Some aspects of dilepton production in HIC

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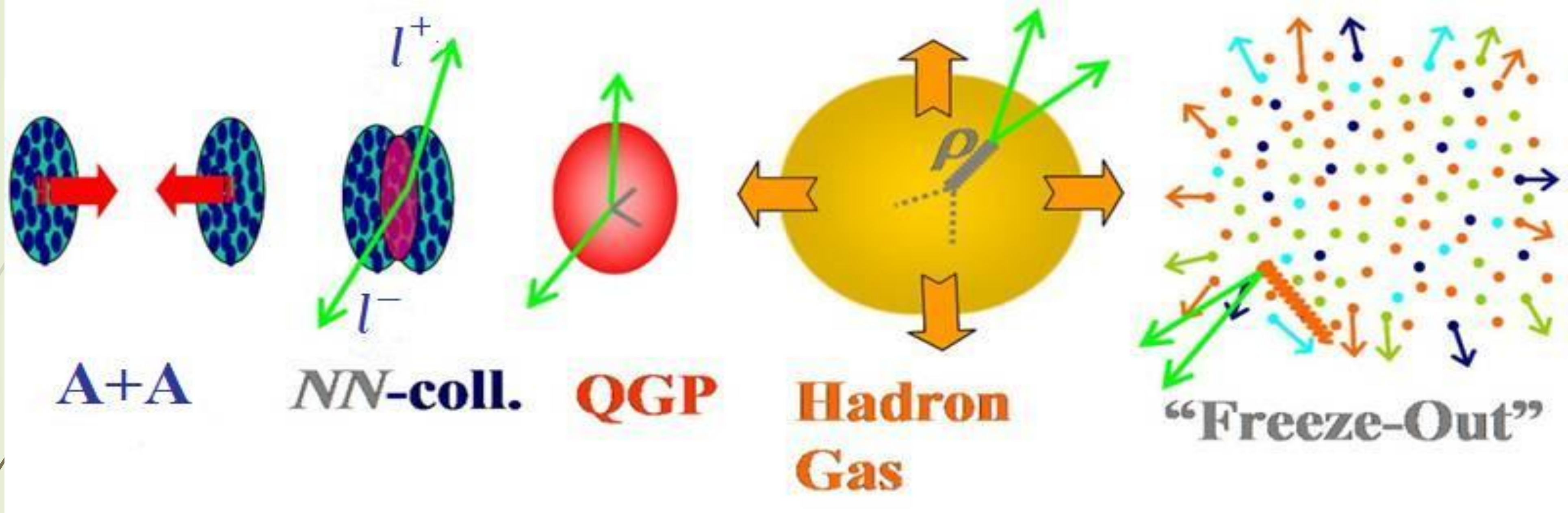
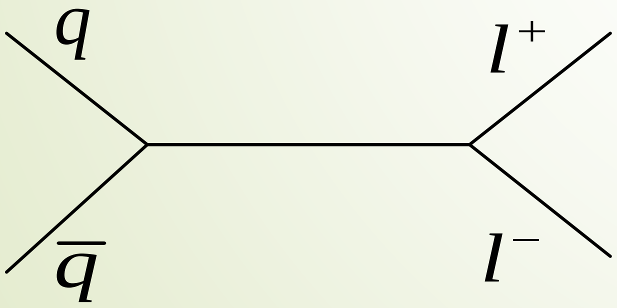
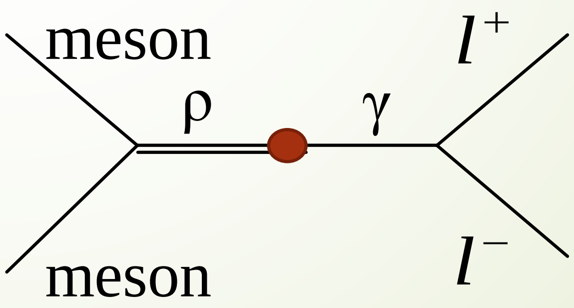
Outline

- 1. Many body effective theory + hydro simulation
- 2. T_{eff} as probe to EOS of dense matter
- 3. Hydro-Langevin simulation for open charm contribution
- 4. Comparison with STAR di-electron data
- 5. Collective flow from Event-by-Event simulation
- 6. Summary and conclusion

Introduction







Dilepton invariant mass spectra

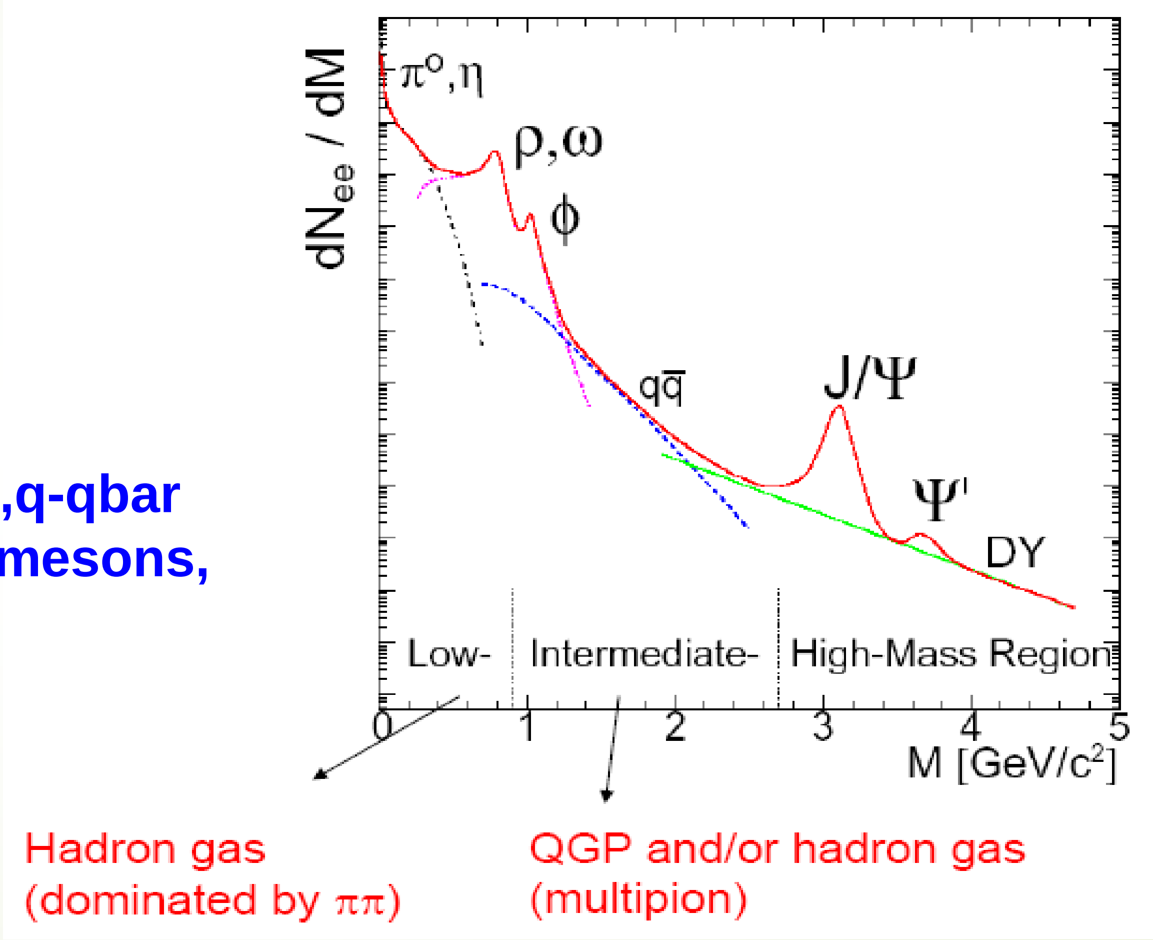
1. **Electromagnetic probe to hot/dense medium**

2. **Chiral symmetry restoration?**

3. **Space-time evolution of fireball**

4. **Drell-Yan,Charmonium, open charm,q-qbar in QGP, Pion-pion in HG via vector mesons, Dalitz decays, 4-pion, ……**

McLerran & Toimela, 1985
Weldon, 1990
Gale & Kapusta, 1991
Rapp & Wambach, 1997



From A. Drees

Strategy

- Dilepton production in Au+Au collisions at 200 GeV in IMR. QGP phase: $q\bar{q}$ annihilation; Hadron phase (many body EFT): D_ρ with vertices ρπX (X: all mesons below 1300 GeV), and vertices of ρNN* and ρNΔ* (N* and Δ*: baryon resonances); D_ω with vertices ωρπ, ω3π; and D_ϕ with vertices $\phi K\bar{K}$.
- Space-time evolution of medium is described by a 2+1 ideal hydro model.
- In-medium T-matrix and Hydro-Langevin simulation to model open charm contribution.
- Collective flow from Event-by-Event simulation.

Vector Meson Dominance Model (VDM)

- VDM (Kroll, Lee, Zumino, 67'). The Lagrangian for $\rho\pi\gamma e$ system:

$$L=(D_\mu\pi)^*(D^\mu\pi)-m_\pi^2\pi^*\pi-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\frac{1}{2}m_\rho^2\rho_\mu\rho^\mu$$
$$+\bar{\psi}(i\gamma_\mu D_A^\mu-m)\psi-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\frac{e}{2g}F_{\mu\nu}G^{\mu\nu}$$

$$D^\mu=\partial^\mu+ig\rho^\mu+ieA^\mu$$
$$D_A^\mu=\partial^\mu-ieA^\mu$$
$$F^{\mu\nu}=\partial^\mu A^\nu-\partial^\nu A^\mu$$
$$G^{\mu\nu}=\partial^\mu\rho^\nu-\partial^\nu\rho^\mu$$

- EOM for EM field

$$\partial_\beta F^{\beta\alpha}\approx e\bar{\psi}\gamma^\alpha\psi-\frac{e}{g}m_\rho^2\rho^\alpha$$

(Keeping terms linear in e/g)

$$J^\alpha=e\bar{\psi}\gamma^\alpha\psi\rightarrow-\frac{e}{g}m_\rho^2\rho^\alpha$$
$$\langle J^\alpha(x)J^\beta(y)\rangle\rightarrow\frac{e^2m_\rho^4}{g^2}\langle\rho^\alpha(x)\rho^\beta(y)\rangle$$
$$\Pi_\gamma(x,y)\rightarrow\frac{e^2m_\rho^4}{g^2}D_\rho^{\alpha\beta}(x,y)$$

Dilepton emission rate (1)

$$\frac{d^4N}{d^4xd^4p} = -\frac{\alpha}{4\pi^4}\frac{1}{M^2}n_B(p\cdot u)\left(1+\frac{2m_l^2}{M^2}\right)\sqrt{1-\frac{4m_l^2}{M^2}}\mathrm{Im}\Pi_\gamma^R(p)$$

u : fluid velocity

T : temperature

Π_γ and n_B depend on space-time via u and T

Photon selfenery (VDM + quark)

$$\mathrm{Im}\Pi_\gamma^R = \begin{cases} \sum_{V=\rho,\omega,\phi} e^2\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}D_V & \text{hadronic source} \\ -\frac{N_cM^2}{12}\left(1+\frac{\alpha_S}{\pi}\right)\sum_{i=u,d,s} e_i^2 & \text{quark source} \end{cases}$$

Imaginary part of Retarded propagator of rho meson

$$\mathrm{Im}D_V(M,q,T) = \frac{1}{3}\mathrm{Im}D_V^L(M,q,T)+\frac{2}{3}\mathrm{Im}D_V^T(M,q,T)$$

$$\mathrm{Im}D_V^{L,T}(M,q,T) = \frac{\mathrm{Im}\Sigma_V^{L,T}(M,q,T)}{|M^2-(m_V^0)^2+\Sigma_V^{L,T}(M,q,T)|^2}$$

Dilepton emission rate (2)

- Freezeout (FO) dilepton rate is related to FO vector meson rate. Most of ρ mesons decay inside medium. But most of ω and ϕ meson decays take place after FO due to their long life time.

$$\frac{dN_{l\bar{l}}^{fo}}{d^4p} = \frac{\alpha}{3}\left(\frac{e}{g}\right)^2 \frac{m_V}{\Gamma_V}\frac{dN_V^{fo}}{d^4p}$$

$$\frac{dN_V^{fo}}{d^4p} = \frac{g_s^\rho}{4\pi^4}\int_{T_f} d\Sigma_\mu p^\mu \mathrm{Im} D_V n_B(p\cdot u)$$

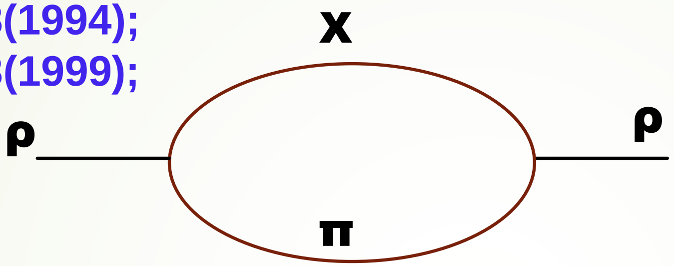
Freezeout Emission rate of vector meson

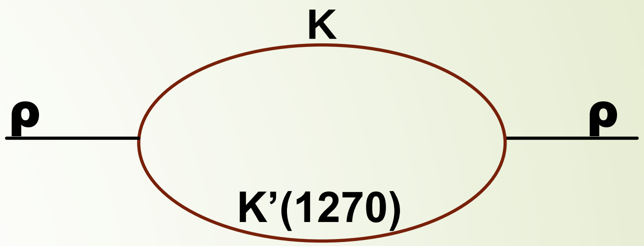
Freezeout hypersurface

In-vacuum vector meson propagator

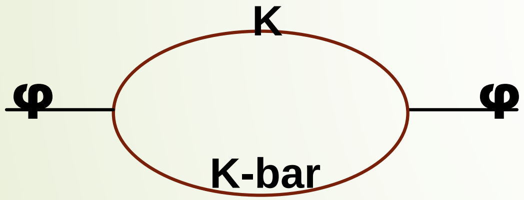
Rho self energy (1)

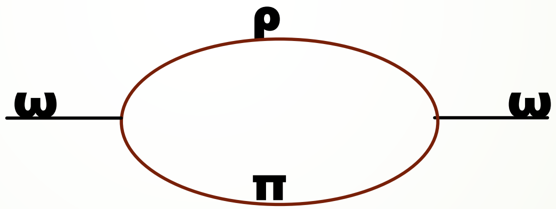
Chanfray,Schuck, NPA555,329(1993);
Herrmann,Friman,Noerenberg, NPA560(1993);
Gale,Lichard, PRD 49,3338(1994);
Rapp,Gale, PRC 60,024903(1999);

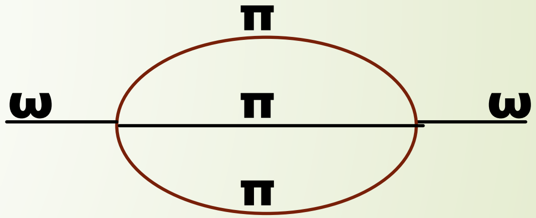




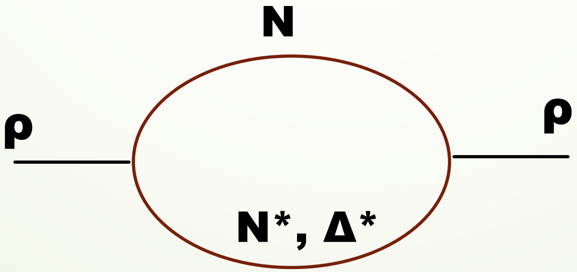
Meson Contribution
X = π, ω, h1(1170)
a1(1260), π'(1300)





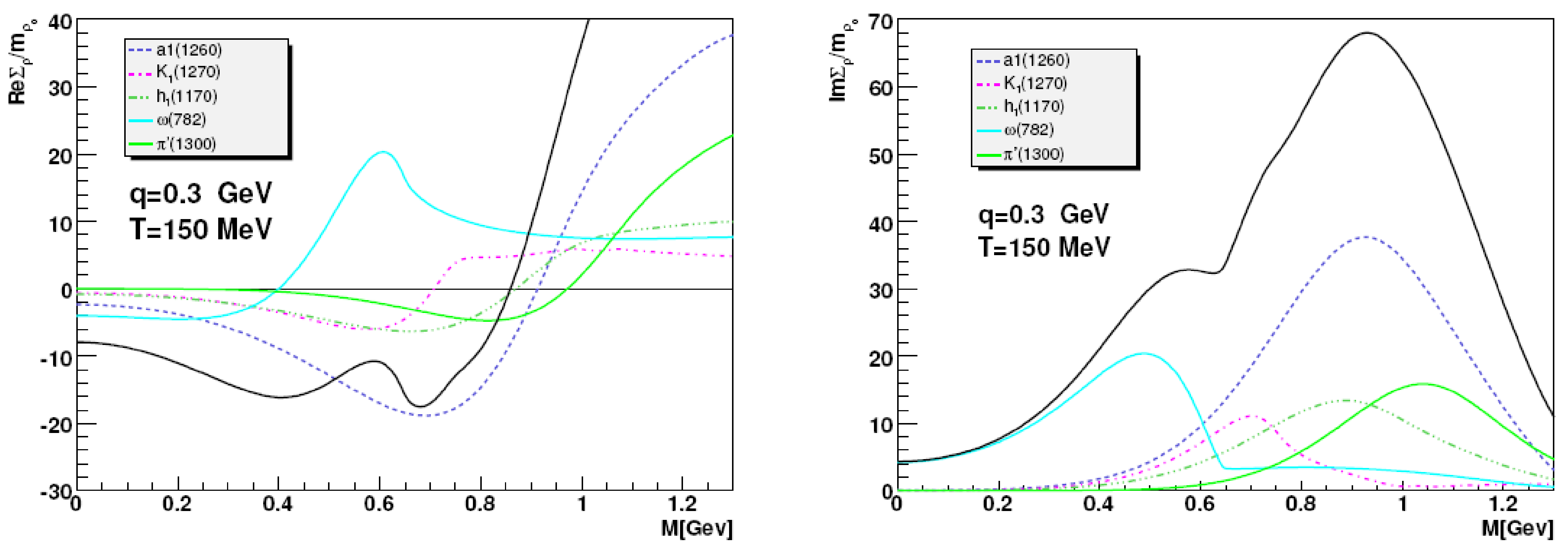


Baryon Contribution:
N(1700), N(1720), N(1900)
N(2000), N(2080), N(2090)
N(2100), N(2190),
Δ(1700), Δ(1900), Δ(1905),
Δ(1940), Δ(2000)



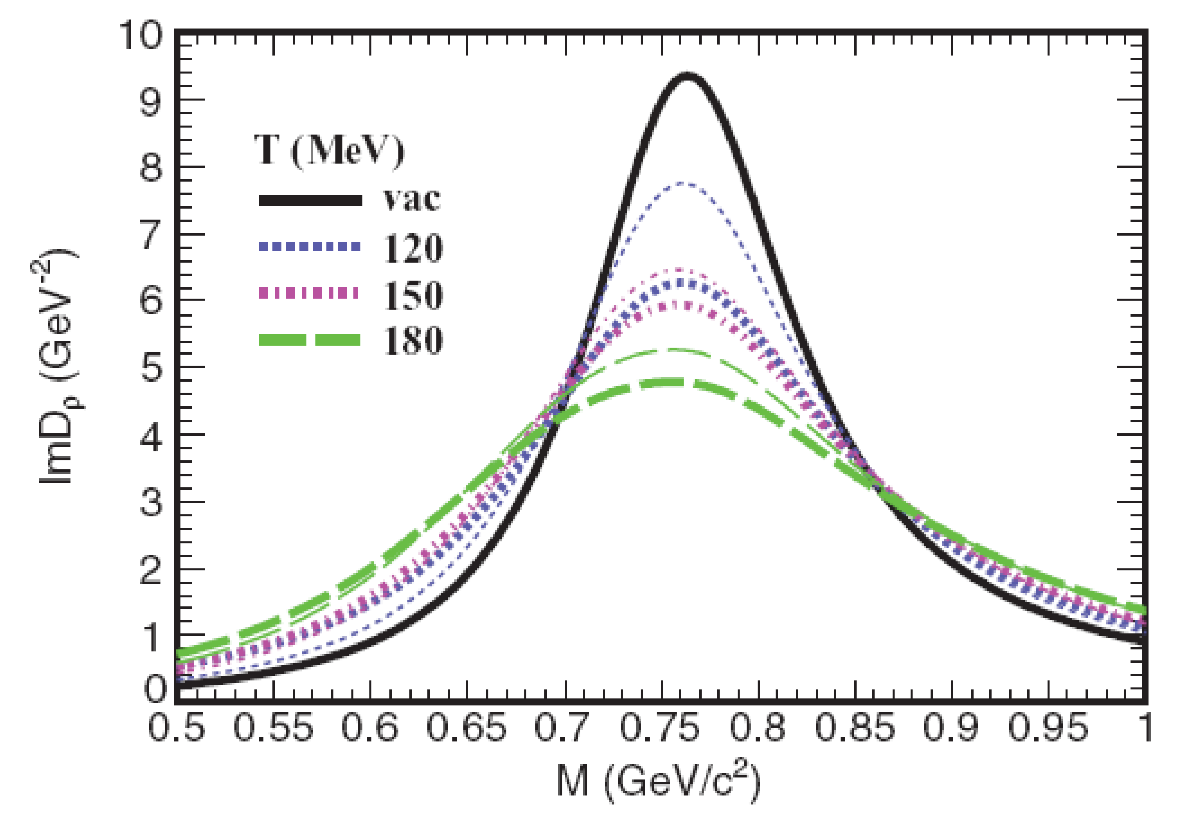
Eletsky, Belkacem,
Ellis, Kapusta,
PRC 64, 035202(2001);
Eletsky, Kapusta,
PRC 59, 2757(1999)

Rho self energy (2): Re and Im from mesons



Rapp & Gale, PRC 60,024903(1999)
H.J.Xu, H.F.Chen, X.Dong, QW, Y.F. Zhang, PRC85, 024906(2012)

Rho self energy (3): Im D_ρ w/o NN*+NΔ* contribution

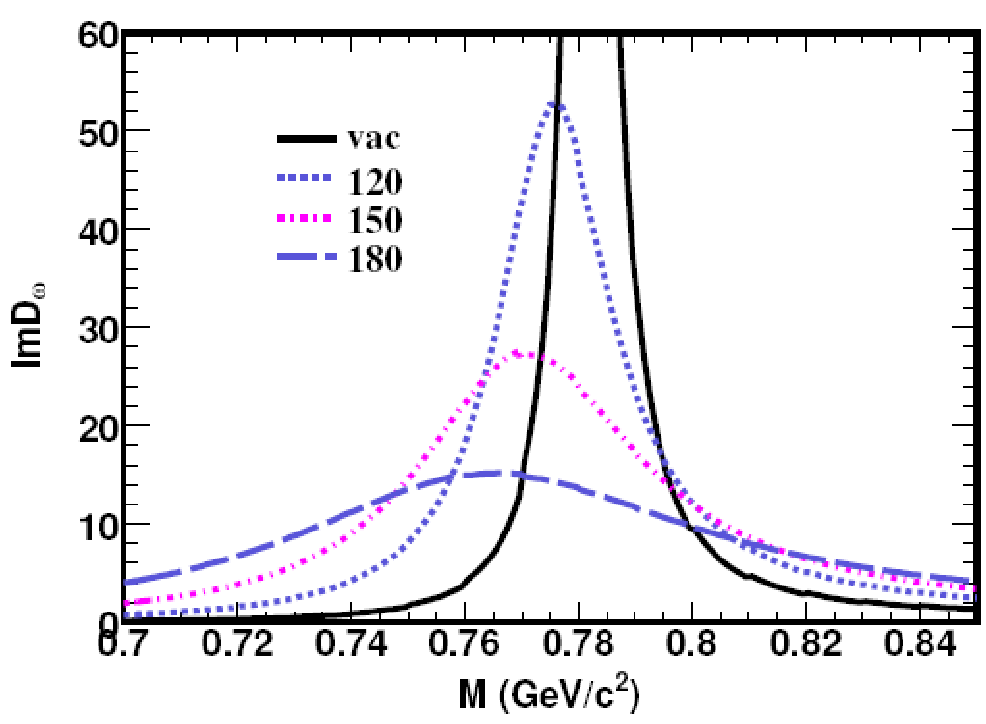


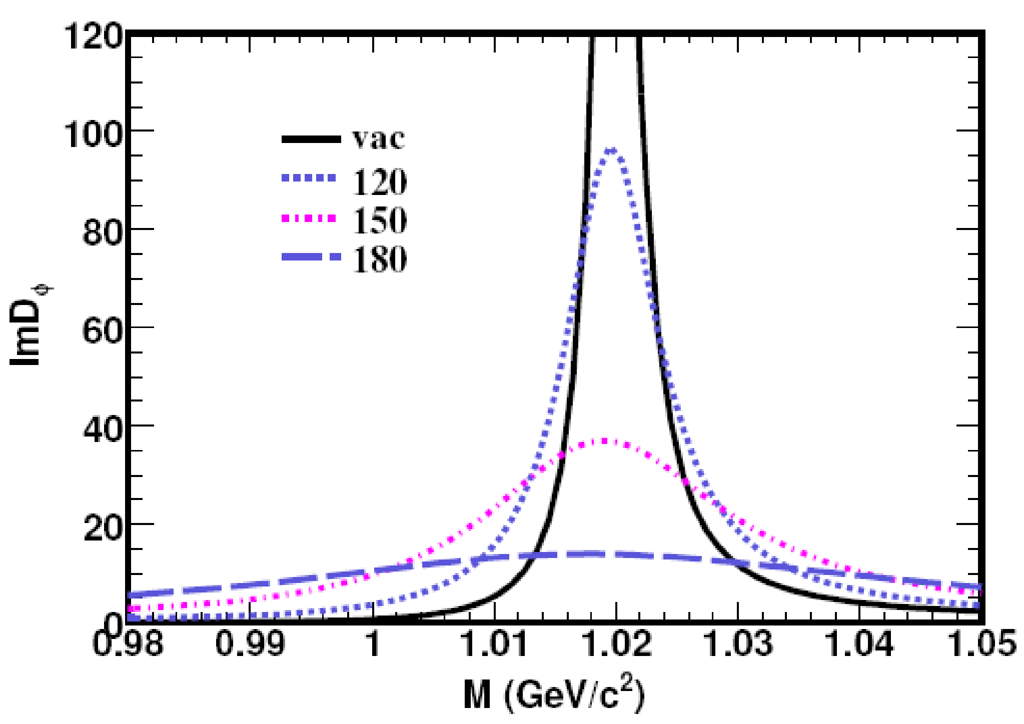
The imaginary parts of the in-medium ρ meson propagators (or in-medium spectral functions) with (thick lines) and without (thin lines) baryonic contributions. The chemical potentials in the PCE EOS are used.

The imaginary part of the porpagator is sensitive to temperature, but insensitive to its momentum.

H.J.Xu, H.F.Chen, X.Dong, QW, Y.F. Zhang, PRC85, 024906(2012)

Im of ω and ϕ propagator

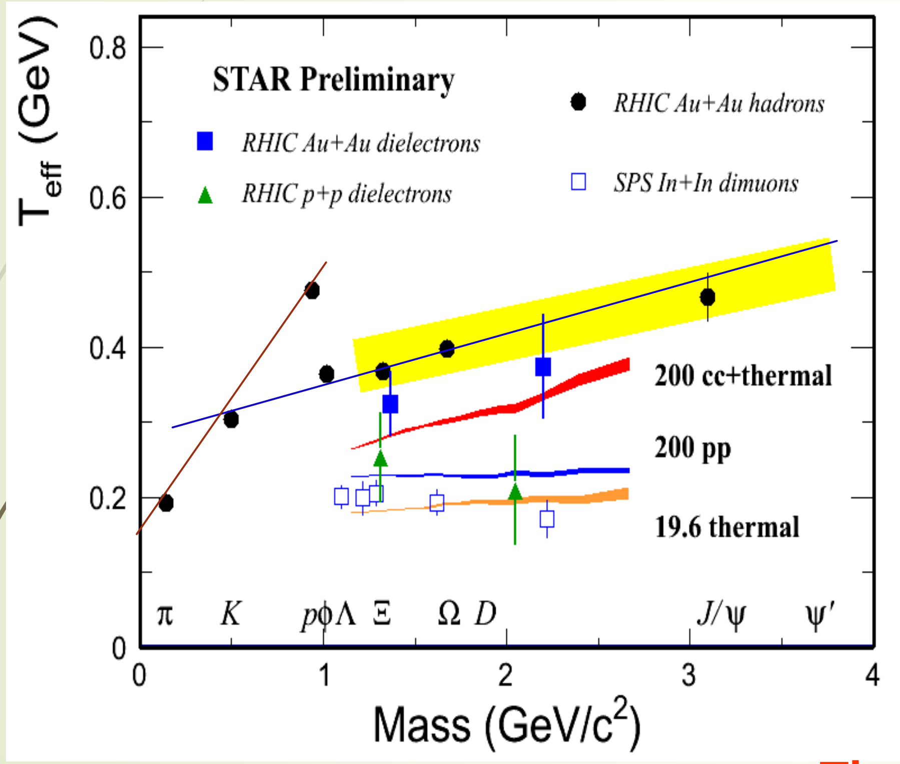


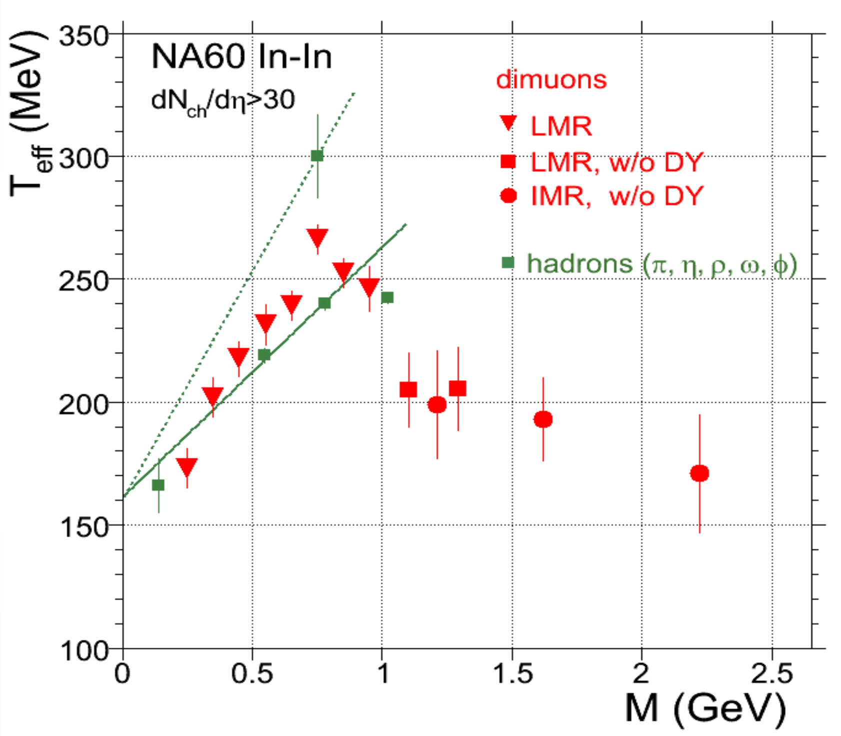


H.J.Xu, H.F.Chen, X.Dong, QW, Y.F. Zhang, PRC85, 024906(2012)

T_{eff} as probe to EOS of dense matter

Effective temperature for hadrons and dileptons





$$T_{\rm eff} = T_0 + M v_T^2$$

The transition tregion may signal a transition from a hadronic source to a partonic source

NA60, PRL100, 022302(2008); EPJC59, 607(2009)

Transverse flow: slope parameter

$$\frac{d^4N}{p_T dp_T M dM d\phi_p} \approx -\frac{\alpha}{2\pi^4}\frac{1}{M^2}\left(1+\frac{2m^2}{M^2}\right)\sqrt{1-\frac{4m^2}{M^2}}$$
$$\times \int d^4x \exp\left[\frac{1}{T}\gamma_T M_T v_T p_T \cos(\phi_v - \phi_p)\right] K_0\left(\frac{\gamma_T M_T}{T}\right) \mathrm{Im}\Pi^R$$

$M_T = \sqrt{M^2 + p_T^2}$

differential rate

space-time integral

transverse fluid velocity

azimuthal angle of fluid velocity

spectra in transverse momentum and invariant mass

$$\frac{d^2N}{m_T dm_T M dM} \sim \sqrt{\frac{\overline{T}}{\overline{\gamma}_T}}\frac{\sqrt{m_T+M}}{m_T}\exp\left(-\frac{m_T+M}{T_{eff}}\right)$$

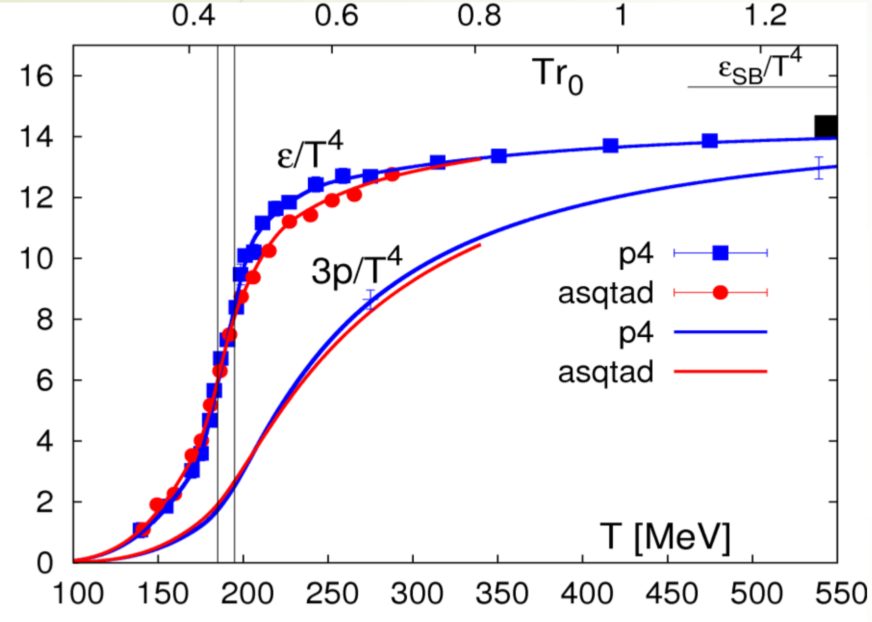
$m_T \equiv M_T - M$

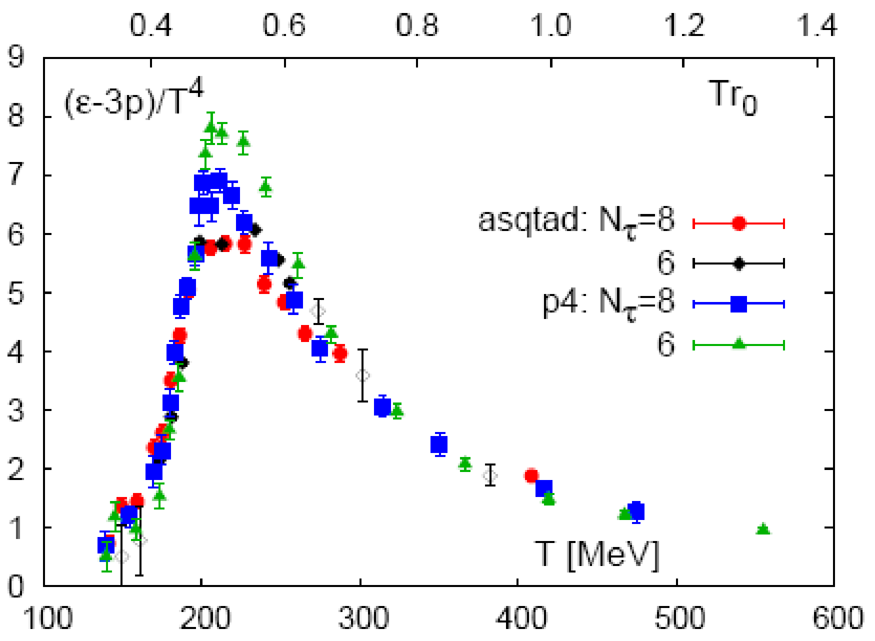
slope parameter

$$T_{eff} \sim \begin{cases} \overline{T} + M^*\overline{v}_T^2, & \text{for } p_T \ll M \\ \overline{T}\sqrt{\frac{1+\overline{v}_T}{1-\overline{v}_T}}, & \text{for } p_T \gg M \end{cases}$$

Doppler effect

Dense or hot QCD matter EOS





Bernard et al, (MILC) PRD 75 (07) 094505,
Cheng et al, (RBC-Bielefeld) PRD 77, 014511(2008);

Bazavov et al, (HotQCD), Phys.Rev.D80, 014504(2009).

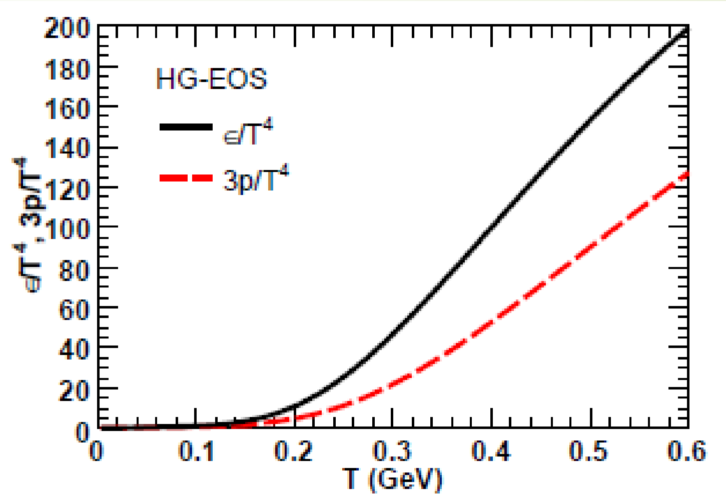
Four equations of state (EOS)

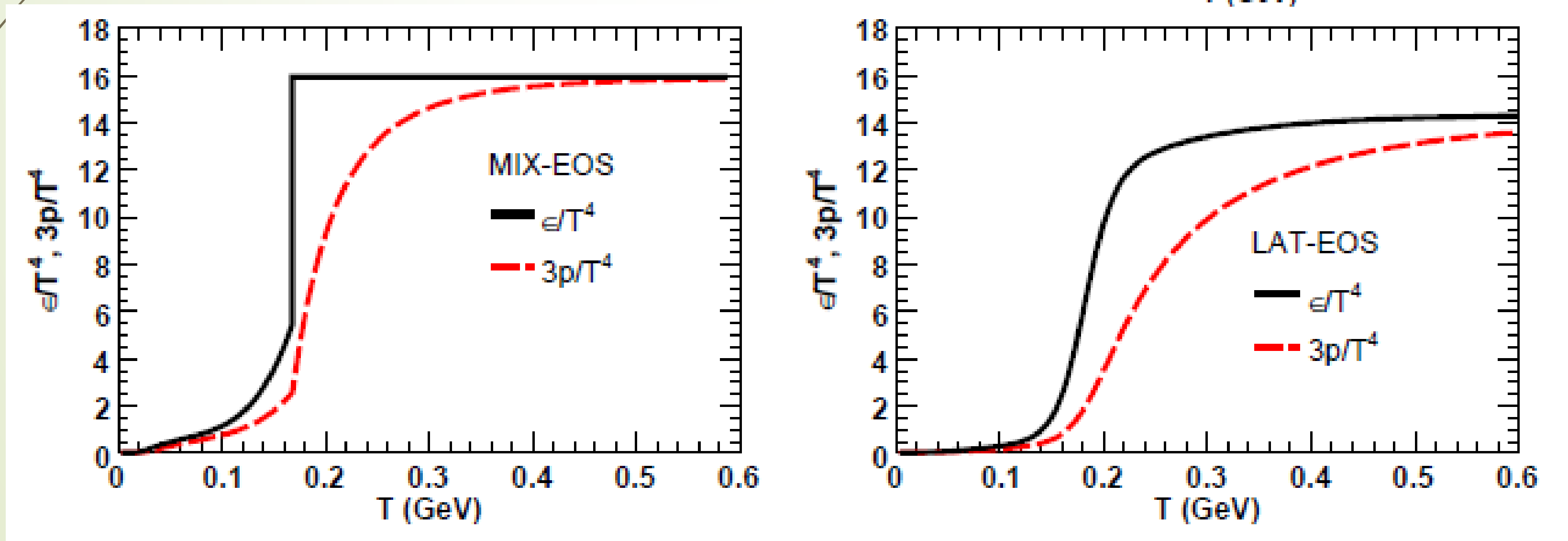
Massless ideal QGP

$$\epsilon = 3p = 16T^4$$

Resonance Hadron gas

[Braun-Munzinger, Redlich, Stachel, nucl-th/0304013]

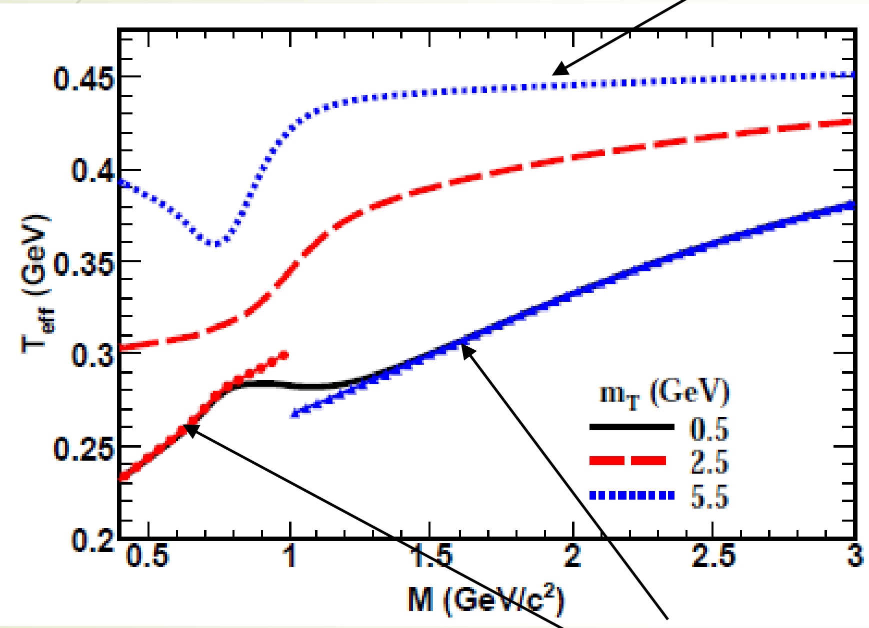




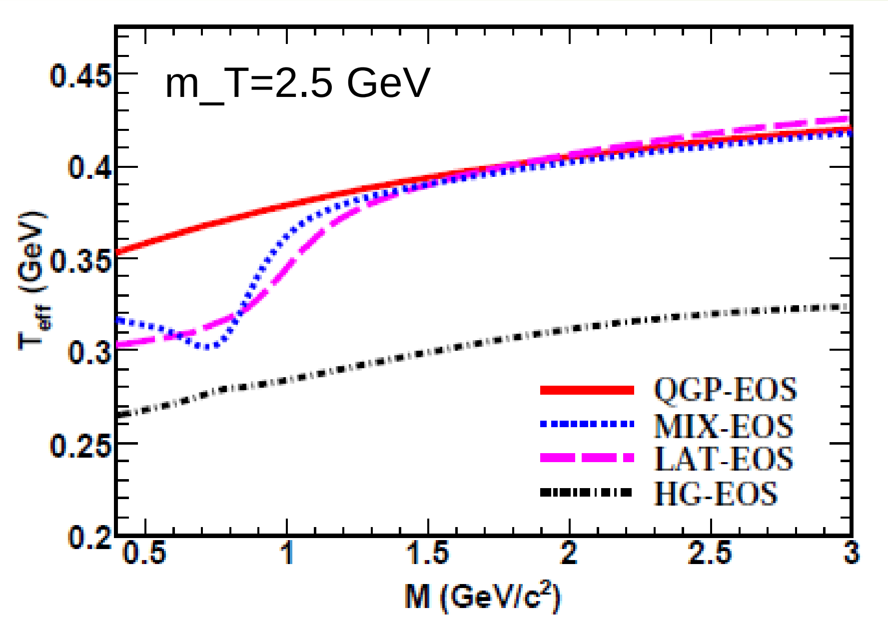
Slope parameter: pt and EOS dependence

$$T_{eff} \sim T\sqrt{\frac{1+v_T}{1-v_T}}$$

pt dependence



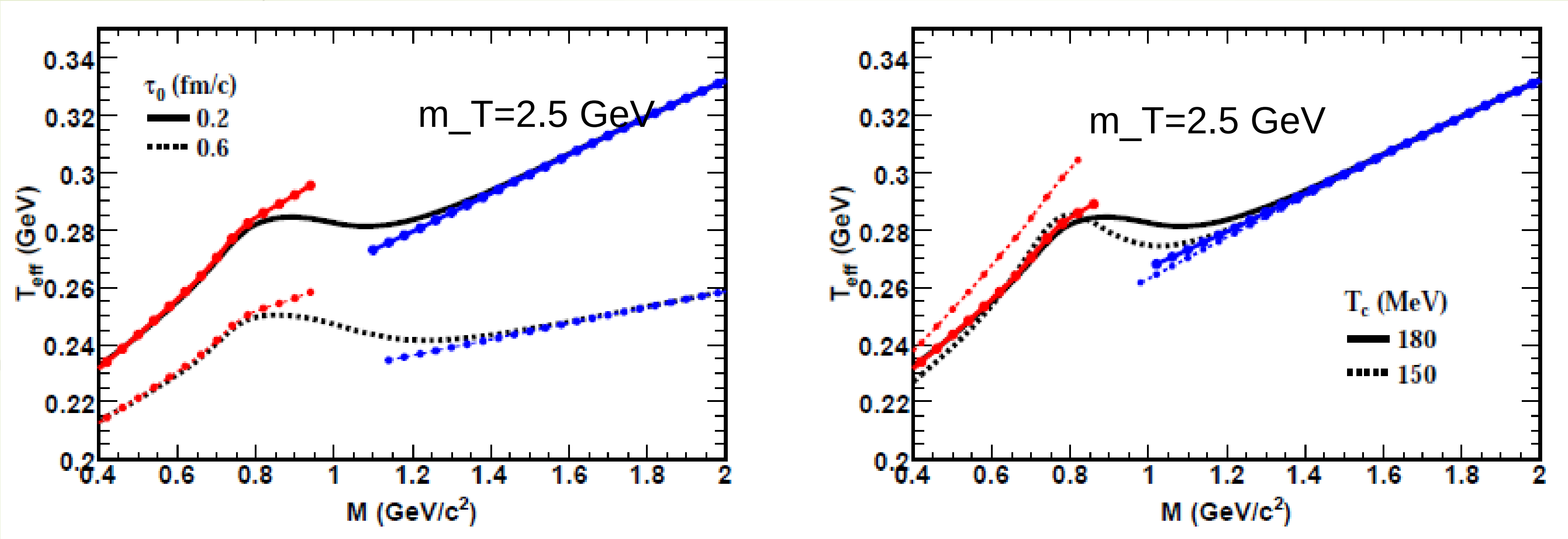
EOS dependence



$$T_{eff} \sim T + M^* v_T^2$$

J.Deng, QW, N.Xu, P.F. Zhuang, PLB701,581(2010)

Slope parameter: parameter dependence



J.Deng, QW, N.Xu, P.F. Zhuang, PLB701,581(2010)

Parameter dependences of the slope parameter with the lattice EOS. Left panel: the initial time for the hydrodynamic evolution τ_0= 0.2; 0.6 fm/c. Right panel: the phase transition temperature T_c = 180, 150 MeV. m_T=2.5 GeV.

Open charm in medium and comparison to STAR dilepton data

Charm quarks in medium: Fokker-Planck-Langevin equation

- Fokker-Planck equation describes the momentum diffusion of a heavy quark in medium (Brownian motion)

$$\frac{\partial f}{\partial t}=\frac{\partial}{\partial p^i}\left[A(E)p^i f+\frac{\partial}{\partial p^j}(B^{ij}(\mathbf{p})f)\right]$$

Svetitsky, PRD37, 2484(1988)

- where

$$A(E)=\frac{1}{2E_p}\int\frac{d^3\mathbf{q}}{(2\pi)^3E_q}f_i(x,q)\int\frac{d^3\mathbf{p}'}{(2\pi)^3E_{p'}}\int\frac{d^3\mathbf{q}'}{(2\pi)^3E_{q'}}\left(1-\frac{\mathbf{p}\cdot\mathbf{p}'}{\mathbf{p}^2}\right)$$
$$\times|\mathrm{M}|^2(2\pi)^4\delta^4(p+q-p'-q')$$

Scatterings of charm quarks by medium partons:
Q (**p**) + (u,d,s,g) (**q**) → Q (**p'**) + (u,d,s,g)' (**q'**)

$f(x,p)$: distribution of thermal partons

Scatterings of charm quark by thermal partons: in-medium T-matrix

- Non-perturbative resonance scatterings of heavy quarks by thermal partons (u,d,s,g)
- BS equation → reduce scheme and relativistic correction
- In-medium T-matrix equation for non-perturbative potential inspired by LQCD

van Hees, Mannarelli, Greco, Rapp, PRL100,192301(‘08);

Riek, Rapp, PRC82,035201('10);

Huggins, Rapp, NPA896,24('12).

Charm quarks in medium: Fokker-Planck-Langevin equation

- Langevin equation describes the phase space change of a heavy quark in medium (test particle method)

$$d\mathbf{x} = \frac{\mathbf{p}}{E} dt$$

$$d\mathbf{p} = -\Gamma(E)\mathbf{p}dt + \sqrt{2D(E)}d\mathbf{B}(t)$$

Drag force   Random force

- where $D(E) = ET\Gamma(E), \quad \Gamma(E) \approx A(E)$

$\gamma(E)$: relaxation rate

$D(E)$: diffusion constant

Hydyo-Langevin simulation

PHYTHIA: $pp \rightarrow$ **initial heavy quarks**

↓

HYDRO (2+1)D: $\mathrm{T}(x_i), u_\mu(x_i) \rightarrow \Gamma, D$

↓

Langevin equation:
$(x_i, p_i) \rightarrow (x_{i+1}, p_{i+1})$ **LRF of fluid cell**
$\rightarrow (x_{i+1}, p_{i+1})$ **Lab frame**

↓

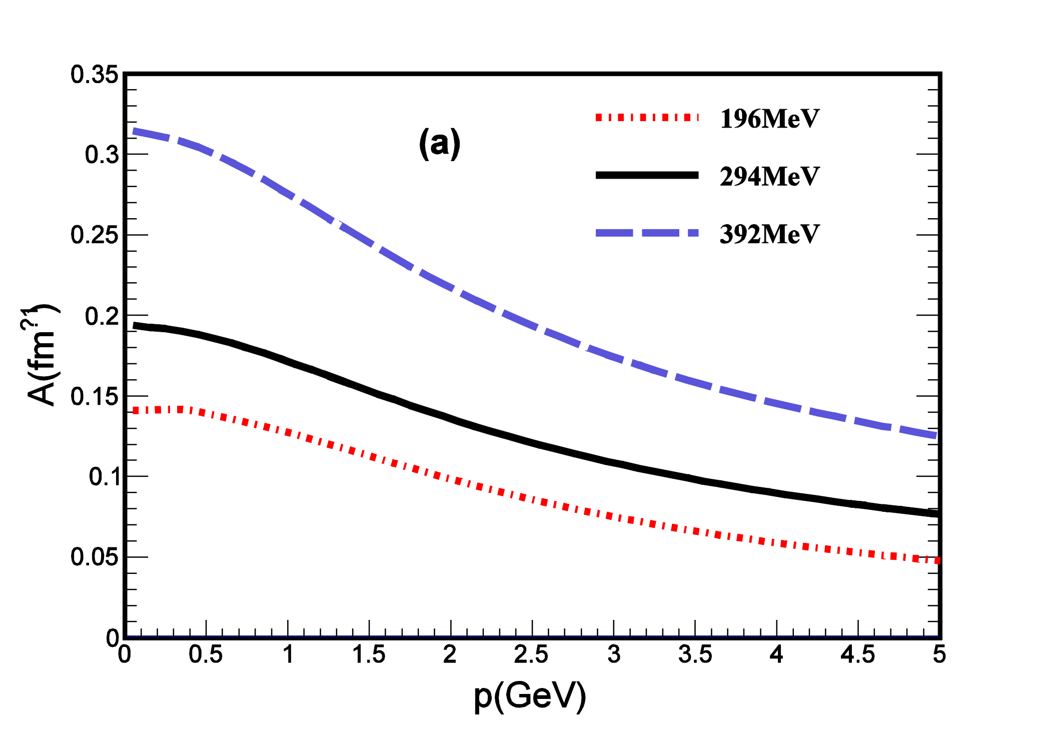
If $\mathrm{T}(x_{i+1}) < T_{out}$

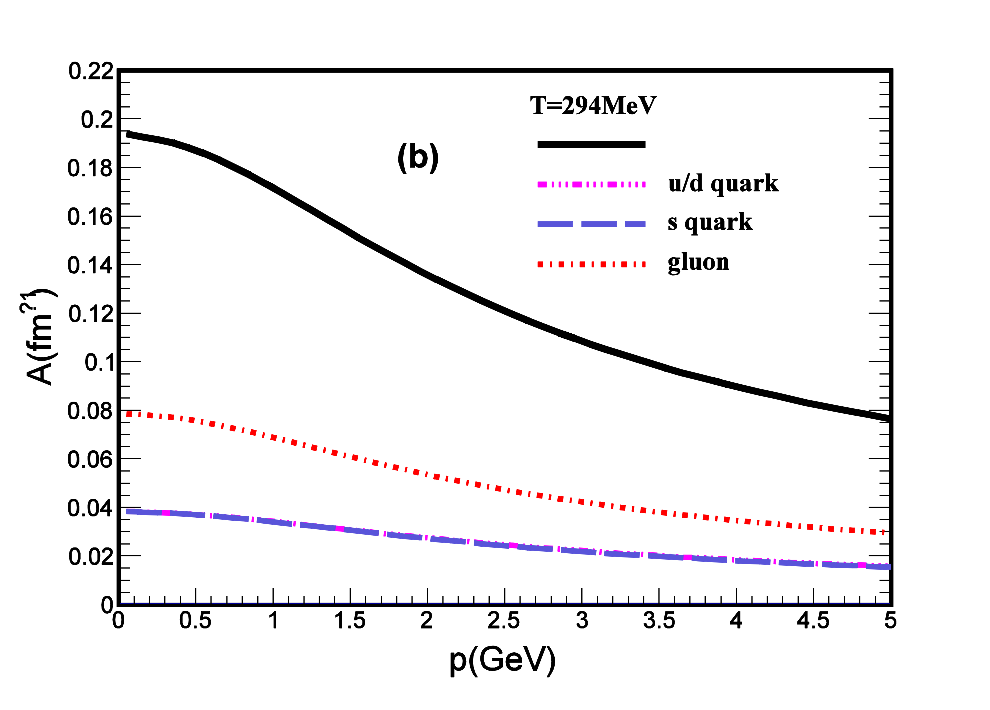
No → $i \rightarrow i+1$ (back to HYDRO)

Yes ↓

$(x_{i+1}, p_{i+1}) \rightarrow$ **PHYTHIA: hadronization + decay**

Charm quark relaxation rate

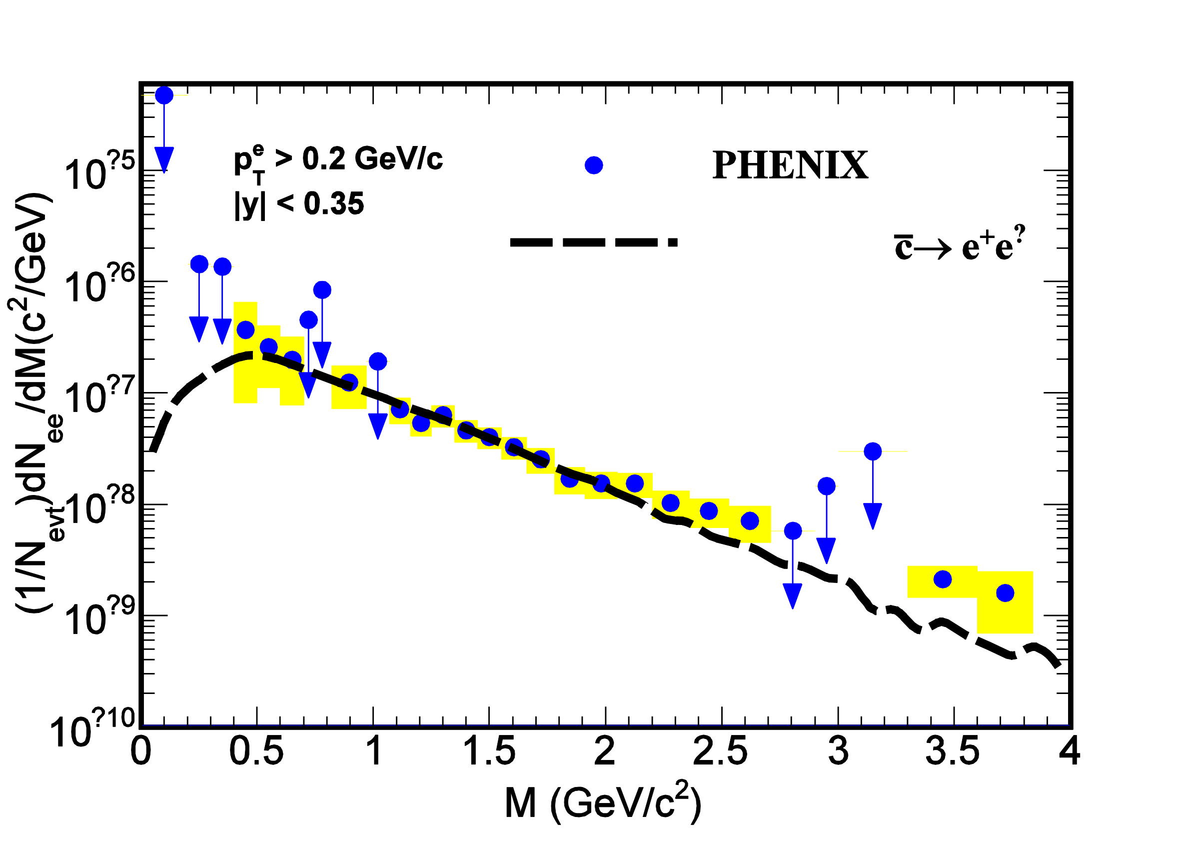




(a) Charm quark relaxation rates as functions of 3-momenta at different temperatures.
(b) Charm quark relaxation rates from scatterings by light and strange quarks and gluon.
(c) The temperature is set to T = 294 MeV.

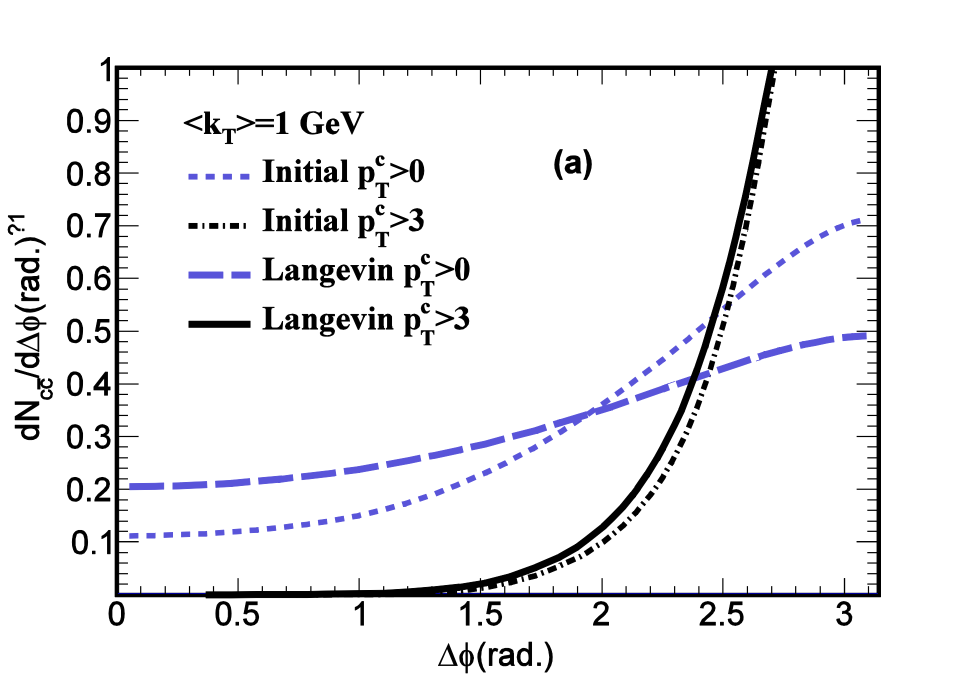
[H.J.Xu, X.Dong, L.J.Ruan, QW, Z.B.Xu, Y.F. Zhang, Phys.Rev. C89 (2014) 024905, arXiv:1305.7302]

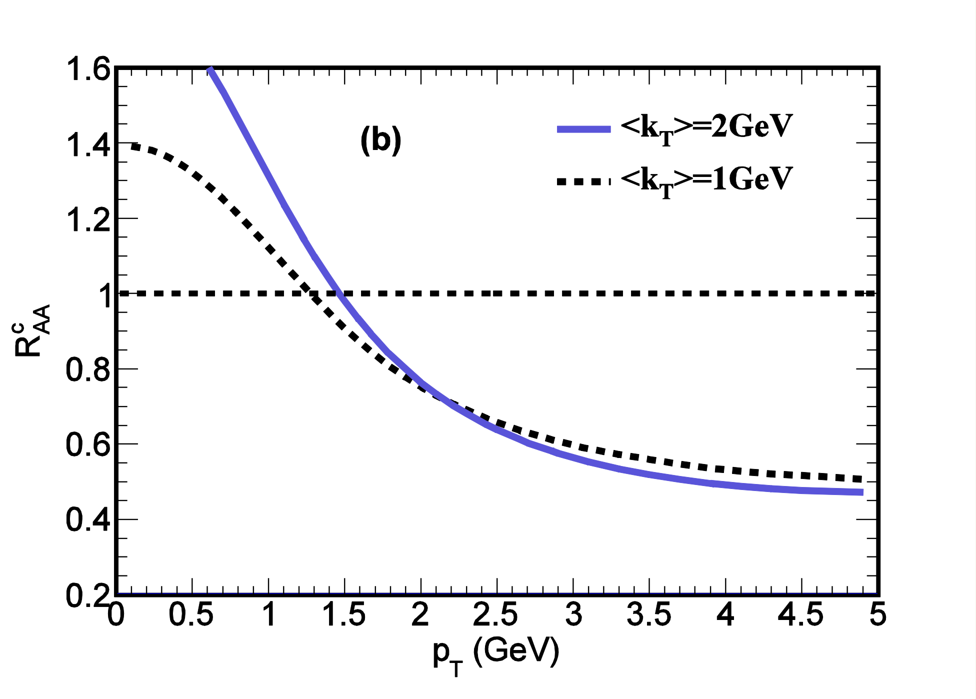
Di-electrons in pp collisions



The rescaled di-electron cross section from semi-leptonic decays of open charm hadrons in p+p collisions by PYTHIA with the PHENIX detector acceptance. The data are taken from PHENIX

Charm quark: angular correlation and R_AA spectra

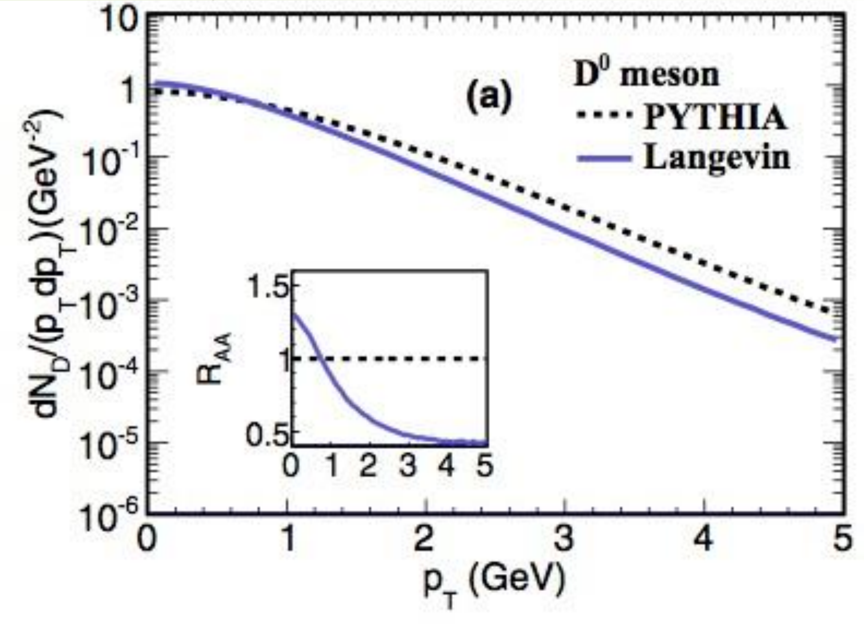


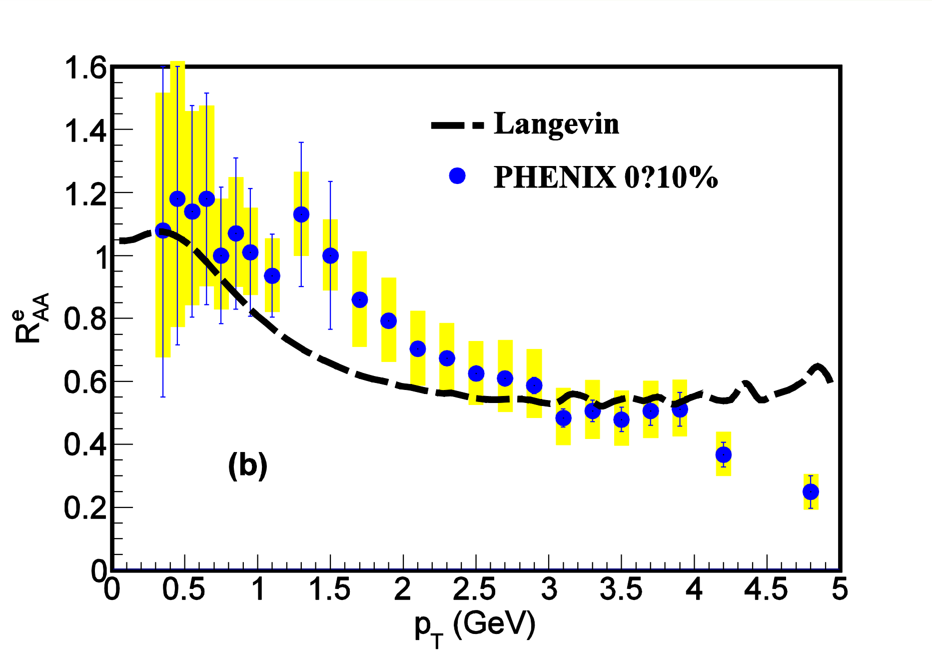


(a) The angular correlation of charm quark pairs in the initial and final states. The different pT cutoffs are chosen. The freezeout temperature is set to Tc= 184 MeV.

(b) The nuclear modification factors with Hydro-Langevin evolution for charm quarks in partonic medium for two values of kT in PYTHIA.

pt spectra of D_0 and R_{AA} of electron from open charm

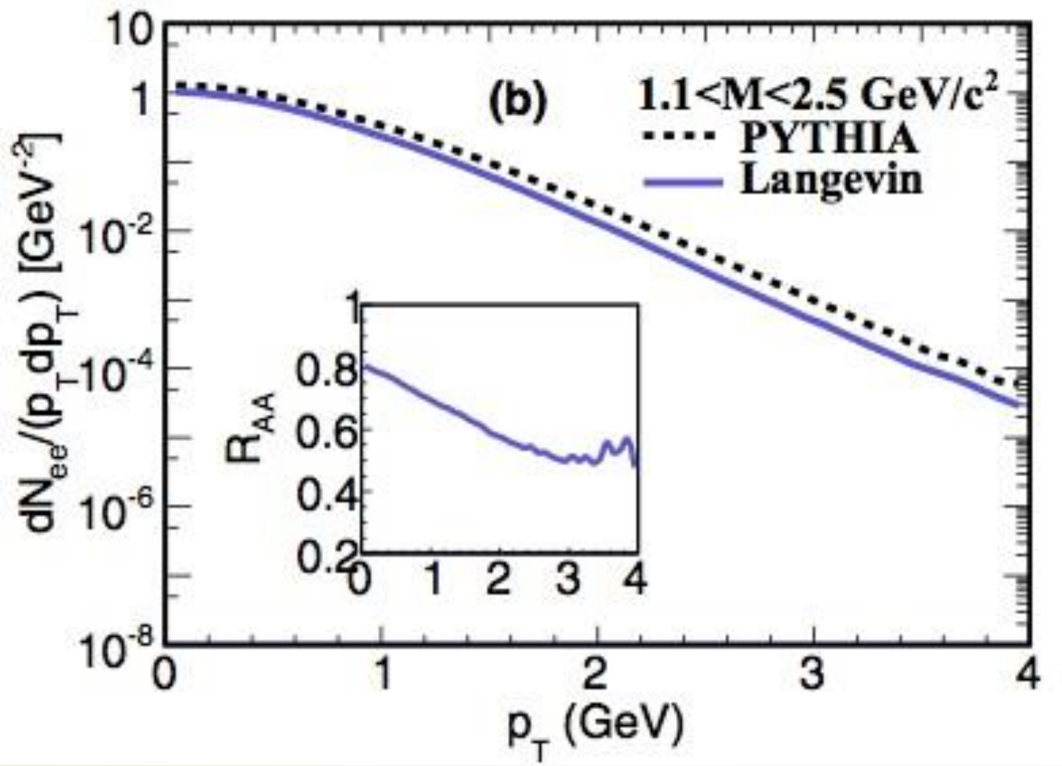




(a) The pT spectra and the nuclear modification factor of D0 mesons.

(b) The nuclear modification factor of electrons from semileptonic decays of charm hadrons. The data are taken from PHENIX.

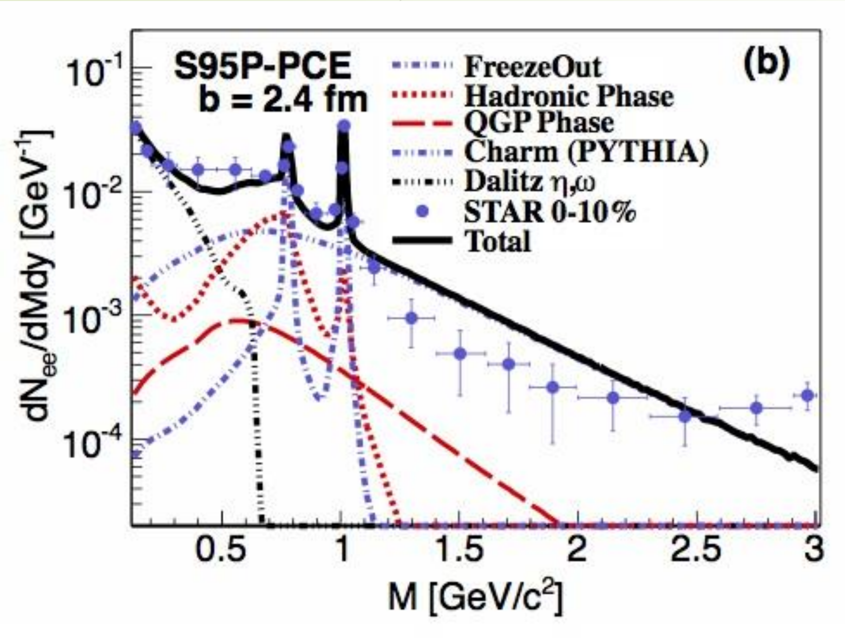
Di-electrons from open charm: pt spectra and R_{AA}



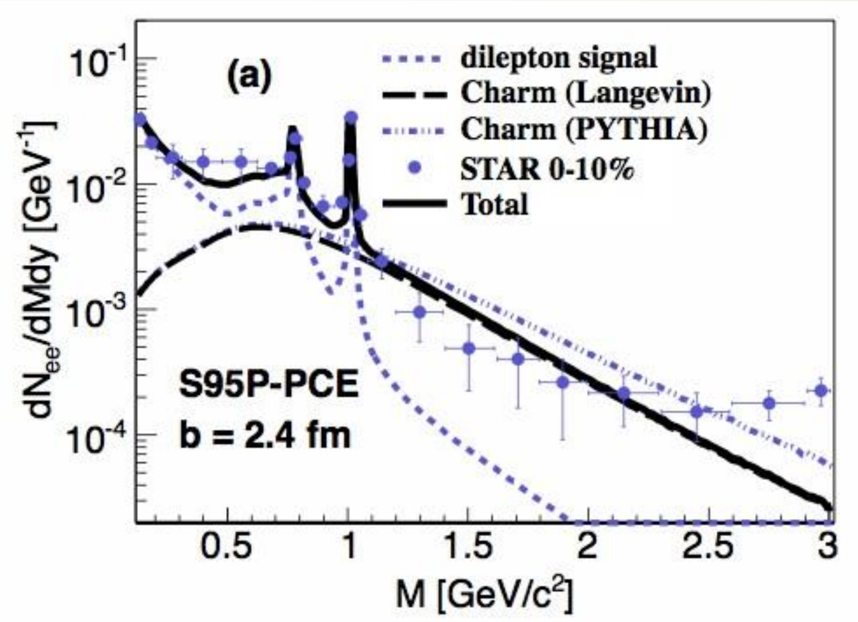
H.J.Xu, X.Dong, L.J.Ruan, QW, Z.B.Xu, Y.F. Zhang, Phys.Rev. C89 (2014) 024905.

The pT spectra of di-electrons from semi-leptonic decays of correlated charm hadrons in the mass range 1.1 < M < 2.5 GeV. The nuclear modification factor of di-electrons is shown in the inset.

Comparison to STAR data



Charm with medium modification



Comparison: charm w/o medium modification

H.J.Xu, X.Dong, L.J.Ruan, Q.Wang, Z.B.Xu, Y.F. Zhang, PRC 89 (2014) 024905.

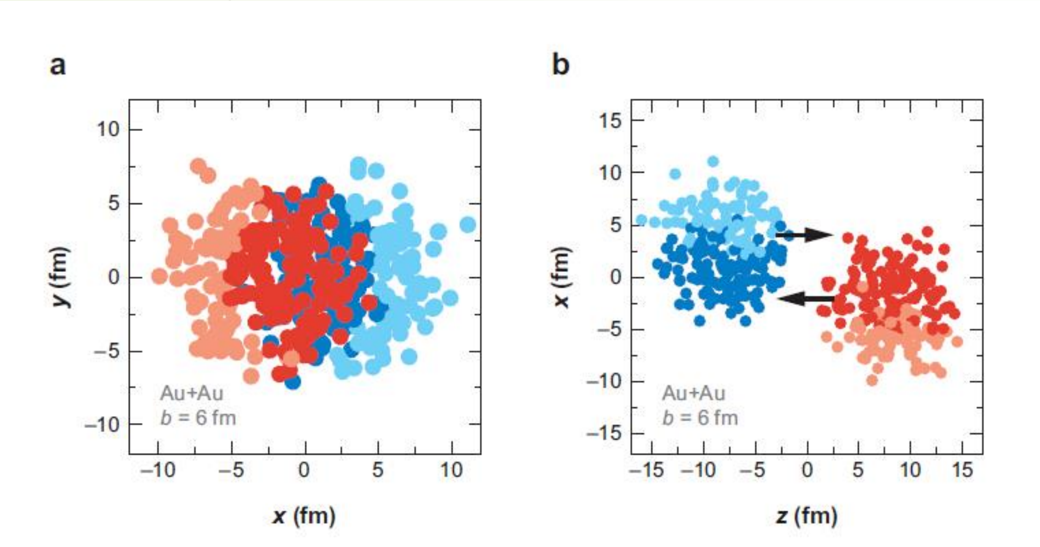
Other work: G.Vujanovic, C.Young, B.Schenke, R.Rapp, S.Jeon, C.Gale, PRC89 (2014) 034904.

The invariant mass spectra of di-electrons in comparison with the STAR data in the most central (0–10%) Au+Au collisions with the STAR detector acceptance. **[STAR Collab., Phys.Rev.Lett. 113 (2014) 022301]**

Anisotropic flow of thermal dilepton: Event-by-Event simulation

Event-by-event initial condition

MC Glauber, MC-KLN, IP-Glasma, AMPT, URQMD, ...



M. Miller, K. Reygers, et. al. (2007)

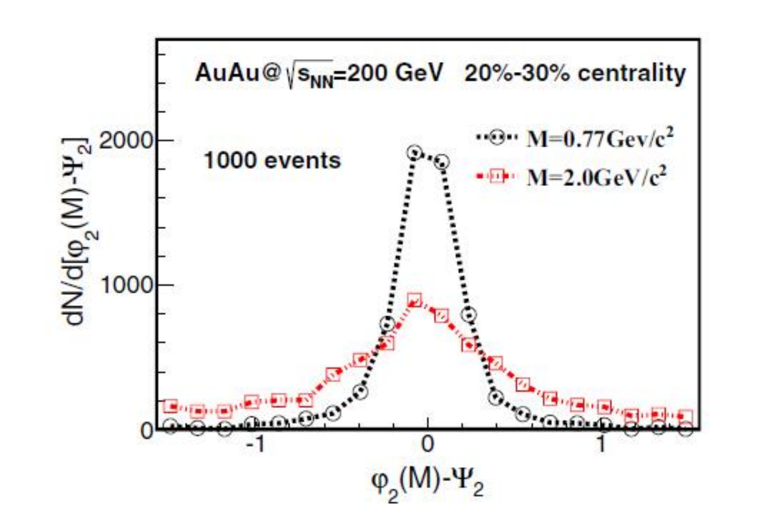
MC Glauber

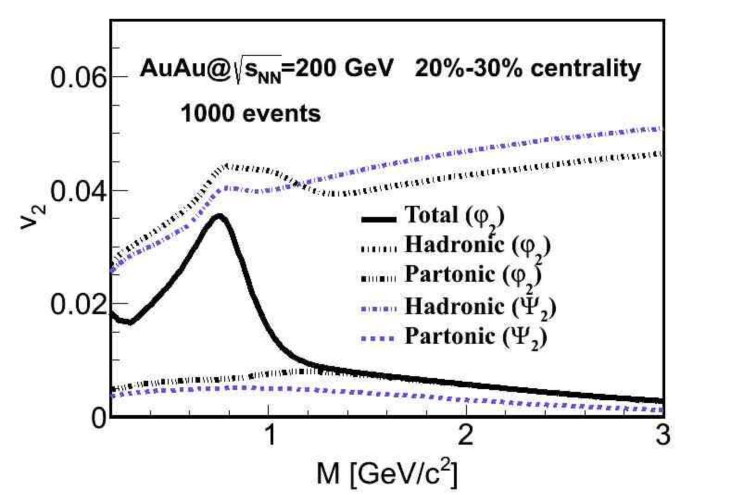
$$s_0(\boldsymbol{x}_\perp) = \left.\frac{dS}{\tau_0\, dx\, dy\, d\eta_s}\right|_{\eta_s=0} = \frac{C}{\tau_0}\left(\frac{1-\delta}{2}\frac{dN_{\text{part}}}{d^2x_\perp} + \delta\frac{dN_{\text{coll}}}{d^2x_\perp}\right).$$

T. Hirano, Y. Nara(2009)

The event-by-event hydrodynamic simulation:
B.Schenke, S.Jeon, C.Gale, 2010; Z. Qiu, U. Heinz, 2011;
L. Pang, Q. Wang, X.-N. Wang, 2012; …….

Correlation between different event plane angle





$$\varphi_n(M) = \frac{1}{n}\arctan\frac{\langle p_T \sin(n\phi)\rangle}{\langle p_T \cos(n\phi)\rangle}$$

average over thermal dileptons

The correlation between $\varphi_2(M)$ and Ψ_2 becomes stronger from higher mass to lower mass.

H.J.Xu, L.G.Pang, Q.Wang, Phys.Rev.C89, 064902 (2014)

$$v_2(M) = \frac{\int d\phi (dN/dMd\phi dy)\cos(2(\phi - \Psi_2))}{\int d\phi (dN/dMd\phi dy)},$$

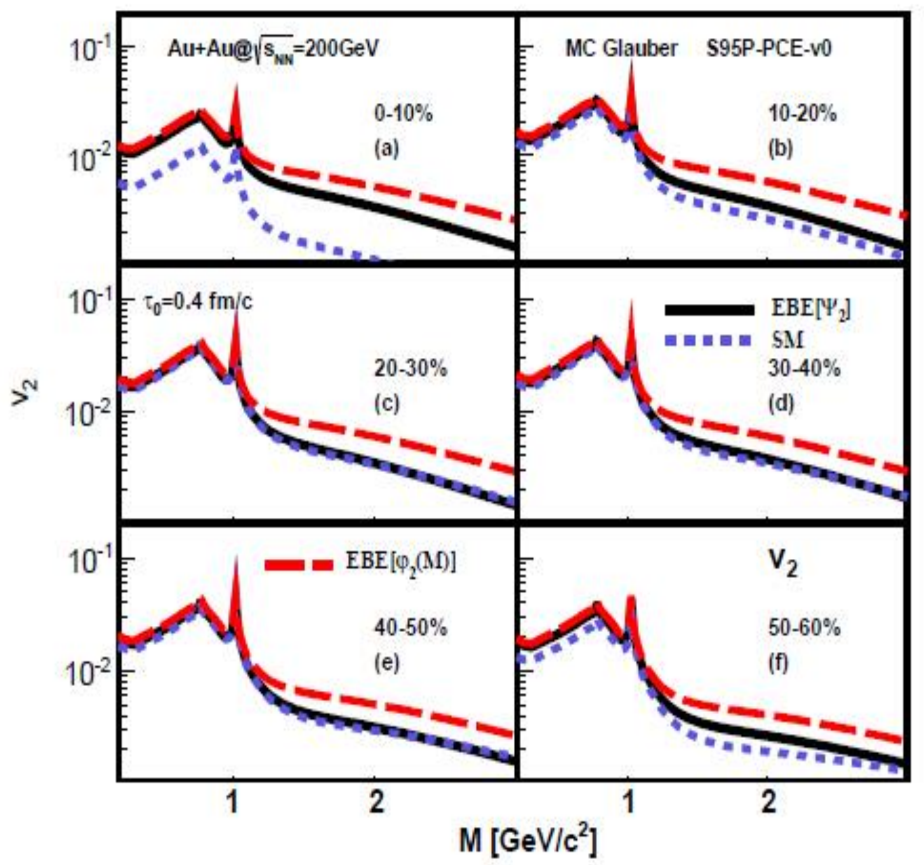
$$v_2(M) = \frac{\int d\phi (dN/dMd\phi dy)\cos(2(\phi - \varphi_2(M))}{\int d\phi (dN/dMd\phi dy)}.$$

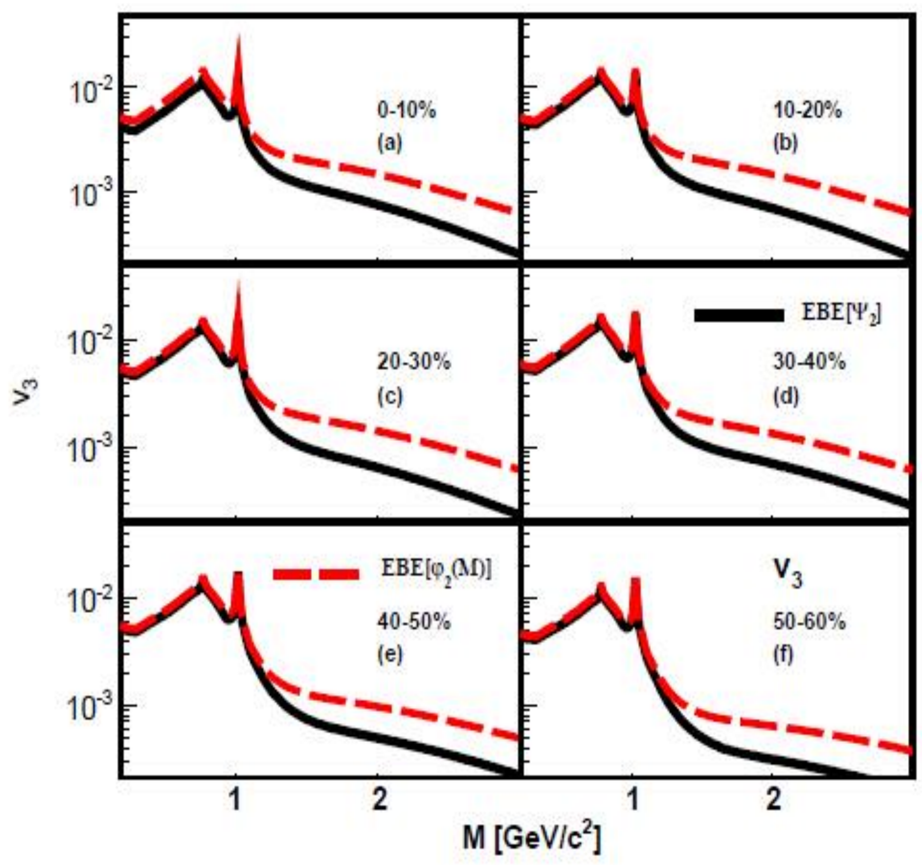
Ψ: EP from charged hadrons

φ: EP from leptons

Bigger fluctuation effects with event plane defined by dileptons at specific M

Flow of thermal dileptons: comparison of event planes





H.J.Xu, L.G.Pang, Q.Wang, to be submitted

Summary

- T_eff of di-lepton can serve as a probe to EOS of the dense matter in high energy HIC
- Rho meson self-energy from meson resonances below 1300 MeV and baryon resonances (from ρNN*+ρN(Δ,Δ*) couplings) are taken into account
- In-medium and freezeout contributions are identified
- Open charm contribution is modeled in Hydro-Langevin simulation with in-medium T-matrix
- Comparison with STAR data is made with good agreement
- Collective flow from Event-by-Event simulation

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