(Personal) Summary of QM2017 conference: Theory

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EMMI NQM Seminar

February 15, 2017

Venue: Hyatt Regency, downtown Chicago

NEWS

MASS MOONING PLANNED AT CHICAGO'S TRUMP TOWER

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Hundreds of people plan to moon the Chicago's Trump Tower in an attempt to persuade Donald Trump to release his tax returns. (Bailey Davis/Facebook)

Friday, February 03, 2017

CHICAGO (WLS) -- Hundreds of people plan to moon the Chicago's Trump Tower in an eye-catching attempt to persuade Donald Trump to release his tax returns.

According to the Facebook event for "Chicago Moons the Trump Tower," interested parties should meet at Trump Tower around 3:30 p.m. on Feb. 12 and be prepared to drop their pants by "the crack" of 4:00 p.m.

The Facebook event reads: "Donald Trump doesn't think the American people want to see his tax returns, so let's show him that we do in the classiest way possible!"

So far, more than 400 people on Facebook said they will attend, and another 1,700 said they're interested.

Topics addressed in QM2017

- New developments.
- QGP in small systems.
- Initial state physics and approach to thermal equilibrium.
- Collective dynamics.
- Electroweak probes.
- Correlations and fluctuations.
- Strongly coupled systems.
- QCD at high temperature.
- Baryon-rich QCD matter.
- Jets and jet quenching.
- Heavy flavor and quarkonium.

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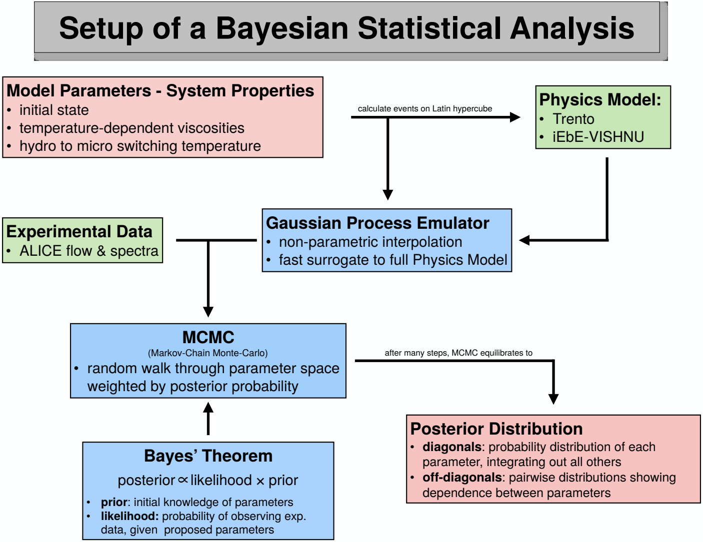
QGP parameters from Bayesian analysis (Steffen Bass)

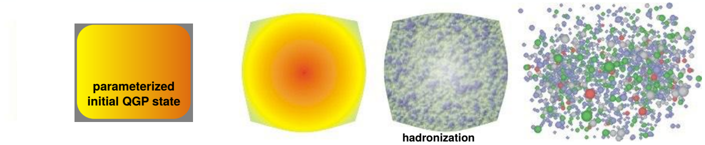


Determination of QGP parameters from Bayesian analysis

Physics Model: Trento + iEbE-VISHNU

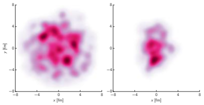
QGP and hydrodynamic expansion

hadronic phase and freeze-out



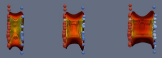
Trento:

- parameterized initial condition model based on phenomenological concepts for entropy deposition to a QGP



iEbE-VISHnew:

- EbE 2+1D viscous RFD
- describes QGP dynamics & hadronization
- EoS from Lattice QCD
- temperature-dependent shear and bulk viscosity as input



UrQMD:

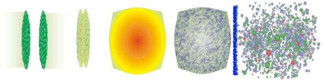
- non-equilibrium evolution of an interacting hadron gas
- hadron gas shear & bulk viscosities are implicitly contained in calculation

Determination of QGP parameters from Bayesian analysis

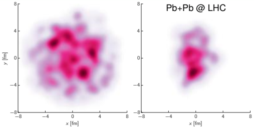
Calibration Parameters

- the calibration parameters are the model parameters that codify the physical properties of the system that we wish to characterize with the analysis

- hydro to micro switching temperature T_{sw}



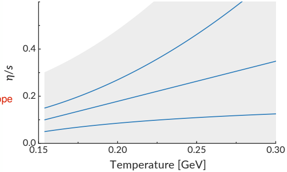
Trento initial condition:
- p: attenuation parameter - entropy deposition
- k: governs fluctuation in nuclear thickness
- w: Gaussian nucleon width



temperature dependent shear viscosity:

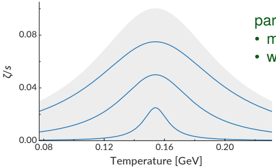
$$\eta/s(T) = (\eta/s)_{min} + (\eta/s)_{slope} \times (T-T_C)\times(T/T_C)^{\beta}$$

parameters:
- intercept: $(\eta/s)_{min}$ at T_C
- slope: $(\eta/s)_{slope}$
- curvature: β



temperature dependent bulk viscosity:

$$\zeta/s(T)=(\zeta/s)_{max} / [1+(T-T_C)^2/\Gamma^2]$$



parameters:
- magnitude $(\zeta/s)_{max}$
- width: Γ

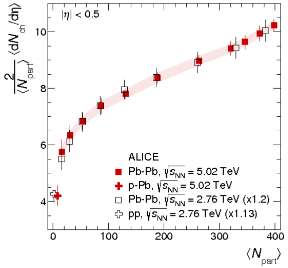
Determination of QGP parameters from Bayesian analysis

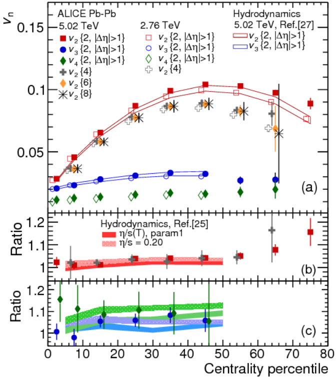
Training Data

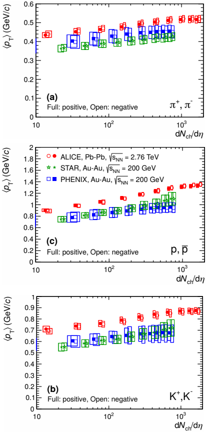
Data:

- ALICE v_2, v_3 & v_4 flow cumulants
- identified & charged particle yields
- identified particle mean p_T
- 2 beam energies:
  2.76 & 5.02 TeV

the entire success of the analysis depends on the quality of the exp. data!



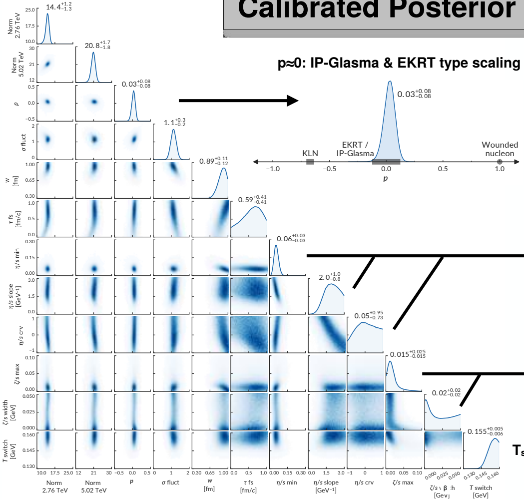




Determination of QGP parameters from Bayesian analysis

Calibrated Posterior Distribution

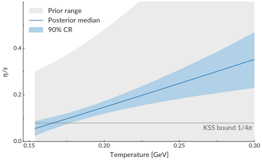
p≈0: IP-Glasma & EKRT type scaling

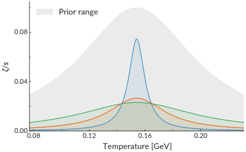


$T_{sw} \lesssim T_c$

- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

temperature-dependent viscosities:



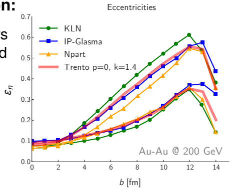


Determination of QGP parameters from Bayesian analysis

Summary I: Key Physics Results

Trento initial condition:

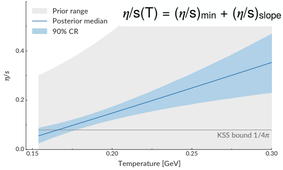
- analysis strongly favors eccentricity scaling and entropy deposition of EKRT & IP-Glasma model
- Glauber and KLN models strongly disfavored



temperature dependent shear viscosity:

- analysis favors small value and shallow rise
- slope vs. curvature needs disambiguation

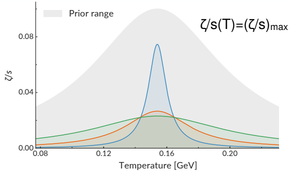
$\eta/s(T) = (\eta/s)_{min} + (\eta/s)_{slope} \times (T-T_C)\times(T/T_C)^{\beta}$



temperature dependent bulk viscosity:

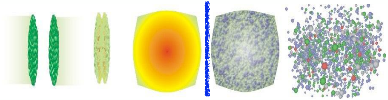
- non-zero value at T_C favored
- ambiguities exist for peak hight vs. width

$\zeta/s(T)=(\zeta/s)_{max} / [1+(T-T_C)^2/\Gamma^2]$



hydro to micro switching temperature T_{sw}

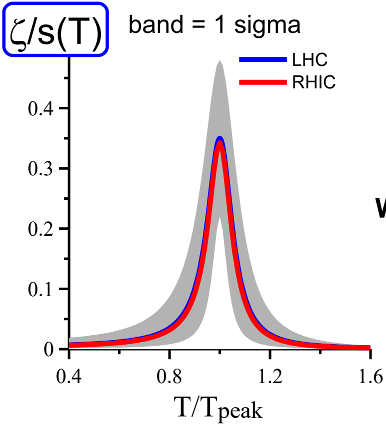
- strong likelihood for a value of T_{sw} just around T_C
- indicative of the non-equilibrium nature and dynamical breakup of the hadronic system



Bulk viscosity from Bayesian analysis (Gabriel Denicol)

Extraction of ζ/s(T) with MADAI Emulator

Model: IP-Glasma + MUSIC (bulk&shear)



ζ/s(T) parametrized as a Breit-Wigner distribution

$$\frac{\zeta}{s}(T) = B_{\text{norm}} \frac{B_{\text{width}}^2}{\left(\frac{T^2}{T_{\text{peak}}^2} - 1\right)^2 + B_{\text{width}}^2}$$

Within this model, shape of bulk viscosity seems to be well determined

But temperature where it peaks is unknown ...

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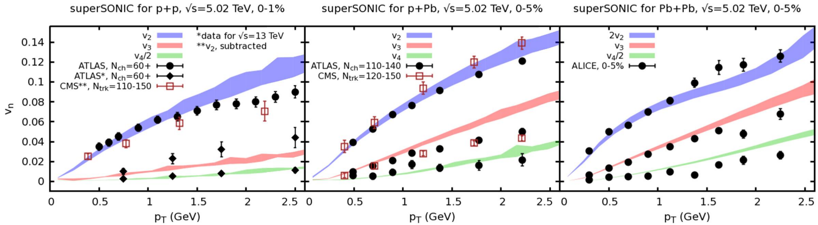
"Unreasonable" success of hydro



[1701.07145, see poster H8 by R. Weller]

- "Blind luck" (?)
- "Full equilibration in p+p" (?)
- something else (?)

When is Hydro applicable?

Answer (version 2001):

System in local thermal equilibrium. For nuclear collisions, happens after

$$\tau \geq 1.5\alpha_s^{-13/5} Q_s^{-1}$$

(or $\tau > 6.9$ fm if $Q_s \sim 1$ GeV, $\alpha_s \sim 0.3$)

[Baier, Mueller, Schiff, Son, 2001]

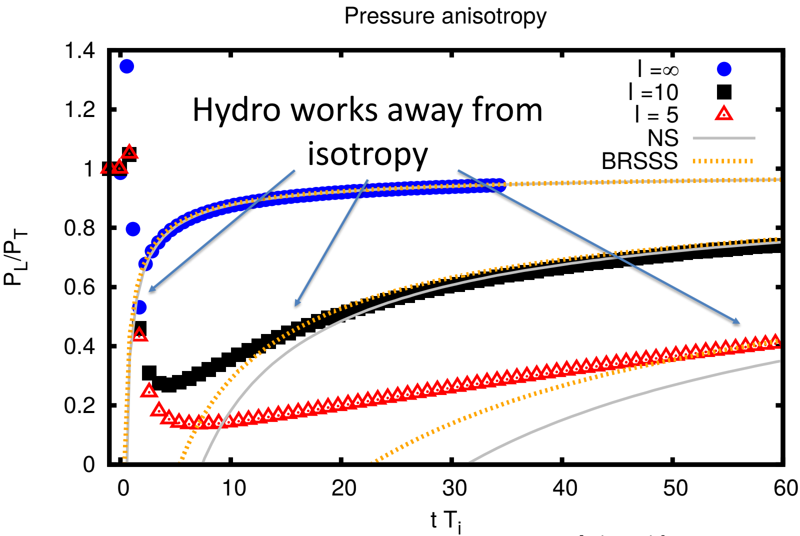
When is Hydro applicable?

Answer (version 2005):

Thermal equilibrium not needed. Local isotropy will suffice, e.g. $T^{ab}=\mathrm{diag}(\varepsilon,p,p,p)$

[Arnold, Lenaghan, Moore, Yaffe, 2005]

Equilibriation?



[adapted from 1512.05347]

When is Hydro applicable?

- Empirical Fact: Hydro works quantitatively even for anisotropic systems
- Onset of quantitative hydro description unrelated to thermalization or isotropization
- New type of phenomenon ("hydrodynamization"=onset of hydro behavior)

[Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann, 1101.0618]

Hydro as an EFT

- Write down quantities using EFT variables and their gradients
- Energy-Momentum Tensor for relativistic fluid

$$T^{ab} = (\epsilon + P)u^a u^b + P g^{ab} - 2\eta\nabla^{\langle a}u^{b\rangle} + \dots$$

- No thermal equilibrium or particle description needed
- Seems we need small gradients!

Hydro as an EFT

- What if we had LARGE gradients?
- Try to improve description by including higher orders in EFT gradient series
- E.g. Bjorken flow, go to order 240 (AdS/CFT)

$$T(\tau) = \hat{\tau}^{-1/3}\left(1 + \sum_{n=1}^{240} \alpha_n \hat{\tau}^{-2n/3}\right)$$

- Find: $\alpha_n \sim n!$, gradient series diverges

[1302.0697, 1503.07514, 1603.05344, 1608.07869, 1609.04803]

Hydro as an EFT

- Gradient series diverges
- But it is Borel-summable! [Heller et al, 1302.0697]
- Borel-resumming AdS/CFT gradient series:

$$T(\tau) = T_{\text{hydro}}(\tau) + \gamma \exp\left[-i \int d\hat{\tau} \left(\hat{\omega}_{\text{Borel}} \hat{\tau}^{-1/3} + \sum_{n=1} \hat{\omega}_n \hat{\tau}^{-(2n+1)/3}\right]\right) + \ldots$$

- T_{hydro} is essentially standard Navier-Stokes
- Extra pieces non-analytic in gradient expansion; this is why grad series diverges!

When is Hydro applicable?

Answer (version 2016):

Hydrodynamics is applicable and quantitatively reliable as long as contribution from non-hydro modes can be neglected[1].

[PR, 1609.02820]

No need of thermal equilibrium!
No need of isotropy!

[1] If a local rest frame exists.

Implications

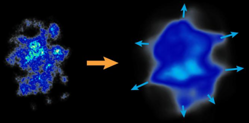
Hydro matching data does not indicate the presence of an equilibrated QGP

Similar results also presented by Jorge Noronha: “The onset of fluid-dynamical behavior in relativistic kinetic theory”.

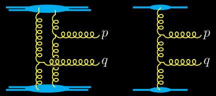
Collectivity in small systems

ORIGINS OF COLLECTIVITY

1. **Final state correlations:**
   Particles acquire momentum space correlations via final state interactions (conversion of spatial structure into momentum correlations e.g. via hydrodynamic flow)

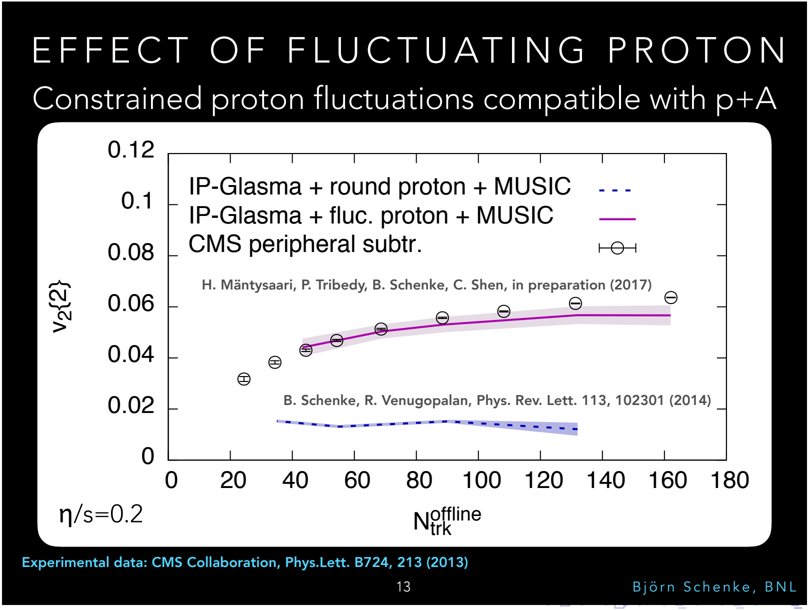


2. **Initial state correlations:**
   Particles are produced with their momentum space correlations



Björn Schenke, BNL

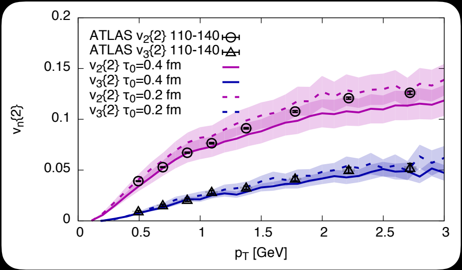
Collectivity in small systems

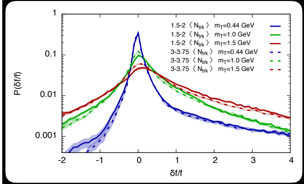


Collectivity in small systems

IP-Glasma+MUSIC p+Pb

H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)





$\eta/s=0.2$

ATLAS Collaboration, Phys.Rev. C90 (2014) 044906

Fair warning: Strong dependence on whether initial shear stress tensor is included and the relaxation time. δf can be $\gg f$ in many freeze-out surface cells

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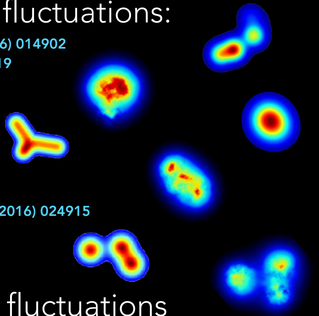
Collectivity in small systems

INCREASED INTEREST IN FLUCTUATING PROTON SHAPE AND SIZE



1. Wounded quarks and shape fluctuations:

   P. Bożek, W. Broniowski, M. Rybczyński, Phys. Rev. C94 (2016) 014902
   K. Welsh, J. Singer, U.W. Heinz, Phys. Rev. C94 (2016) 024919
   R. D. Weller and P. Romatschke arXiv:1701.07145
   P. Bozek, W. Broniowski, arXiv:1701.09105
   ...

   TALK BY S. MORELAND, WED. 10:40

2. Size fluctuations

   D. McGlinchey, J.L. Nagle, D.V. Perepelitsa, Phys. Rev. C94 (2016) 024915
   ...

3. Shape fluctuations from spin fluctuations

   M. Habich, G.A. Miller, P. Romatschke, W. Xiang, Eur.Phys.J. C76 (2016) 408
   ...

Proton substructure also important for particle production:
PHENIX Collaboration, Phys.Rev. C89 (2014) 044905

16 Björn Schenke, BNL

Dilepton flow within hydro (Gojko Vujanovic)

Viscous hydrodynamics & bulk pressure

4

- Dissipative hydrodynamic equations including coupling between bulk and shear viscous terms:

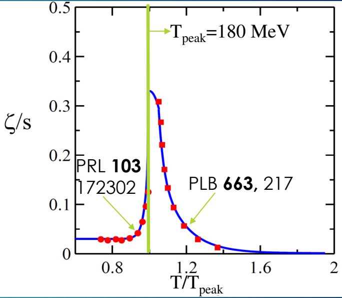
$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = T_0^{\mu\nu} - \Pi\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$T_0^{\mu\nu} = \varepsilon u^\mu u^\nu - P\Delta^{\mu\nu}$$

$$\tau_\Pi\dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_\pi\dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \phi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma_\alpha^{\nu\rangle} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$



$\eta/s = constant$

- Other than ζ and η, all transport coefficients are in G.S. Denicol et al. PRD **85** 114047, PRC **90** 024912.
- $P(\varepsilon)$: Lattice QCD EoS [P. Huovinen & P. Petreczky, NPA **837**, 26]. (s95p-v1)

Rates from hadronic medium

Thermal dilepton rates from HM

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- The rate involves:

$$\frac{d^4R}{d^4q} = \frac{\alpha^2}{\pi^3}\frac{L(M)}{M^2}\frac{m_V^4}{g_V^2}\left\{-\frac{1}{3}\left[Im\, D_V^R\right]_\mu^\mu\right\} n_{BE}\left(\frac{q\cdot u}{T}\right)$$

- Self-Energy [Eletsky, et al., PRC **64**, 035202]

$$\Pi_{Va} = -\frac{m_a m_V T}{\pi q}\int \frac{d^3k}{(2\pi)^3}\frac{\sqrt{s}}{k^0} f_{Va}(s) n_a(x)\,; \quad where \quad x = \frac{u\cdot k}{T}$$

- Viscous extension to thermal distribution function

$$T_0^{\mu\nu} + \pi^{\mu\nu} - \Pi\Delta^{\mu\nu} = \int \frac{d^3k}{(2\pi)^3 k^0} k^\mu k^\nu \left[n_{a,0}(x) + \delta n_a^{shear}(x) + \delta n_a^{bulk}(x)\right]$$

$$\delta n_a^{shear} = n_{a,0}(x)\left[1 \pm n_{a,0}(x)\right]\frac{k^\mu k^\nu \pi_{\mu\nu}}{2T^2(\varepsilon + P)}$$

→ The usual 14-moment expansion of Boltzmann equation in the RTA limit, see e.g. PRC **68**, 034913

$$\delta n_a^{bulk} = -\frac{\Pi\left[\frac{z^2}{3x} - \left(\frac{1}{3} - c_s^2\right)x\right]}{15(\varepsilon + P)\left(\frac{1}{3} - c_s^2\right)^2} n_{a,0}(x)\left[1 \pm n_{a,0}(x)\right]; \quad where\ z = \frac{m}{T}$$

→ RTA limit of Boltzmann equation, see PRC **93**, 044906

- Therefore: $\Pi_{Va} \to \Pi_{Va}^{ideal} + \delta\Pi_{Va}^{shear} + \delta\Pi_{VA}^{bulk}$

Rates from QGP

Bulk viscous corrections: QGP rate

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- The Born rate

$$\frac{d^4R}{d^4q} = \int \frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3} n_q(x) n_{\bar{q}}(x)\sigma v_{12}\delta^4(q-k_1-k_2); \quad where \;\; x = \frac{u\cdot k}{T}$$

- Shear viscous correction is obtained using the usual 14-moment expansion of the Boltzmann equation in the RTA limit.

- Bulk viscous correction derived from a generalized Boltzmann equation, which includes thermal quark masses (m) [PRD **53**, 5799]

$$k^\mu \partial_\mu n - \frac{1}{2}\frac{\partial(m^2)}{\partial \boldsymbol{x}} \cdot \frac{\partial n}{\partial \boldsymbol{k}} = C[n]$$

- In the RTA approximation with α_s a constant [PRC **93**, 044906]

$$\delta n_q^{bulk} = -\frac{\Pi\left[\frac{z^2}{x} - x\right]}{15(\varepsilon + P)\left(\frac{1}{3} - c_s^2\right)} n_{FD}(x)[1 - n_{FD}(x)]; \quad where \; z = \frac{m}{T}$$

- Therefore: $\dfrac{d^4R}{d^4q} = \dfrac{d^4R^{ideal}}{d^4q} + \dfrac{d^4\delta R^{shear}}{d^4q} + \dfrac{d^4\delta R^{bulk}}{d^4q}$

Various sources

Dilepton Cocktail

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- For $M > 0.3\ GeV$, sources of cocktail dileptons considered here are originating from $\eta, \eta', \omega, \phi$ mesons.
- Dileptons originate from Dalitz decays $\eta, \eta' \rightarrow \gamma \ell^+ \ell^-$, $\omega \rightarrow \pi^0 \ell^+ \ell^-$ and $\phi \rightarrow \eta \ell^+ \ell^-$ as well as direct decays $\omega, \phi \rightarrow \ell^+ \ell^-$.
- Using the Vector Dominance Model (VDM), the dynamics of these decays has been computed in Phys. Rept. **128**, 301.
- The goal here to obtain the final hadronic distribution of $\eta, \eta', \omega, \phi$ to be decayed into dileptons. Two methods will be used:
    1. *Direct hadron production from hydrodynamic simulation (Cooper-Frye prescription including only hadronic resonance decays)*
    2. *Hadrons produced after UrQMD (to capture hadronic collisions, in addition to resonance decays).*

Thermal vs cocktail

Thermal + Cocktail dileptons: LHC/RHIC

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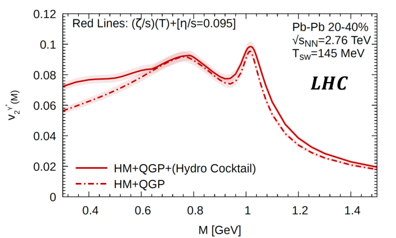
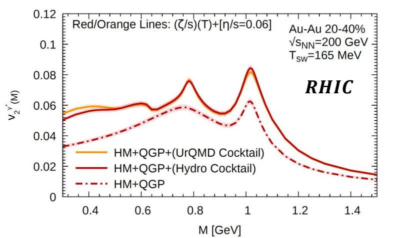
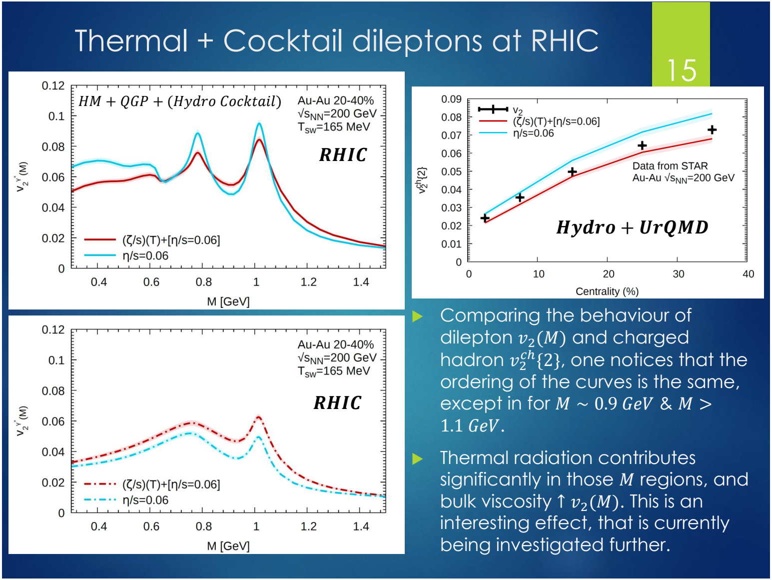


- At the LHC, as $T_{sw} = 145$ MeV, the contribution of the dilepton cocktail from a hydro simulation does not play a prominent role as far as the total $v_2(M)$, except in the region $M < 0.65\ GeV$.



- At RHIC, as $T_{sw} = 165$ MeV, the footprint of the dilepton cocktail left onto the total $v_2(M)$ is more significant. However, the method employed to obtain the cocktail (e.g. Hydro vs UrQMD) is less important.

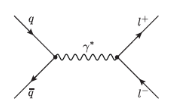
Viscous effects



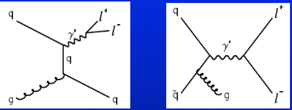
Virtual photon polarization (Gordon Baym)

Virtual photon polarization

Off-shell photon, γ^*, with $Q^2 > 0$



Drell-Yan

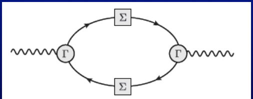


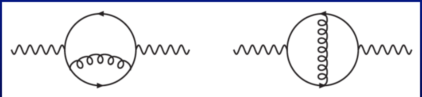
with gluons

p, p' = lepton 4-momenta

Q = p+p'
s = p - p

Production rate of virtual photons ~ imaginary part of photon polarization diagram $\rho_{\mu\nu}(q)$





times ME squared $L^{\mu\nu}$ for making dilepton pair (Drell-Yan)

$$\frac{dR_{l^+l^-}}{d^3\bar{p}d^3\bar{p}'} = \frac{\alpha^2}{4\pi^4 Q^4}\,\rho_{\mu\nu}(q)L^{\mu\nu}(p,p')$$

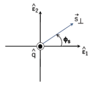
Dilepton anisotropy

Dilepton rate

$$\frac{dR_{l^+l^-}}{d^3\bar{p}\,d^3\bar{p}'} = \frac{\alpha^2}{4\pi^4 Q^4}\,\rho_{\mu\nu}(q)L^{\mu\nu}(p,p')$$

$$\frac{1}{2}\rho^{\mu\nu}L_{\mu\nu} = 2Q^2\bar{\rho}^{\mathrm{T}} + \left(s_\perp^2 + 4m^2\right)\rho^{\mathrm{L}} + \left(Q^2 + (qn)^2 - (sn)^2\right)\rho_n - s_\perp^2\left(\bar{\rho}^{\mathrm{T}} + \delta\rho^{\mathrm{T}}\cos 2\phi_s\right)$$

$$\bar{\rho}^{\mathrm{T}} \equiv (\rho_1^{\mathrm{T}} + \rho_2^{\mathrm{T}})/2 \qquad \delta\rho^{\mathrm{T}} \equiv (\rho_2^{\mathrm{T}} - \rho_1^{\mathrm{T}})/2 \qquad \vec{s}_\perp = s_1\vec{\varepsilon}_1 + s_2\vec{\varepsilon}_2$$



Real photon emission

$$\frac{dR_\gamma}{d^3\bar{q}} = \frac{\alpha}{2\pi^2}\left(\bar{\rho}^{\mathrm{T}} + \delta\rho^{\mathrm{T}}\cos 2\phi_\varepsilon\right)$$

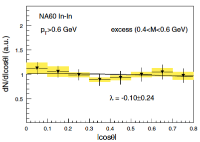
$$d^3\bar{q} = d^3q/2|\vec{q}|$$

$$(\varepsilon\varepsilon_1) \equiv -\cos\phi_\varepsilon$$

Dilepton angular distribution

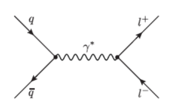
$$\propto 1 + \lambda\cos^2\theta_s + \mu\sin 2\theta\cos\phi_s + (\nu/2)\sin^2\theta\cos 2\phi_s$$

$$\lambda = \frac{\bar{\rho}^{\mathrm{T}} - \rho^{\mathrm{L}}}{\bar{\rho}^{\mathrm{T}} + \rho^{\mathrm{L}}}, \qquad \nu = 2\frac{\delta\rho^{\mathrm{T}}}{\bar{\rho}^{\mathrm{T}} + \rho^{\mathrm{L}}} \qquad \mu = 0$$



cf. NA60 (In-In at 158GeV/A SPS, PRL102, 2009) find λ, μ, ν consistent with 0. But average of data over all directions of total dilepton pair momenta loses anisotropy information.

Drell-Yan rate as illustrative example



rate for quark pair to produce virtual photon

$$H_{\mu\nu}(q,t) = 2(q_\mu q_\nu - g_{\mu\nu}Q^2 - t_\mu t_\nu) \qquad t = k - k'$$

$$\rho^{\mu\nu}(q) = 2(q_\mu q_\nu - g_{\mu\nu}Q^2)\langle 1\rangle - 2\langle t_\mu t_\nu\rangle$$

$$\langle X\rangle \equiv 3\sum_{\mathrm{f}} \frac{e_{\mathrm{f}}^2}{4\pi^2}\int d^3\bar{k}d^3\bar{k}'\, X\,\delta^{(4)}(q-k-k')f(\vec{k})\bar{f}(\vec{k}')$$

$$\begin{aligned} \rho_1^{\mathrm{T}} + \sin^2\theta\,\rho_n &= 2Q^2\langle 1\rangle - 2\langle(\varepsilon_1 t)^2\rangle, \\ \rho_2^{\mathrm{T}} &= 2Q^2\langle 1\rangle - 2\langle(\varepsilon_2 t)^2\rangle, \\ \rho^{\mathrm{L}} + (\bar{q}^0)^2\cos^2\theta\,\rho_n &= 2Q^2\langle 1\rangle - 2\langle(\varepsilon_{\mathrm{L}} t)^2\rangle \end{aligned}$$

$$\rho_n = -\frac{4}{\bar{q}^0\sin 2\phi}\langle(\varepsilon_1 t)(\varepsilon_{\mathrm{L}} t)\rangle \Rightarrow 0$$

Assume angular dep. temperature $f(\vec{k}) = \frac{1}{e^{\beta(\hat{k})k}+1}$

Weak anisotropy: $\delta\rho^{\mathrm{T}} \sim \beta_2 = \frac{1}{2}\int_{-1}^{1} d\cos\theta\,\beta(\theta)P_2(\cos\theta)$

Dileptons measure the second spherical harmonic of temperature

Other important developments

- QCD Equation of state and critical end-point estimates at $\mathcal{O}(\mu_B^6)$ (Sayantan Sharma).
- 3-D Glasma initial state from small-x evolution (Soren Schlichting).
- Angular structure of jet quenching within a hybrid strong/weak coupling model (Krishna Rajagopal).
- Lattice calculations of heavy quark potential at non-zero temperature (Peter Petreczky).
- Effective field theory for QCD thermodynamics (Sourendu Gupta).
- Hydrodynamics with critical slowing down (Misha Stephanov).
- Cumulants and correlation functions vs. the QCD phase diagram (Adam Bzdak).
- Several talks on anisotropic hydrodynamics (Michael Strickland, Mauricio Martinez, Harri Niemi).
- Several talks on chiral magnetic effects (Dmitri Kharzeev, Yuji Hirono, ...).