Some aspects of dilepton production in HIC

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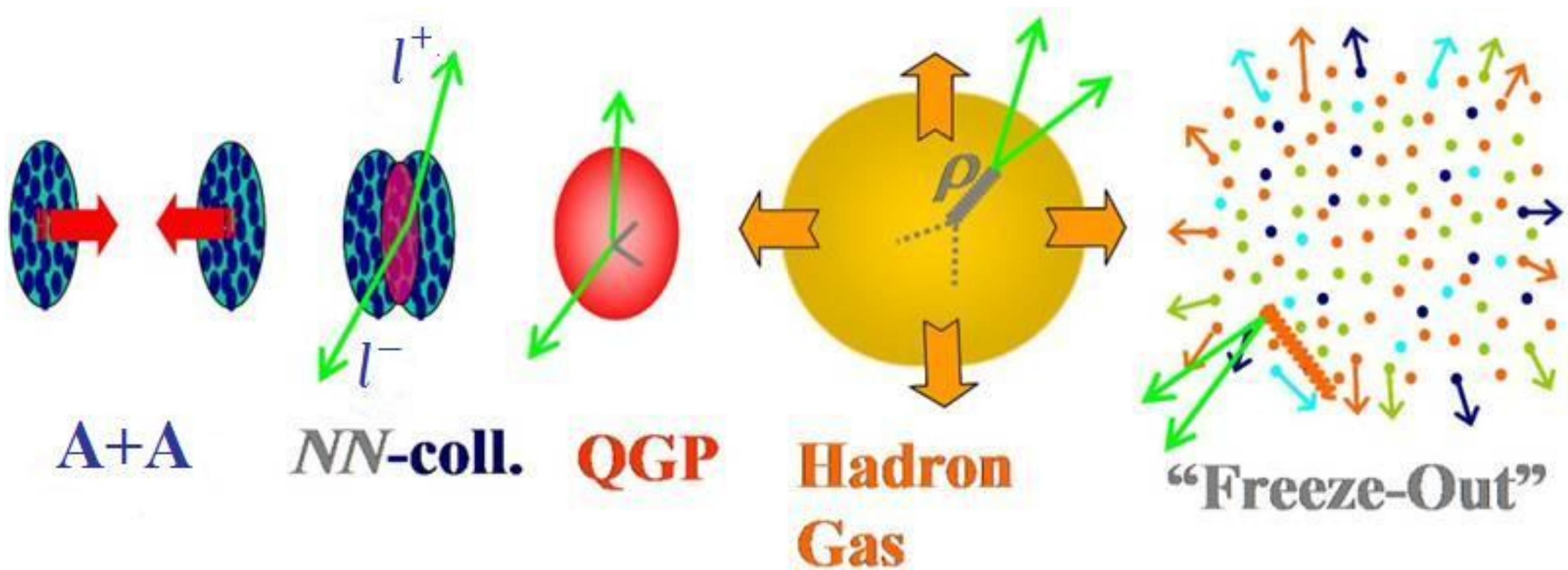
J.Deng, Q.Wang, N.Xu, P.-f. Zhuang, PLB701,581(2010);
H.-j. Xu, H.-f. Chen, X.Dong, Q.Wang, Y.-f. Zhang, PRC85, 024906(2012)

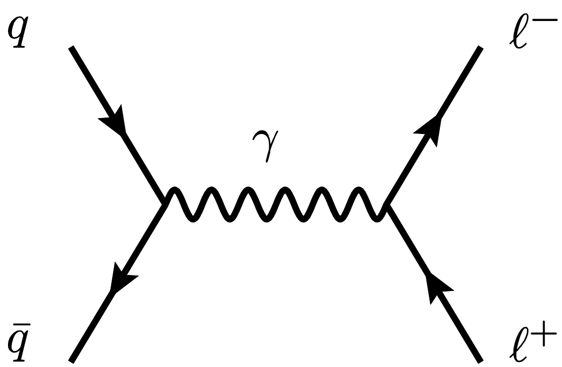
Thermal radiation workshop, RBRC-BNL, Dec 4-7, 2012

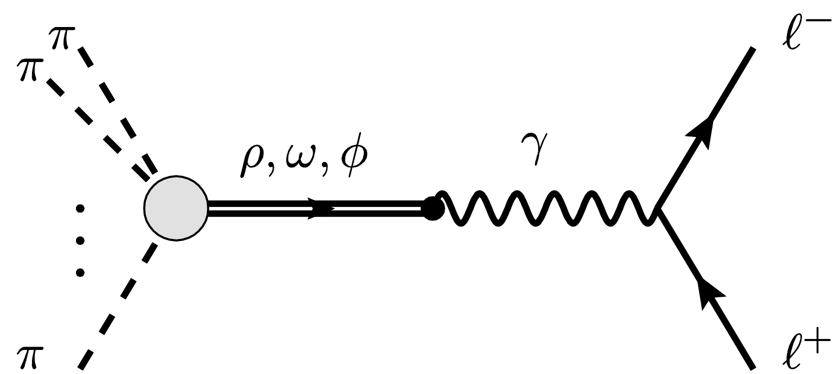
Outline

1. Introduction: a very brief timeline (history) of dilepton production in HIC (R. Rapp's talk, I. Tserruya's talk)
2. Vector meson contribution via Vector Meson Dominance model (VDM)
3. T_eff as probe to EOS of dense matter
4. Comparison with STAR data
5. Summary and conclusion

Di-lepton sources in HIC







A little history (1)

Why dileptons ?

(1985) McLerran & Toimela, PRD31, 545
(1990) Braaten,Pisarski,Yuan, PRL64, 2242
(1993) Shuryak,Xiong, PRL70, 2241

- Suffer less interaction after their production
- Emitted in the whole space-time volume of the fireball
- Provide crucial information of the medium properties created by HIC

Earlier experiments

(1997) DLS collaboration, PRL79,1229
(1998) DLS collaboration, PRC57,1865

- Rare production
- Complex background

Ca+Ca, C+C, C+Ca, d+Ca

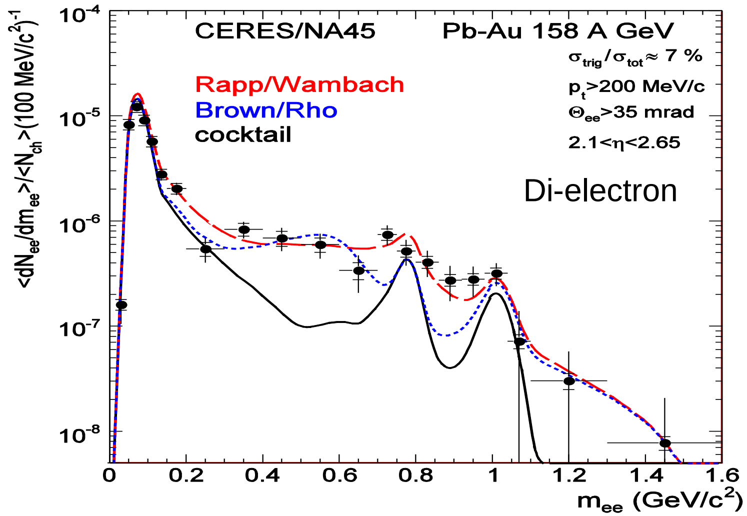
M<0.7 GeV

A little history (2)

Low statistics

(1998) HELIOS-3, EPJC 5, 63
(1998) CERES/NA45, PLB422,405
(2000) NA50, EPJC 13,69

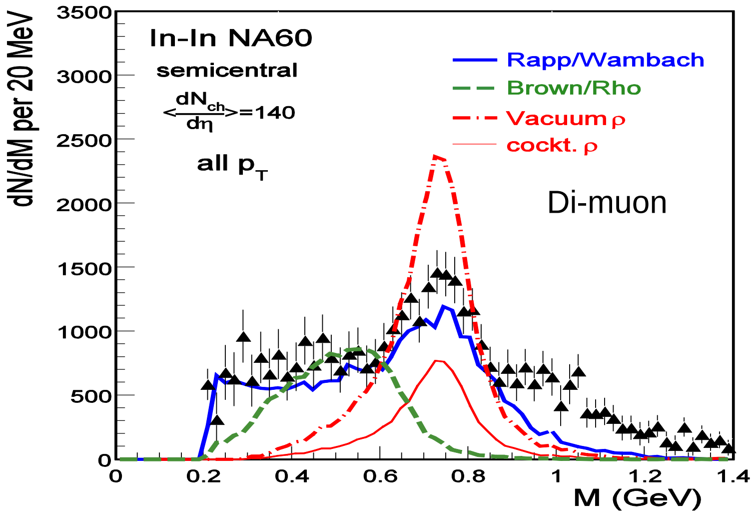
Low mass enhancement



High statistics

(2006) NA60, PRL96,162302

In-medium rho spectra



A little history (3)

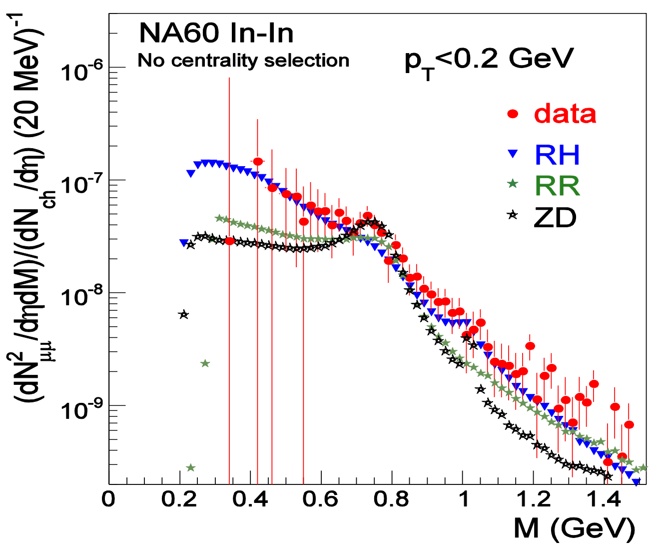
Low statistics

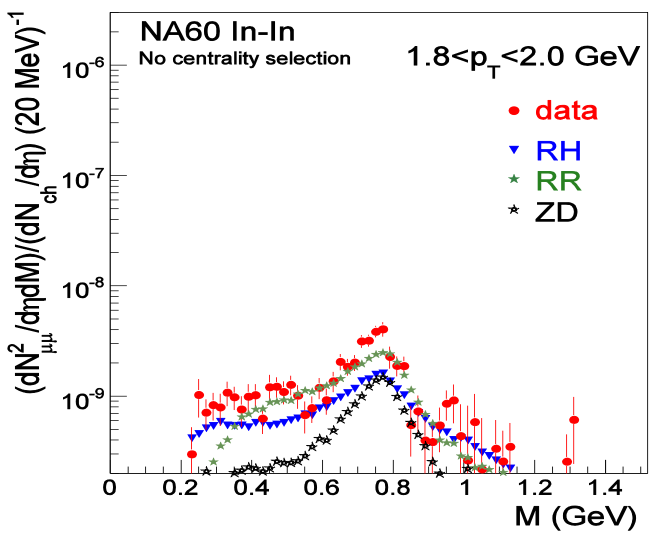
(2004) Brown & Rho, Phys.Rept 398, 301

Broadening spectra vs Dropping mass

High statistics

(2006) van Hees & Rapp. PRL97, 102301
(2008) Ruppert, Gale, et al. PRL100, 162301
(2007) Dusling, Teaney & Zahed. PRC75, 024908



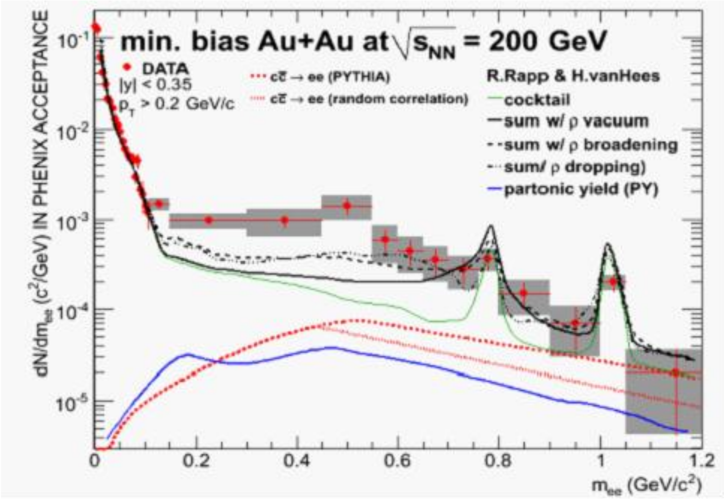


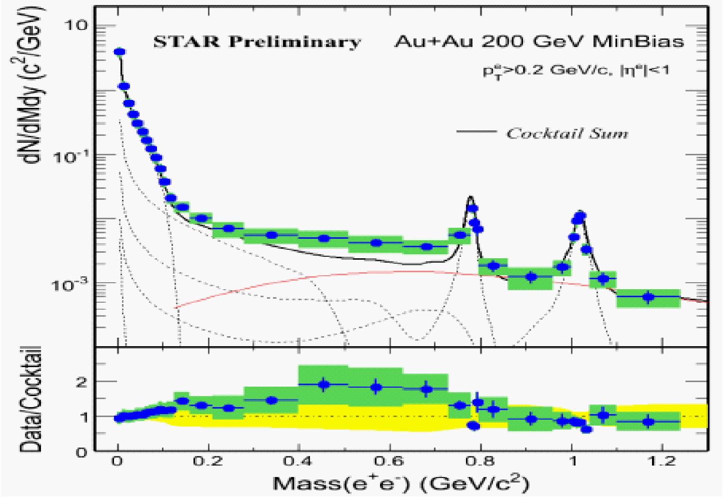
A little history (4)

RHIC energy

(2010) PHENIX, PRC81, 034911
(2011) J. Zhao, JPG38 , 124134

PHENIX puzzle





Future

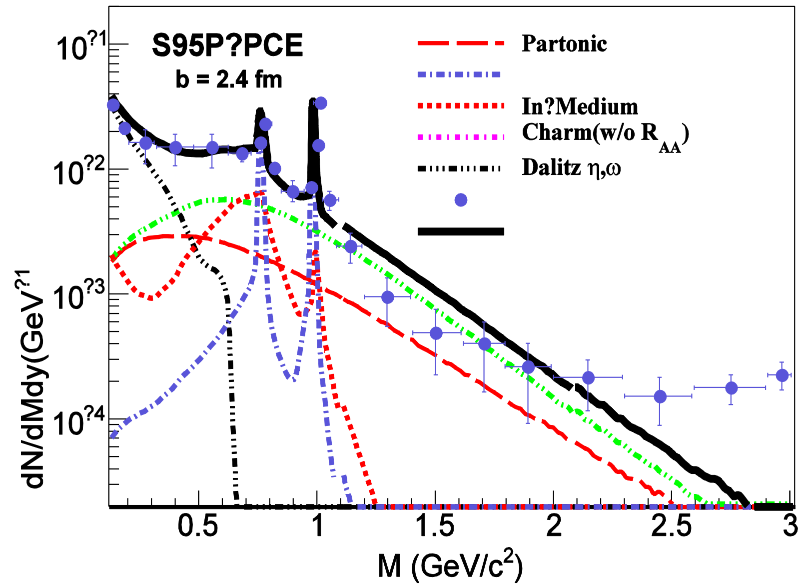
- STAR-BES
- LHC
- CMB

A little history (5)

RHIC energy

(2009) Rapp, Wambach, 0901.3289
(2012) Linnyk et al, PRC85, 024910
(2012) Xu, et al, PRC85, 024906

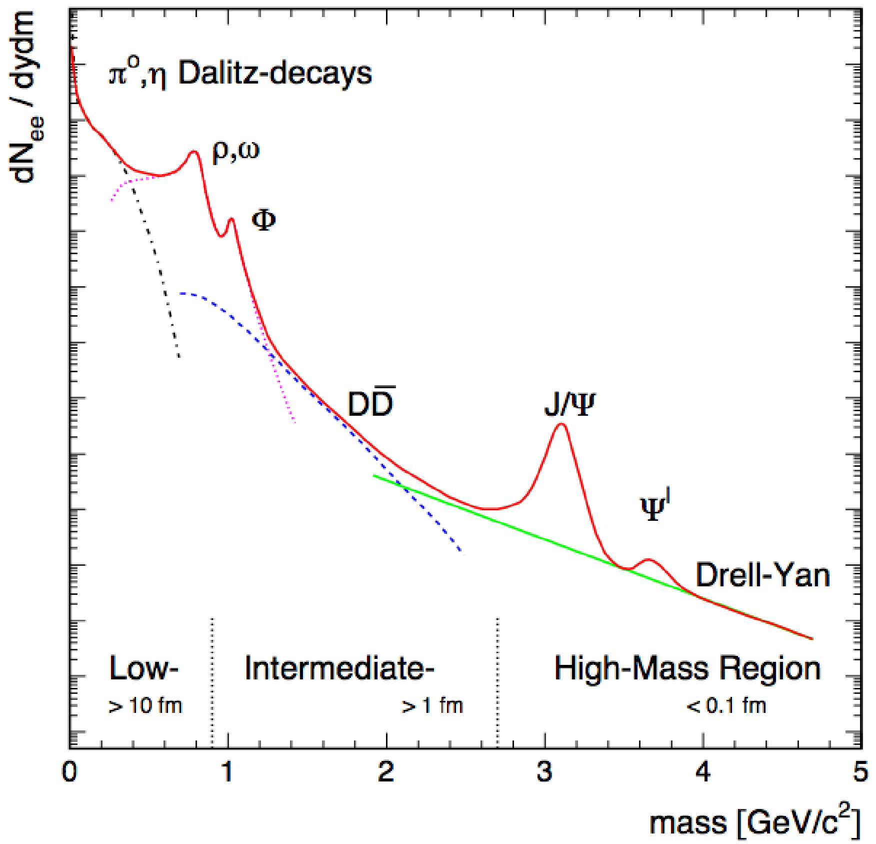
phenomenology study



- **PHENIX puzzle**
- **The signals from BES**
- **v2, HBT**
- **etc. ……**

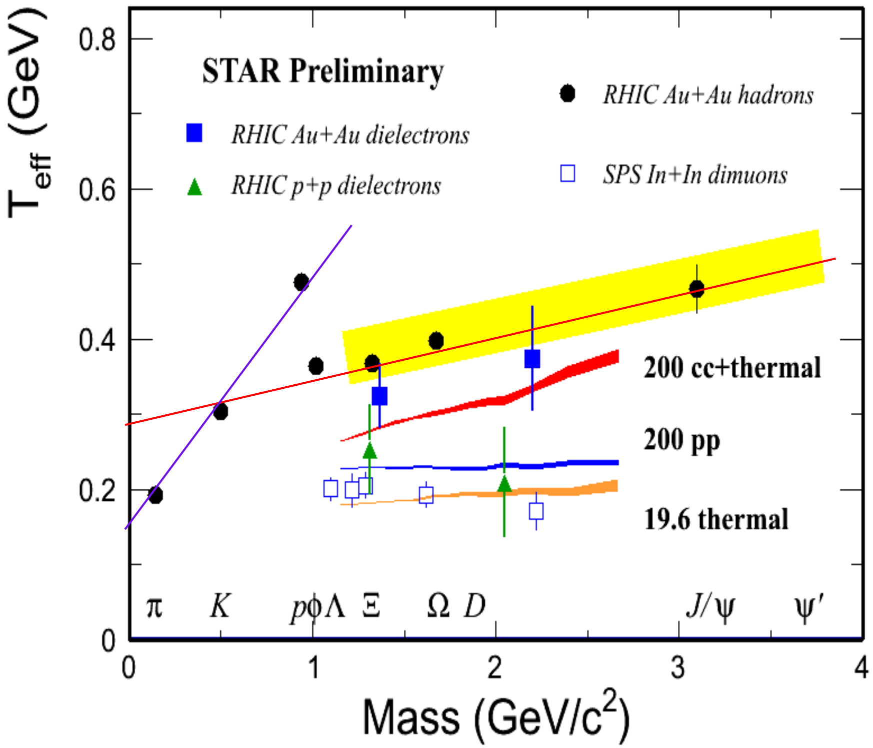
(2006) Chatterjee , et al. PRC75, 054909
(2008) Dusling et al. NPA809, 246
(2011) Deng, et al. PLB701,581
(2011) Mohanty, et al. PRC84, 024903
……

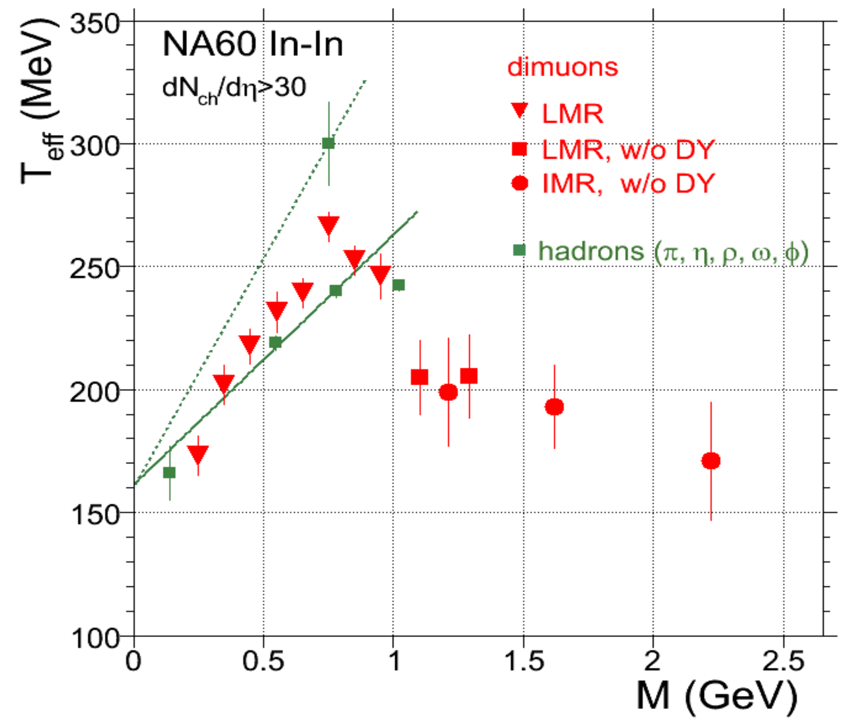
Invariant mass spectra



LMR	**Chiral symmetry restoration, Vector meson production, in-medium effect**
IMR	**Heavy quark, QGP thermal radiation**
HMR	**Heavy quarkonia, Drell-Yan**

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)

Strategy

- Dilepton production in Au+Au collisions at 200 GeV in IMR, QGP phase: q-qbar annihilation; Hadron phase: 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, ωπππ; and D_φ with vertices φKK-bar.
- Space-time evolution of medium is described by a 2+1 ideal hydro model, different EOS are used for hydro-simulation.
- Slope parameters and elliptic flows show distinct features from two phases
- Comparison to recent STAR data.

Hydrodynamics for HIC

- **Assumption:** thermalization, Ideal or Viscous
- **Inputs:** EOS, initial conditions, freeze-out conditions
- **Outputs:** space-time evolution
- **Comparison with data:** pt-spectra, flows, …
- **Further application:** fluctuation & correlation, non-equilbrium statistics, ...

Baym, Friman, Blaizot et al 86', Rischke 98', Kolb, Huovinen, Heinz, 00-01’, Romatschke, 08’, Song, Heinz, 08’, Schenke, Jeon, Gale, 10’ , Pang, Q.W., Wang 12’, ……

Vector Meson Dominance Model (VDM)

- VDM (Kroll, Lee, Zumino, 67'). The Lagrangian for ρπγe-system:

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

← Photon-rho coupling

where

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

- EOM for EM field

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

⇒

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

(keep terms linear in e/g)

Dilepton emission rate (1)

In-medium rate

$$\frac{d^8N}{d^4x d^4p} = -\frac{\alpha}{4\pi^4}\frac{1}{M^2} n_B(p\cdot u) L(M) \mathrm{Im}\Pi_\gamma^R(p)$$

$$L(M) = \left(1+\frac{2m_l^2}{M^2}\right)\sqrt{1-\frac{4m_l^2}{M^2}}$$

u: fluid velocity
T: temperature
Π_γ and n_B depend on space-time via u and T

Photon selfenery (VDM + quark)

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

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.**

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

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

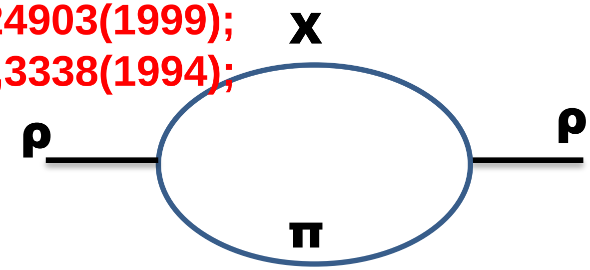
Freezeout Emission rate of vector meson

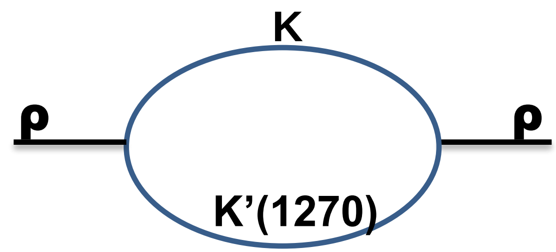
Freezeout hypersurface

In-vacuum vector meson propagator

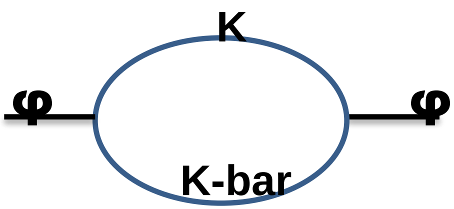
Rho self energy (1)

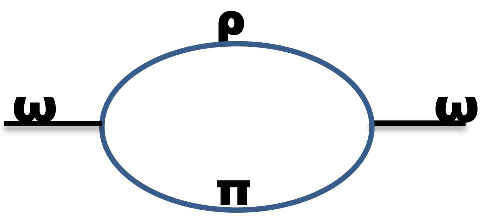
Chanfray,Schuck, NPA555,329(1993);
Herrmann,Friman,Noerenberg, NPA560(1993);
Rapp,Gale, PRC 60,024903(1999);
Gale,Lichard, PRD 49,3338(1994);

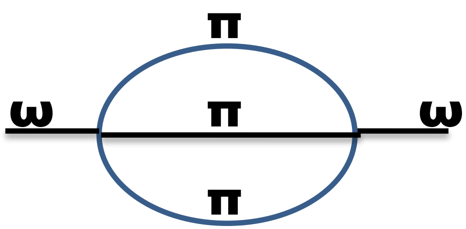




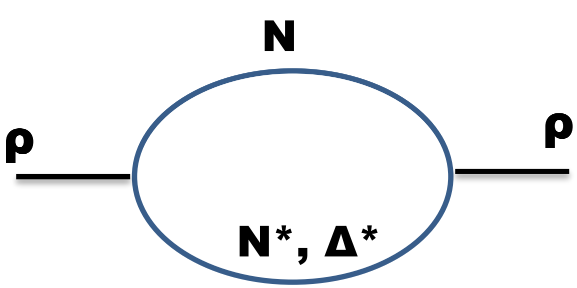
Meson Contribution
X = π, ω, h1(1170)
a1(1260), π'(1300)





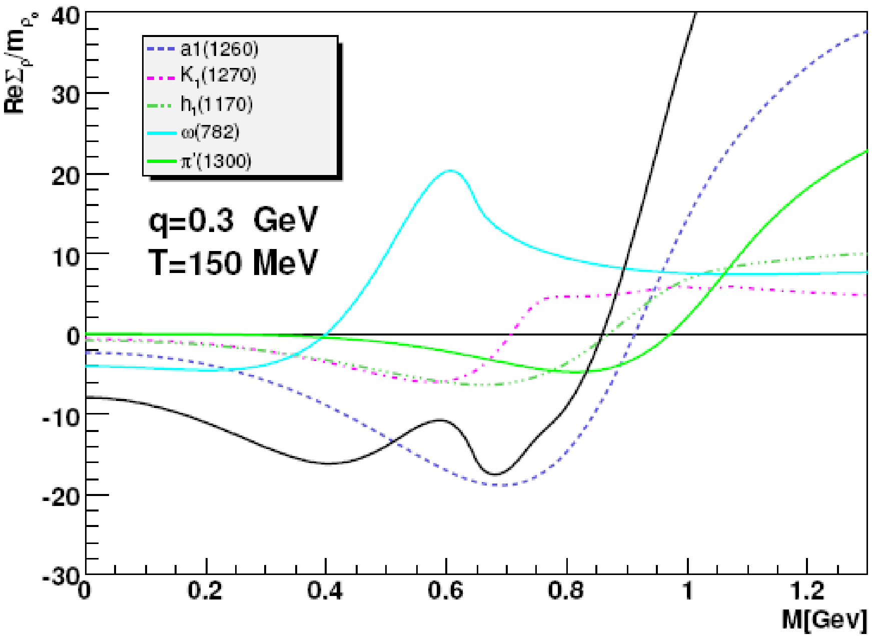


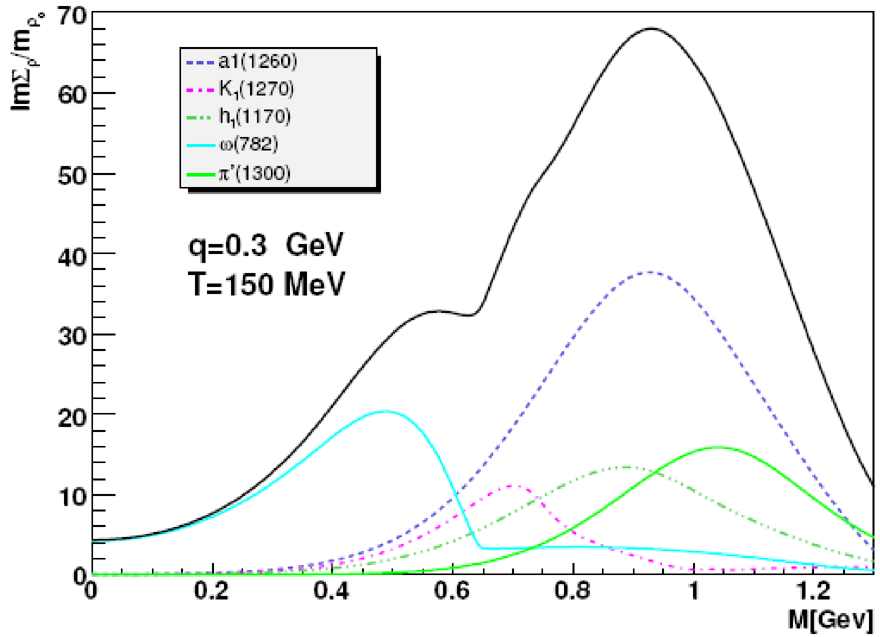
Baryon Contribution:
N(1700), N(1720), N(1900)
N(2000), N(2080), N(2090)
N(2100), N(2190),
Δ(1700), Δ(1900), Δ(1905),
Δ(1940), Δ(2000)



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

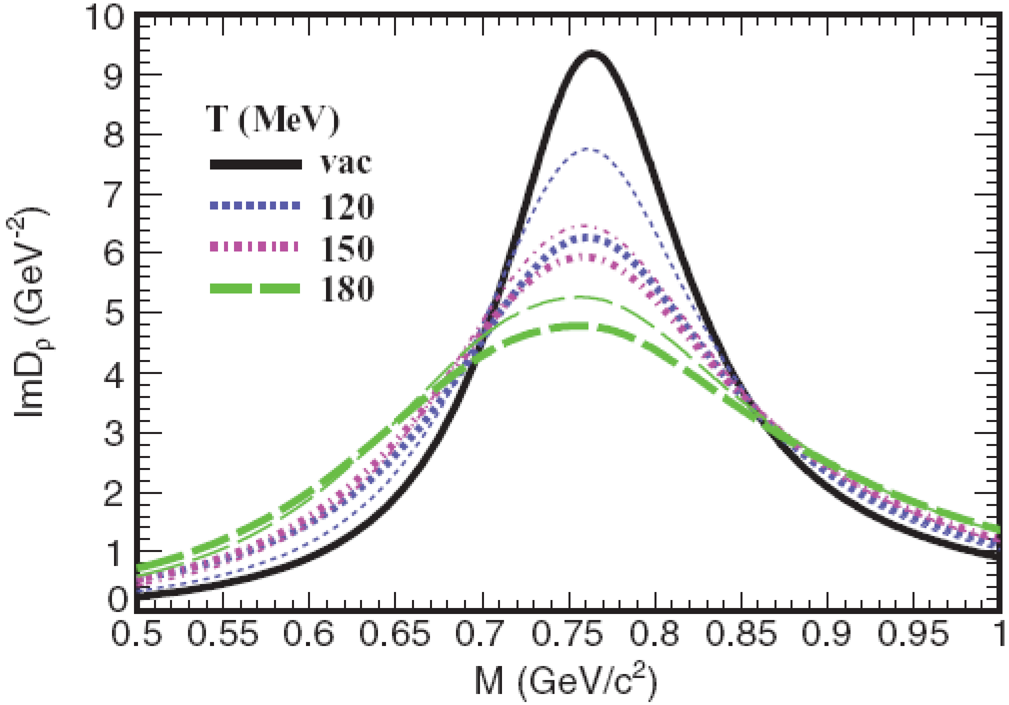
Rho self energy (2) Re and Im from mesons





Rapp & Gale, PRC 60,024903(1999)

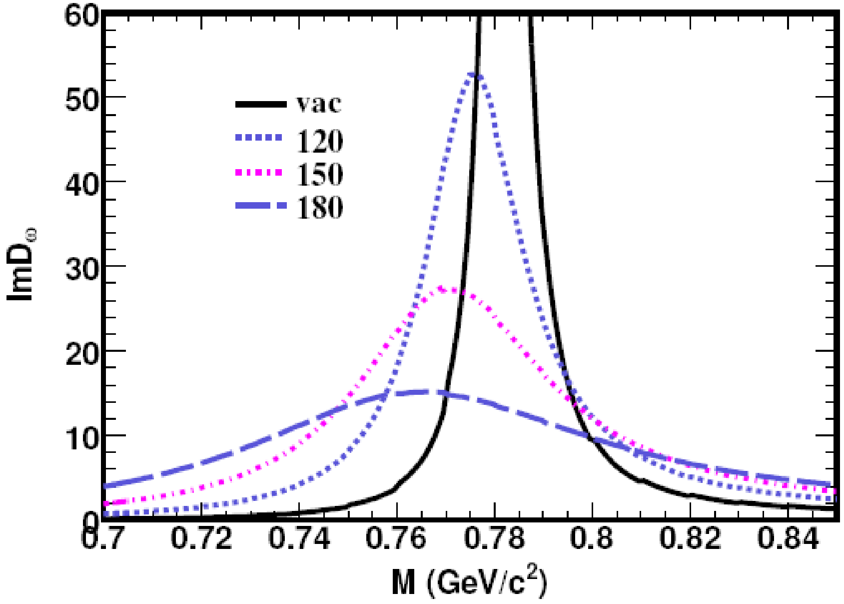
Rho self energy (3): Im D_ρ w/o NN*+NΔ* contribution

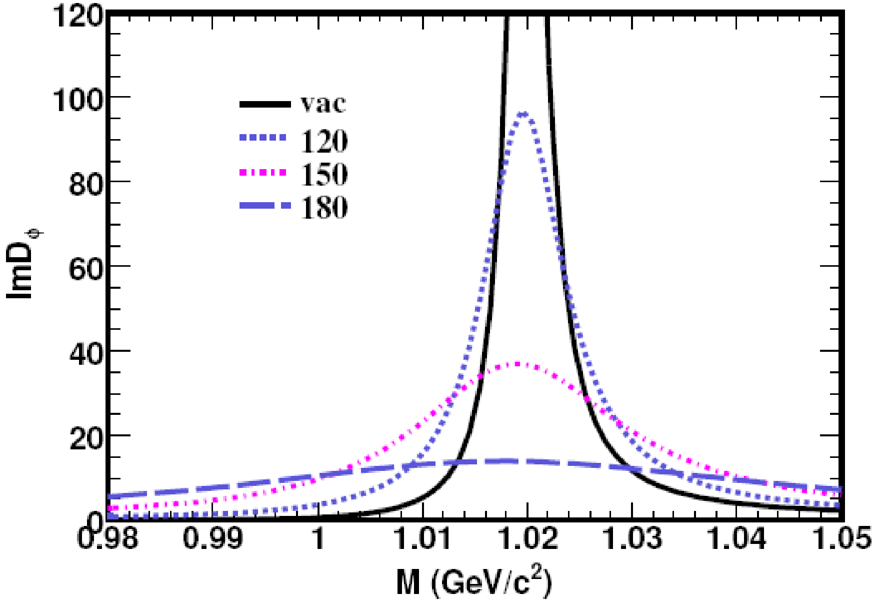


The imaginary parts of the in-medium ρ meson propagators (or in-medium spectral functions) with (thick lines) and without (thin lines) baryonic contributions. The chemical potentials in the PCE EOS are used.

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

Im of ω and φ propagator





T_eff as probe to EOS of dense matter

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

spectra in transverse momentum and invariant mass

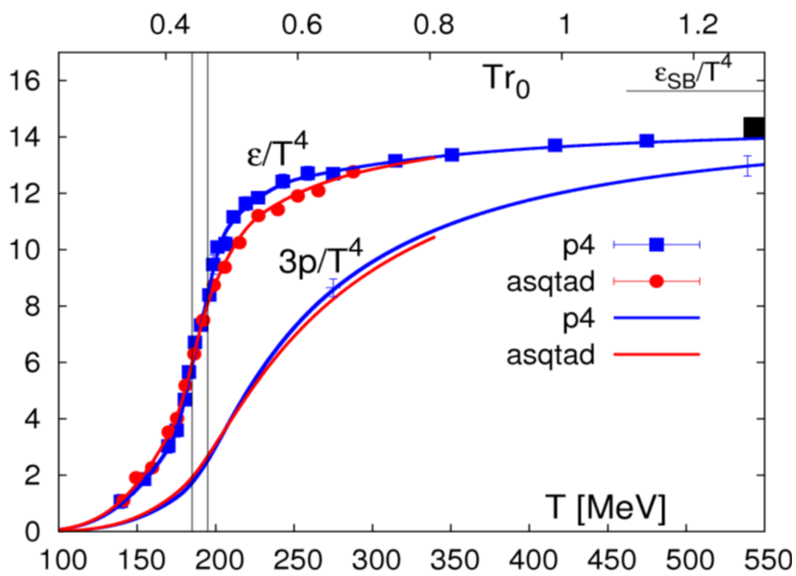
$$\frac{d^2N}{m_T dm_T M dM} \sim \sqrt{\frac{\overline{T}}{\overline{\gamma}_T}} \frac{\sqrt{m_T + M}}{m_T} \exp\left(-\frac{m_T + M}{T_{eff}}\right)$$

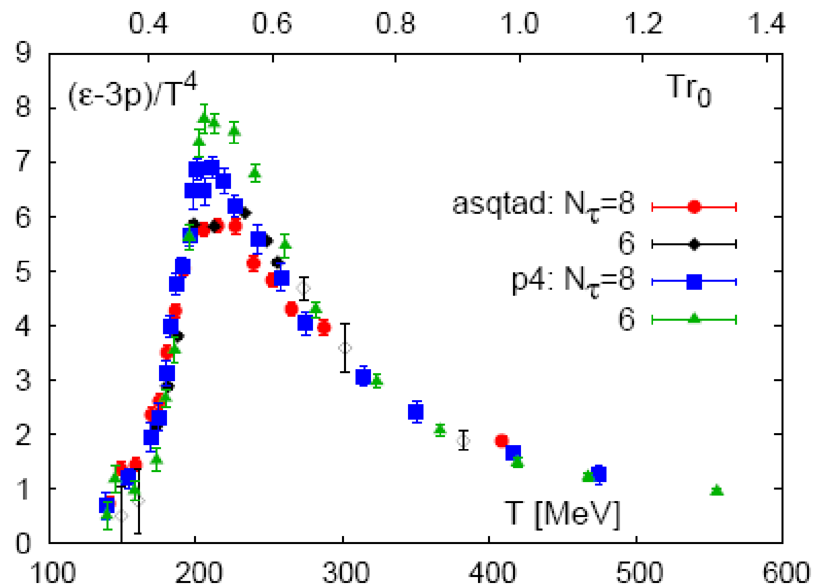
$m_T \equiv M_T - M$

slope parameter

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

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).

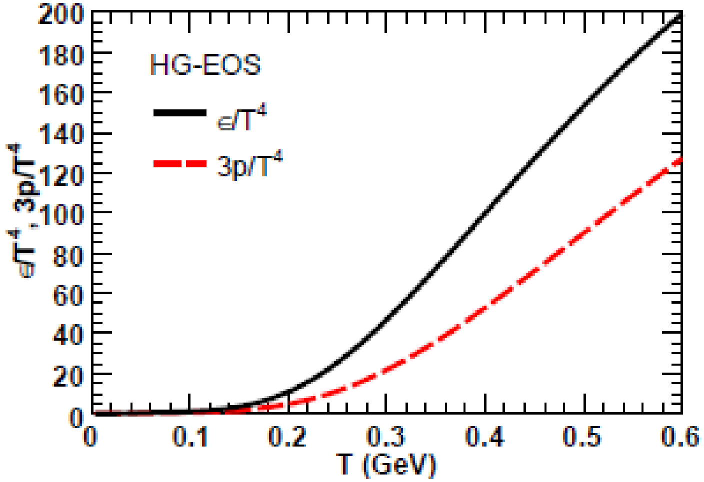
Four equations of state (EOS)

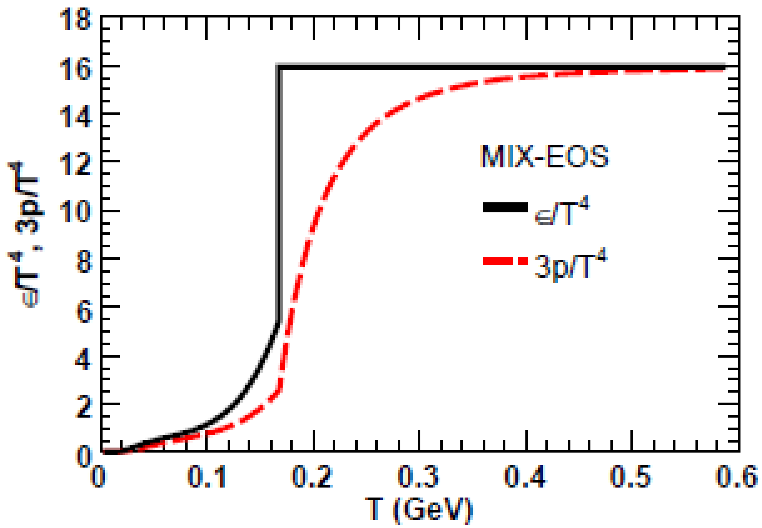
Massless ideal QGP

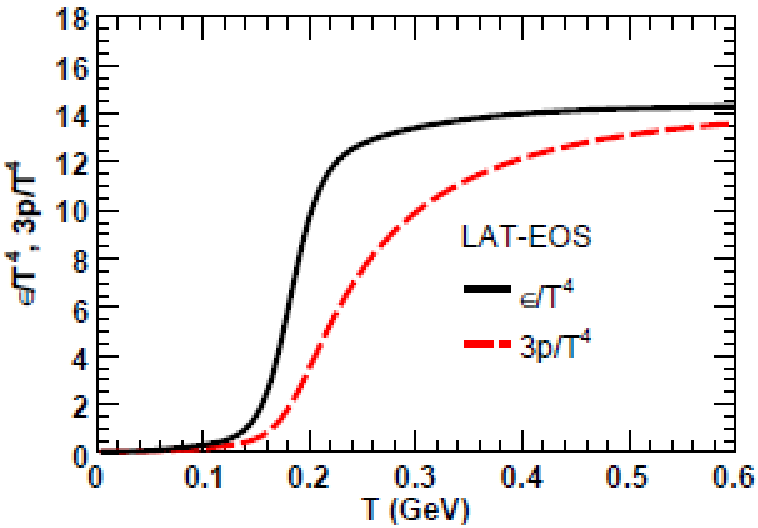
$$\epsilon = 3p = 16T^4$$

Resonance Hadron gas

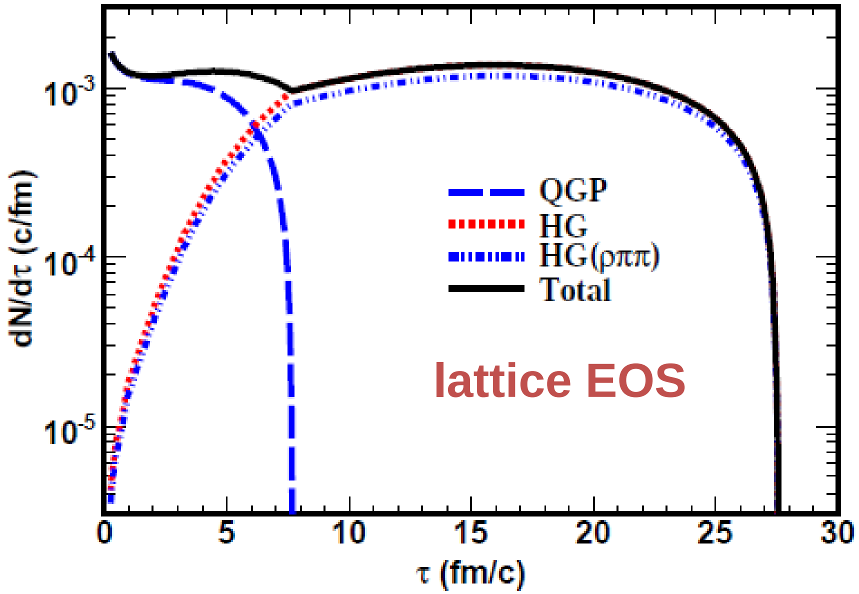
[Braun-Munzinger, Redlich, Stachel, nucl-th/0304013]

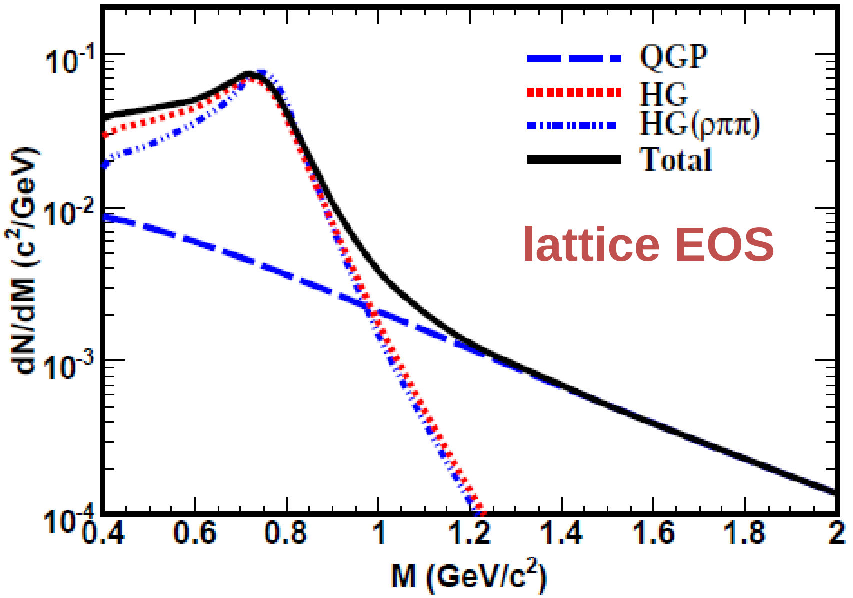






Time evolution of the rate





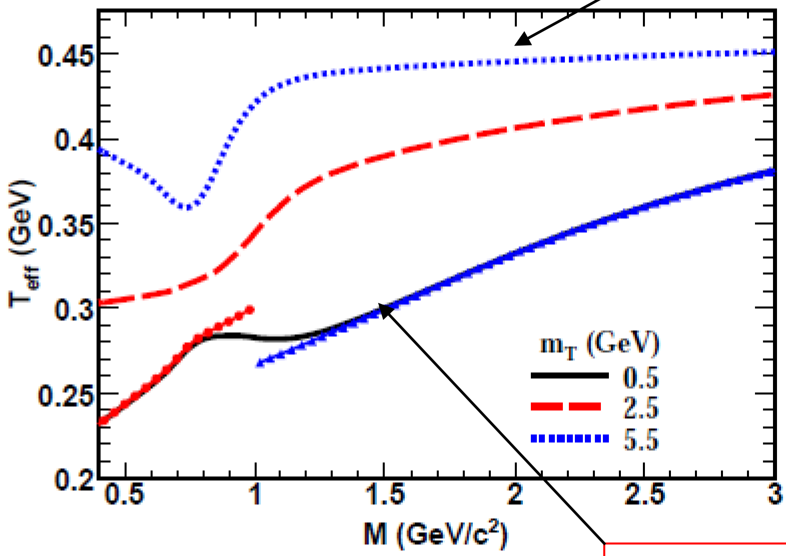
Differential multiplicity as functions of the dilepton invariant mass and proper time. The lattice EOS is used. The unit is arbitrary.
The contributions from QGP and HG are shown in dashed and dotted lines.

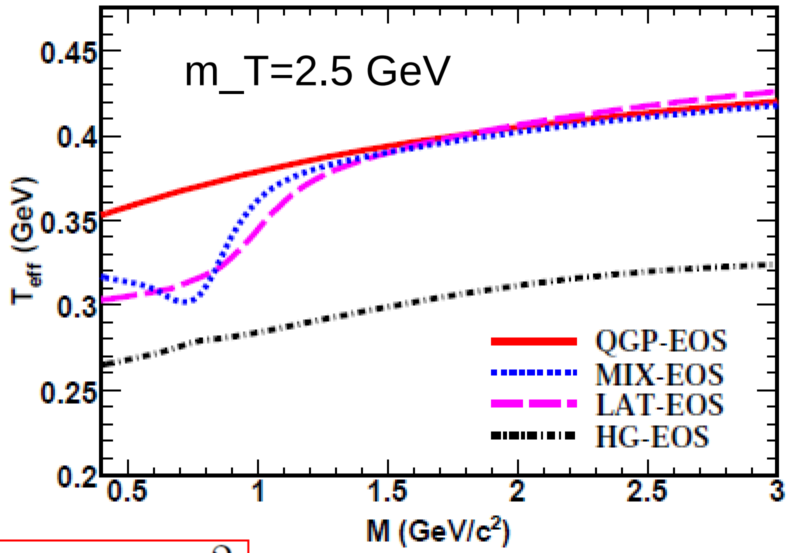
Slope parameter: pt and EOS dependence

pt dependence

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

EOS dependence

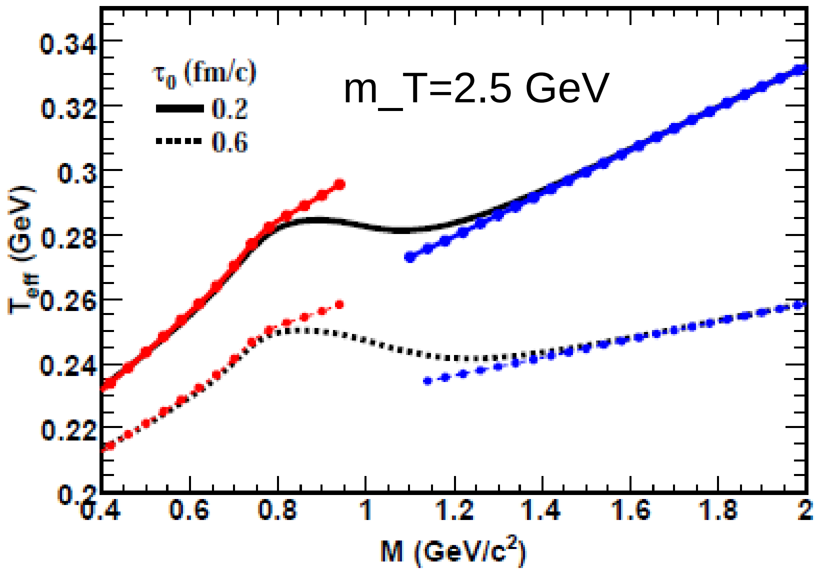


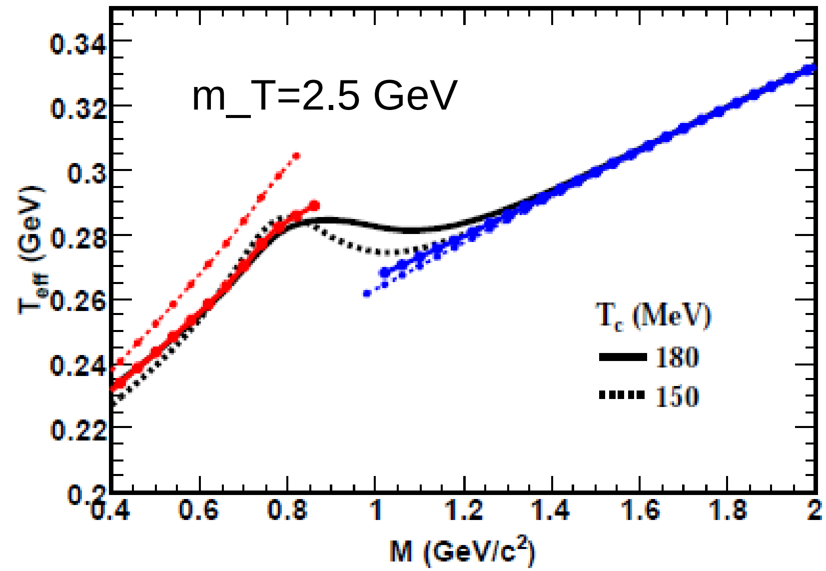


$$T_{eff} \sim T + M^* v_T^2$$

Slope parameter as functions of *M* for the mixed phase (left panel) and the lattice (right panel) EOS. The results for different values of *mT* are shown in the solid, dashed and dotted lines. The lines with hollowed circles/triangles are extracted from the HG/QGP components.

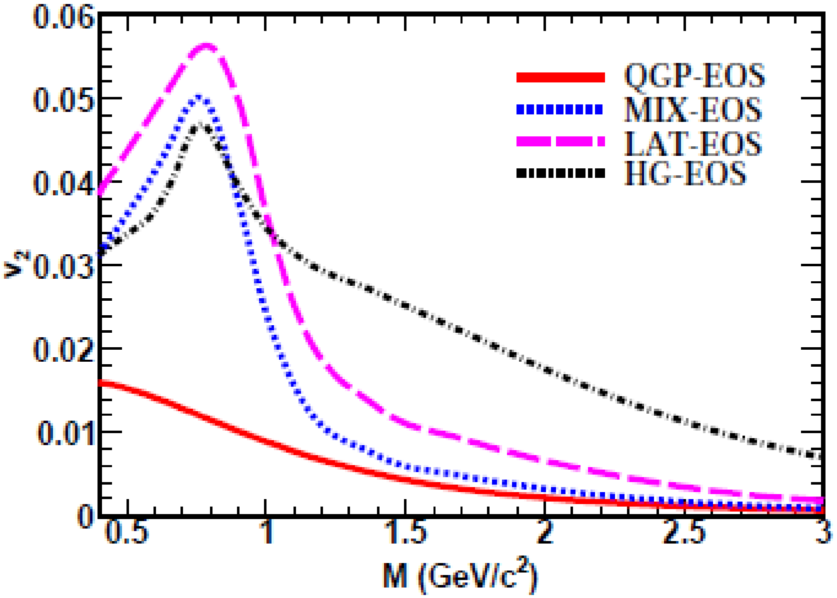
Slope parameter: parameter dependence

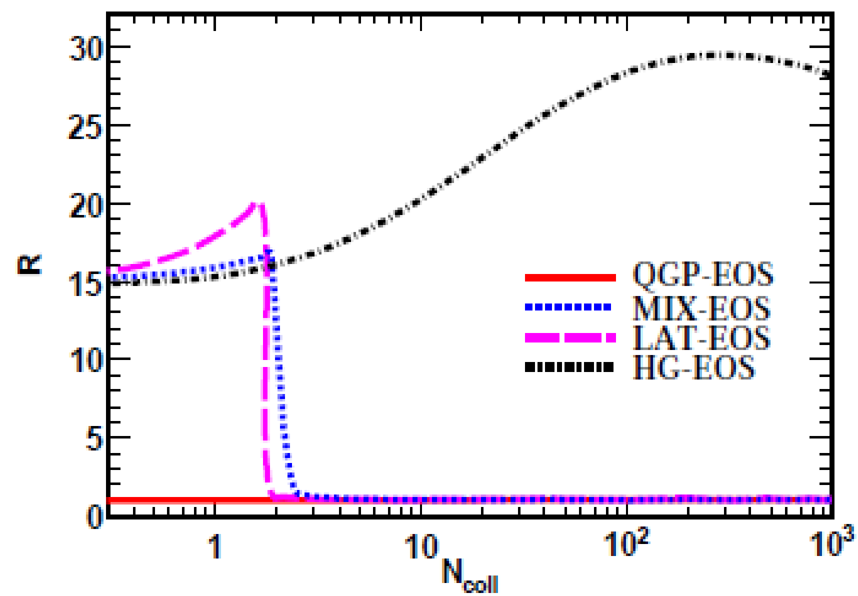




Parameter dependences of the slope parameter with the lattice EOS. Left panel: the initial time for the hydrodynamic evolution τ_0= 0.2*;* 0.6 fm/c. Right panel: the phase transition temperature *Tc* = 180*,* 150 MeV. m_T=2.5 GeV.

Elliptic flow v2 and R





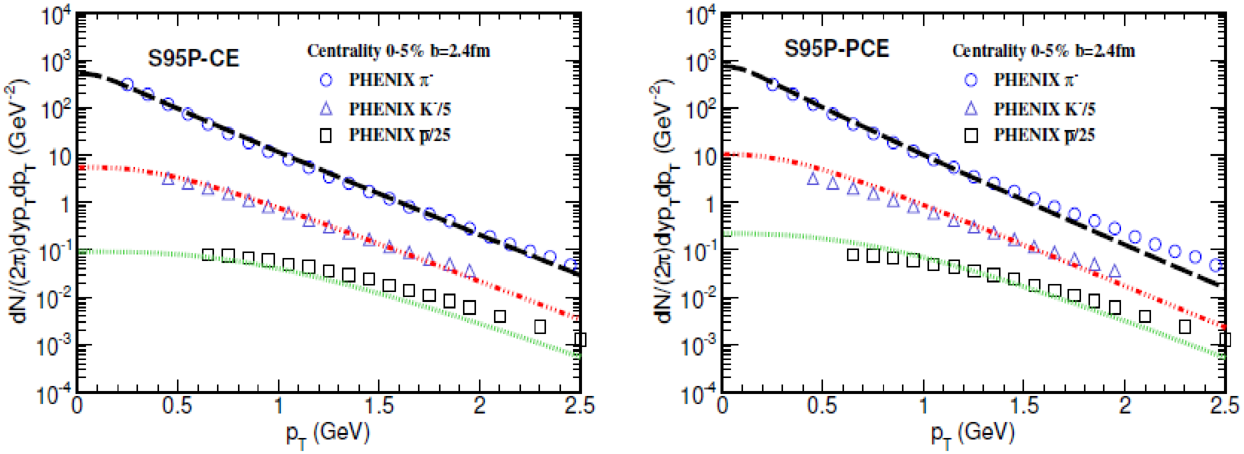
$$v_2(p_T, M) = \langle \cos(2\phi_p) \rangle$$

$$R = \frac{dN/dM_T^2 dp_T^2 dy|_{M_T=2.6GeV, p_T=2GeV}}{dN/dM_T^2 dp_T^2 dy|_{M_T=2.6GeV, p_T=0GeV}}$$

Asakawa,Ko,Levai, PRL70,398(1993).

Comparison to STAR dilepton data

Transverse momentum spectra

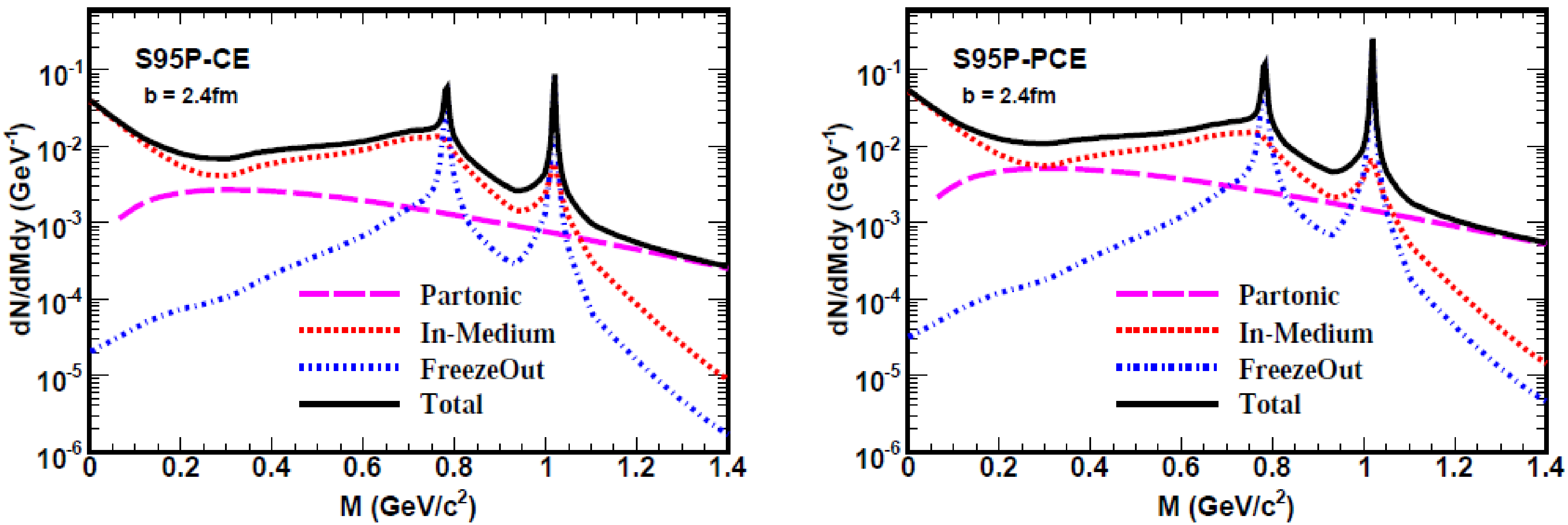


	π	ρ/π	ω/π	ϕ/π
CE	312.65	5.95×10^{-2}	5.7×10^{-2}	1.27×10^{-2}
PCE	349.47	7.8×10^{-2}	9×10^{-2}	2.8×10^{-2}
PHENIX	281.8	1.03×10^{-1}	8.98×10^{-2}	2.14×10^{-2}
STAR	-	1.69×10^{-1}	-	2.65×10^{-2}

Parameters

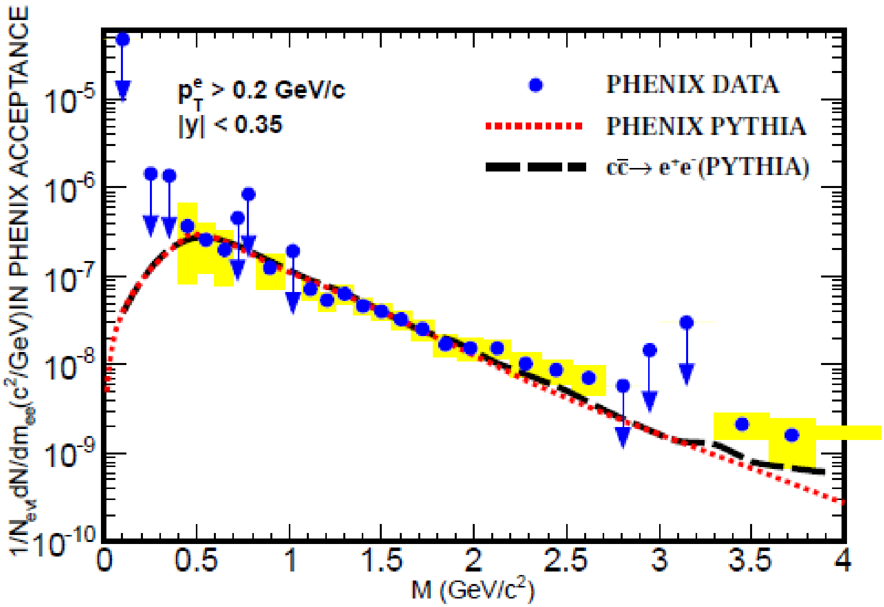
- S95-CE: e0=40 GeV/fm^3, τ0=0.4 fm, T0=375 MeV, Tf=128 MeV
- S95-PCE: e0=60 GeV/fm^3, τ0=0.4 fm, T0=413 MeV, Tf=140 MeV

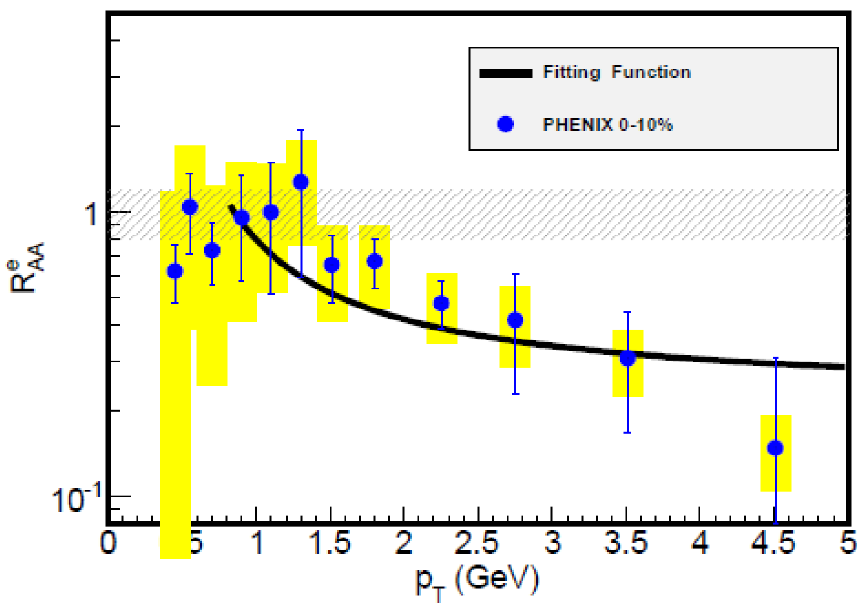
Cocktail of in-medium and freezeout contribution in full space



Total = Partonic + In-medium hadronic + Freezeout

Semi-leptonic decays of charm hadrons



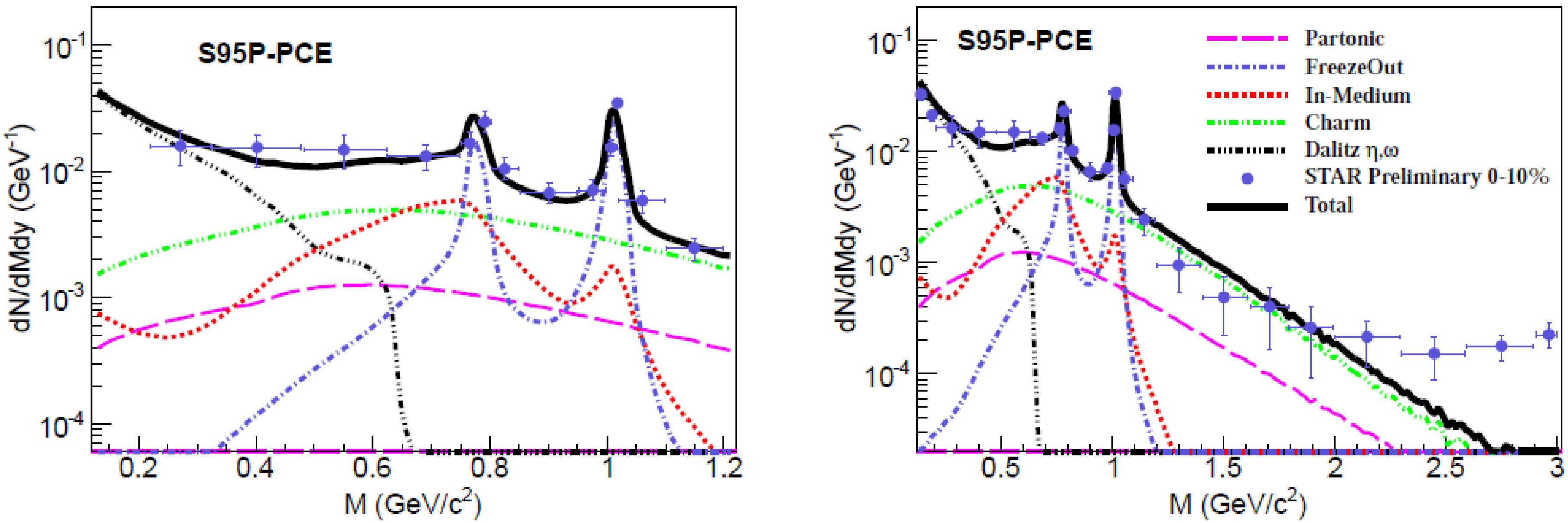


Re-scaled di-electron cross section from charm mesons of semi-leptonic decays in p+p collisions by PYTHIA.

the nuclear modification factor for nonphotonic electrons in central Au+Au collisions from the PHENIX.

Branch ratios from PDG: $D^{\pm}, D^0, D^s, \Lambda^c$

Comparison with STAR preliminary data



Comparison with STAR preliminary data in most central (0-10%) Au+Au collisions with the STAR acceptance.

$$\text{STAR acceptance: } |\eta^e| < 1, p_T^e > 0.2GeV, |y^{ee}| < 1$$

Summary and Conclusion

- 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 $\rho NN^* + \rho N\Delta^*$ couplings) are taken into account
- In-medium and freezeout contributions are identified, open charm contribution is modeled
- Comparison with STAR data is made with good agreement

Thanks!