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PRC 90, 025204 (2014)

Electromagnetic Radiation in Hot QCD Matter

rates, electric conductivity, flavor susceptibility, and diffusion

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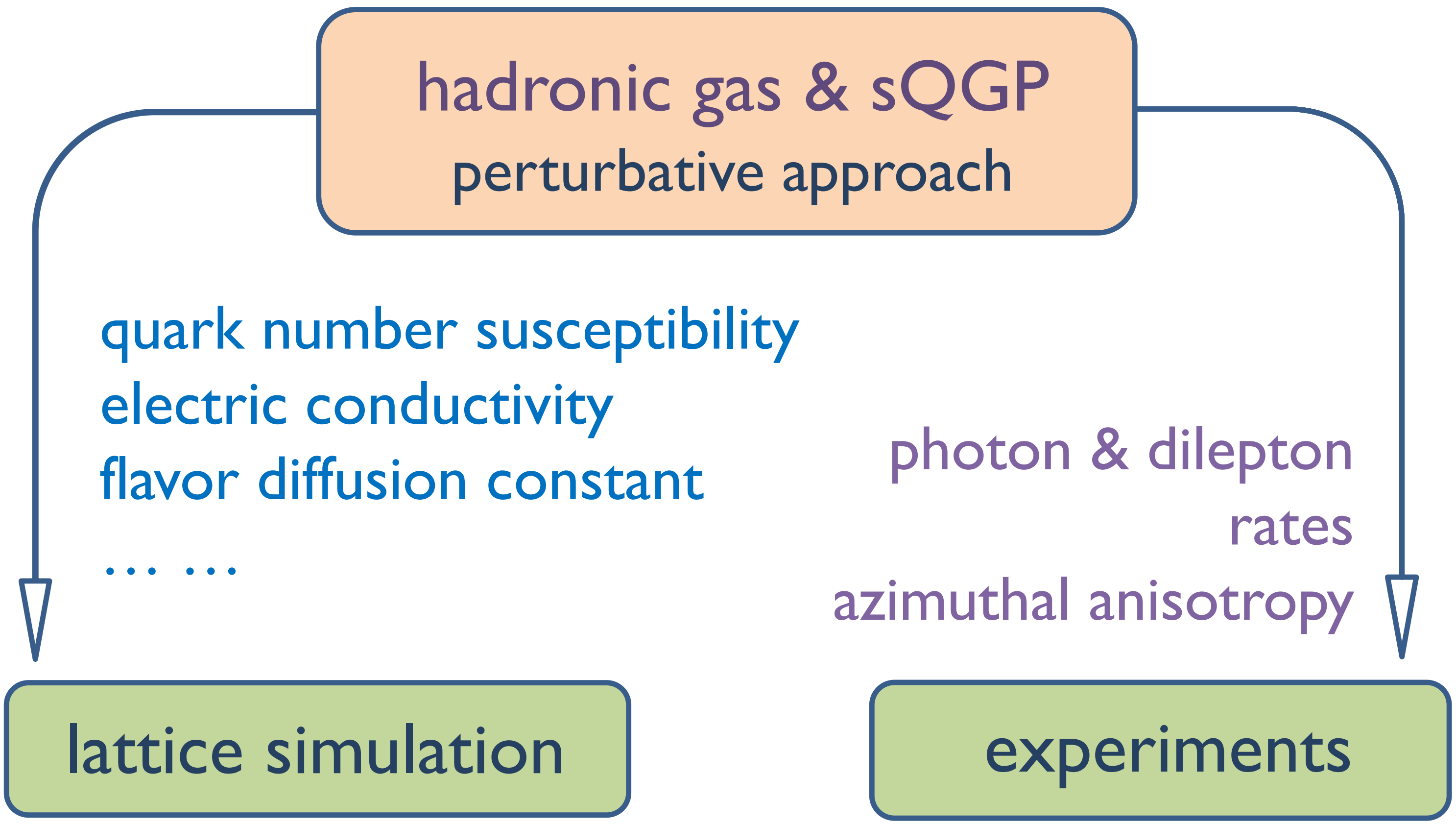
contents

- Experiments : current motivation
- EM radiation from hadronic gas
  - rates
  - mixing of vector and axial correlators
  - electric conductivity
- EM radiation from sQGP
  - rates
  - electric conductivity
- Future work

theory vs experiment

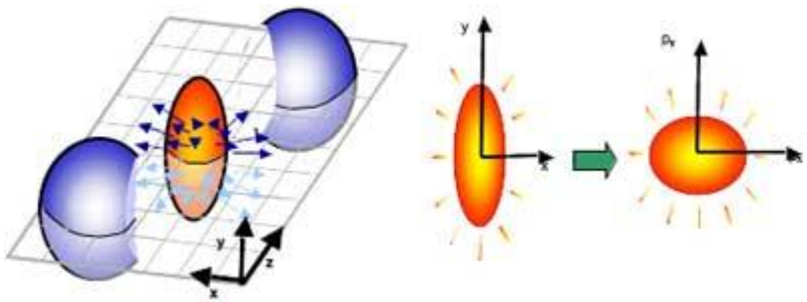


why photons & dileptons?

- no strong interaction
- can provide us direct information on dense medium

rates

$$\frac{d^4N}{MdMq_Tdq_Tdyd\phi}(M,q_T,y,\phi) = \mathbf{DetAcc}(M,q_T,y,\phi) \times \int_{\tau_0}^{\tau_{f,o}} \tau d\tau \int_{-\infty}^{\infty} d\eta \int_0^{r_{\max}} r dr \int_0^{2\pi} d\theta \times \left[\frac{dR}{d^4q}(q;T,\mu_B,\mu_\pi) \otimes \mathbf{Hydro}(T,\mu_B,\mu_\pi;\tau,\eta,r,\theta)\right]$$



azimuthal anisotropy

$$\frac{d^3N}{q_Tdq_Tdyd\phi} = \frac{1}{2\pi}\frac{d^2N}{q_Tdq_Tdy}\left(1+\sum_{n=1}^{\infty} 2v_n(q_T,y)\cos(n\phi)\right)$$

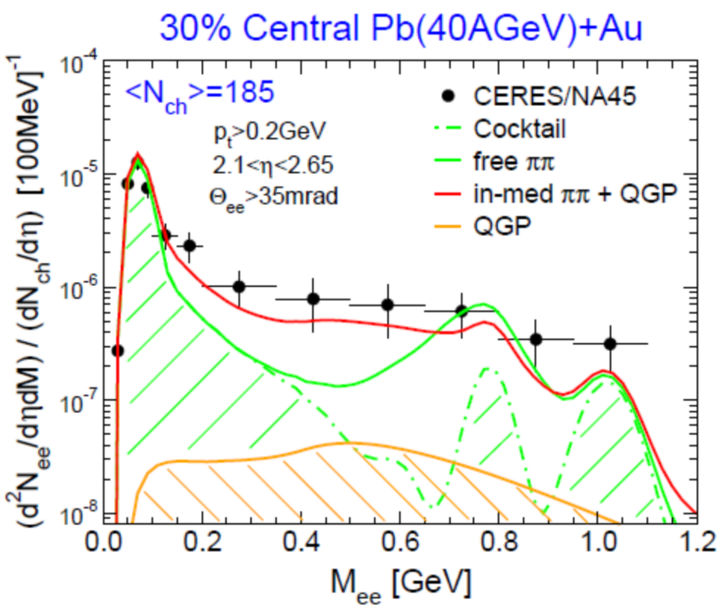
$$v_n(q_T,y) = \langle\cos(n\phi)\rangle_{q_T,y} = \frac{\int d\phi\cos(n\phi)[d^3N/q_Tdq_Tdyd\phi]}{\int d\phi\,[d^3N/q_Tdq_Tdyd\phi]}$$

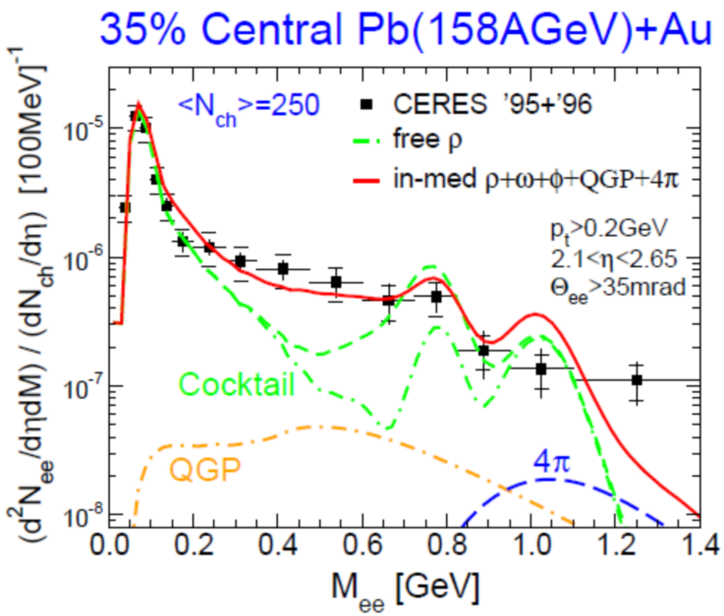
$$v_n(y) = \frac{\int q_Tdq_T\ v_n(q_T,y)\times[d^2N/q_Tdq_Tdy]}{\int q_Tdq_T\ [d^2N/q_Tdq_Tdy]},$$

$$v_n(q_T) = \frac{\int dy\ v_n(q_T,y)\times[d^2N/q_Tdq_Tdy]}{\int dy\ [d^2N/q_Tdq_Tdy]}.$$

CERES/NA45 (Pb+Au, 8.8 & 17.3 GeV)

R.Rapp, arXiv:1306.6394



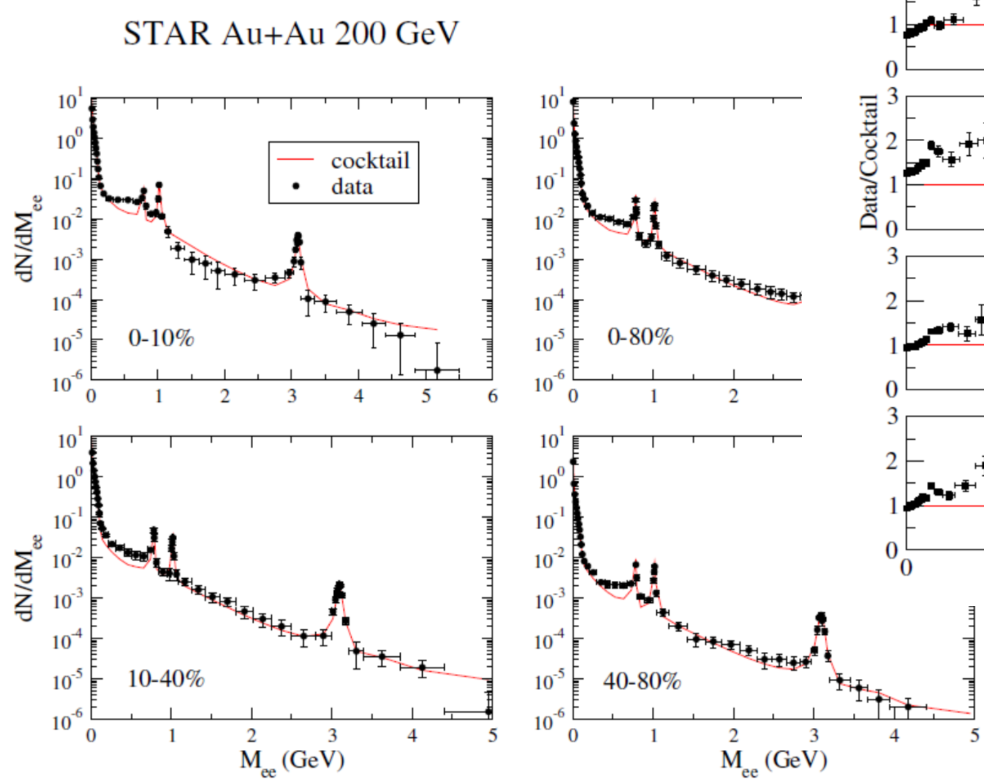


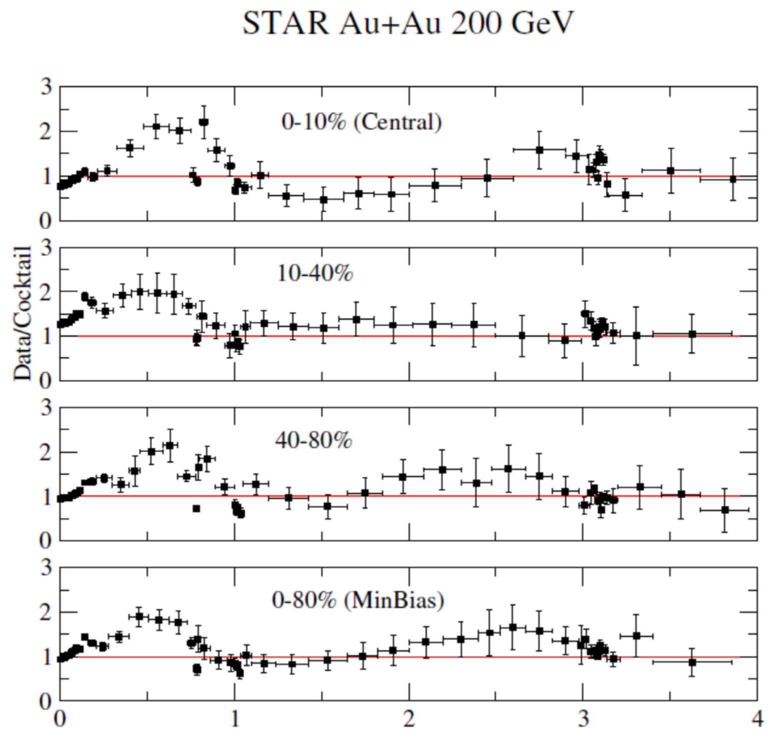
key question : low-mass dilepton enhancement

STAR (Au+Au, 200 GeV)

arXiv:1305.5447

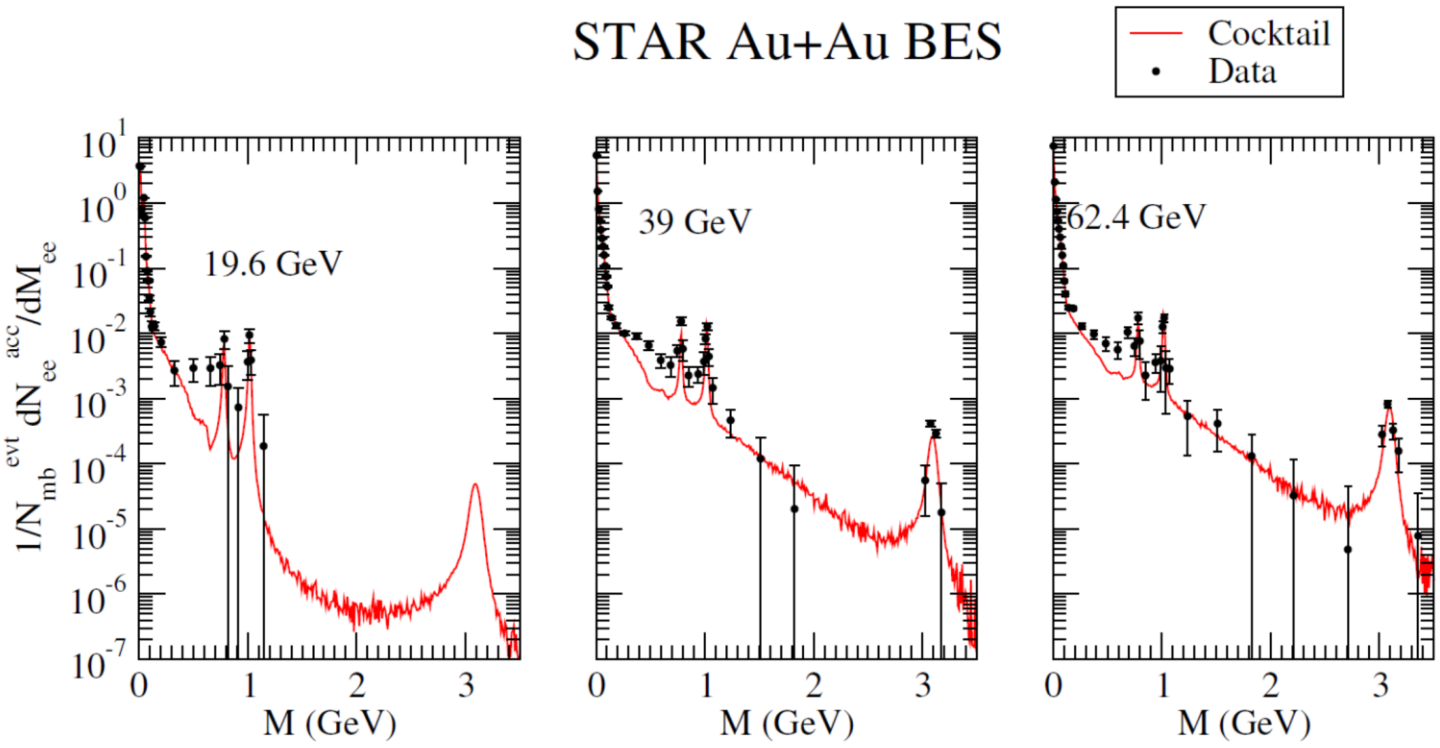
dilepton enhancement





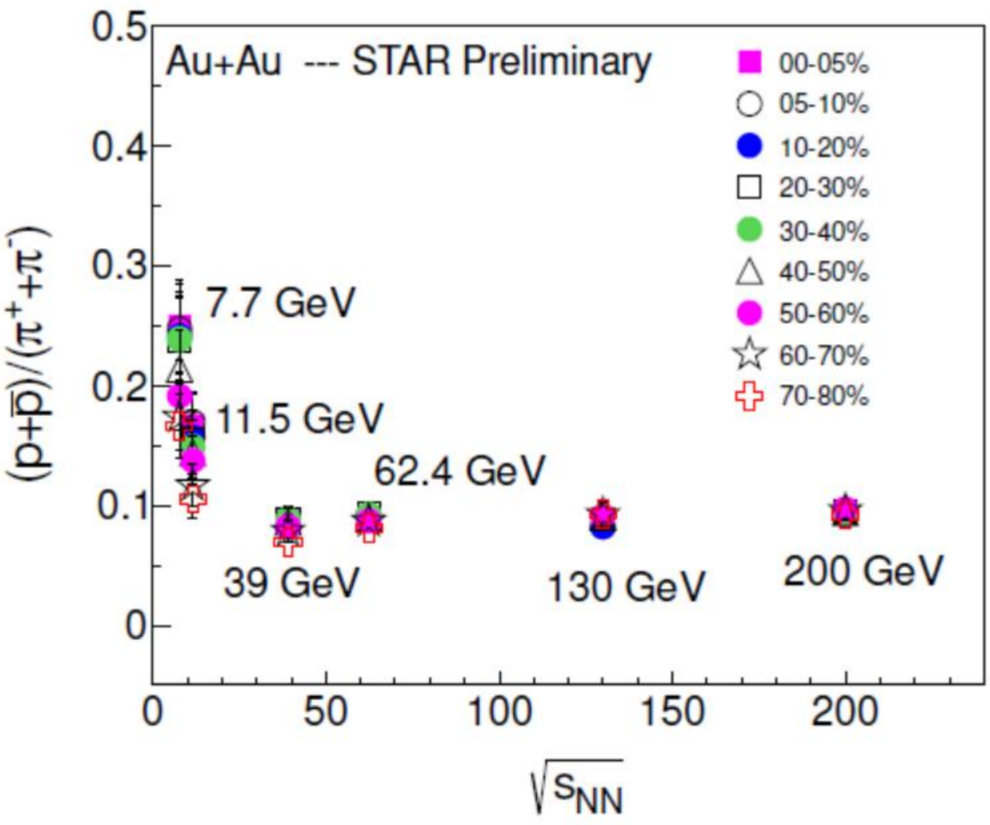
STAR (BES)

arXiv:1305.5447



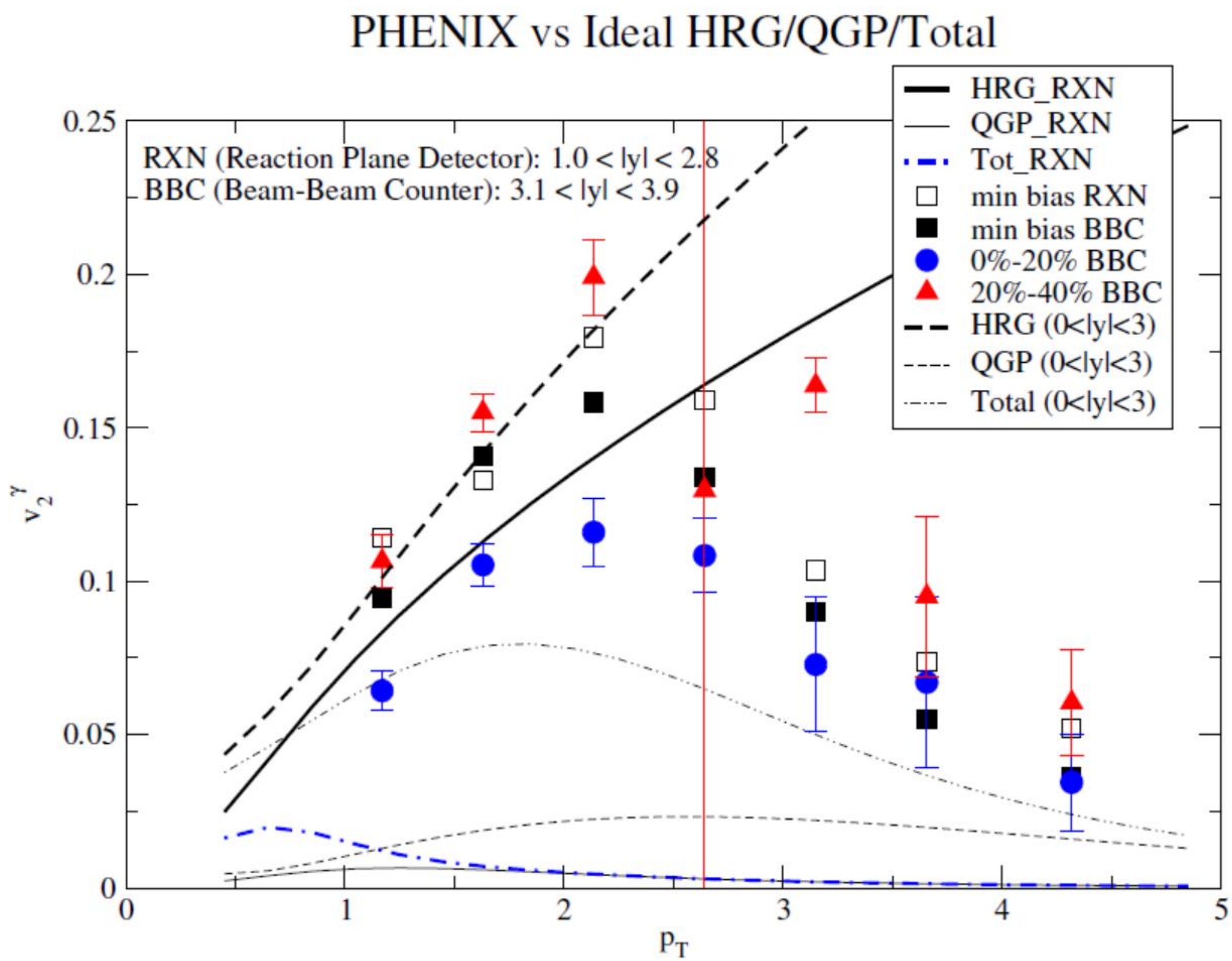
STAR (BES)

arXiv:1305.5447



PHENIX (Au+Au, 200 GeV)

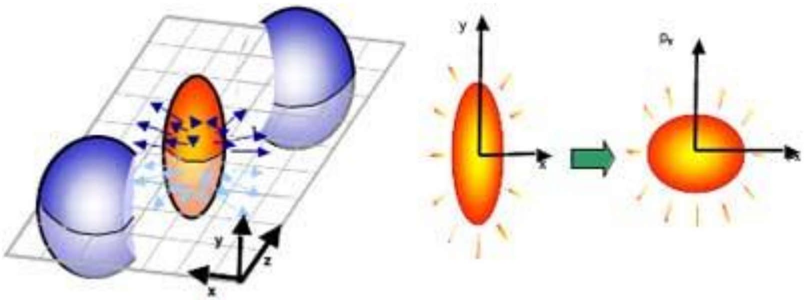
PRL 109, 122302 (2012)

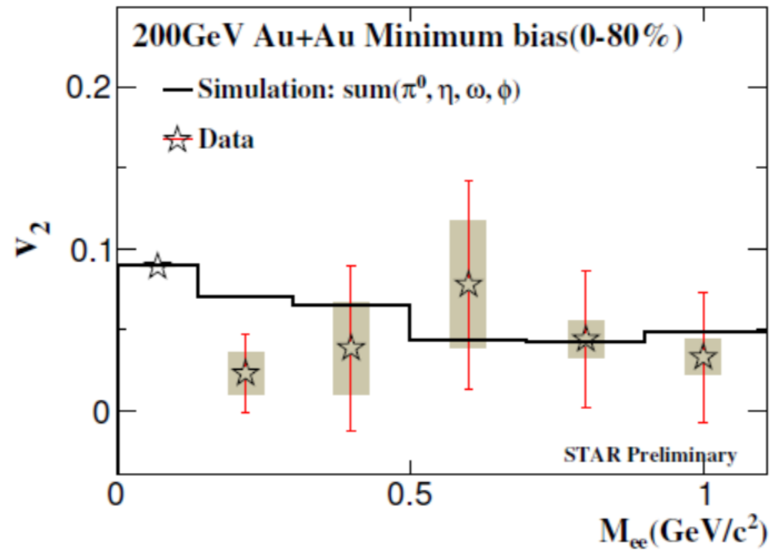


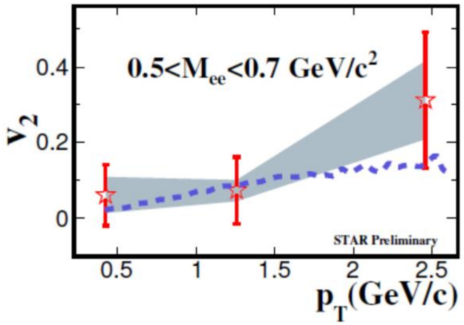
Dusling
Zahed

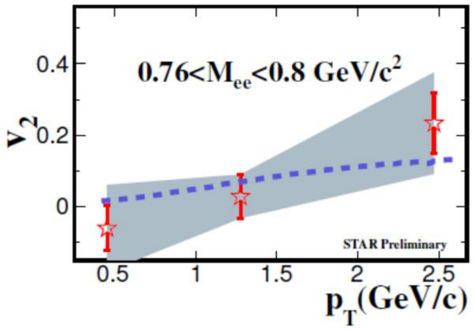
STAR (Au+Au, 200 GeV)

arXiv:1305.5447

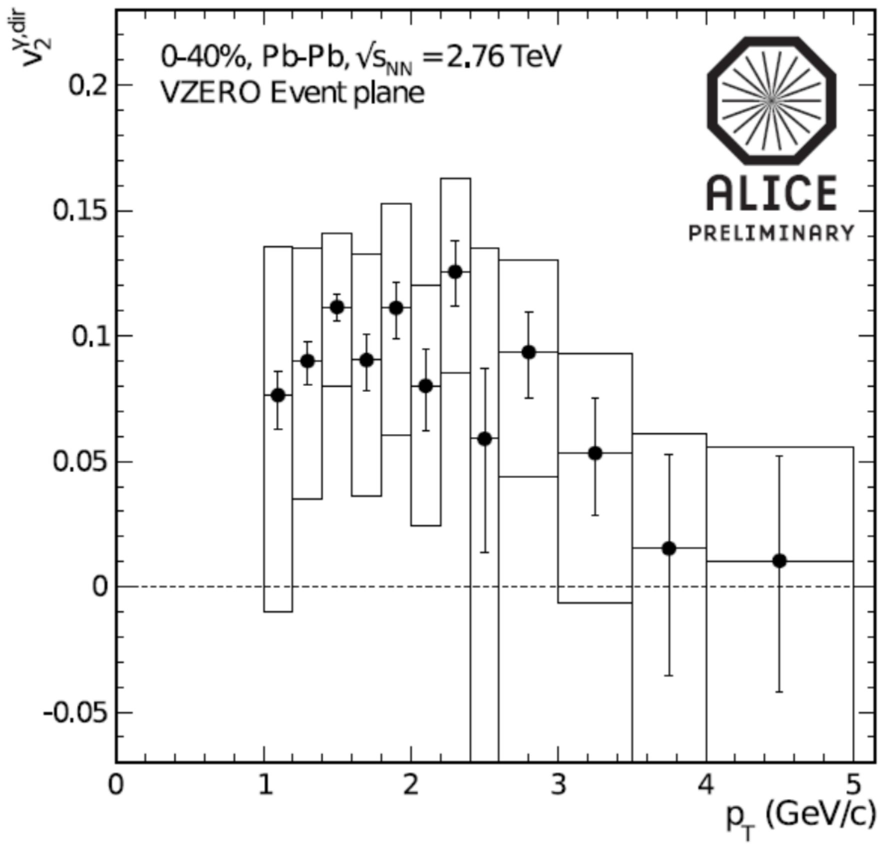








ALICE (Pb+Pb, 2.76 TeV) arXiv:1212.3995



motivation

right time to revisit dilepton & photon

in this work

- investigated on the basic properties of EM radiation from pionic gas & sQGP
- hydro evolution is not included, yet
- comparison with experiments is on-going

rate, hydro evolution, detector acceptance

$v_2(M)$ $v_2(p_T)$

$\frac{dN}{dM}$

$$\frac{d^4N}{MdMq_Tdq_Tdyd\phi}(M,q_T,y,\phi) = \mathbf{DetAcc}(M,q_T,y,\phi) \times \int_{\tau_0}^{\tau_{f,o}} \tau d\tau \int_{-\infty}^{\infty} d\eta \int_0^{r_{\max}} r dr \int_0^{2\pi} d\theta$$
$$\times \left[\frac{dR}{d^4q}(q;T,\mu_B,\mu_\pi) \otimes \mathbf{Hydro}(T,\mu_B,\mu_\pi;\tau,\eta,r,\theta)\right]$$

$\frac{dN}{dp_T}$

$\frac{dN}{dMd\eta}$

detector acceptance

hydro evolution

in this work

$$\frac{dR}{d^4q} \equiv \frac{dN}{d^4qd^4x}$$

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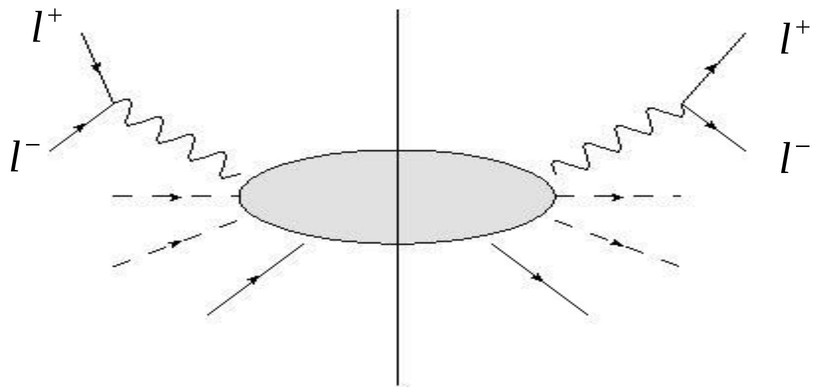
dilepton rates from correlation functions

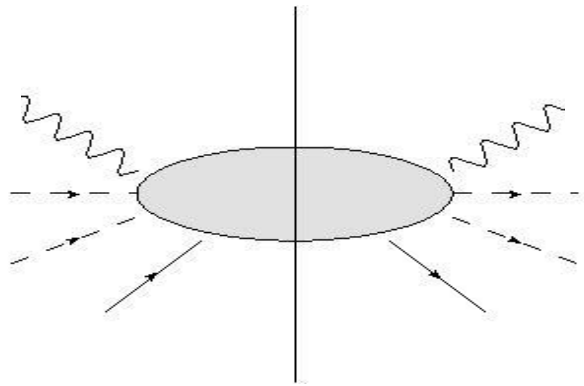


$$\frac{dR}{d^4q} = \frac{-\alpha^2}{6\pi^3 q^2}\left(1+\frac{2m_l^2}{q^2}\right)\left(1-\frac{4m_l^2}{q^2}\right)^{1/2}\mathbf{W}(q)$$

$$\mathbf{W}(q) = \int d^4x e^{-iq\cdot x}\mathrm{Tr}\left[e^{-(\mathbf{H}-\mathbf{F})/T}\,\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)\right]$$

$$\mathbf{J}_\mu(x) = \sum_f \tilde{e}_f\,\overline{\mathbf{q}}_f\gamma_\mu\mathbf{q}_f(x)$$

direct/virtual photon rates



$$\frac{q^0 dN}{d^3q} = -\frac{\alpha}{4\pi^2}\,\mathbf{W}(q)$$

$$M \to 0,\; N^* \approx N$$

$$\frac{dR}{d^4q} = \frac{2\alpha}{3\pi M^2}\left(1+\frac{2m_l^2}{M^2}\right)\left(1-\frac{4m_l^2}{M^2}\right)^{1/2}\left(\frac{q^0 dN^*}{d^3q}\right)$$

pionic gas : current work

$$\mathbf{W}^F(q) = \mathbf{W}_0^F(q) + \frac{1}{f_\pi^2}\int d\pi \mathbf{W}_\pi^F(q,k) + \frac{1}{2!}\frac{1}{f_\pi^4}\int d\pi_1 d\pi_2 \mathbf{W}_{\pi\pi}^F(q,k_1,k_2) + \cdots$$

$$\int d\pi = \int \frac{d^3k}{(2\pi)^3}\frac{n(E-\mu_\pi)}{2E}$$

$$\begin{aligned}
\mathbf{W}_0^F(q) &= i\int d^4x e^{iq\cdot x}\langle 0|T^*\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)|0\rangle \\
\mathbf{W}_\pi^F(q,k) &= i f_\pi^2\int d^4x e^{iq\cdot x}\langle \pi^a(k)|T^*\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)|\pi^a(k)\rangle \\
\mathbf{W}_{\pi\pi}^F(q,k_1,k_2) &= i f_\pi^4\int d^4x e^{iq\cdot x}\langle \pi^a(k_1)\pi^b(k_2)|T^*\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)|\pi^a(k_1)\pi^b(k_2)\rangle
\end{aligned}$$

vector & axial correlators & spectral functions

Steele, Yamagishi, Zahed, PLB (1996) : SU(2)
Lee, Yamagishi, Zahed, PRC (1998) : SU(3)

$$\mathbf{J}_\mu = \bar{q}\gamma_\mu Q^{\rm em} q = \mathbf{V}^3_\mu + \frac{1}{\sqrt{3}}\mathbf{V}^8_\mu$$

$$\mathrm{Im}\left(i\int_y e^{-iq\cdot y}\langle 0|T^*(\mathbf{V}^c_\mu(y)\mathbf{V}^d_\nu(0)|0\rangle\right) = \left(-q^2 g_{\mu\nu} + q_\nu q_\nu\right)\mathrm{Im}\mathbf{\Pi}^{cd}_V(q^2)$$

$$\mathrm{Im}\left(i\int_y e^{-iq\cdot y}\langle 0|T^*(\mathbf{j}^c_{A,\mu}(y)\mathbf{j}^d_{A,\nu}(0)|0\rangle\right) = \left(-q^2 g_{\mu\nu} + q_\nu q_\nu\right)\mathrm{Im}\mathbf{\Pi}^{cd}_A(q^2)$$

		$I^G(J^{PC})$	Mass (m_i)	Decay width (G_i)	Decay constant (f_i)
Π^I_V	$\rho(770)$	$1^+(1^{--})$	768.5	150.7	130.67
	$\rho(1450)$		1465	310	106.69
	$\rho(1700)$		1700	235	75.44
Π^Y_V	$\omega(782)$	$0^-(1^{--})$	781.94	8.43	46
	$\omega(1420)$		1419	174	46
	$\omega(1600)$		1649	220	46
	$\phi(1020)$	$0^-(1^{--})$	1020	4.43	79
	$\phi(1680)$		1680	150	79
Π^I_A	$a_1(1260)$	$1^-(1^{++})$	1230	400	190 (f_ρ)
Π^{UV}_A	$K_1(1270)$	$\frac{1}{2}(1^+)$	1273	90	90
	$K_1(1400)$		1402	174	90

$\Pi^I_V \equiv \Pi^{33}_V$

$\Pi^Y_V \equiv \frac{4}{3}\Pi^{88}_V$

spectral functions

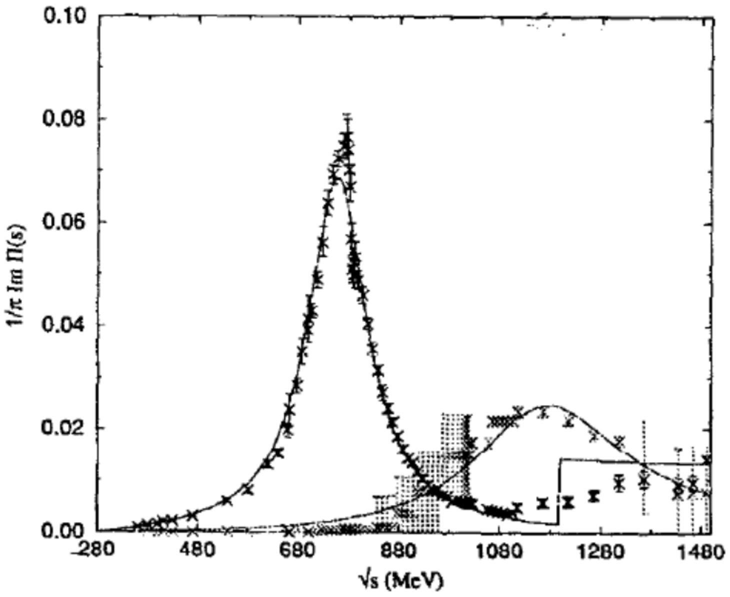
Steele, Yamagishi, Zahed, PLB (1996) : SU(2)
Lee, Yamagishi, Zahed, PRC (1998) : SU(3)

$$\Pi_V^I(q^2) = \frac{f_\rho^2}{q^2} \frac{m_\rho^2 + \gamma q^2}{m_\rho^2 - q^2 - i m_\rho \Gamma_\rho(q^2)}$$

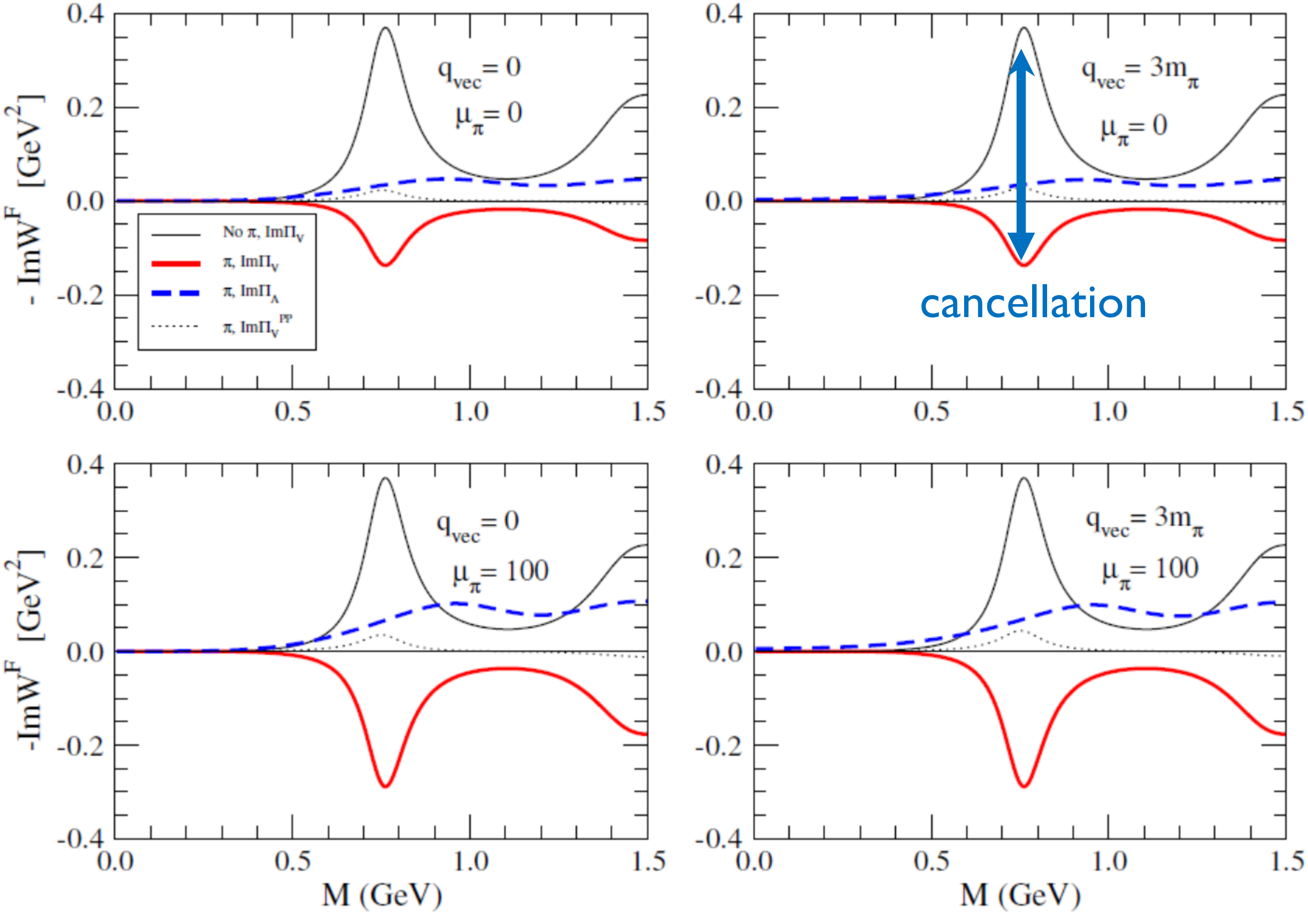
$$\Pi_A^I(q^2) = \frac{f_{a_1}^2}{m_{a_1}^2 - q^2 - i m_{a_1} \Gamma_{a_1}(q^2)}$$

$$\Gamma_\rho(q^2) = \theta(q^2 - 4m_\pi^2)\Gamma_{0,\rho} \frac{m_\rho}{\sqrt{q^2}} \left(\frac{q^2 - 4m_\pi^2}{m_\rho^2 - 4m_\pi^2} \right)^{3/2}$$

$$\Gamma_{a_1}(q^2) = \theta(q^2 - 9m_\pi^2)\Gamma_{0,a_1} \frac{m_{a_1}}{\sqrt{q^2}} \left(\frac{q^2 - 9m_\pi^2}{m_{a_1}^2 - 9m_\pi^2} \right)^{3/2}$$

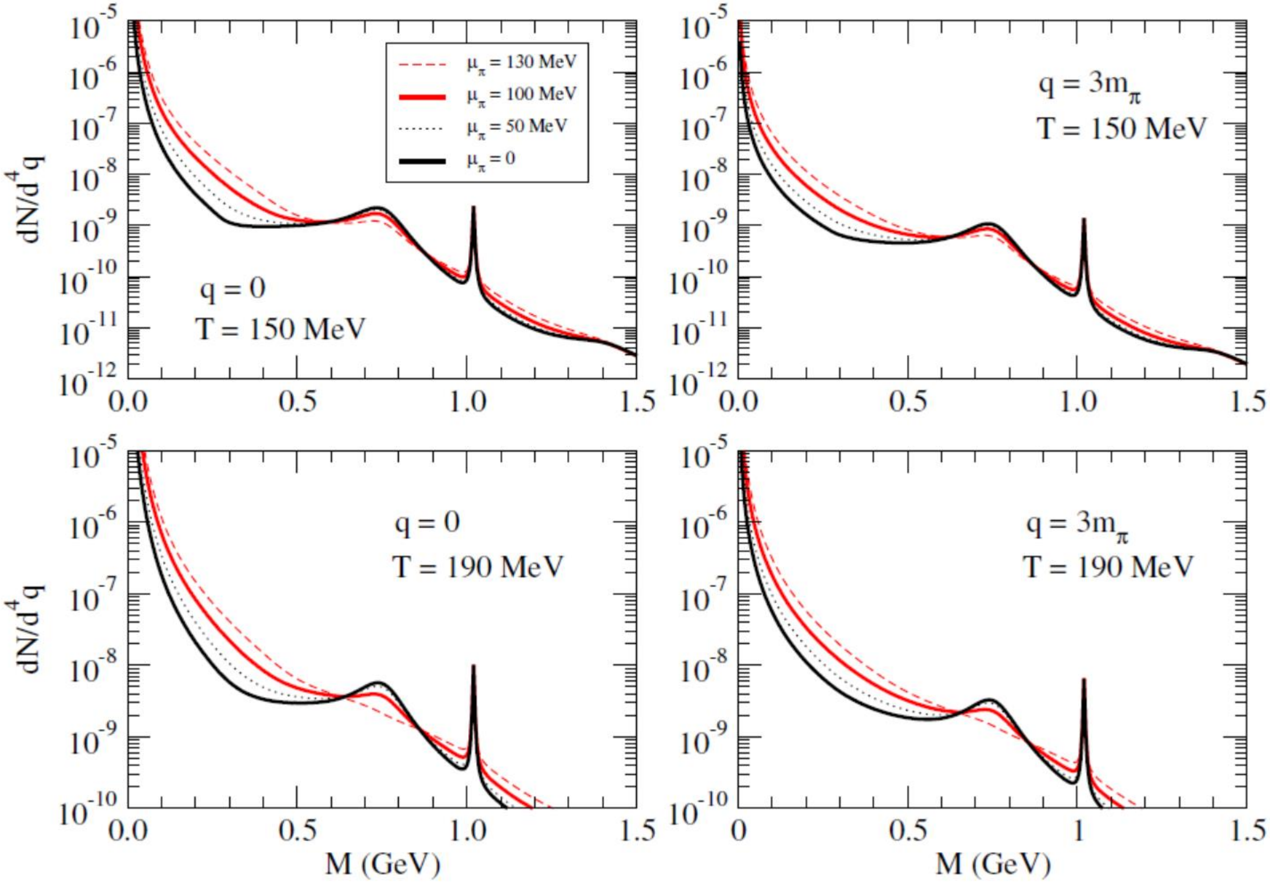


mixing between vector & axial (full up to one pion)



mixing between vector & axial → partial chiral symmetry restoration

dilepton rates (full up to two pion)



Low-mass enhancement due to mixing between vector & axial

electric conductivity (full up to two pion)

$$\rho_V(M,\vec{q}) = -\frac{2}{\tilde{\mathbf{e}}^2}\,\mathrm{Im}\mathbf{W}^R(M,\vec{q})$$

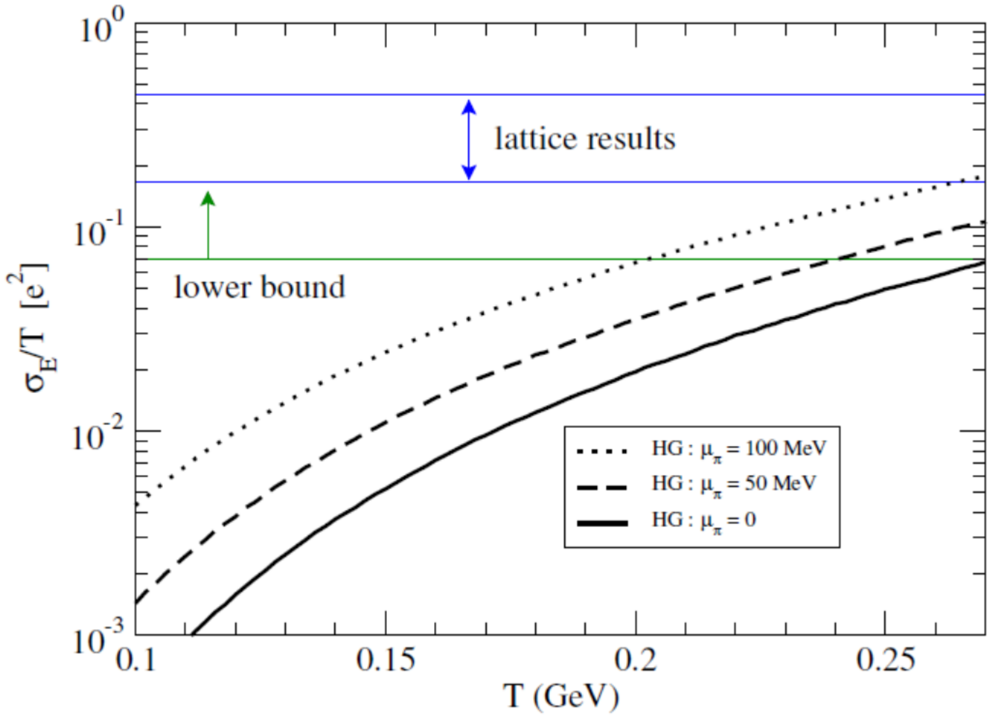
$$\tilde{\mathbf{e}}^2 \equiv \sum_f \tilde{e}_f^2$$

$$\rho_V = -\rho_{00} + \rho_{ii}$$

$$\rho_{ii}(M,\vec{0}) = \rho_V(M,\vec{0})$$

$$\sigma_E = \lim_{M\to 0}\frac{\tilde{\mathbf{e}}^2\rho_{ii}(M,\vec{0})}{6M} = \lim_{M\to 0}\frac{-\mathrm{Im}\mathbf{W}^R(M,\vec{0})}{3M} = \lim_{M\to 0}\frac{-\mathrm{Im}\mathbf{W}^F(M,\vec{0})}{6T}$$

electric conductivity (full up to two pion)



arXiv:1312.5609

$0.3 < \sigma_E/\tilde{\mathbf{e}}^2 T < 0.8$

$\sigma_E/T \geq 0.07$

EPJC 72, 1902 (2012)

comparable to unitarized ChPT [arXiv:1205.0782]

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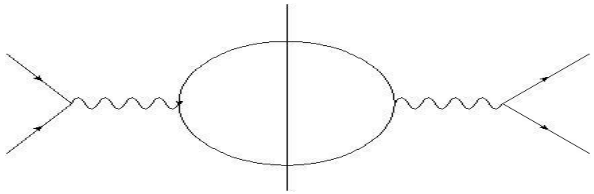
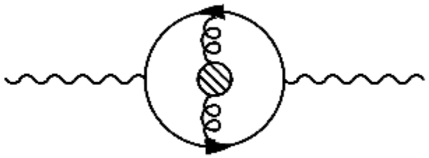
sQGP

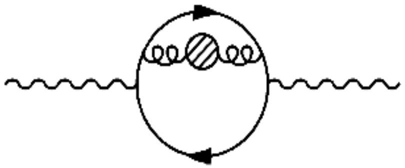
Lee,Yirstam, Zahed,Hansson, PLB (1999)



$$\mathrm{Im}\,\mathbf{W}_0^R(q) = \frac{N_c\tilde{\mathbf{e}}^2}{4\pi} q^2 \left[1 + \frac{2T}{|\vec{q}|}\ln\left(\frac{n_+}{n_-}\right)\right]$$

$$n_\pm = \frac{1}{e^{(q_0 \pm |\vec{q}|)/2T} + 1}$$





$$\mathrm{Im}\,\mathbf{W}_2^R(q) = \frac{N_c\tilde{\mathbf{e}}^2}{4\pi} q^2 \left\langle \frac{\alpha_s}{\pi} A_4^2 \right\rangle \left(\frac{4\pi^2}{T|\vec{q}|}\right) (n_+(1-n_+) - n_-(1-n_-))$$

$$\mathrm{Im}\,\mathbf{W}_4^R(q) = \frac{N_c\tilde{\mathbf{e}}^2}{4\pi} \left[-\frac{1}{6}\left\langle \frac{\alpha_s}{\pi} E^2 \right\rangle + \frac{1}{3}\left\langle \frac{\alpha_s}{\pi} B^2 \right\rangle\right] \left(\frac{4\pi^2}{T|\vec{q}|}\right) (n_+(1-n_+) - n_-(1-n_-))$$

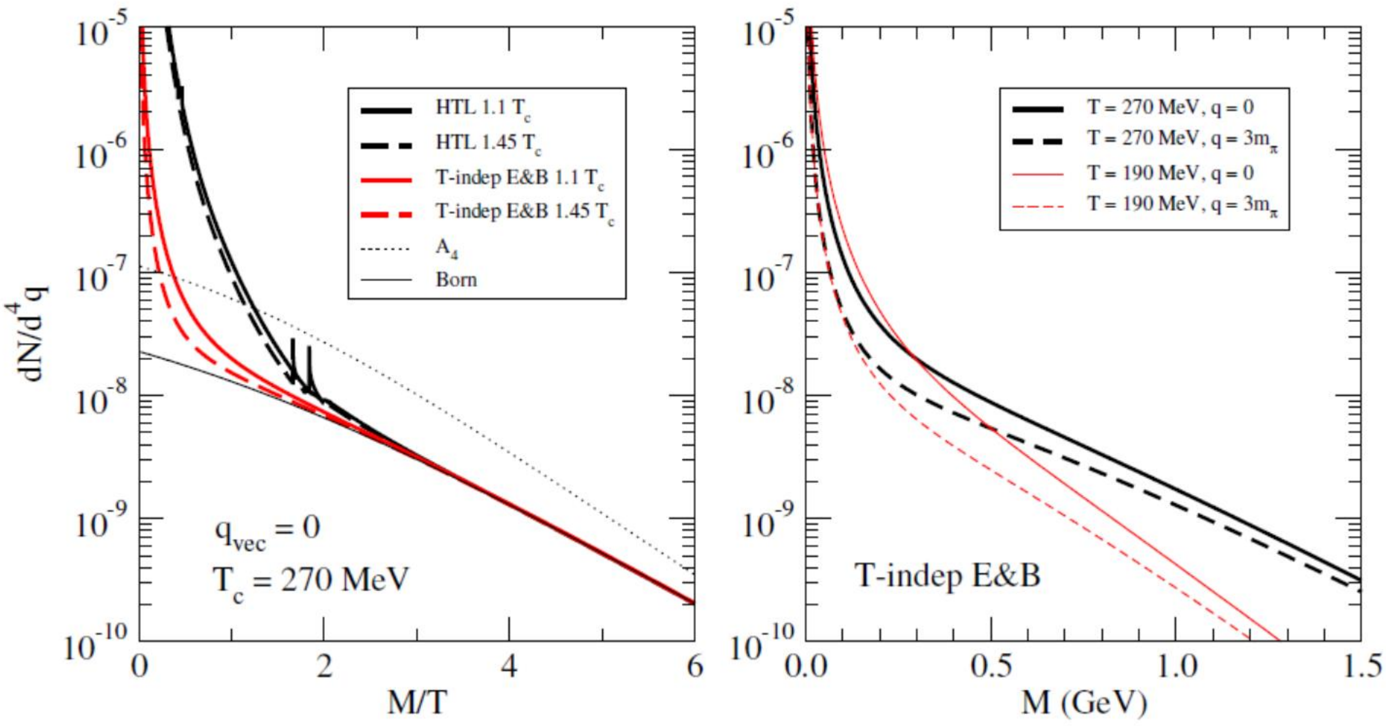
$\langle \frac{\alpha_s}{\pi} A_4^2 \rangle / T^2 \approx 0.4$ → ruled out by Kaczmarek et al., arXiv:1301.7436

sQGP (T-indep E&B)

$$\langle \alpha_s B^2 \rangle \approx \langle \alpha_s E^2 \rangle \approx \frac{1}{2} \times \frac{1}{4} \langle \alpha_s G^2 \rangle_0$$

$$\langle \alpha_s G^2 \rangle_0 = 0.068 \text{ GeV}^4$$

[Narison, PLB (2009)]

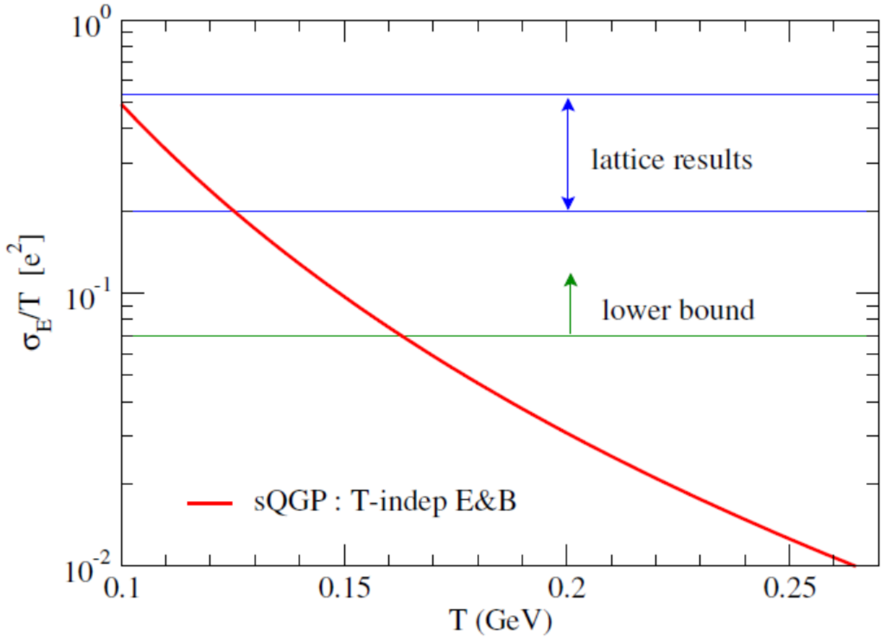


sQGP (T-indep E&B)

$$\langle \alpha_s B^2 \rangle \approx \langle \alpha_s E^2 \rangle \approx \frac{1}{2} \times \frac{1}{4} \langle \alpha_s G^2 \rangle_0$$

$$\langle \alpha_s G^2 \rangle_0 = 0.068 \ \mathrm{GeV}^4$$ [Narison, PLB (2009)]

$$\sigma_E \approx \frac{\pi N_c \tilde{\mathbf{e}}^2}{48 T^3} \left(-\frac{1}{6} \left\langle \frac{\alpha_s}{\pi} E^2 \right\rangle + \frac{1}{3} \left\langle \frac{\alpha_s}{\pi} B^2 \right\rangle \right)$$



arXiv:1312.5609

$0.3 < \sigma_E/\tilde{\mathbf{e}}^2 T < 0.8$

$\sigma_E/T \geq 0.07$

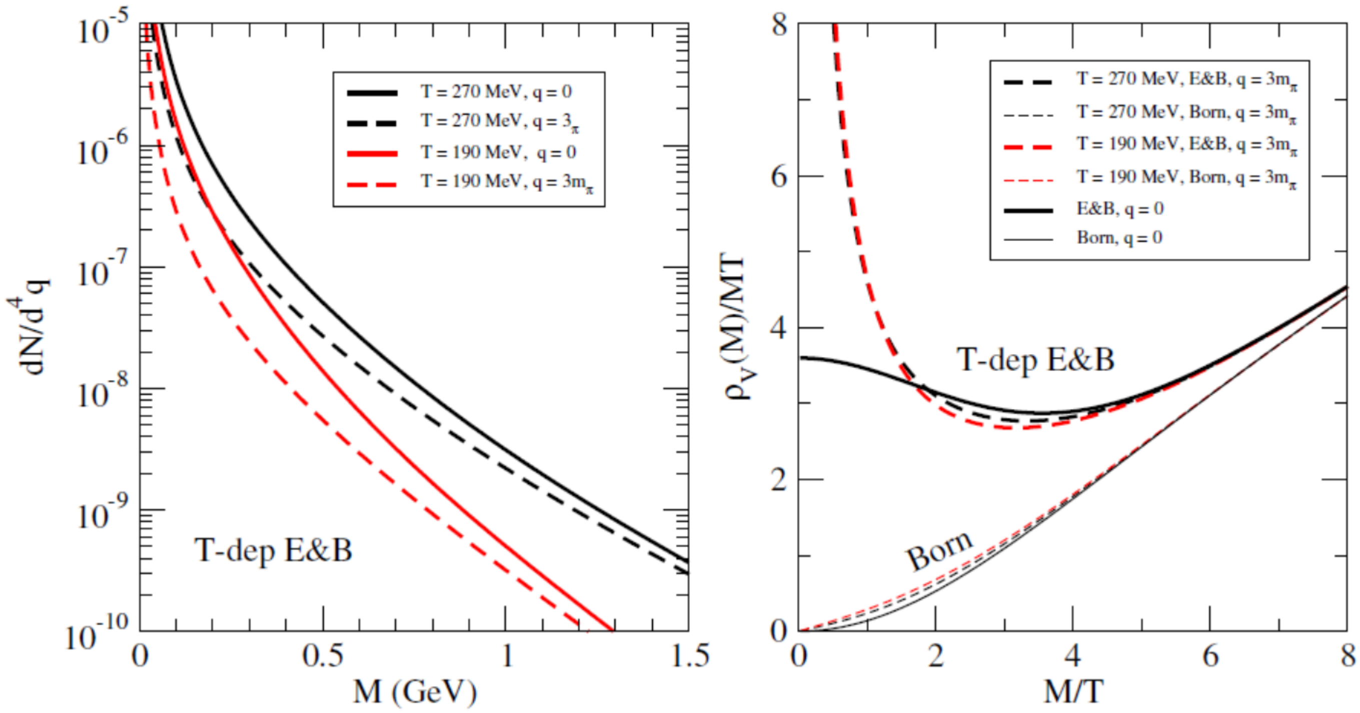
EPJC 72, 1902 (2012)

sQGP (T-dep E&B; fixed by E-conductivity)

$$\langle \alpha_s E^2 \rangle \approx \langle \alpha_s B^2 \rangle \approx \frac{288}{N_c} \left\langle \frac{\sigma_E}{\tilde{\mathbf{e}}^2 T} \right\rangle T^4 \approx 48\, T^4$$

$\langle \sigma_E / \tilde{\mathbf{e}}^2 T \rangle \sim 0.5$

arXiv:1312.5609



what we have confirmed

- partial restoration of chiral symmetry through the mixing between vector & axial correlators
  → low-mass dilepton enhancements
- our systematic expansion of resonance gas allows us to obtain the electric conductivity, … …
- gluon condensates in sQGP constrained by lattice results allow us to describe the transition from sQGP to resonance gas

on-going/future works

$$
\frac{d^4N}{MdMq_Tdq_Tdyd\phi}(M,q_T,y,\phi) = \mathbf{DetAcc}(M,q_T,y,\phi) \times \int_{\tau_0}^{\tau_{f,o}} \tau d\tau \int_{-\infty}^{\infty} d\eta \int_0^{r_{\max}} r dr \int_0^{2\pi} d\theta
\times \left[\frac{dR}{d^4q}(q;T,\mu_B,\mu_\pi) \otimes \mathbf{Hydro}(T,\mu_B,\mu_\pi;\tau,\eta,r,\theta) \right]
$$

- dilepton/photon with nucleons
- rates + hydro evolution
- comparison with recent experimental data

for the future

Many Thanks