熱場の量子論とその応用
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Electromagnetic radiation through transport process in quark-gluon plasma

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Ref: Akamatsu, Hamagaki, Hatsuda, Hirano, arXiv:1107.3612 [nucl-th]

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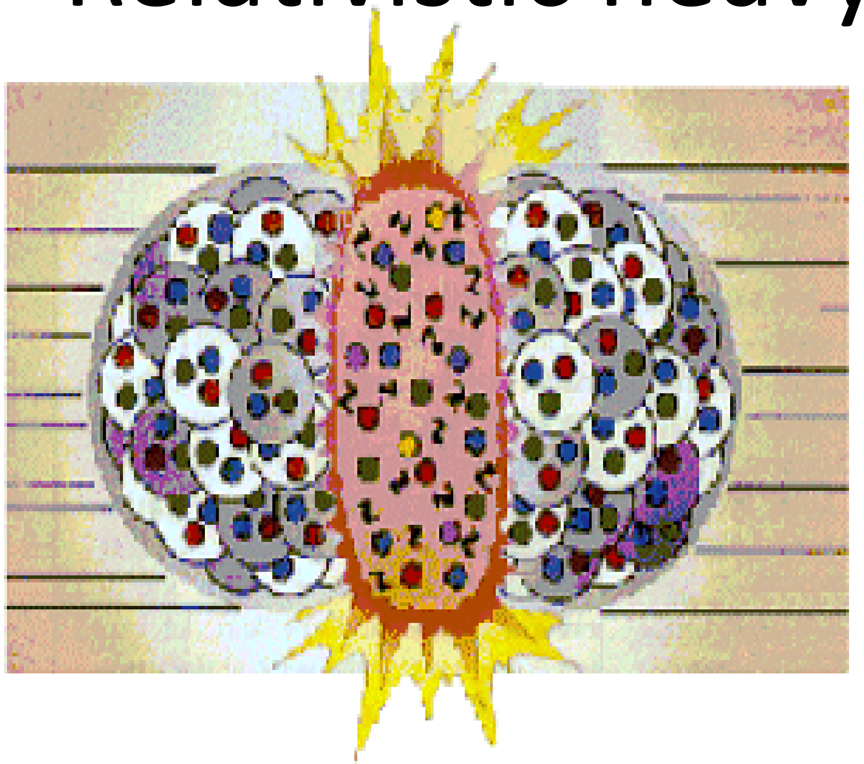
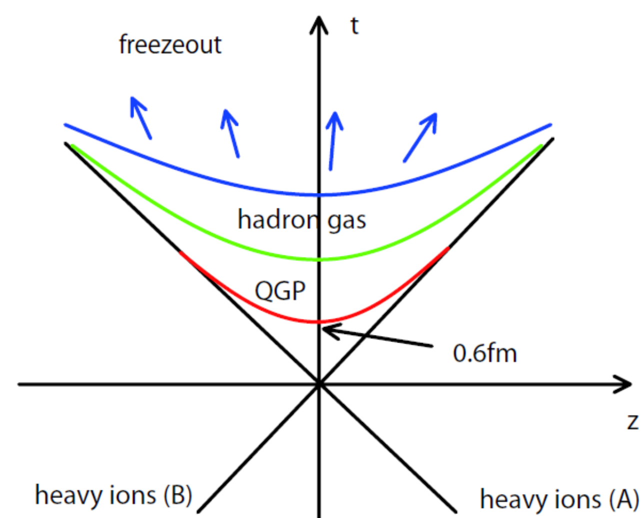
1. Introduction

Relativistic heavy ion collisions



RHIC
Au+Au, √sNN=200GeV

LHC
Pb+Pb, √sNN=5.6TeV
(2.76TeV at present)



Hydrodynamic model gives spacetime evolution profile of the created matter.

Dilepton production at PHENIX

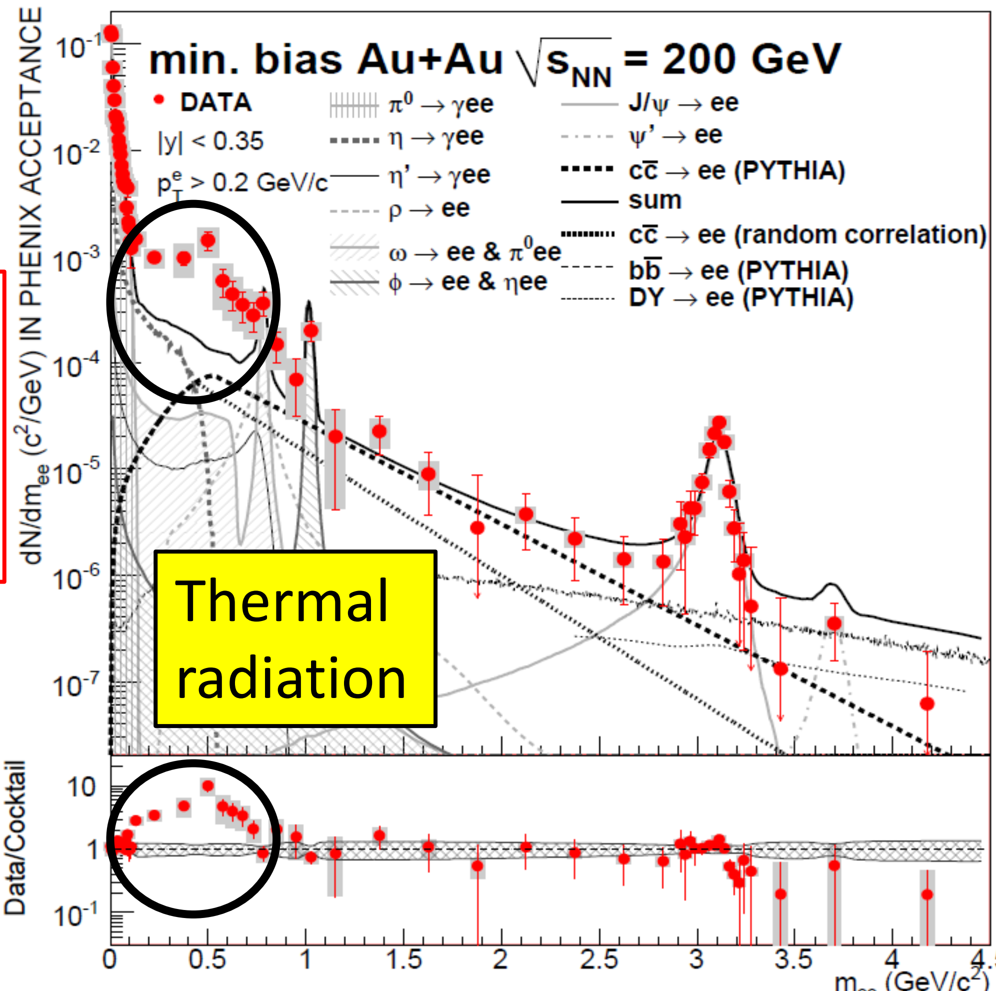
Low-mass (m_{ee}<0.6GeV) enhancement has been a challenge to theorists:

Rapp ('01,'10)
Dusling, Zahed ('07,'09)
Bratkovaskaya, Cassing, Linnyk ('09,'10)
Ghosh, Sarkar, Alam ('10)
…

Hadron interaction, chiral symmetry (Hadronic phase) / pQCD(QGP phase)

⬇ Successful at SPS but not at RHIC

Non-perturbative process in QGP phase is important.



AuAu collision @ PHENIX

2. Spectral function from causal dissipative hydrodynamics

Formula for thermal radiation

Retarded correlator (or spectral function) of QCD-EM current

$$\frac{E_1 E_2 dN_{\mathrm{ee}}}{d^3 p_1 d^3 p_2 d^4 x} = \frac{2e^4 L_{\mu\nu}(p_1, p_2)}{(2\pi)^6 q^4} \mathrm{Im}\, G_{\mathrm{R}}^{\mu\nu}(q;T) f_{\mathrm{BE}}(q^0;T), \; q^\mu \equiv p_1^\mu + p_2^\mu.$$

$$G_R^{\mu\nu}(\omega, k) \equiv \int d^4 x e^{iqx} i\theta(t) \left\langle \left[J^\mu(x), J^\nu(0) \right] \right\rangle_T$$

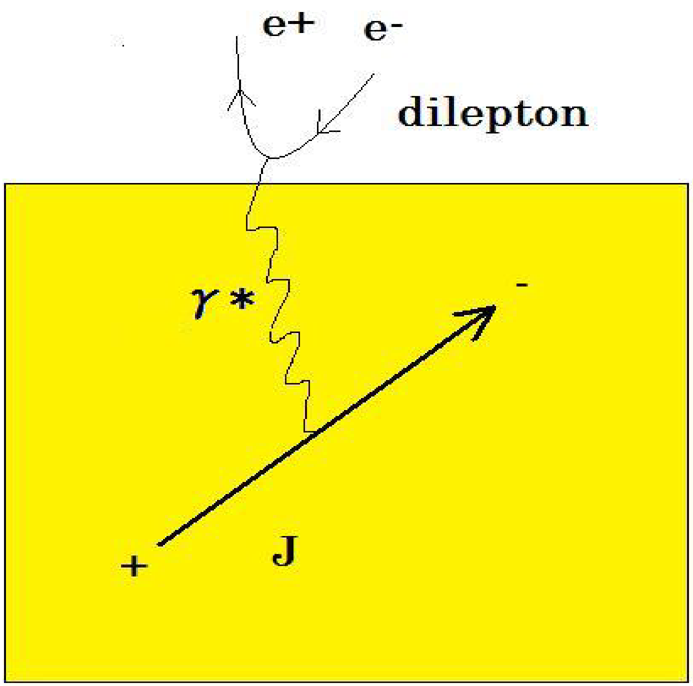
What's in the spectral function?

- Large ω : Towers of higher resonances/Quark pair annihilation
- Intermediate ω : Vector correlation (vector meson/qqbar)
- Small ω : Transport phenomena

Charge transport and dilepton

In each fluid element:

1. charge fluctuation → current
2. current → dileptons



*Remark:

net charge = 0 at RHIC/LHC

→ only induced current flows

Spectral function at small ω & k

Linear response theory:

$$\delta H(t) = \int d^3x J^{\mu}(x)\delta A_{\mu}(x)$$

$$\rightarrow \left\langle \delta J^{\mu}(q) \right\rangle_T = -G_R^{\mu\nu}(q;T)\delta A_{\nu}(q)$$

2nd order relativistic dissipative hydrodynamics in external electromagnetic field:

Israel ('76)
Israel, Stewart ('79)

$$J^{\mu}(x) = \left(\delta\rho(x), \vec{v}(x)\right), \ \partial_{\mu}J^{\mu} = 0,$$

$$\vec{v}(x) = \sigma\vec{E}(x) - D\nabla\delta\rho(x) - \tau_{\mathrm{J}}\frac{\partial\vec{v}}{\partial t},$$

$$\sigma \equiv \chi D, \ \chi \equiv \frac{\partial\rho}{\partial\mu}.$$

Ohm's law, **Fick's law**
Memory effect

→ Linear response theory

$$\mathrm{Im}\, G_{\mathrm{R}}^{(\mathrm{L})}(q;T) = -\frac{\chi D\omega q^2}{\omega^2 + (\tau_{\mathrm{J}}\omega^2 - Dk^2)^2},$$

$$\mathrm{Im}\, G_{\mathrm{R}}^{(\mathrm{T})}(q;T) = -\frac{\chi D\omega}{\tau_{\mathrm{J}}^2\omega^2 + 1}.$$

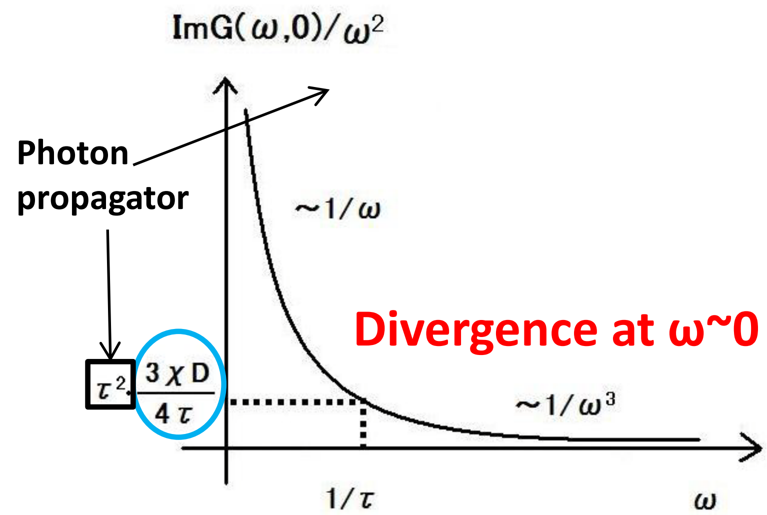
Spectral shape & strength

Spectral shape:

$$\mathrm{Im}\,G_{\mathrm{R}}^{(\mathrm{L})}(q;T) = -\frac{\chi D\omega q^2}{\omega^2 + (\tau_{\mathrm{J}}\omega^2 - Dk^2)^2},$$

$$\mathrm{Im}\,G_{\mathrm{R}}^{(\mathrm{T})}(q;T) = -\frac{\chi D\omega}{\tau_{\mathrm{J}}{}^2\omega^2 + 1},$$

$$\mathrm{Im}\,G_{\mathrm{R}}^{\mu\mu} = 2\,\mathrm{Im}\,G_{\mathrm{R}}^{(\mathrm{T})} + \mathrm{Im}\,G_{\mathrm{R}}^{(\mathrm{L})}$$



Stronger at larger χ, D and smaller τ:

- Susceptibility χ : how large the charge fluctuation is.
- Diffusion constant D : how effectively current is induced.
- Relaxation time τ_{J} : how swiftly current is induced.

$$\text{induced current}: \vec{v}(x) = \sigma\vec{E}(x) - D\vec{\nabla}\,\delta\rho(x) - \tau_{\mathrm{J}}\frac{\partial\vec{v}}{\partial t}$$

Parameterization

$$D \propto 1/T, \tau_J \propto 1/T.$$

	D	τJ
pQCD	4/T	15/T
AdS/CFT	1/2πT	ln2/2πT

Arnold et al. ('00,'03), Hong, Teaney ('10)

Natsuume, Okamura ('08)

$$\chi(T) = 0.28T^2\left[1 + \tanh\left(\frac{T - 0.155\mathrm{GeV}}{0.023\mathrm{GeV}}\right)\right].$$

χ(T)：Using lattice result for quark number susceptibility

Allton et al. ('05)

3. Dilepton production at RHIC (PHENIX)

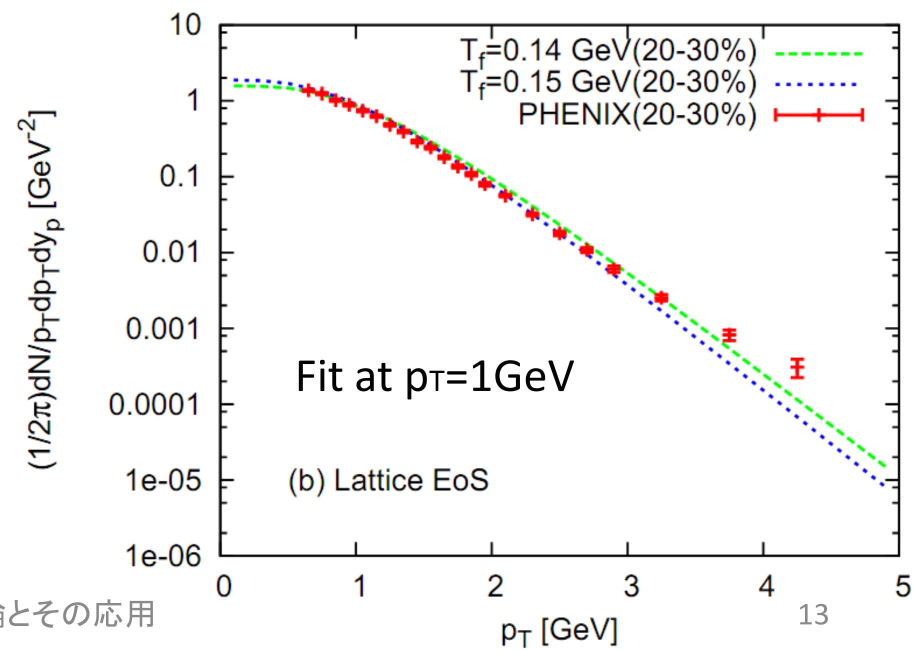
Hydro model setting

Viscosity	EoS	Initial	Hadronic phase
Perfect fluid	**Lattice**	**Modified BGK**	**Chemical equilibrium**

How far the matter evolves under hydrodynamics

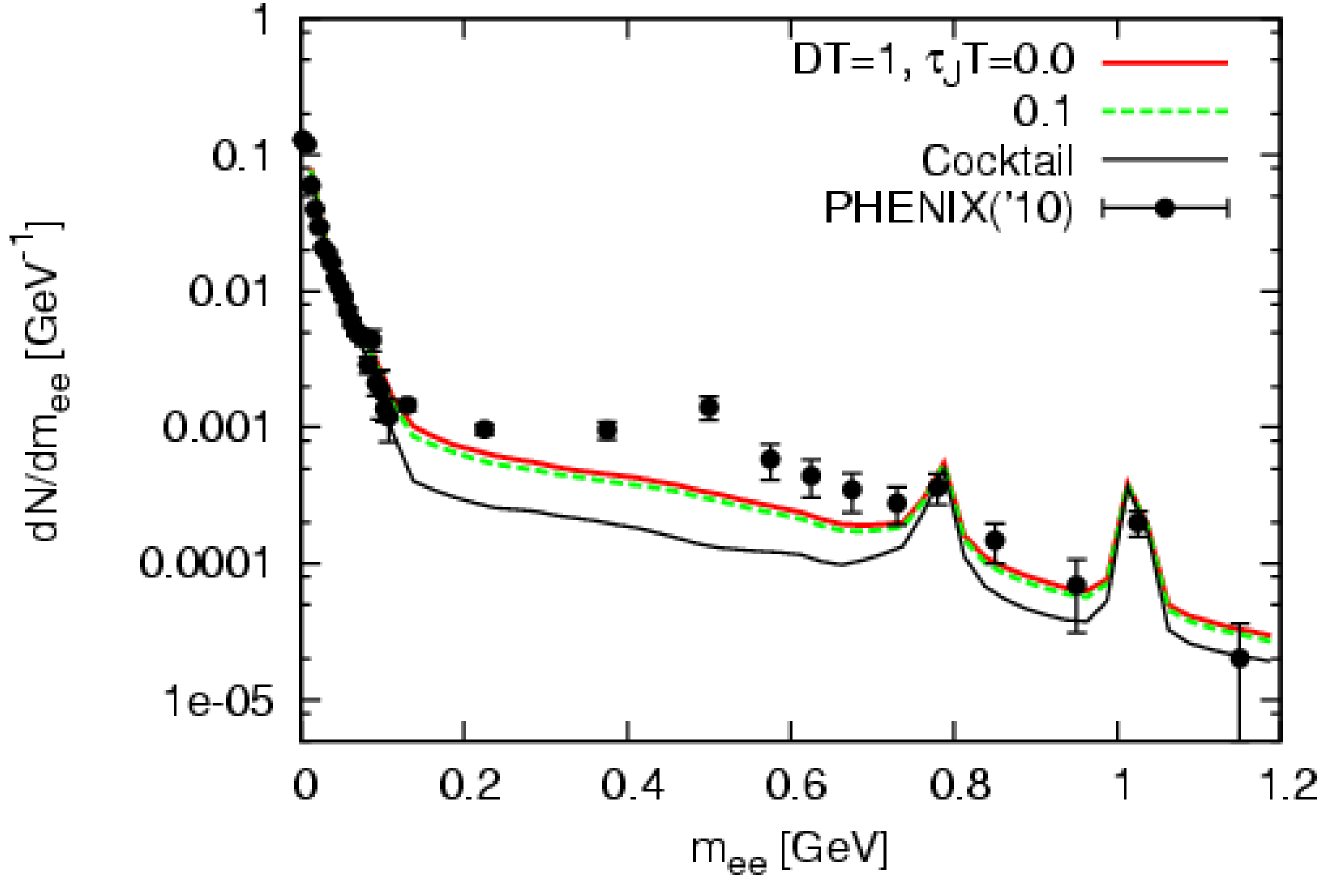
Until T_f =0.15 GeV

Proton spectra: theory vs. experiment



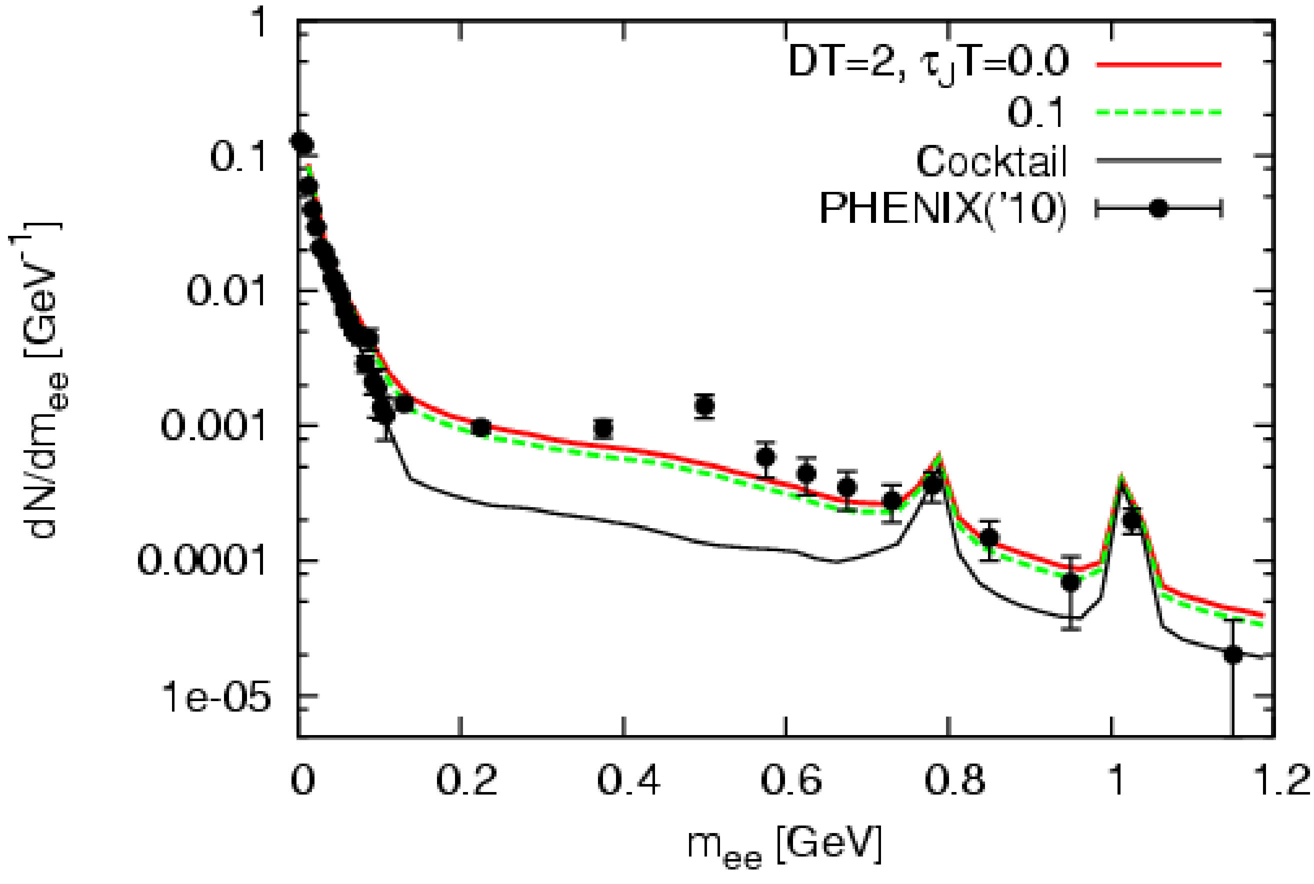
Invariant mass spectra

DT=1 : no solution



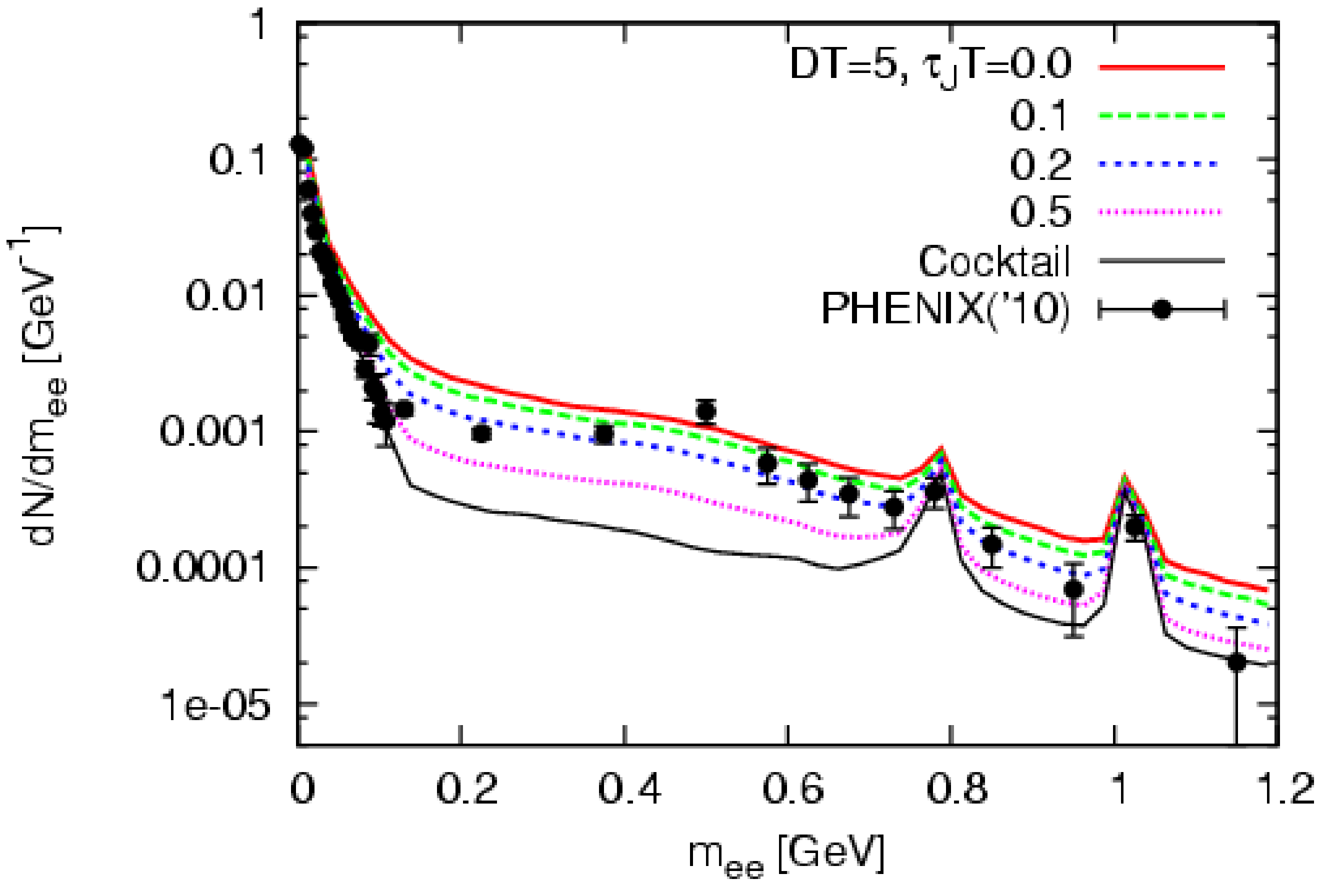
Invariant mass spectra

(DT, τJT)=(2, 0-0.1) : good agreement



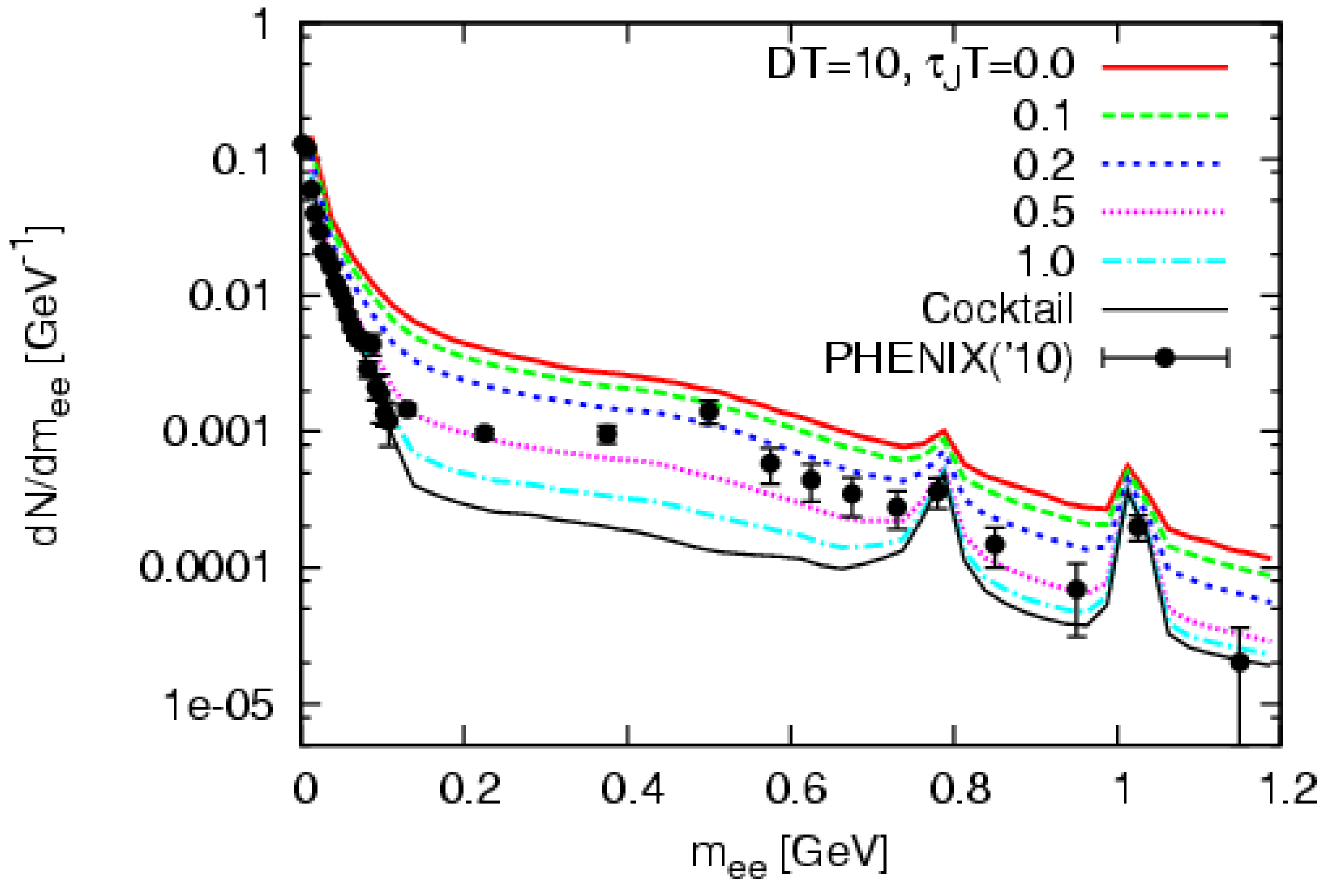
Invariant mass spectra

(DT, τJT)=(5, 0.2), (2, 0-0.1) : good agreement



Invariant mass spectra

(DT, τJT)=(10, 0.5), (5, 0.2), (2, 0-0.1) : good agreement
DT=1 : no solution

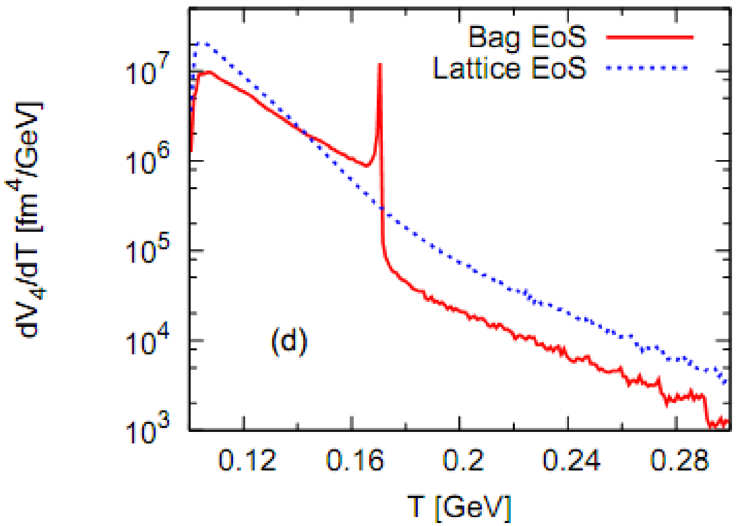


Main source: fluctuation or volume?

- Large charge fluctuation at high-T

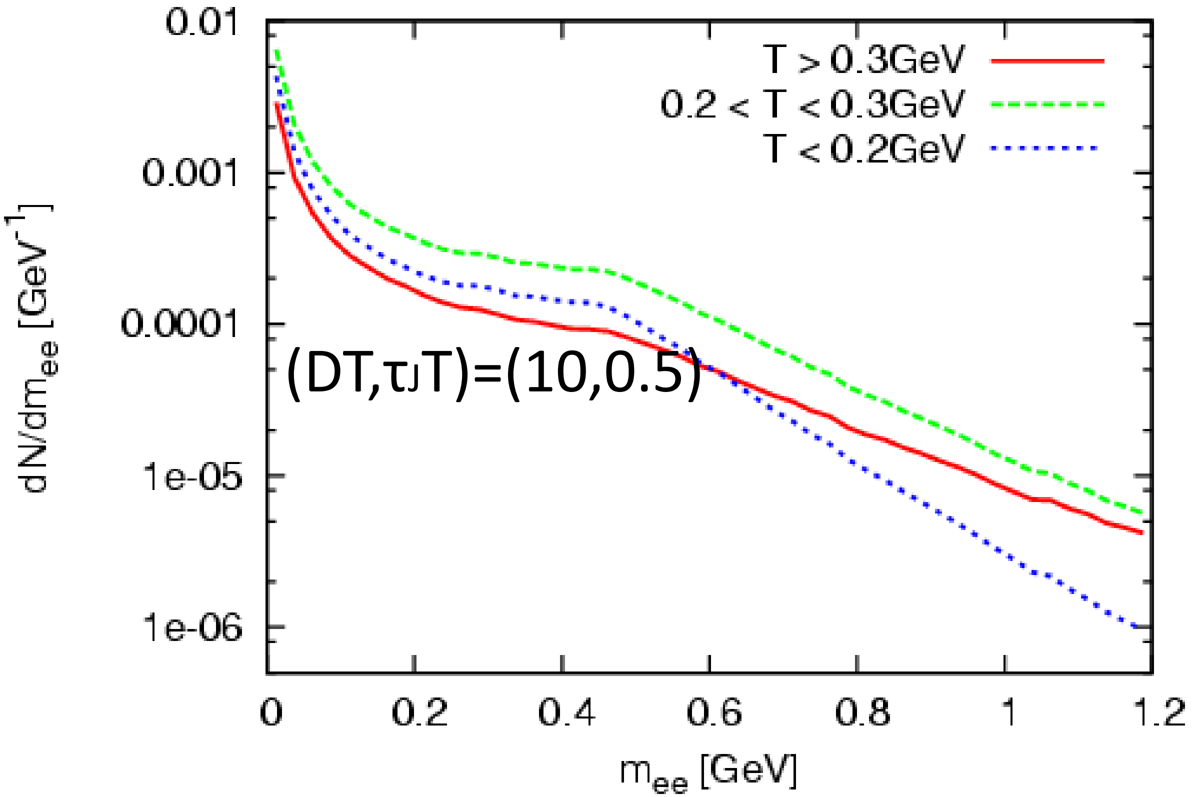
$$\text{Spectral strength} \propto \chi(T)$$
$$= 0.28T^2\left[1+\tanh\left(\frac{T-0.155\text{GeV}}{0.023\text{GeV}}\right)\right]$$

- Large spacetime volume at low-T



Main source: volume or fluctuation?

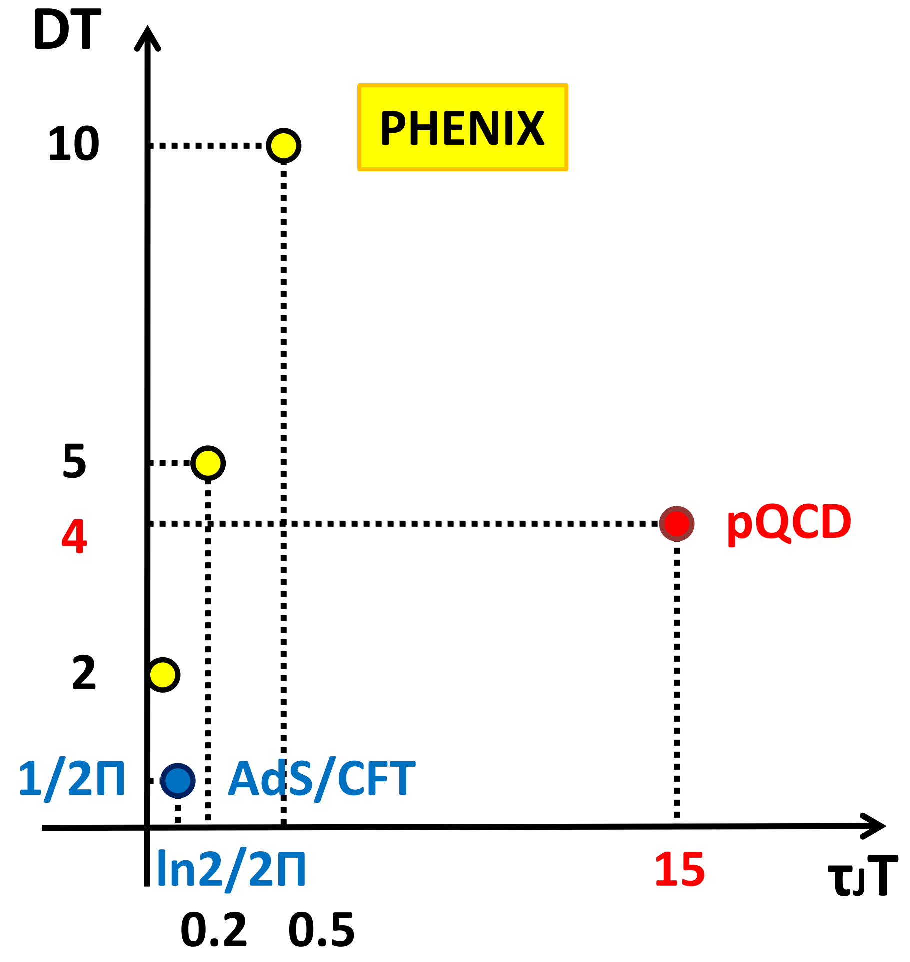
Large production rate due to thermal fluctuation of charge in hot region strongly compensates smallness of volume !



Transport coefficients

Assumptions made:

- Validity of transport-SPF
- Hydro with chem.eq.
- No radiation from pre-eq. stage



4. Summary

- Dilepton production via transport phenomena is studied. Transport spectral function is parameterized with diffusion constant D, relaxation time τ_J, and susceptibility χ.

- PHENIX Data requires $D \geqq 2/T$. Solution (D, τ_J) is not uniquely obtained, but all the solutions are far from both pQCD and AdS/CFT results.

- Main source of thermal dilepton radiation is high-T QGP phase due to the large fluctuation.

- Application to dilepton/photon radiation at LHC.

Backup

5. Spectral function from causal dissipative hydrodynamics

Hydrodynamic equations

Hydrodynamic equations in external field

$$\partial_\nu T^{\nu\mu} = F^{\mu\nu} J_\nu,$$
$$\partial_\mu J^\mu = 0,$$

Tensor decomposition

$$T^{\mu\nu} = e u^\mu u^\nu - (P + \Pi)\triangle^{\mu\nu} + \pi^{\mu\nu},$$
$$J^\mu = \rho u^\mu + \nu^\mu,$$
$$\triangle^{\mu\nu} \equiv g^{\mu\nu} - u^\mu u^\nu,$$

Entropy current and constitutive equations

Entropy current

$$s^\mu = su^\mu - \frac{\mu}{T}\nu^\mu - \frac{1}{T}(\alpha_0 \Pi \nu^\mu + \alpha_1 \pi^{\mu\nu}\nu_\nu) - \frac{u^\mu}{2T}(\beta_0 \Pi^2 - \beta_1 \nu^\mu \nu_\mu + \beta_2 \pi^{\rho\sigma}\pi_{\rho\sigma}),$$

Constitutive equations (to ensure 2^{nd} law of thermodynamics)

$$-\Pi = \zeta(\partial_\mu u^\mu + \alpha_0 \partial_\mu \nu^\mu + \beta_0 \dot{\Pi}),$$

$$\pi_{\mu\nu} = 2\eta \langle\langle \partial_\mu u_\nu - \alpha_1 \partial_\mu \nu_\nu - \beta_2 \dot{\pi}_{\mu\nu} \rangle\rangle,$$

$$\nu^\mu = \sigma \triangle^{\mu\rho}\left[T\partial_\rho\left(\frac{\mu}{T}\right) + F_{\rho\sigma}u^\sigma + \alpha_0 \partial_\rho \Pi + \alpha_1 \partial_\sigma \pi^\sigma_\rho - \beta_1 \dot{\nu}_\rho\right]$$

Linear response theory and spectral function

Linear response theory $\langle \delta J^\mu(q) \rangle_T = -G_{\mathrm{R}}^{\mu\nu}(q;T)\delta A_\nu(q),$

Linearized equation → spectral function

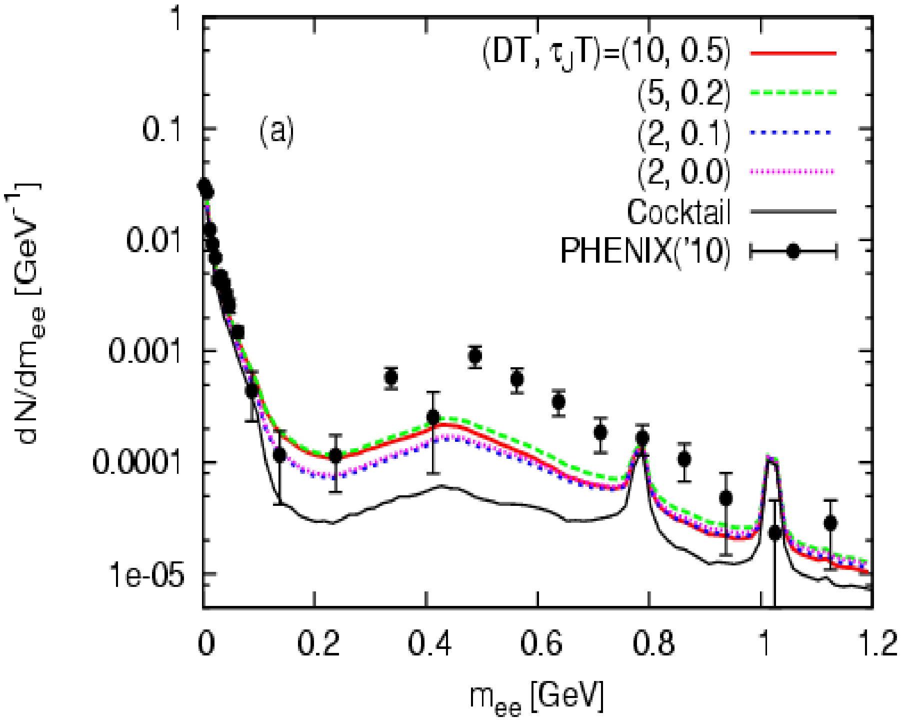
$$\begin{aligned} J^\mu(x) &= (\delta\rho(x), \vec{\nu}(x)), \\ \vec{\nu}(x) &= \sigma\vec{E} - D\vec{\nabla}\delta\rho - \tau_{\mathrm{J}}\frac{\partial\vec{\nu}}{\partial t}, \\ D &\equiv \frac{\sigma}{\chi},\ \tau_{\mathrm{J}} \equiv \beta_1\sigma,\ \chi \equiv \frac{\partial\rho}{\partial\mu}. \end{aligned}$$

➡

$$\begin{aligned} G_{\mathrm{R}}^{00}(\omega,\vec{k};T) &= \frac{\sigma k^2}{-\tau_{\mathrm{J}}\omega^2 - i\omega + Dk^2}, \\ G_{\mathrm{R}}^{0i}(\omega,\vec{k};T) &= G_{\mathrm{R}}^{i0}(\omega,\vec{k};T) = \frac{\sigma\omega k^i}{-\tau_{\mathrm{J}}\omega^2 - i\omega + Dk^2}, \\ G_{\mathrm{R}}^{ij}(\omega,\vec{k};T) &= \frac{\sigma\omega}{-\tau_{\mathrm{J}}\omega - i}\left(\delta^{ij} - \frac{k^i k^j}{k^2}\right) + \frac{\sigma\omega^2}{-\tau_{\mathrm{J}}\omega^2 - i\omega + Dk^2}\frac{k^i k^j}{k^2}, \end{aligned}$$

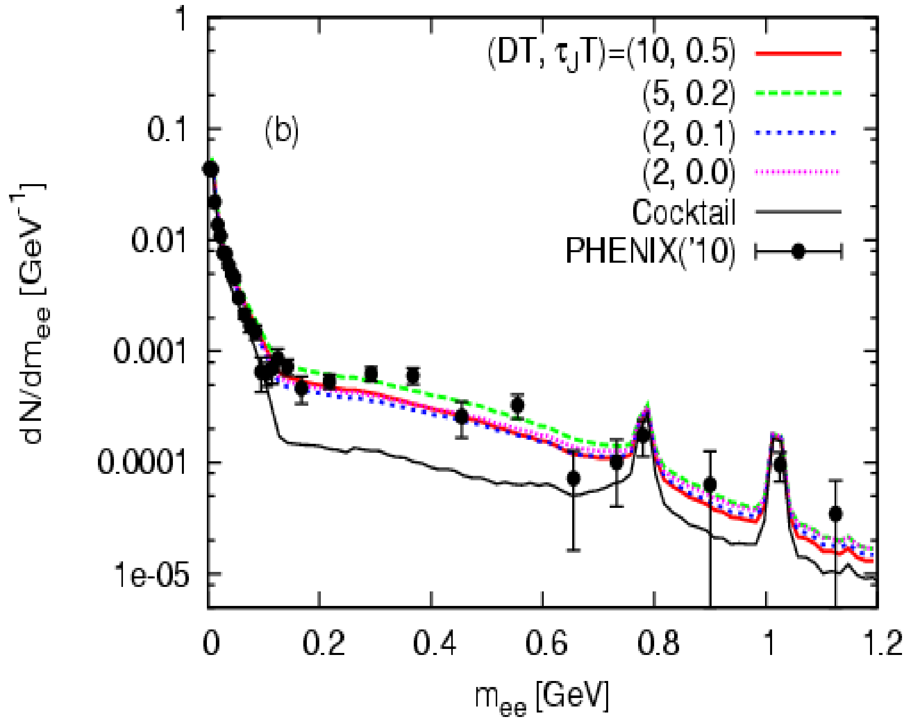
6. More results of dileptons and photons

Invariant mass spectra (p_T-window)



0<p_T<0.5GeV

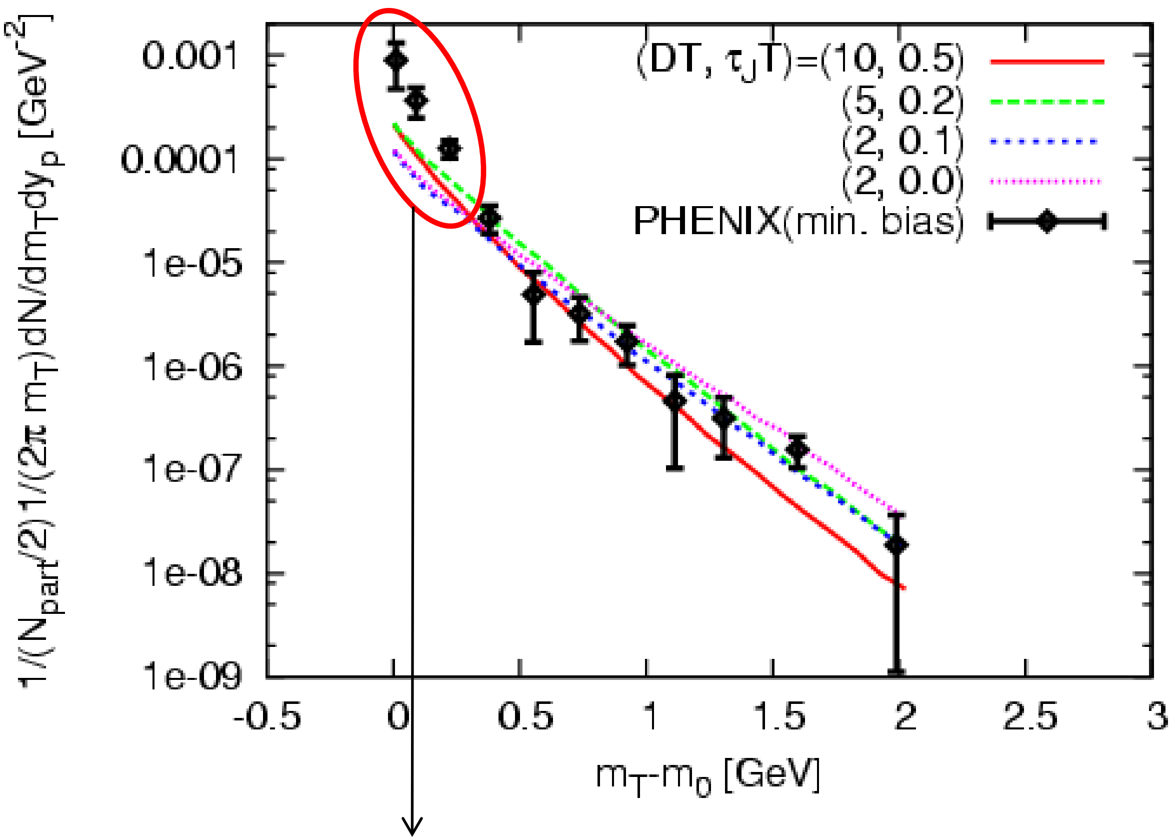
Cannot explain the spectrum for the lowest pT window



0.5<p_T<1.0GeV

Can explain the spectrum for this pT window

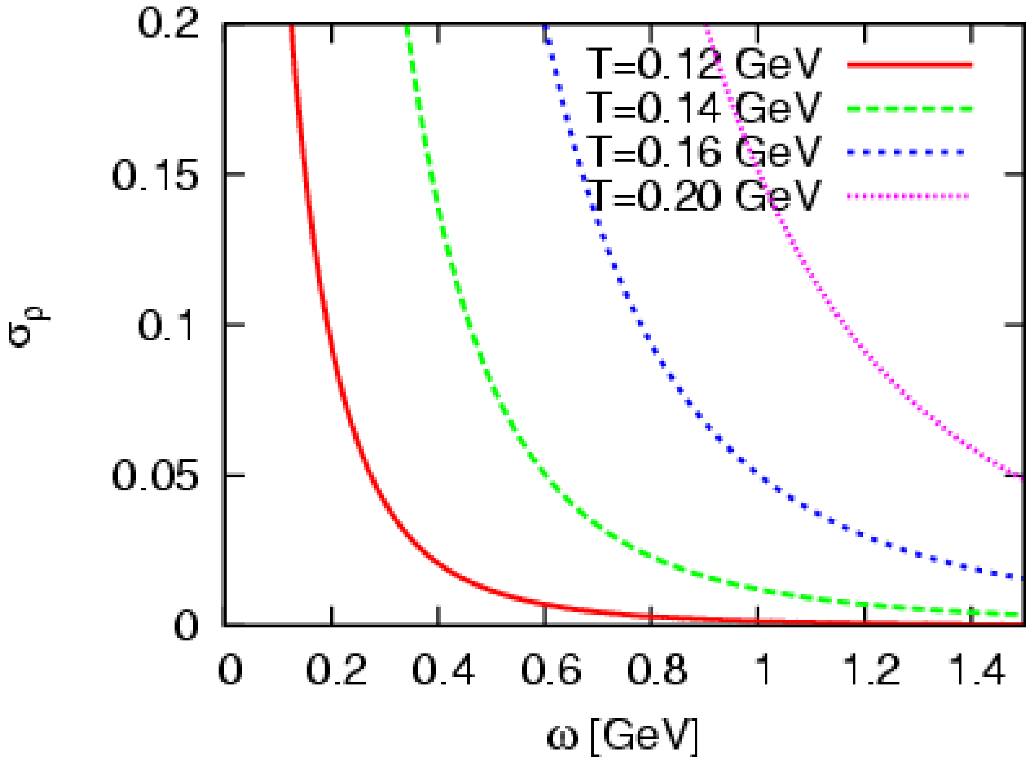
MT-slope



m_T-slope of the data is much steeper than those of theoretical ones.

Transport-SPF

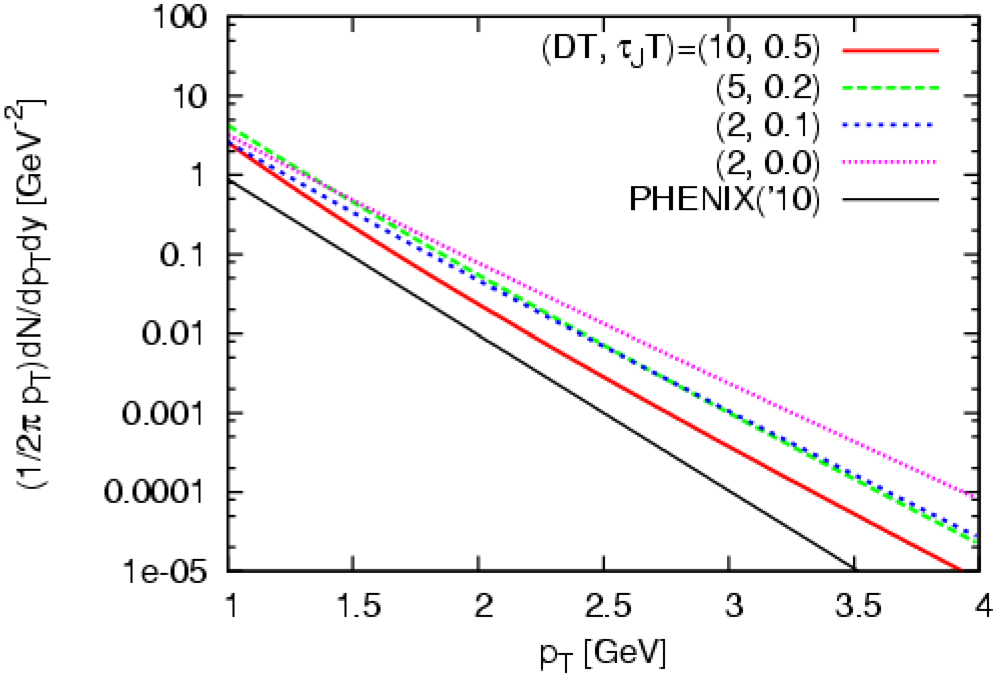
Transport-SPF(DT=10,τJT=0.5)



Wow !

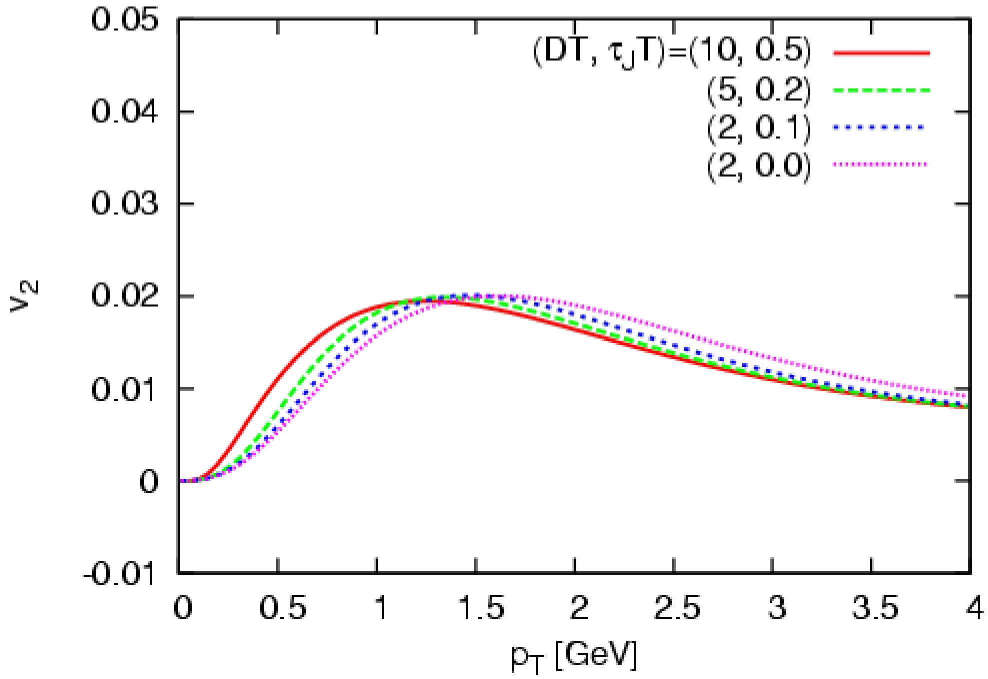
$$\sigma(\omega) \equiv -\mathrm{Im}\, G_R^{\mu\mu}(\omega,0)/3\omega^2$$

Photon : p_T-spectra

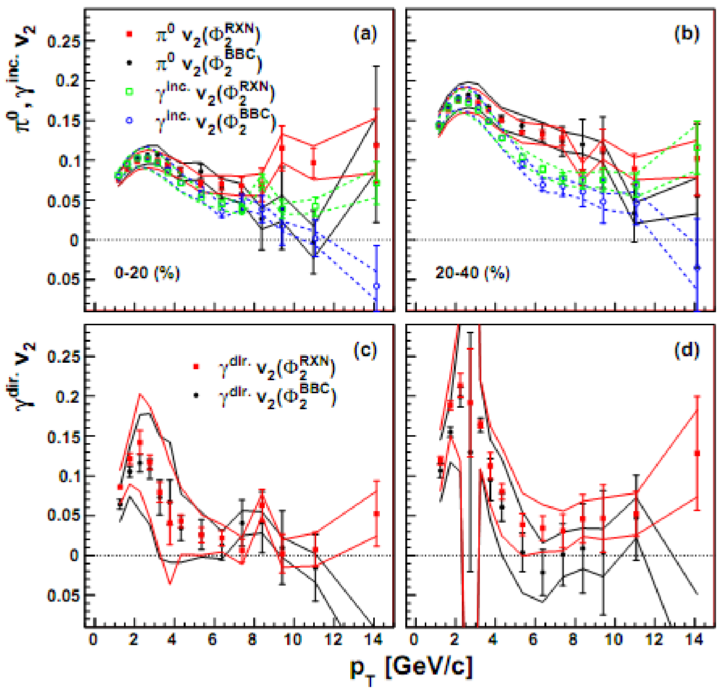


Parameters favored by dileptons overpredict the data.

Photon : v2



PHENIX('11)



Parameters favored by dileptons do not explain data.
(v_2~0.1 up to p_T~2GeV !!)