Dileptons - Theoretical Overview

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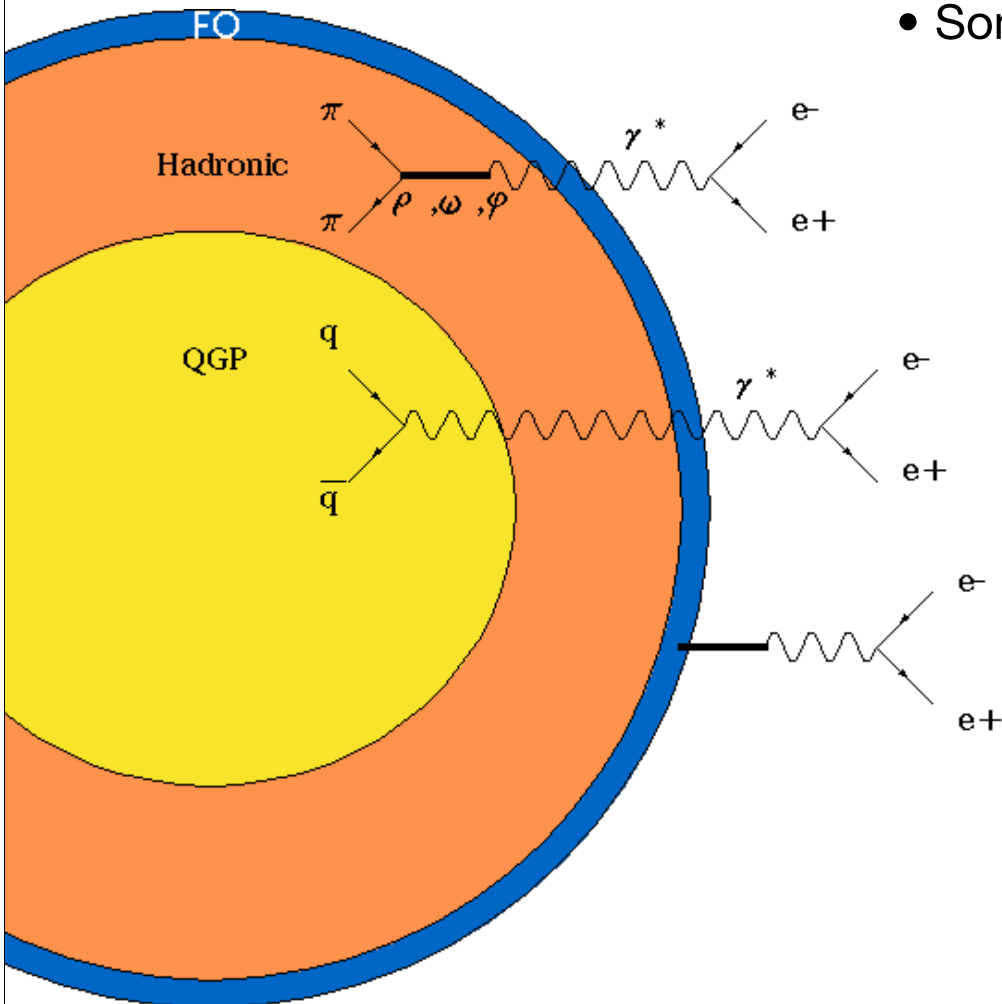
Contents

- Why Electromagnetic (EM) probes? What are our objectives?
- Theoretical Overview
    - focused on the NA60 and PHENIX experiments
- How viscosity modifies electromagnetic spectrum

Introduction



- Some goals:
  - Initial State: τ_0, T_0
  - Direct signal of the QGP
  - signal of χSR
  - Transport Coefficients of QGP

Thermal Dilepton Production

- Rates given to lowest order in α_{em} but to all orders in α_s:

$$\frac{dR}{d^4q} = \frac{4\alpha_{\rm em}^2}{3(2\pi)^3}\frac{1}{q^4}\left(q^\mu q^\nu - q^2 g^{\mu\nu}\right) W_{\mu\nu}(q)$$

$$W_{\mu\nu}(q) = \int d^4x\ e^{-iqx}\left\langle j_\mu{}^{\rm em}(x) j_\nu^{\dagger{\rm em}}(0)\right\rangle_\beta$$

- There are two ways to evaluate W:
  - Relativistic Kinetic Theory
  - Spectral Function Approach

Kinetic Theory to Spectral Function and Back

- Kinetic Theory

$$W_{\mu\nu}(q) = \sum_I \sum_F \int d^4x \; e^{-iqx} \left\langle I | j_\mu^{\rm em}(x) | F \right\rangle \left\langle F | j_\mu^{\dagger \rm em}(0) | I \right\rangle \frac{e^{-\beta E_I}}{\mathcal{Z}}$$

- Spectral Function
  - Switch initial and final states using $E_I = E_F + q_0$

$$\begin{aligned} W_{\mu\nu}(q) &= e^{-\beta q_0} \sum_F \int d^4x \; e^{iqx} \left\langle F | j_\mu^{\dagger \rm em}(x) j_\mu^{\rm em}(0) | F \right\rangle \frac{e^{-\beta E_F}}{\mathcal{Z}} \\ &\equiv e^{-\beta q_0} \rho_{\mu\nu}(q,T) \end{aligned}$$

Low Density Expansion

$$
\begin{aligned}
\rho_{\mu\nu}(q,T) &\approx \int d^4x\; e^{iqx} \left\langle 0 | j_\mu^{\dagger \mathrm{em}}(x) j_\mu^{\mathrm{em}}(0) | 0 \right\rangle \\
&+ \int d^4x\; e^{iqx} \int d\Gamma_\pi n_\pi(k_0/T) \left\langle \pi(k) | j_\mu^{\dagger \mathrm{em}}(x) j_\mu^{\mathrm{em}}(0) | \pi(k) \right\rangle \\
&+ \int d^4x\; e^{iqx} \int d\Gamma_N n_N(k_0/T) \left\langle N(k) | j_\mu^{\dagger \mathrm{em}}(x) j_\mu^{\mathrm{em}}(0) | N(k) \right\rangle \\
&+ \cdots
\end{aligned}
$$

- Leading order terms consist of all reaction with one pion / nucleon in FINAL state

Simple Example: Soft & Chiral Limit

- LSZ + PCAC

$$\langle \pi^a | V(x) V(0) | \pi^b \rangle \to \frac{1}{m_\pi^2 f_\pi} \langle 0 | \partial^\mu A_\mu^a(z) V(x) V(0) | \pi^b \rangle$$

- Current Algebra $\left[A_0^a(x), V_\mu^b(y) \right] = i\epsilon^{abc} A_\mu^c(x) \delta^3(x-y)$

- Result:

$$\left\langle \pi(k) | j_\nu^{\dagger \mathrm{em}}(x) j_\mu^{\mathrm{em}}(0) | \pi(k) \right\rangle = \frac{2}{f_\pi^2} \langle 0 | A_\nu^3(x) A_\mu^3(0) - V_\nu^3(x) V_\mu^3(0) | 0 \rangle$$

Simple Example: Soft & Chiral Limit

- Result (**Dey, Eletsky & Ioffe**):

$$\rho_{\mu\nu}(q,T) \quad \approx \quad \rho^{\mathrm{em}}_{\mu\nu}(q) - \frac{T^2}{6f_\pi^2}\left[\rho^V_{\mu\nu}(q) - \rho^A_{\mu\nu}(q)\right]$$

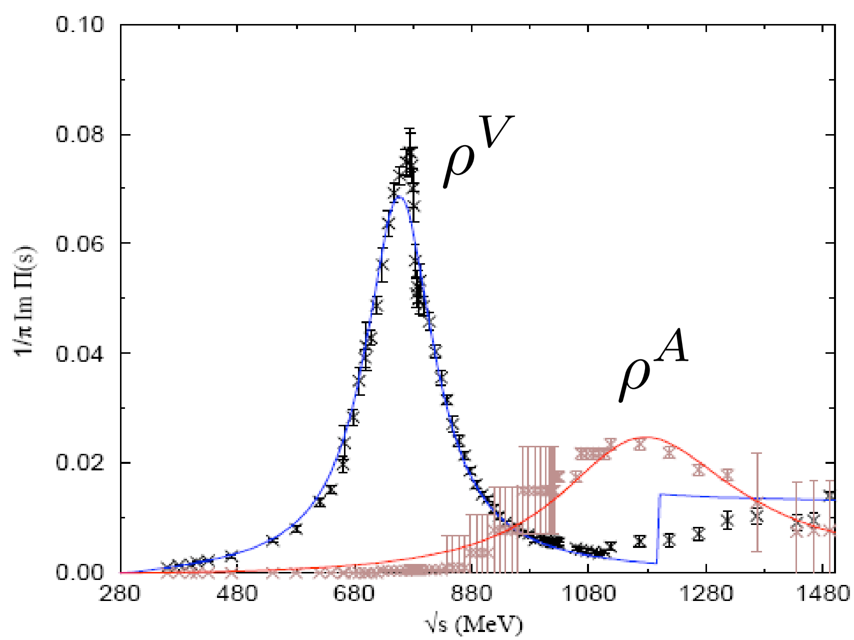
- Chiral Symmetry restored when $\rho^V(q,T) = \rho^A(q,T)$

$$T = \sqrt{3} f_\pi \approx 160 \ \mathrm{MeV}$$

- The mixing stems from $a_1 \longrightarrow \pi\rho \longrightarrow a_1$ in the heat bath

Experimental Data

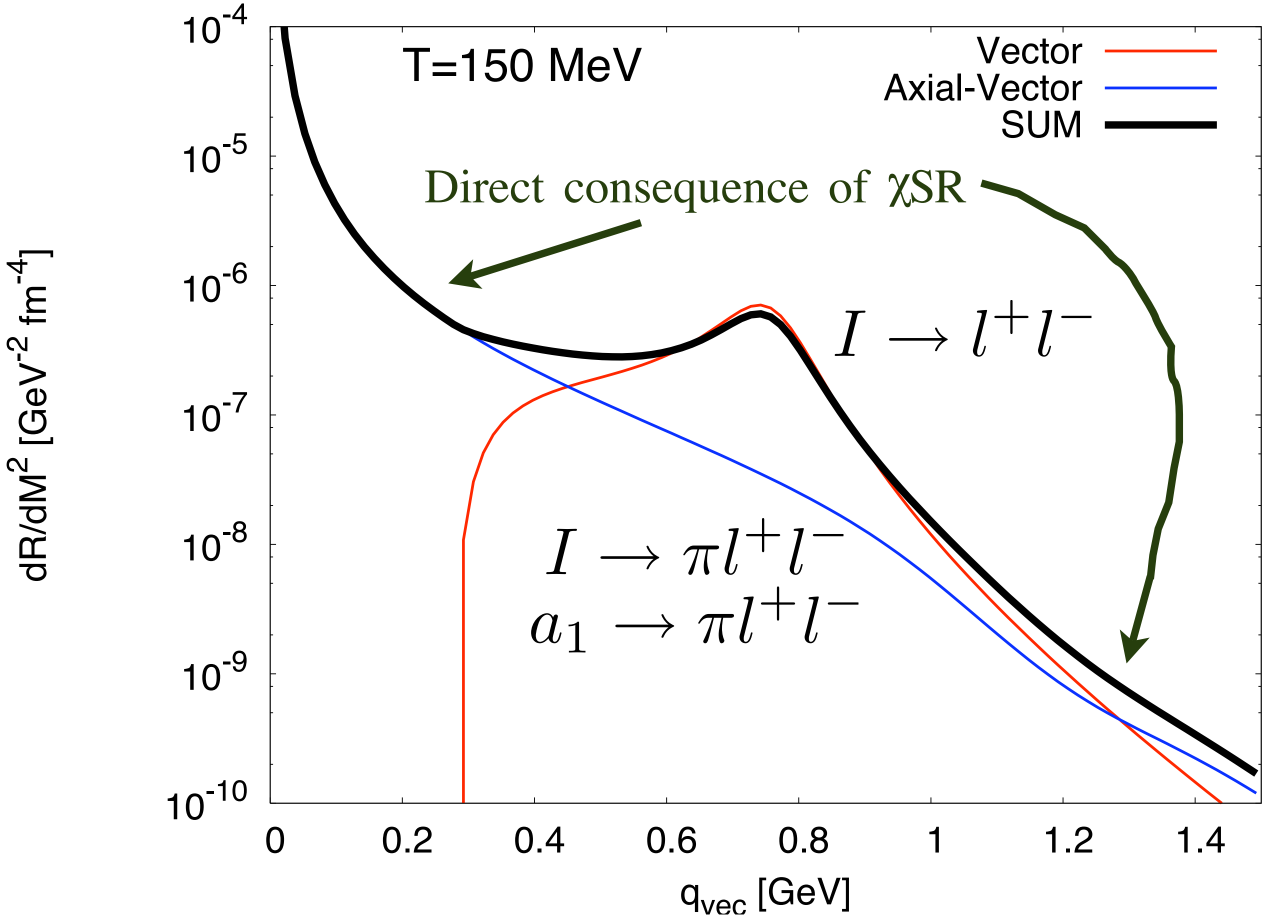
$$\rho_{\mu\nu}(q,T) \approx \rho^{\rm em}_{\mu\nu}(q) - \frac{T^2}{6f_\pi^2}\left[\rho^V_{\mu\nu}(q) - \rho^A_{\mu\nu}(q)\right]$$



Compilation by Zheng Huang: hep-ph/9506399

Going beyond Soft / Chiral Limit

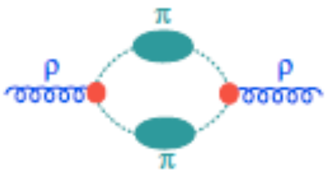
- Reduce matrix elements via Chiral Reduction Forumla (χRF) (**Yamagishi & Zahed**)

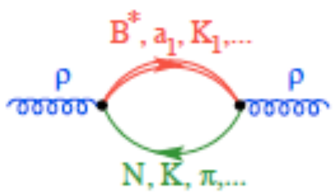


Kinetic Approaches

- Why use SFA?
  - Model Independent
  - Trivial to go to photon point: *two calculations for one price*
- Shortcomings of SFA
  - Requires kinetic and chemical equilibrium
  - Physical reactions blurred by density expansion

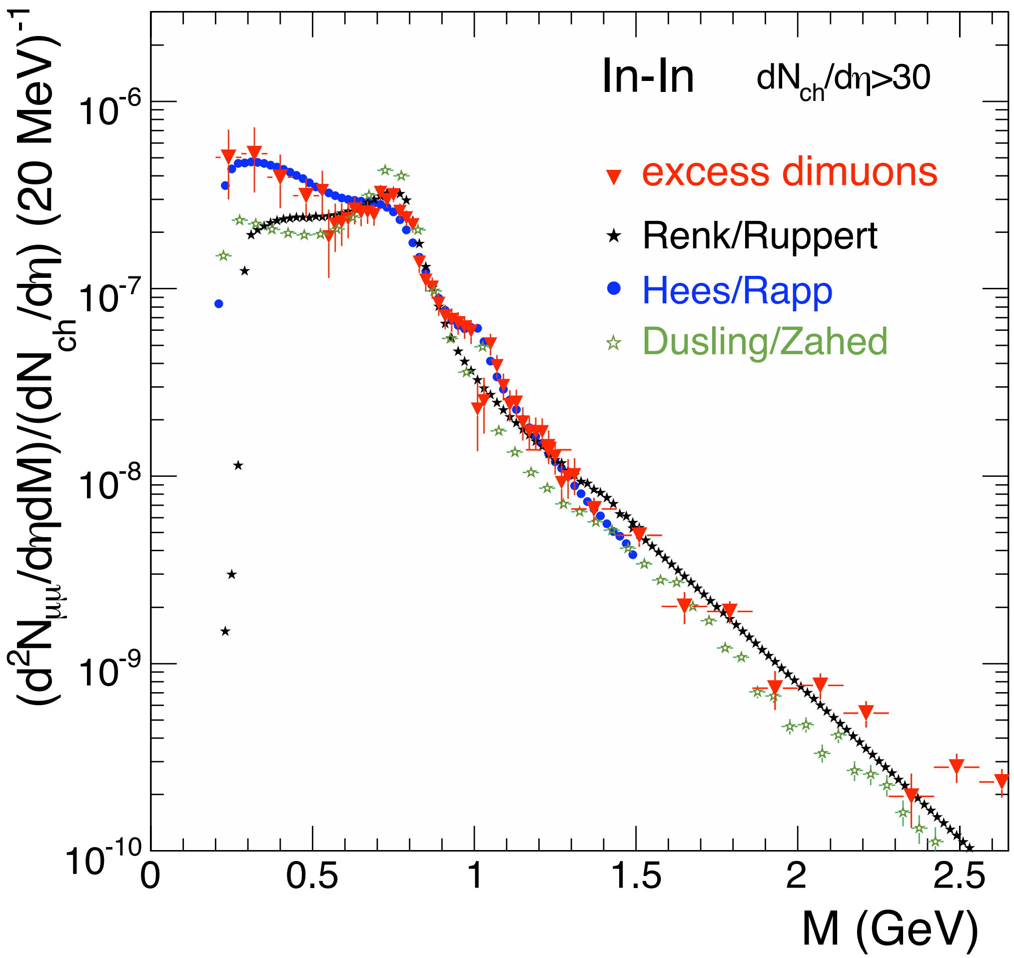
- Many more works using a Kinetic Theory
  - HMBT: Rapp, Wambach
  - HSD: Bratkovskaya, Cassing



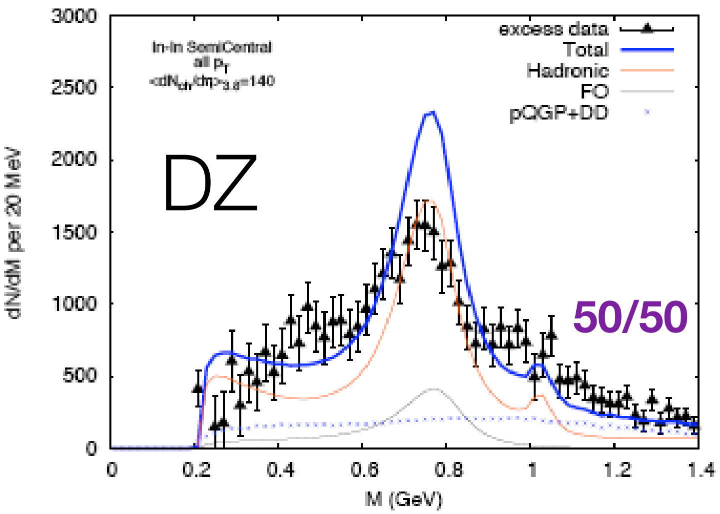


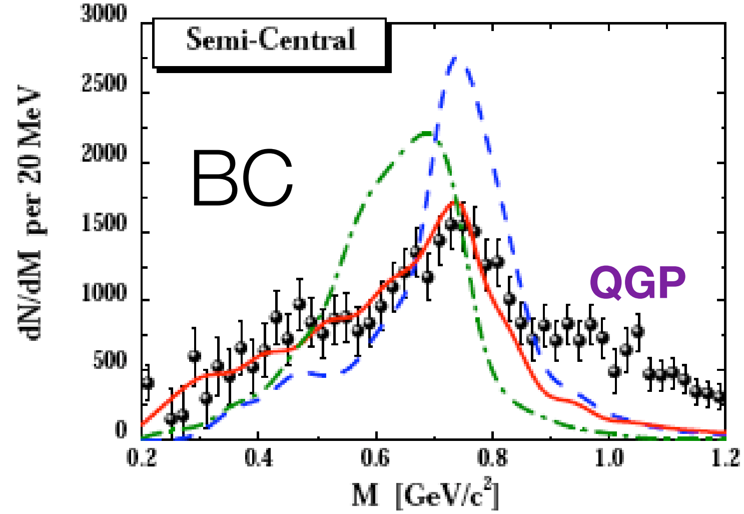
Courtesy: Rapp

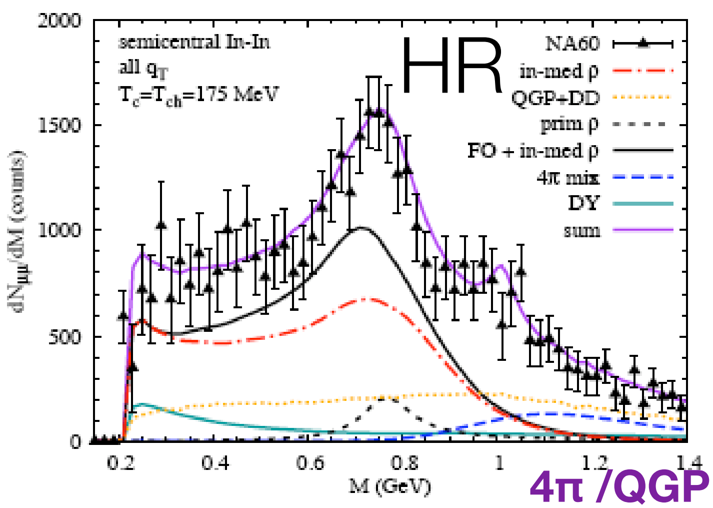
NA60: Theory Comparision

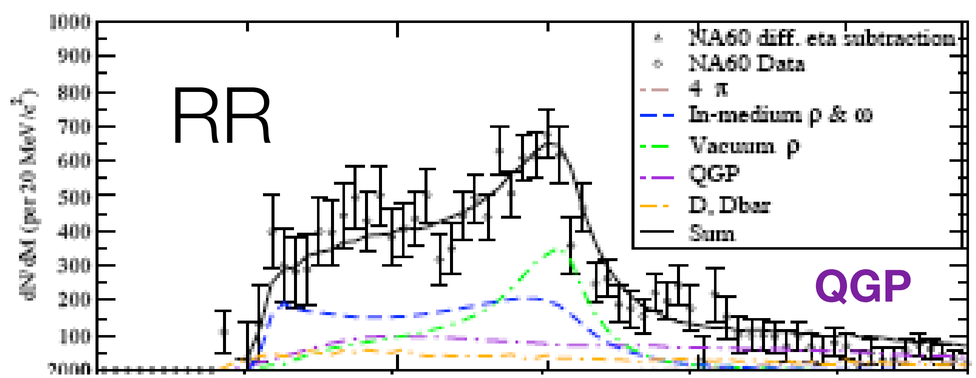


NA60: Theory Comparison





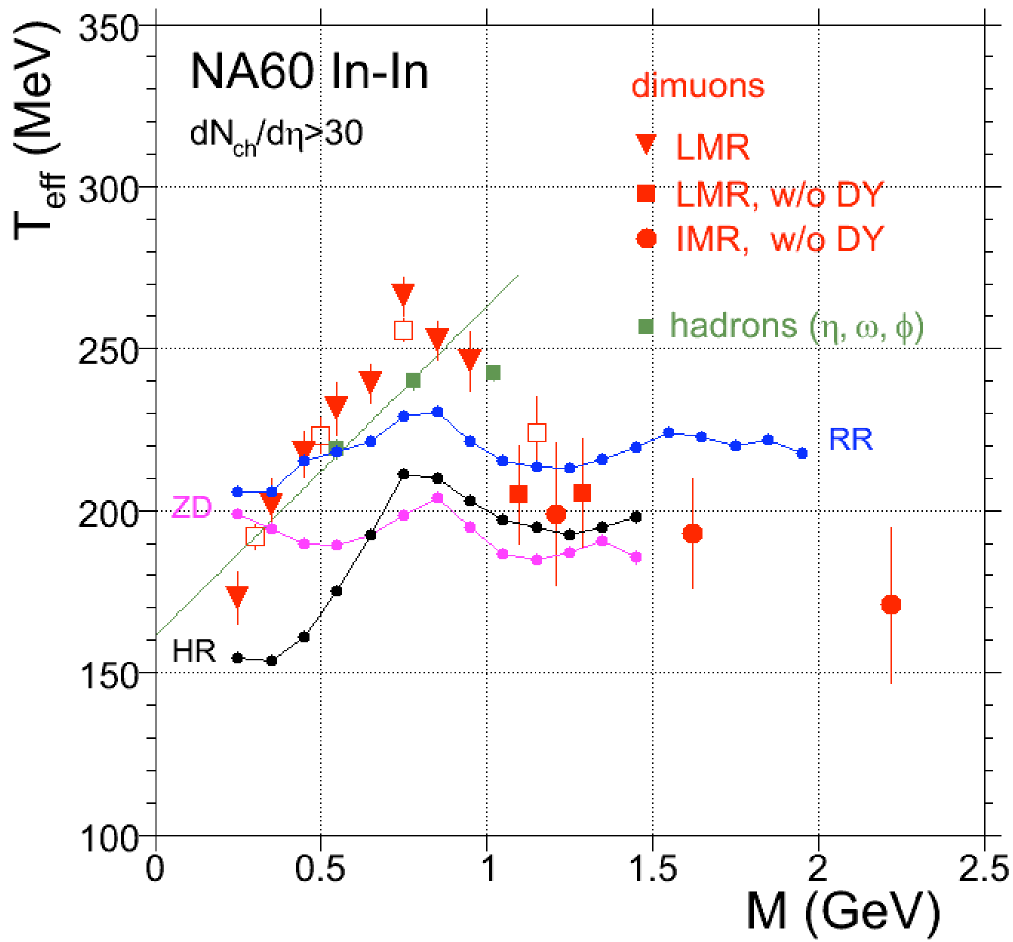




4π /QGP
(EoS Dependent)

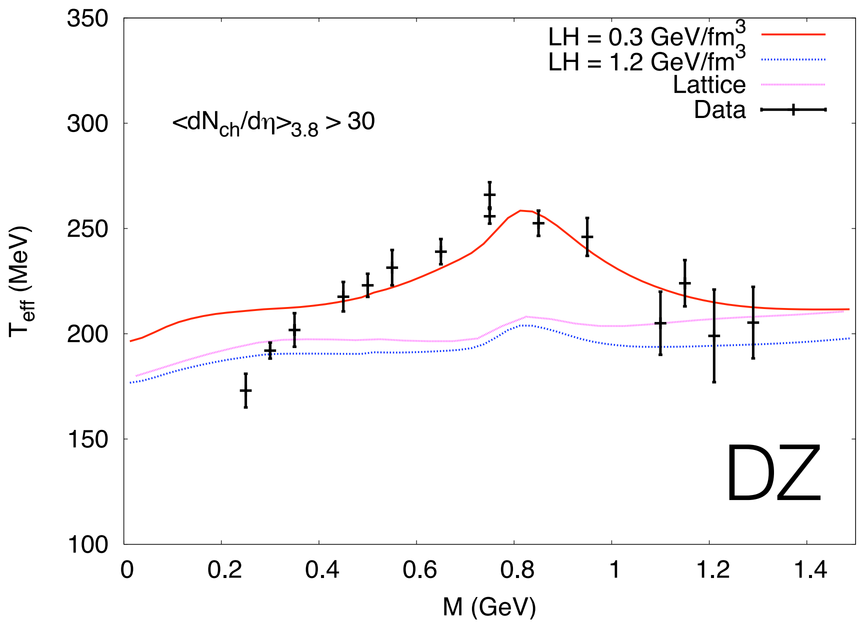
NA60 T_{eff}: Theory Comparison

- Consistently underestimate T near ρ mass

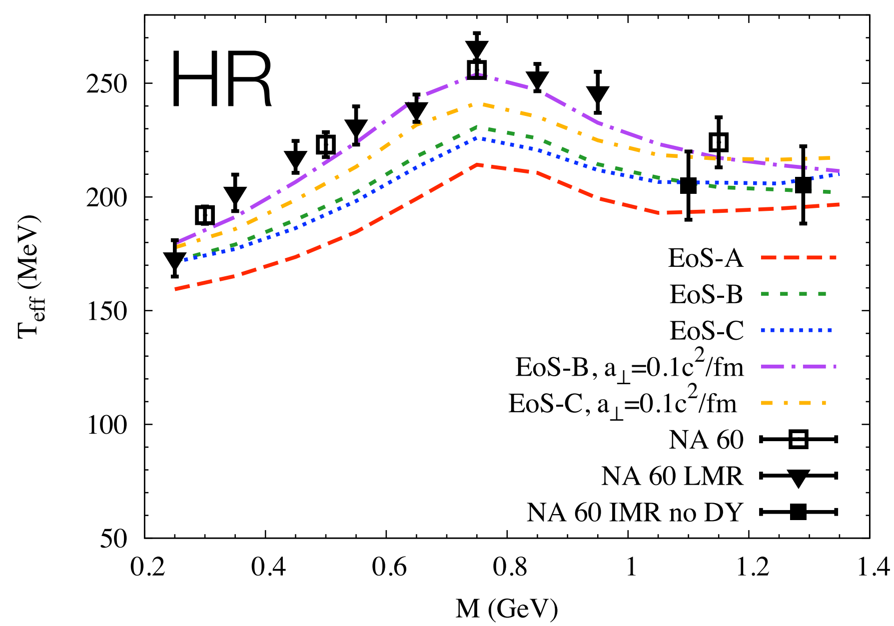


NA60 T_{eff}: Theory Comparison (II)

- Effect of EoS



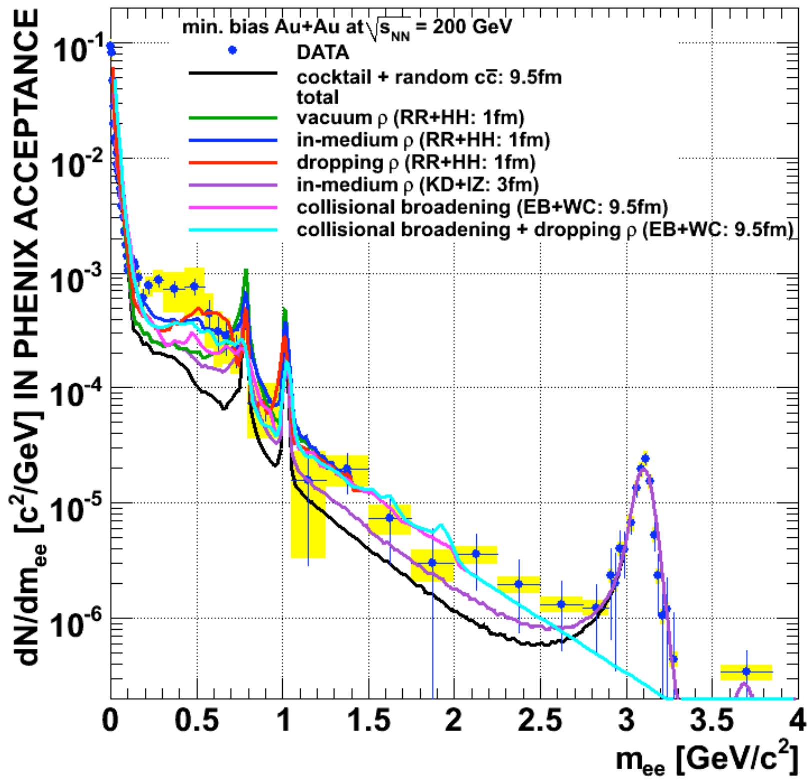
- Flow Velocity



NA60: My Open Questions

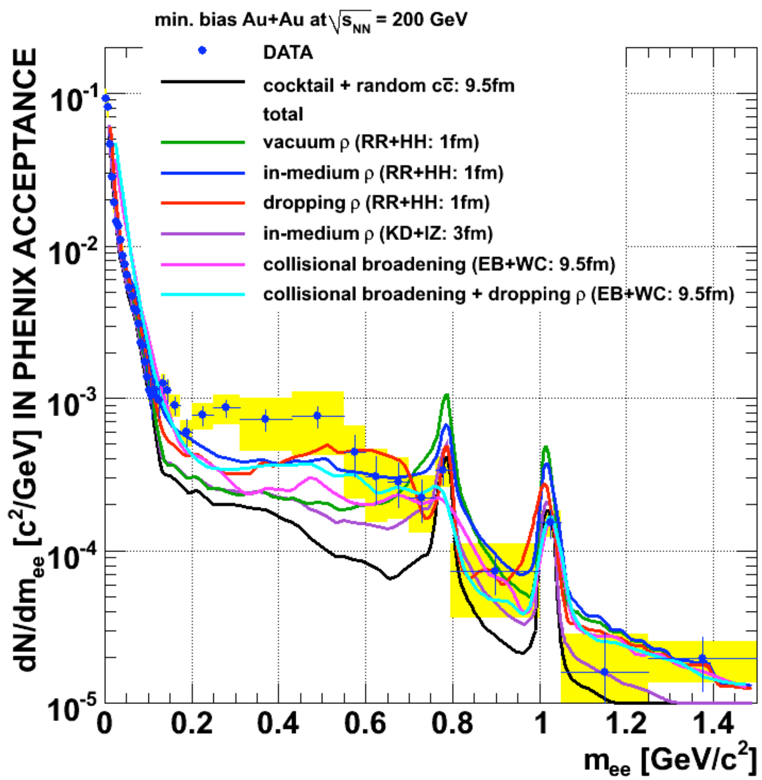
- T_{eff} near rho mass not satisfactorily explained
    - Can be *fixed* by changing EoS or equivalently the flow profile
- Still controversy over dimuon source at M = 1.0 - 1.5 GeV
- In my opinion these questions can only be answered by detailed modeling

PHENIX: Theory Comparison



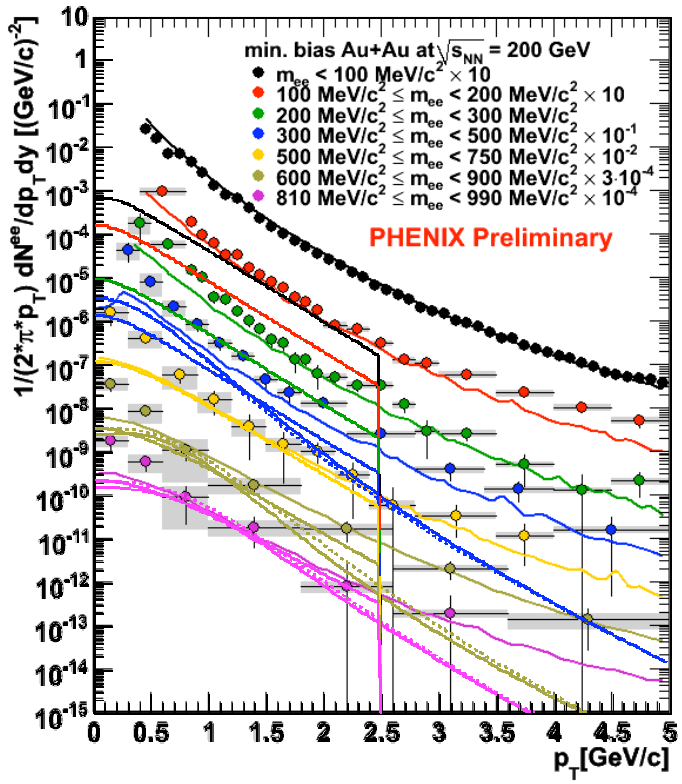
PHENIX: Theory Comparison (II)

- All theory groups underestimate yield in M = 0.2 - 0.5 GeV



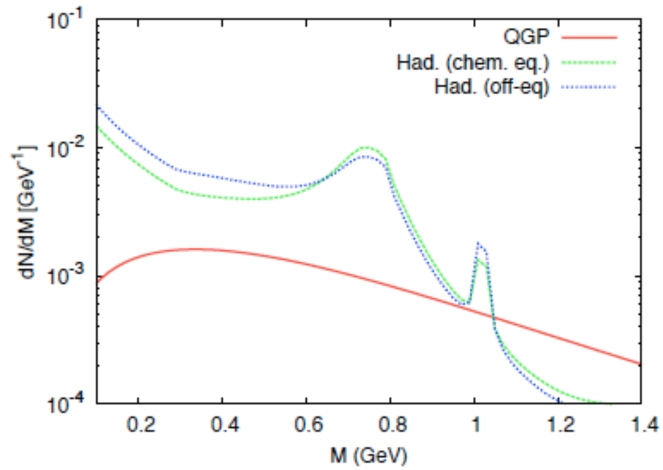
PHENIX: Theory Comparison (III)

- Source is coming from low p_T (p_T < 1 GeV)

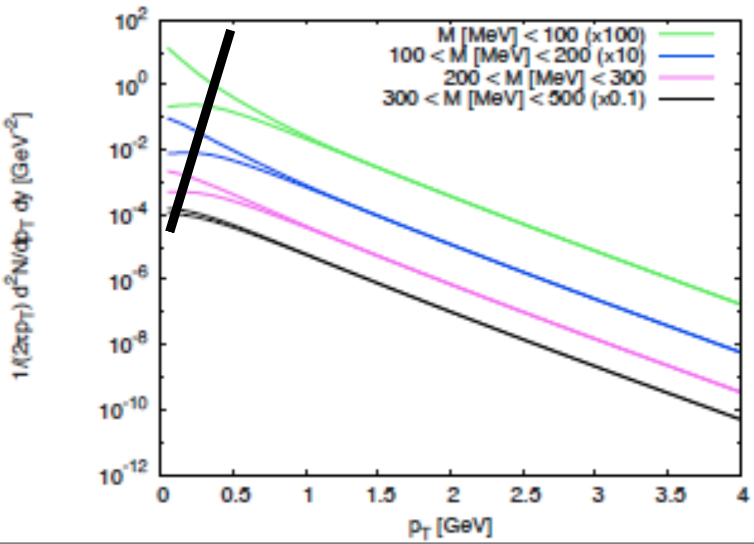


Other Scenarios (which don't seem to help)

- Chemical off-equilibrium



- Two final-state pions (i.e. pion Bremsstrahlung)

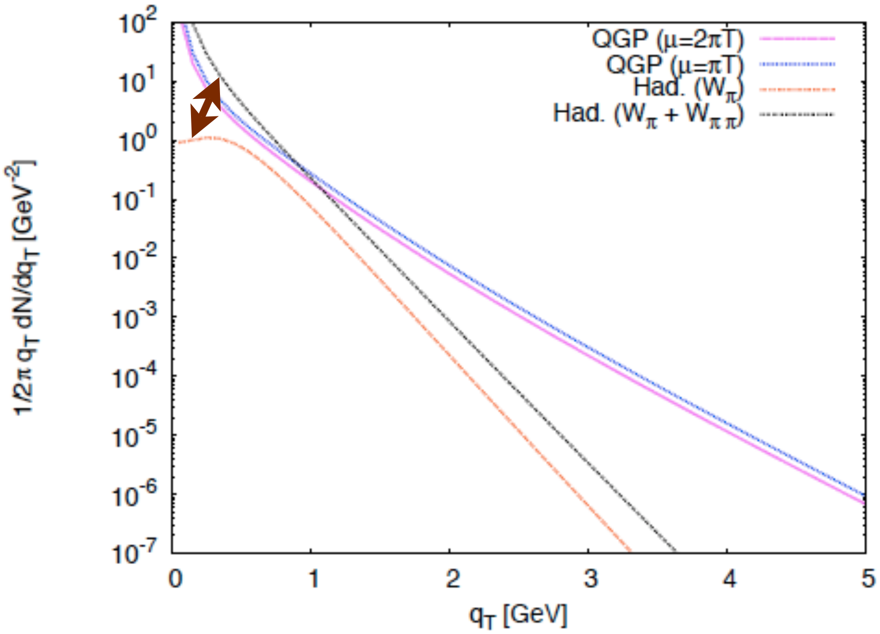


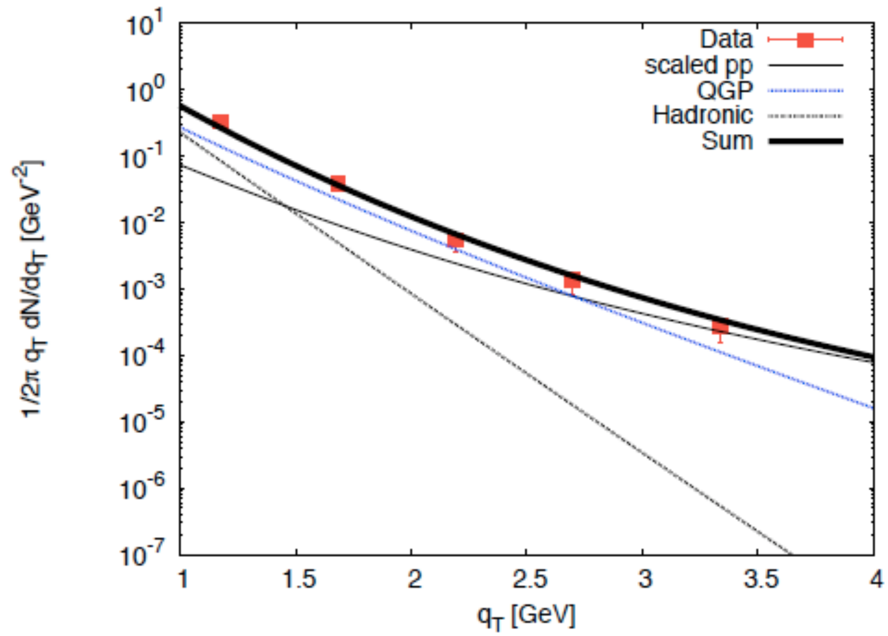
We find a low pT enhancement from processes like

$$I \to F\pi\pi e^+e^-$$

2π piece important for low p_T photons though

$$I \to F\pi\pi e^+e^-$$





Dusling / Zahed: work in progress

PHENIX: My Open Questions

- Di-electron source at M = 200 - 500 MeV ???
  - QGP Compton & Annihilation? (work in progress)
- Di-electron at M = 1.0 - 2.5 GeV
  - “Normal” charm?
  - Or Thermalized charm + Partonic source?
    - P_T spectra can answer this (work in progress)

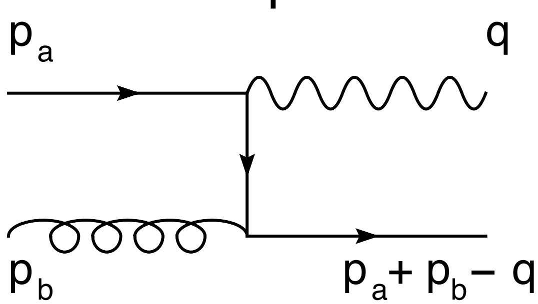
Some new work.

- With all that said...
- What about the possibility of extracting transport coefficients from the data
- Let’s look at the effect of a finite shear viscosity

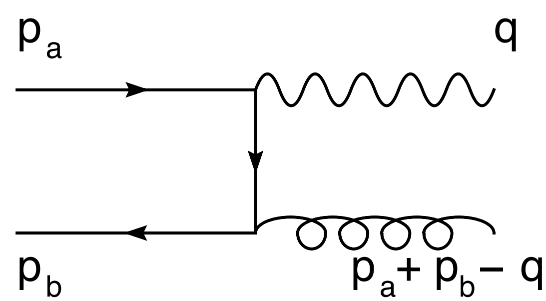
Photon production at leading log

- Let's look at viscous correction to photon spectra

Compton



Annihilation



- At Leading log $p^{\mu}_{\rm quark} \approx q^{\mu}_{\rm photon}$
- So the distribution of emitted photons is the same as the quarks

Photons from a viscous medium

- The photon production rate (at leading log) is

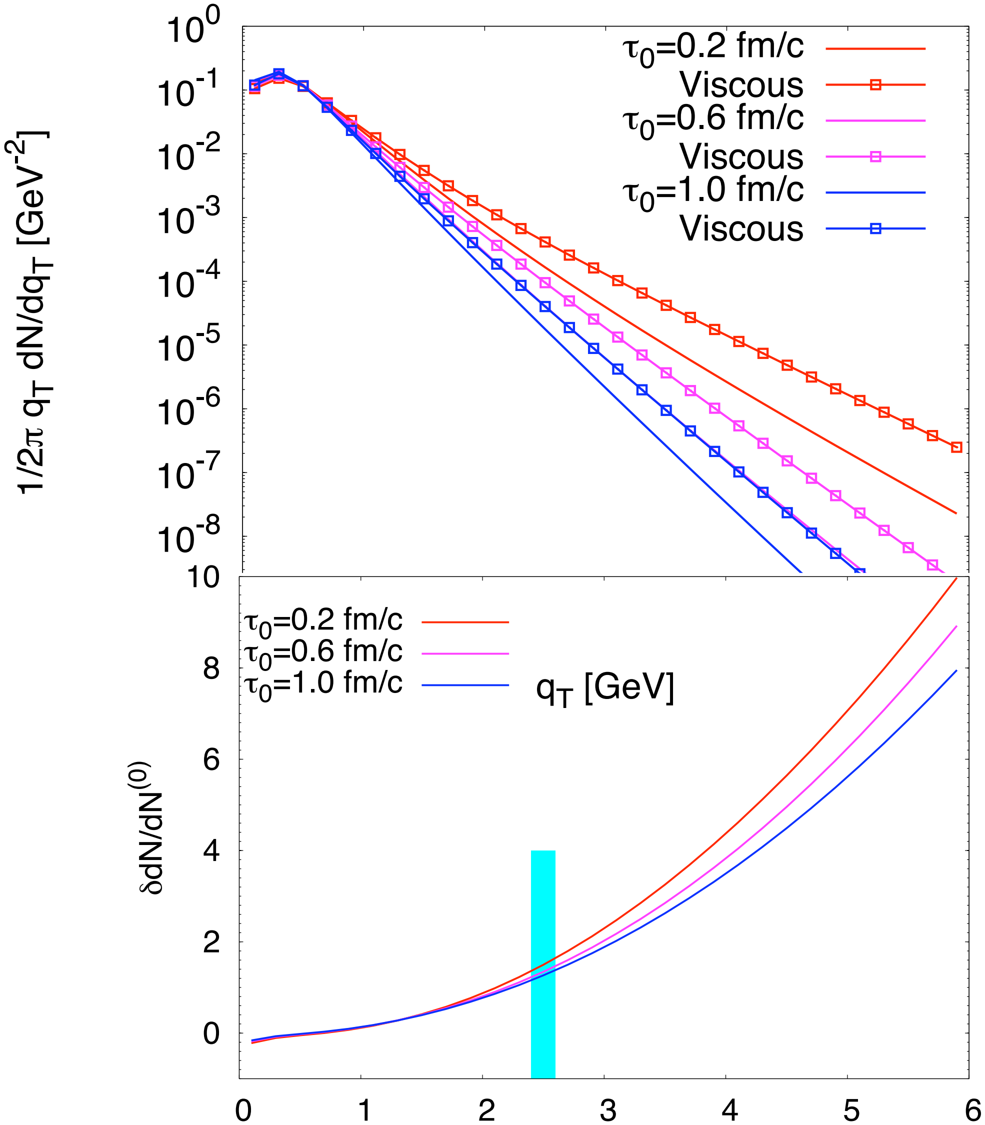
$$E_\gamma \frac{dN_\gamma}{d^3 q_\gamma} = \frac{5}{9}\frac{\alpha_e \alpha_s}{2\pi^2} f_q(q_\gamma) T^2 \ln\left(\frac{3.7E_\gamma}{g^2 T}\right)$$

- where f_q should take the form of the quarks’ distribution function.

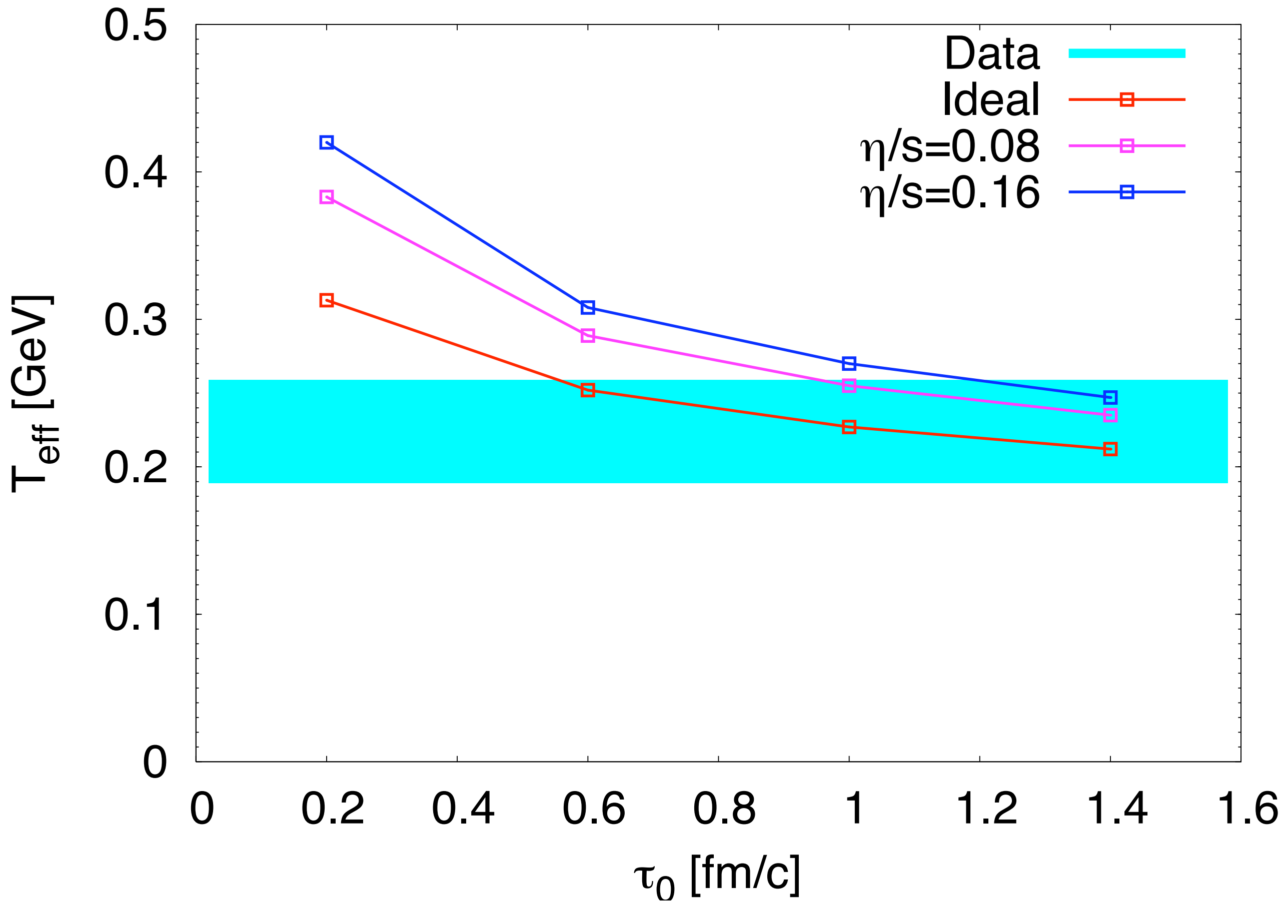
- With finite viscosity this is

$$f_q(q) = f_0(q) + 1.3\frac{\eta}{2sT^3} f_0(q) q^i q^j \partial_{\langle i} u_{j\rangle}$$

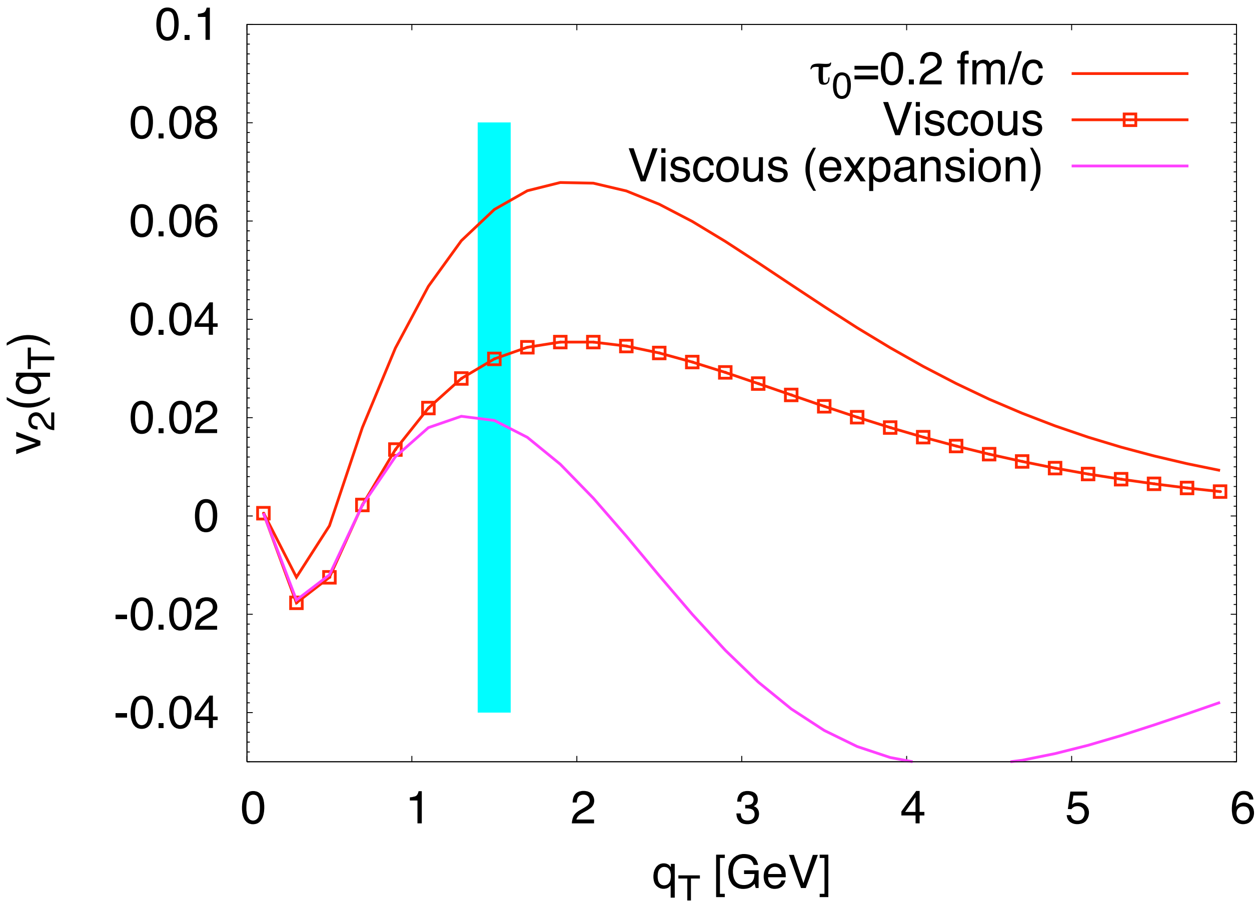
Viscous correction to photon p_T spectra



Viscous correction to photon T_{eff}



Viscous correction to photon v_2



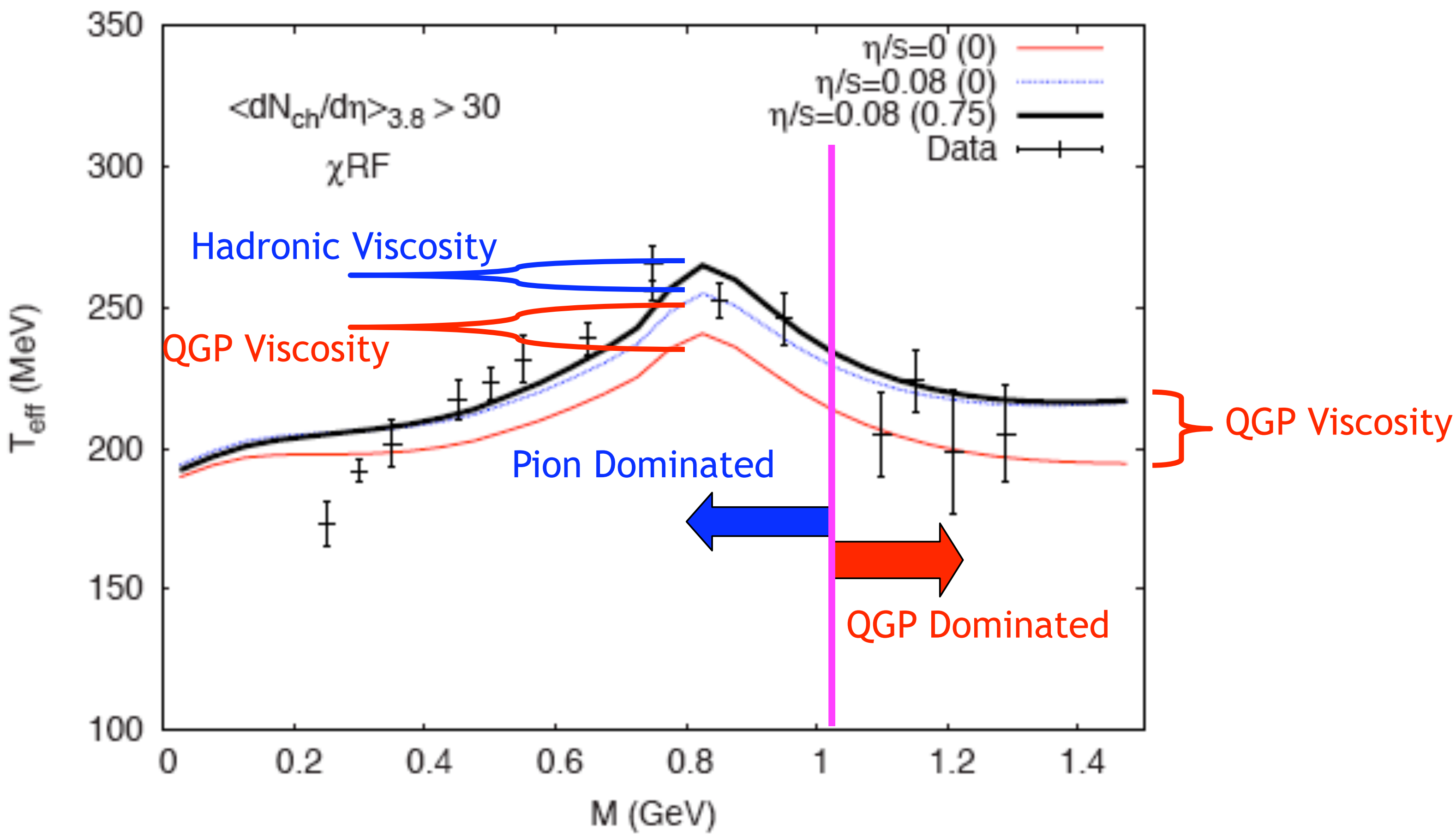
Dilepton Production (cont.)

- Result

$$\frac{dN}{d^4q d^4x} = \frac{N_c \alpha^2 e_q^2}{12\pi^4} e^{-q_0/T} \left[1 + \frac{1}{3(\epsilon + p)T^2} q^\alpha q^\beta \pi_{\alpha\beta}\right]$$

- Invariant mass spectrum unchanged
- P_T spectrum harder

Viscosity and T_{eff} at NA60

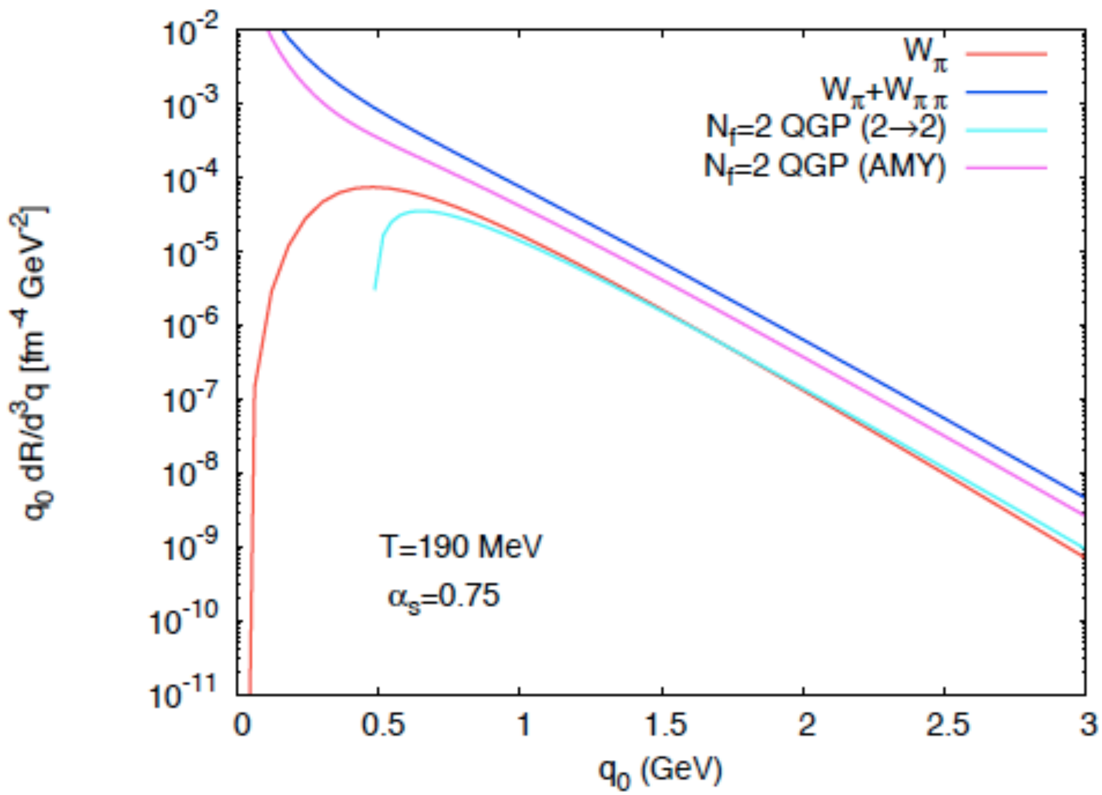


Conclusions

- Qualitatively Understand NA60 Data
  - Need detailed modeling for IMR and T_{eff}
- No theory group can explain LMR excess at PHENIX
  - Low mass, Low p_T source - difficult to handle theoretically
- Proposed a method to use EM radiation to constrain viscosity
  - Going to take *really really* detailed modeling for this to work

Backup Slides

QGP vs. Pion Rates



Kinetic Theory Comparison