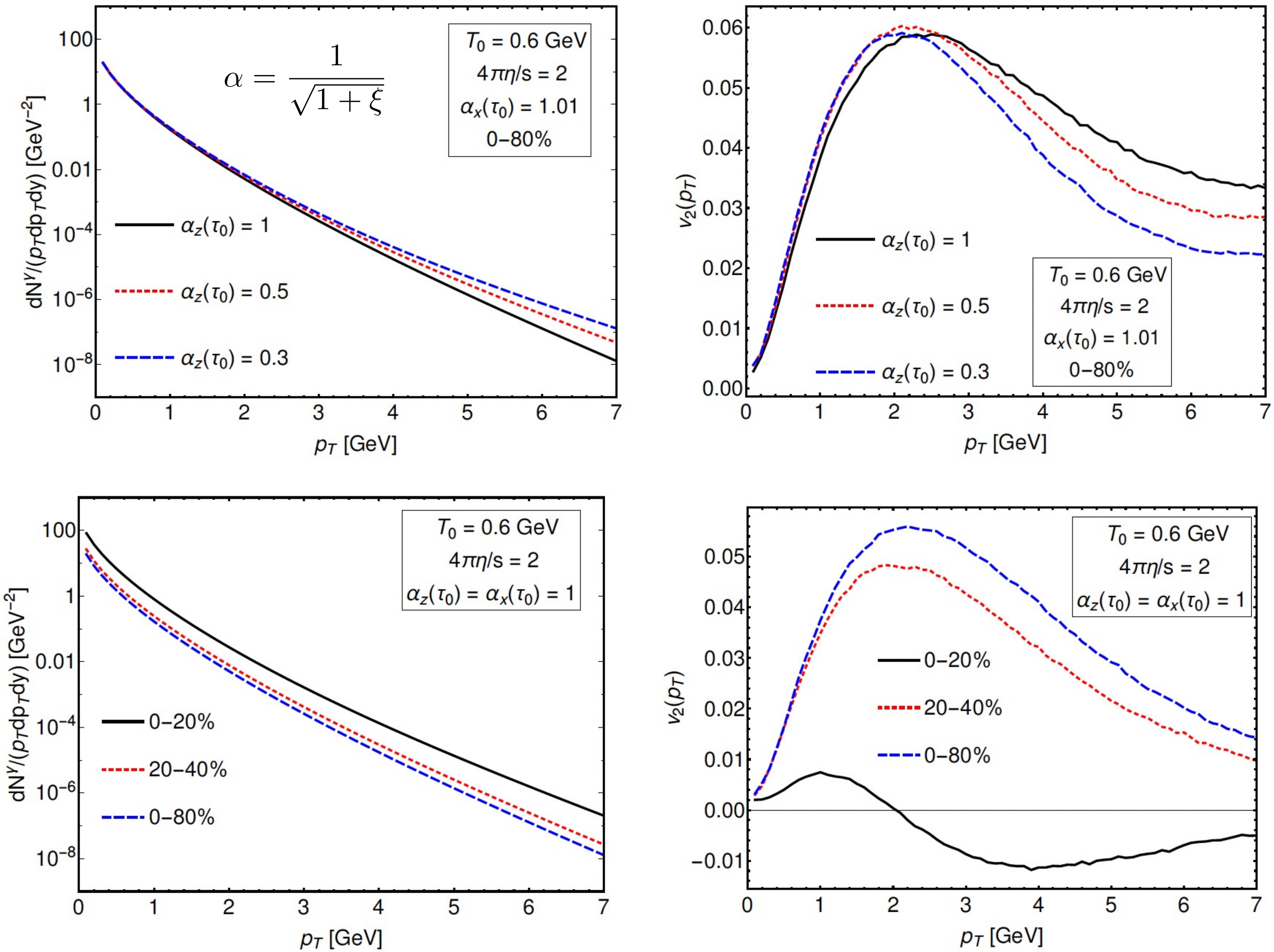




$$\frac{dR^{l^+l^-}}{d^4P} = \int \frac{d^3\mathbf{p}_1}{(2\pi)^3} \frac{d^3\mathbf{p}_2}{(2\pi)^3} f_q(\mathbf{p}_1)\, f_{\bar{q}}(\mathbf{p}_2)\, v_{q\bar{q}}\, \sigma^{l^+l^-}_{q\bar{q}}\, \delta^{(4)}(P^\mu - p_1^\mu - p_2^\mu)\,,$$

Photon results – Using 3+1D aHydro

B. Kasmaei and M. Strickland, Phys. Rev. D 102, 014037 (2020)

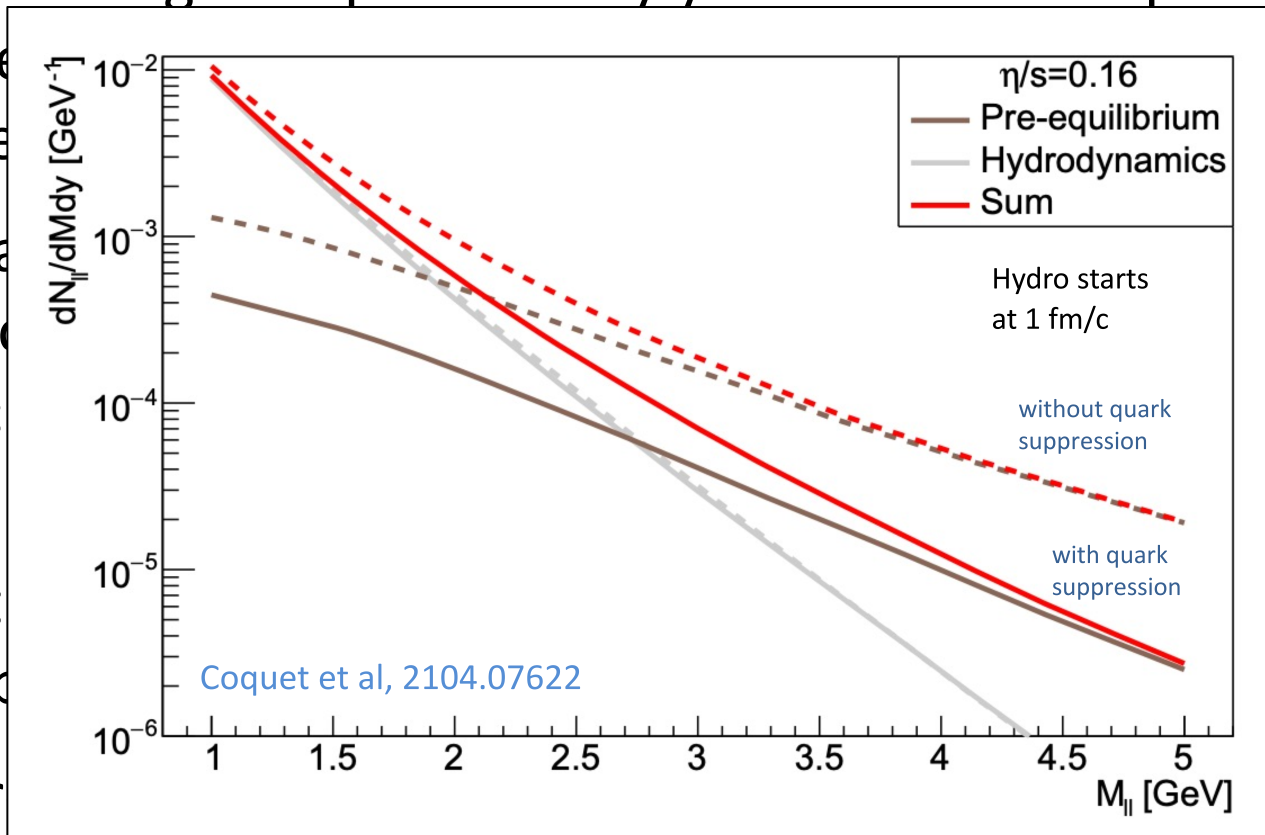


Conclusions

- Electromagnetic probes may yet be able to help us understand the early-time dynamics of the QGP thanks to experimental advances, but still not easy.
- Attractor makes it much harder, since precise momentum-anisotropy of the initial conditions is wiped out rather quickly → system follows universal anisotropic attractor.
- The best information comes from M and/or $p_T > 1$ GeV; putting cuts on both emphasizes initial state photons or dileptons.
- More realistic modeling of anisotropy and chemical non-equilibrium effects are needed. Interesting work along these lines by Coquet et al, 2104.07622.

Conclusions

- Electromagnetic probes may yet be able to help us unde… nks to expe…



- Attra… entum- anis… er quic… ctor.
- The … GeV; putt… ns and dilep…
- Mor… non-equilibrium effects are needed. Interesting work along these lines by Coquet et al, 2104.07622.

Quark production in heavy ion collisions: formalism and boost invariant fermionic light-cone mode functions

JHEP02(2016)126

François Gelis,[a] and Naoto Tanji[b]

[a] Institut de physique théorique, Université Paris Saclay, CEA, CNRS, F-91191 Gif-sur-Yvette, France
[b] Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120, Heidelberg, Germany

E-mail: francois.gelis@cea.fr, tanji@thphys.uni-heidelberg.de

Abstract: We revisit the problem of quark production in high energy heavy ion collisions, at leading order in α_s in the color glass condensate framework. In this first paper, we setup the formalism and express the quark spectrum in terms of a basis of solutions of the Dirac equation (the mode functions). We determine analytically their initial value in the Fock-Schwinger gauge on a proper time surface $Q_s\tau_0 \ll 1$, in a basis that makes manifest the boost invariance properties of this problem. We also describe a statistical algorithm to perform the sampling of the mode functions.

...sions

...et be able to help us
...amics of the QGP thanks to

...r, since precise momentum-
...ions is wiped out rather
quickly → system follows universal anisotropic attractor.

- The bes...
  putting...
  dilepton...

- More re...
  equilibr...
  these li...

PHYSICAL REVIEW D **87,** 125035 (2013)

Formulation of the Schwinger mechanism in classical statistical field theory

François Gelis[1] and Naoto Tanji[1,2]

[1] Institut de Physique Théorique (URA 2306 du CNRS), CEA/DSM/Saclay, 91191 Gif-sur-Yvette Cedex, France
[2] High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

(Received 1 May 2013; published 27 June 2013)

In this paper, we show how classical statistical field theory techniques can be used to efficiently perform the numerical evaluation of the nonperturbative Schwinger mechanism of particle production by quantum tunneling. In some approximation, we also consider the backreaction of the produced particles on the external field, as well as the self-interactions of the produced particles.

DOI: 10.1103/PhysRevD.87.125035 PACS numbers: 11.15.Kc

Some references

B. Kasmaei and M. Strickland, Phys. Rev. D 102, 014037 (2020) **[photons]**

B. Kasmaei and M. Strickland, Phys. Rev. D 99, 034015 (2019) **[dileptons]**

L. Bhattacharya, R. Ryblewski, and M. Strickland, Phys. Rev. D 93, 065005 (2016) **[dileptons]**

R. Ryblewski and M. Strickland, Phys. Rev. D 92, 025026 (2015) **[dileptons]**

M. Martinez and M. Strickland, Phys. Rev. Lett. 100, 102301 (2008) **[dileptons]**

B. Schenke and M.Strickland, Phys. Rev. D76, 025023 (2007) **[photons]**

M. Strickland, Phys. Lett. B 331, 245 (1994) **[both]**