Critical Enhancement of Thermal Photons

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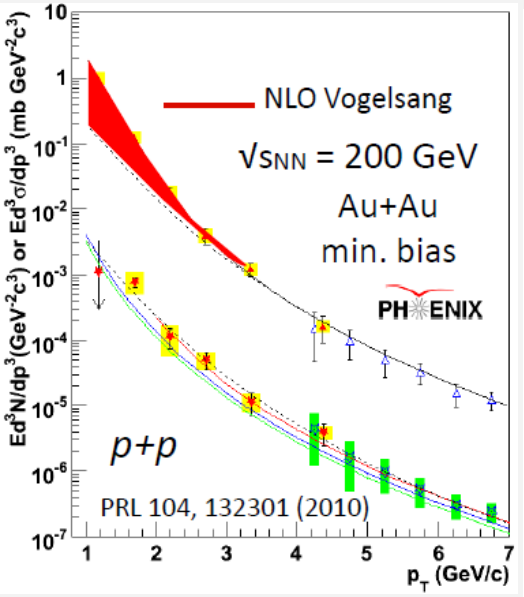
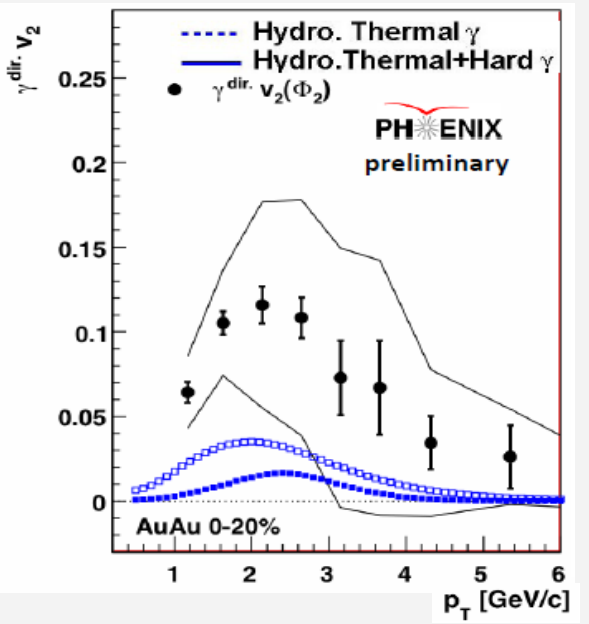
1.) Direct Photon "Puzzle"

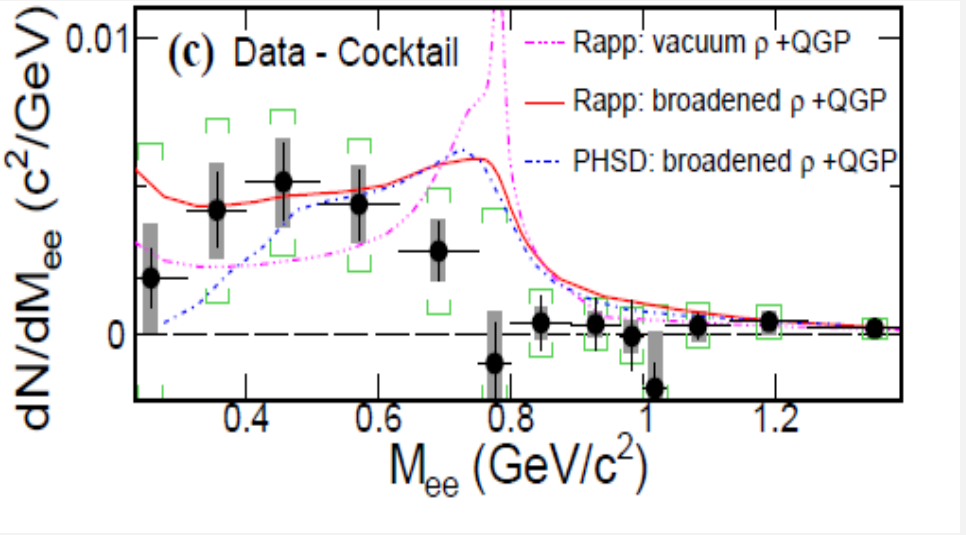
- Large enhancement
- Soft slope
- Large v_2





Low-mass Dileptons:

- Universal source SPS → RHIC
- Radiation around T_{pc} ~ 160MeV
- M→0 limit!?



1.2 Phenomenology of Thermal Photons

$$q_0 \frac{dN_\gamma^{therm}}{d^3q} = \int_{\tau_0}^{\tau(T_{fo})} d^4x \; q_0 \frac{dR_\gamma^{therm}}{d^3q}(q \cdot u; T, \mu_i)$$

Medium evolution:

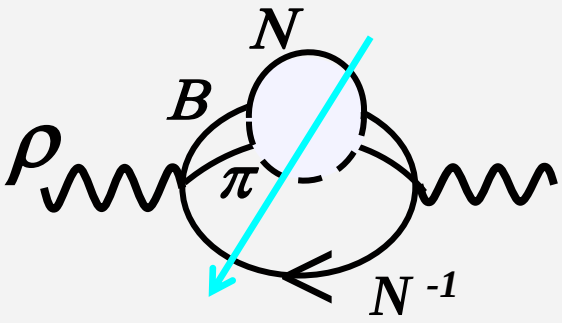
- **Fireball or hydro**

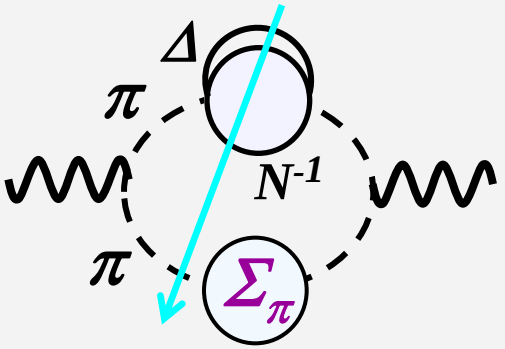
Emission rates:

- **Hadronic matter**
- **QGP**

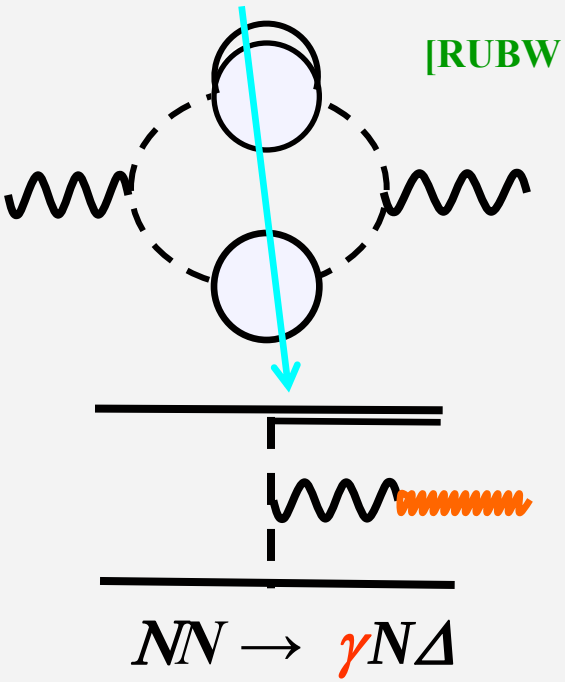
2.1 Thermal Photon Rates I: Hadronic Matter

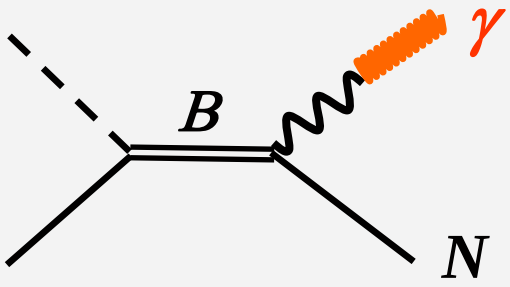
- **Thermal Field Theory:** $q_0 \frac{dR_\gamma}{d^3q} = -\frac{\alpha_{em}}{\pi^2} f^B(q_0;T)\,\mathrm{Im}\Pi^T_{em}(q_0 = q;\mu_B,T)$

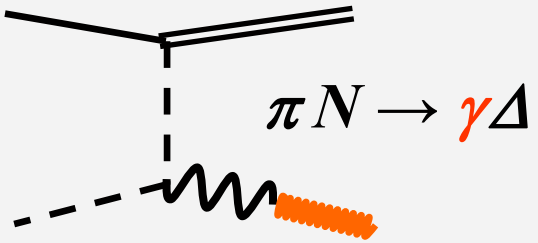




[RUBW '99]

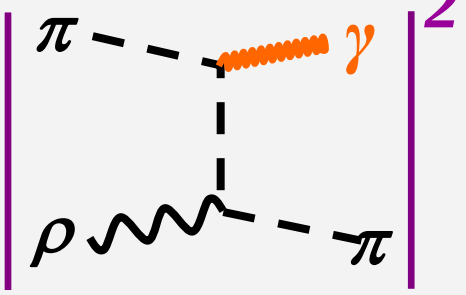






- **Kinetic Theory:**

$$q_0 \frac{dR}{d^3q} = N \int \frac{d^3p_{1,2,3}}{8E_{1,2,3}} \delta^{(4)}(...)\, f_1 f_2 (1 \pm f_3) |M|^2$$



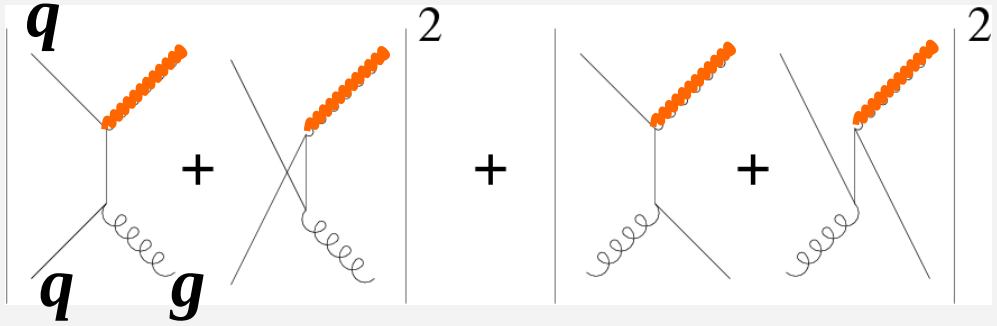
$\pi\rho\, a_1 KK^*$

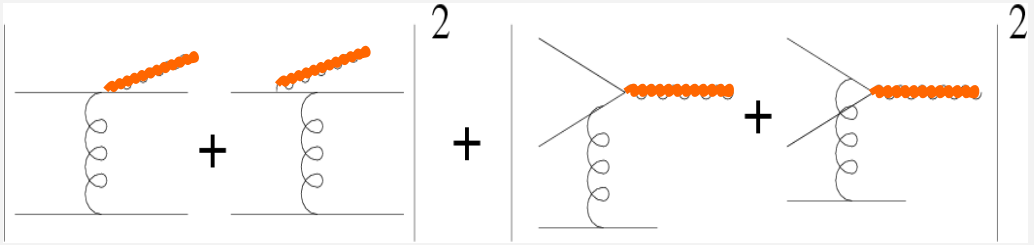
[TRG '04]

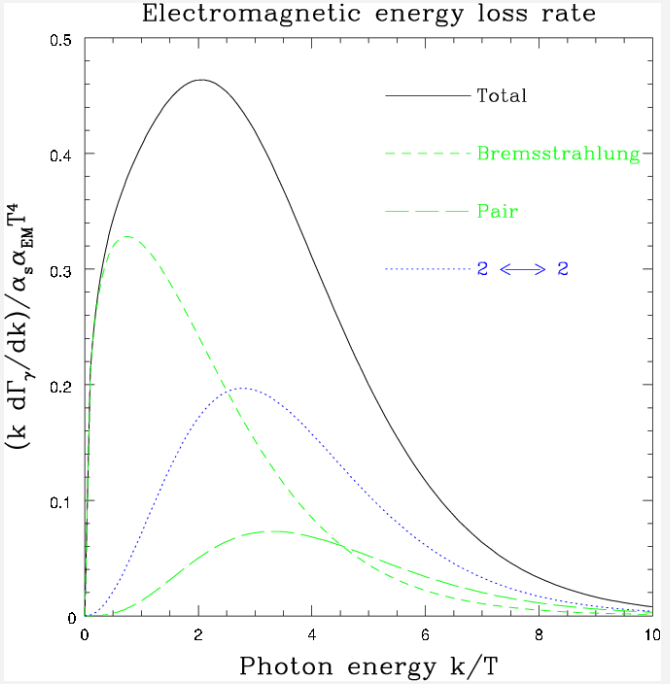
2.2 Thermal Photon Rates II: Quark-Gluon Plasma

- "**AMY-QGP**": complete LO rates (resummed perturbative)

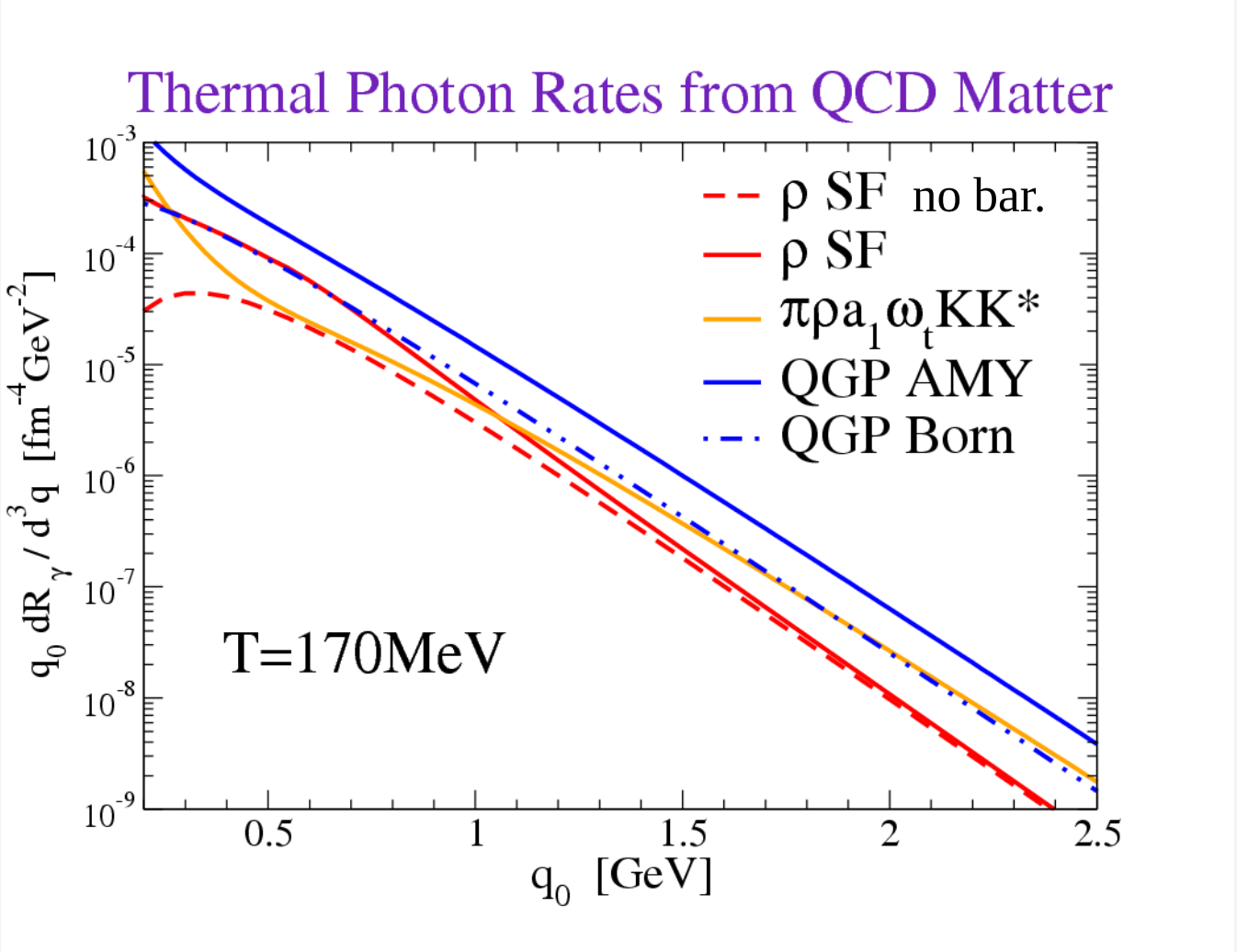
[Arnold,Moore+Yaffe '01]







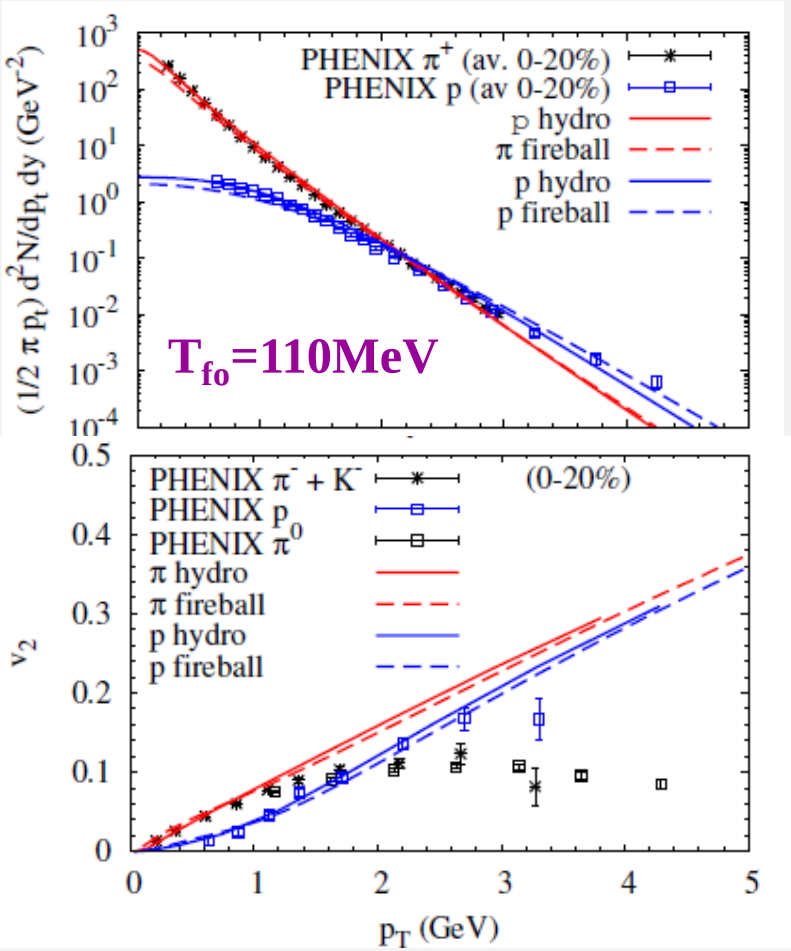
2.3 Thermal Rate Summary



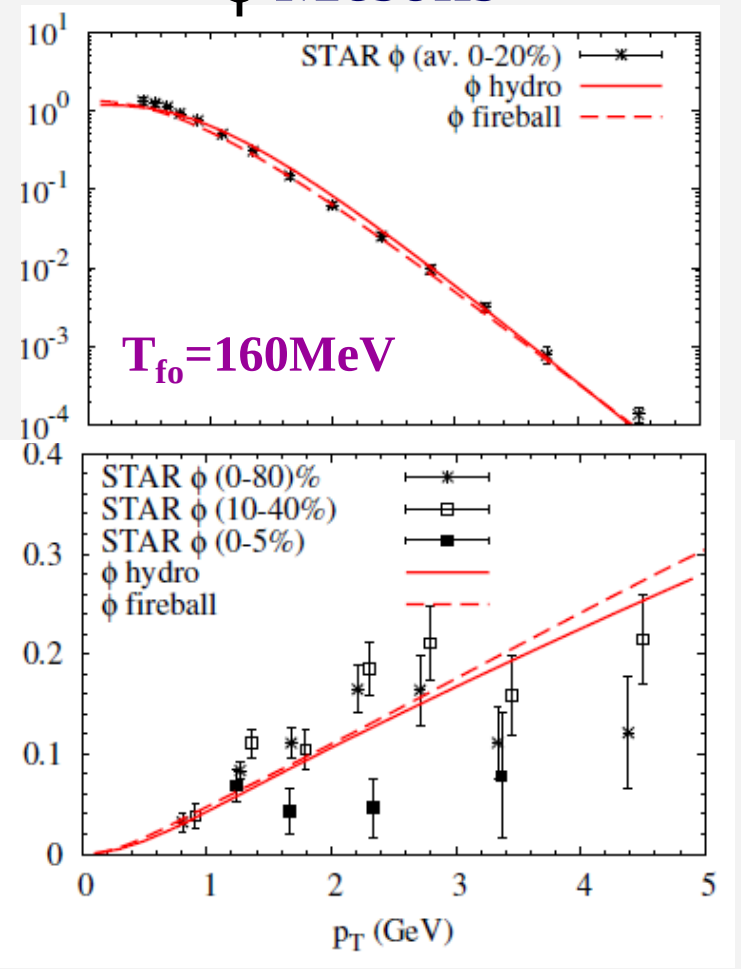
- ρ spectral function dominates hadronic for $q_0 \leq 1$ GeV ($q_0^{lab} \leq 2$GeV)
- total hadronic ≈ LO QGP

3.) Bulk-Medium Evolution: Fireball vs. Hydro

Pions + Protons



ϕ Mesons

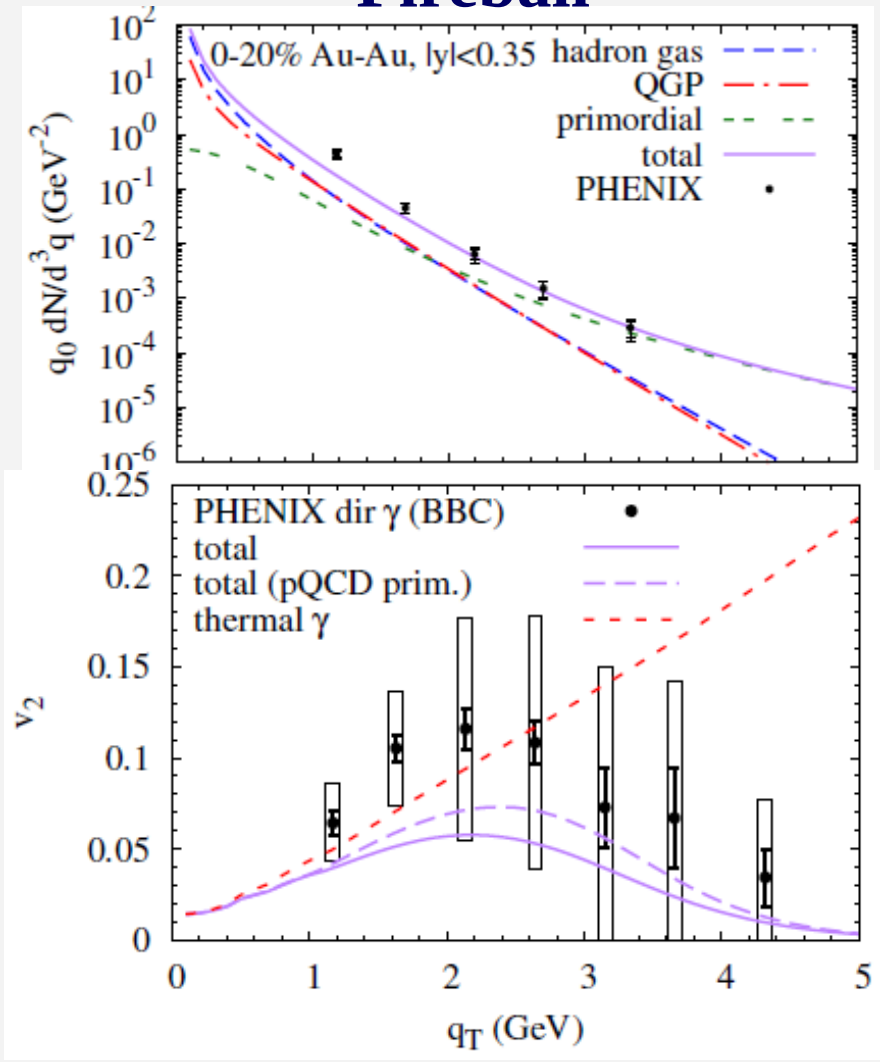


- lattice-EoS (T_{pc}~170MeV) + hadronic phase (T_{ch}=160MeV)
- **multi-strange freezeout at T_{ch} → bulk-v_2 saturates at T_{ch}**

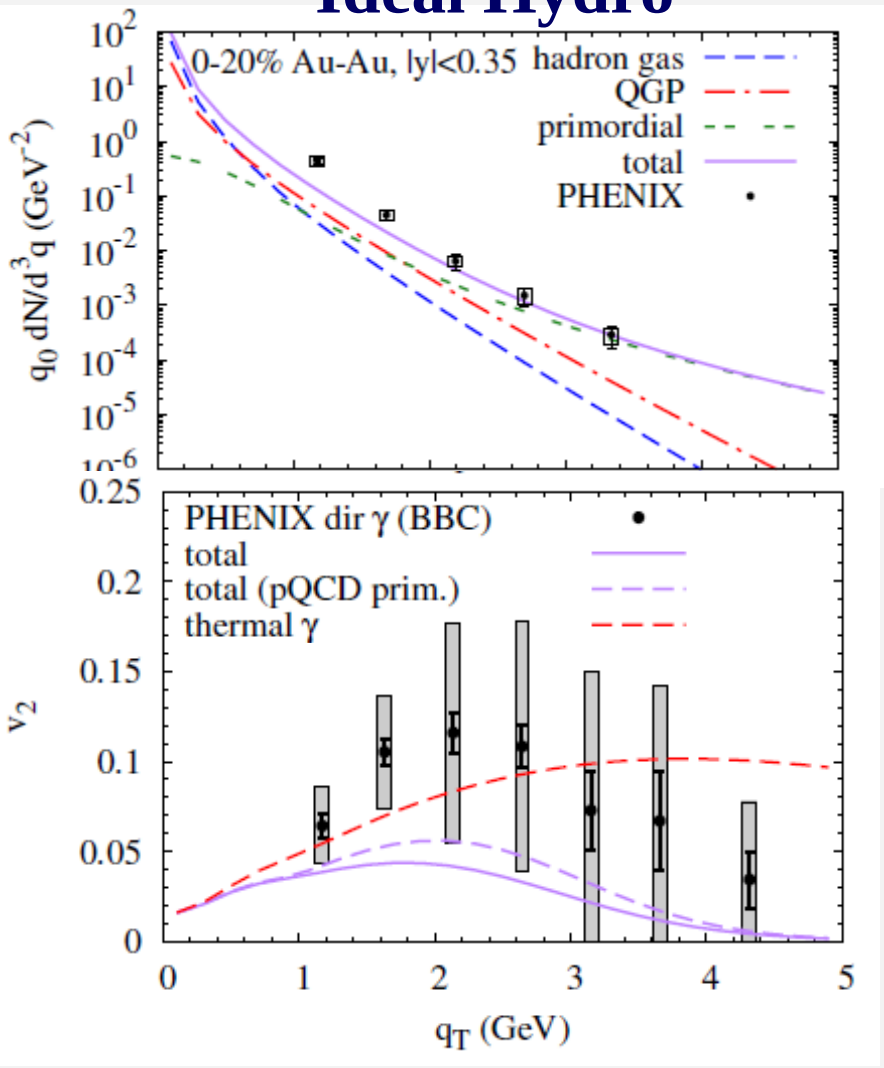
[He et al '11, Hees et al `11]

4.1 Direct Photons I: RHIC

Fireball



Ideal Hydro

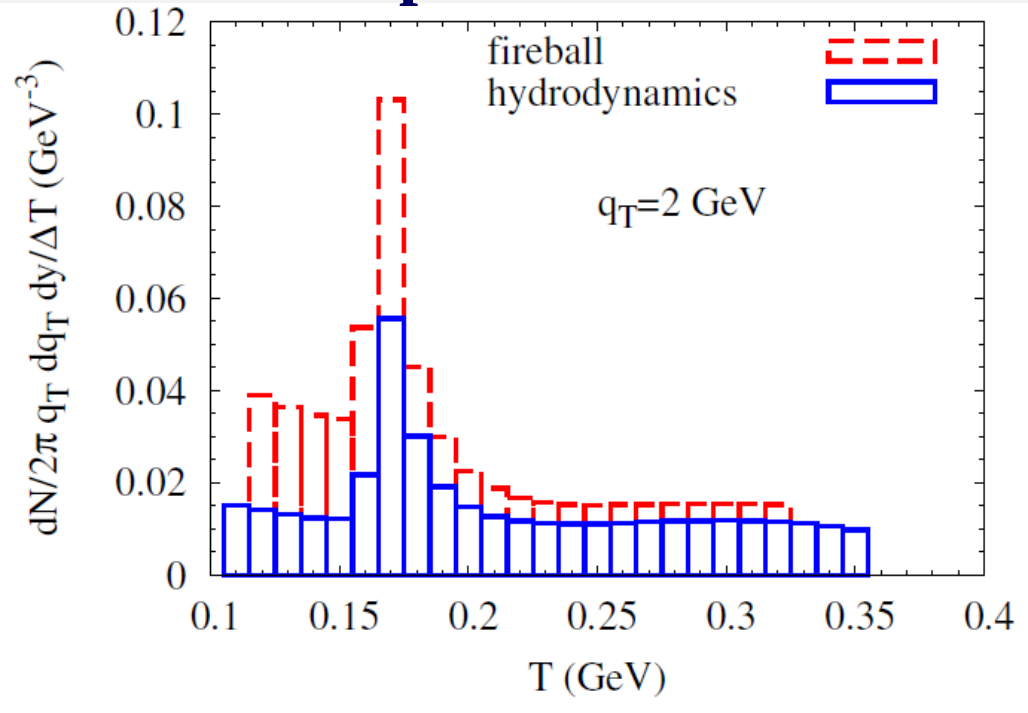


- similar QGP, larger hadronic yield in fireball
- **largest emission around T_{pc}**

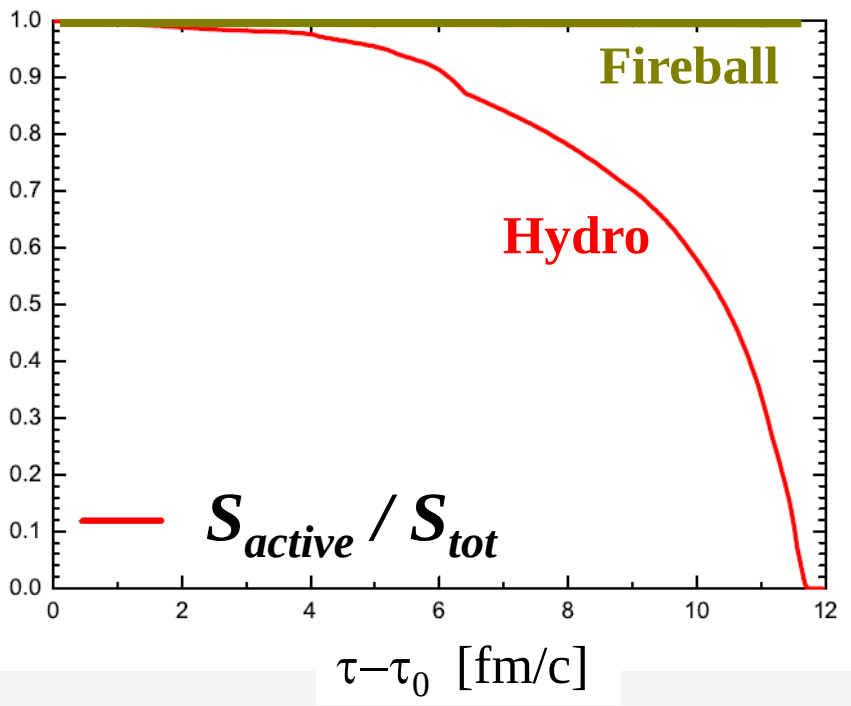
[van Hees, He+RR '14]

4.1.2 Emission Characteristics

Temperature Profile



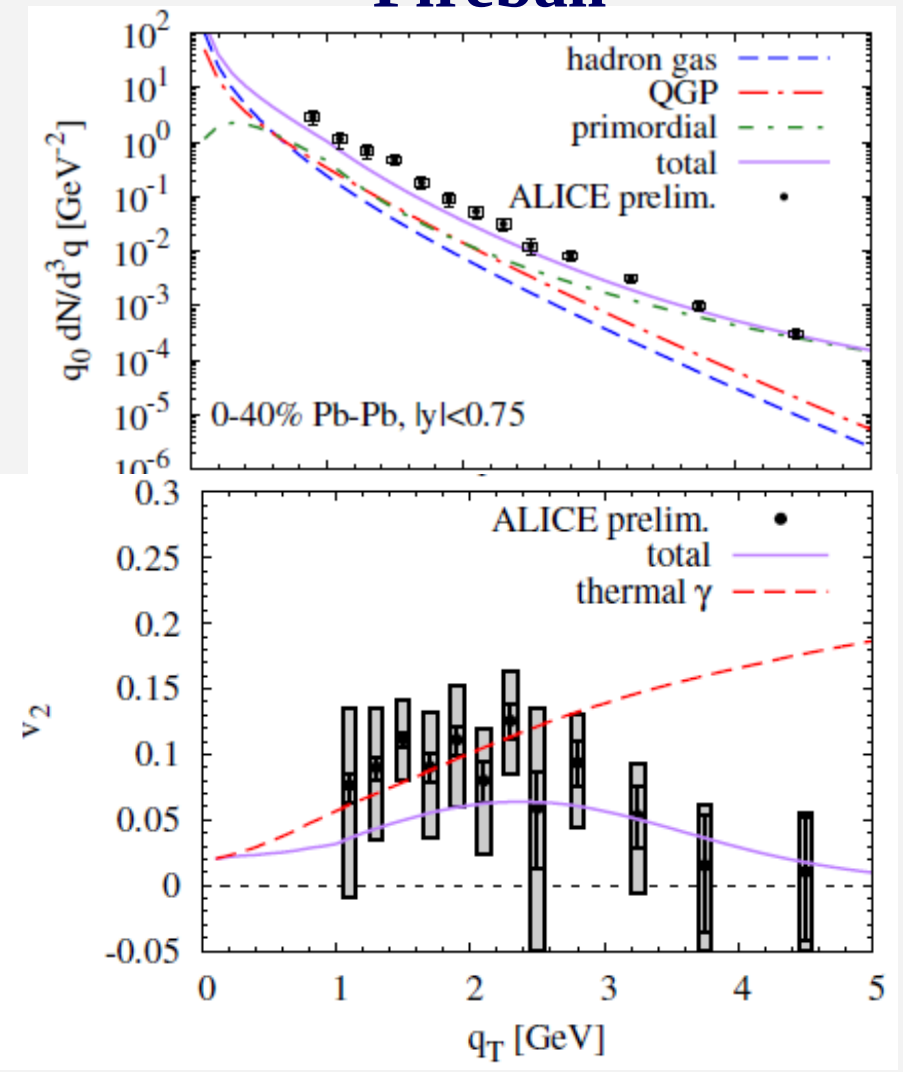
Fraction of Matter with $T>T_{fo}$



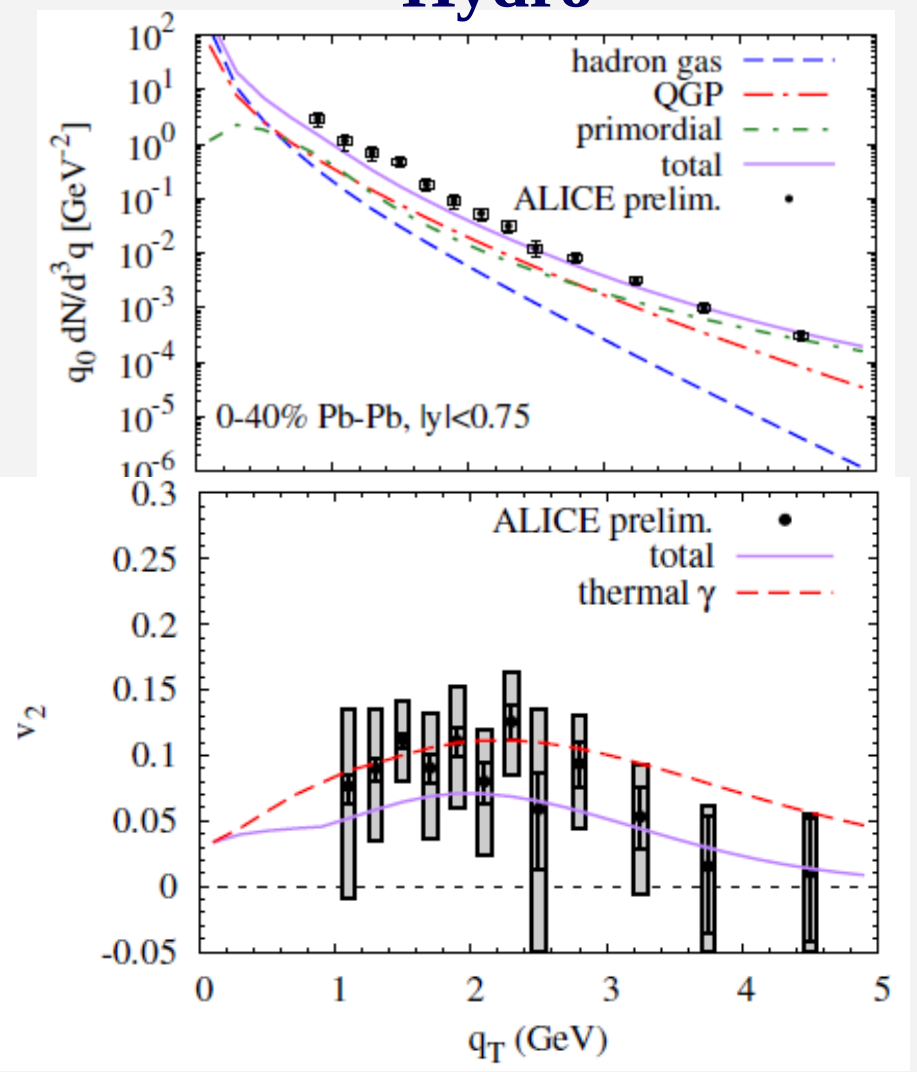
- Gradual freeze-out in hydro, cells never re-thermalize

4.2 Direct Photons II: LHC

Fireball



Hydro

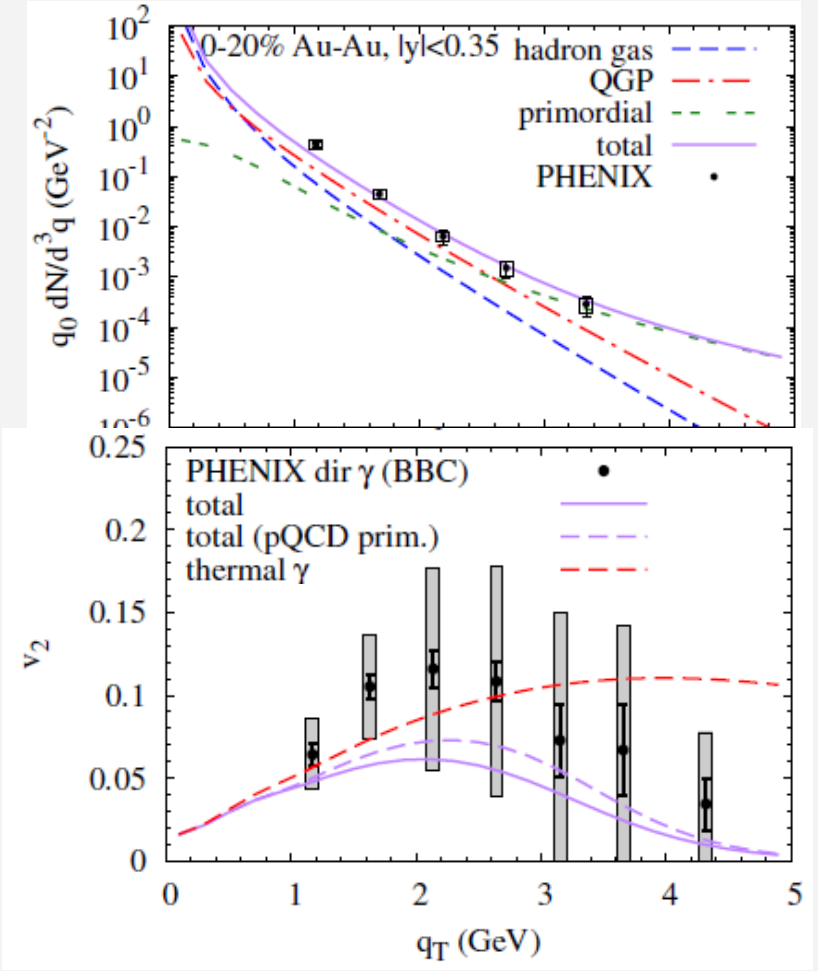


- increased QGP part → closer agreement fireball - hydro

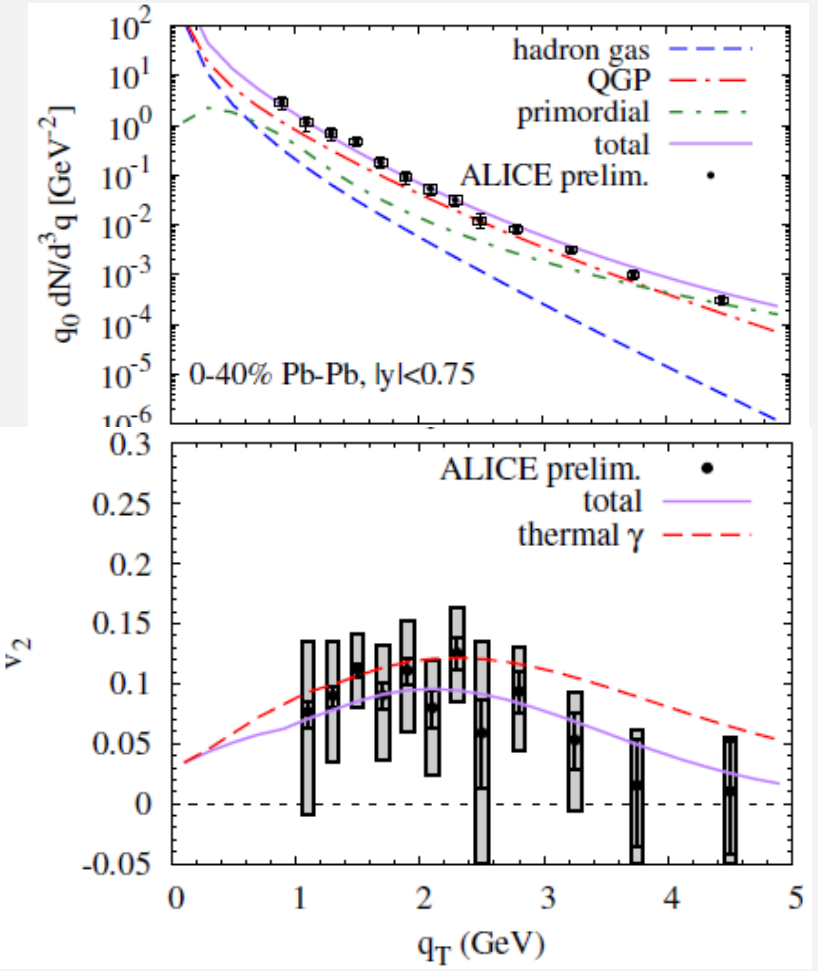
4.3 Enhanced Photon Rates in Hydro

- **upscale photon rates by factor of 2, up to 3 for $T_{pc} \pm 30$MeV**

RHIC



LHC



- getting close(r) to the data (more so with fireball)

5.) Conclusions

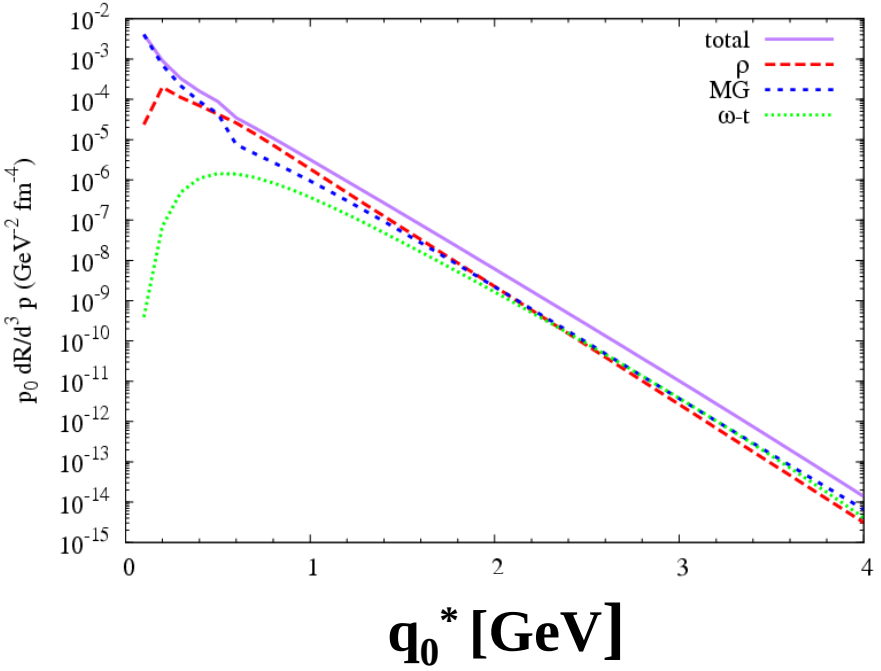
- **Thermal photon spectra with:**
  - **LO-QGP + (ρ SF + meson exchange)**
  - **Medium evol. with sequential f.o. → bulk-v_2 saturates at ~T_{pc}**
  - **Radiative final-state decays**

⇒ **Not (very) far from spectra + v_2 data**

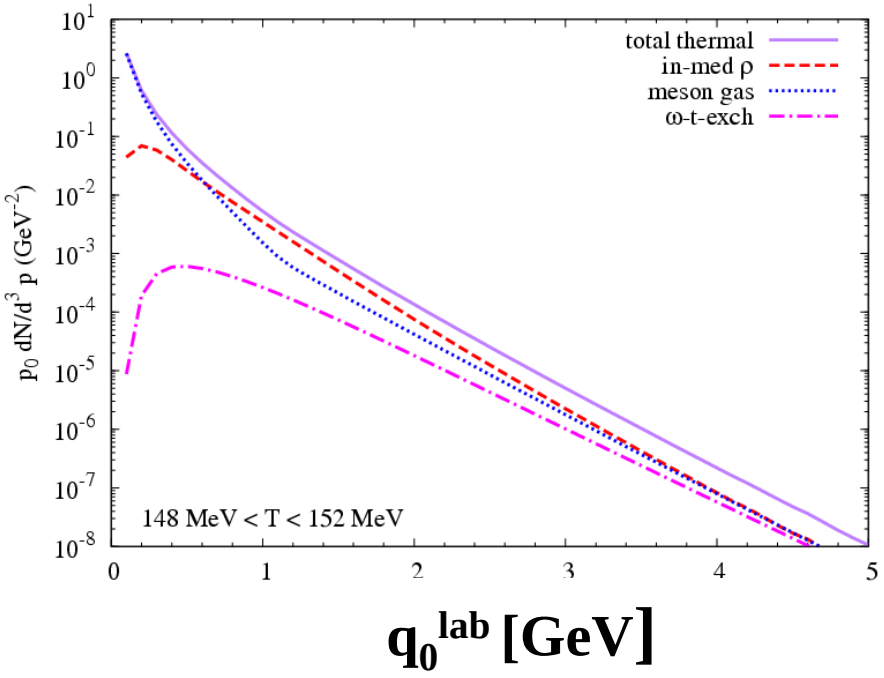
- **Possible need for enhanced rate (natural around T_{pc})**

4.x Collective Flow Effect on Spectra

Rate in Rest Frame



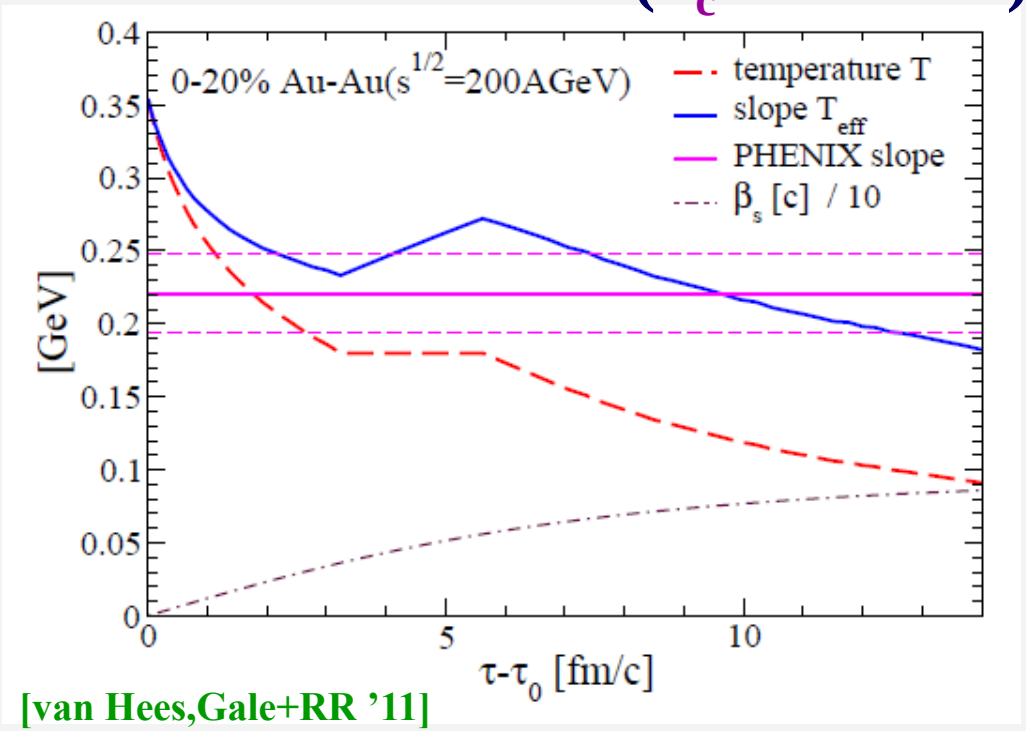
Spectrum in Lab Frame



- Doppler shift $q_0^{lab} \sim 2\, q_0^* = 2\, q^{lab} \cdot u$

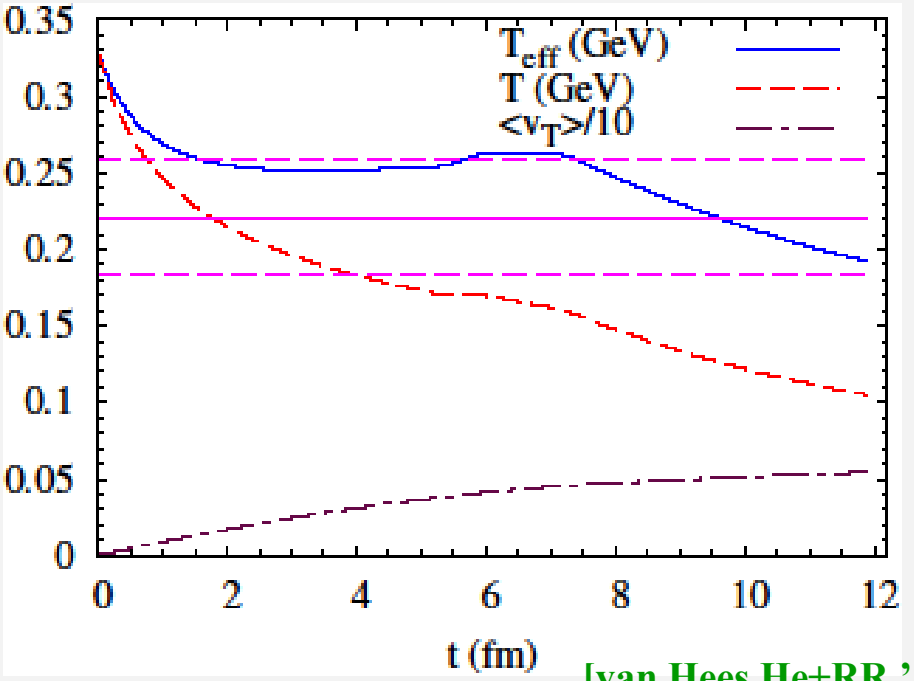
4.x Effective Slope Parameters

First-Order EoS (T_c=180MeV)



[van Hees,Gale+RR '11]

Lattice EoS (T_{pc}=170MeV)

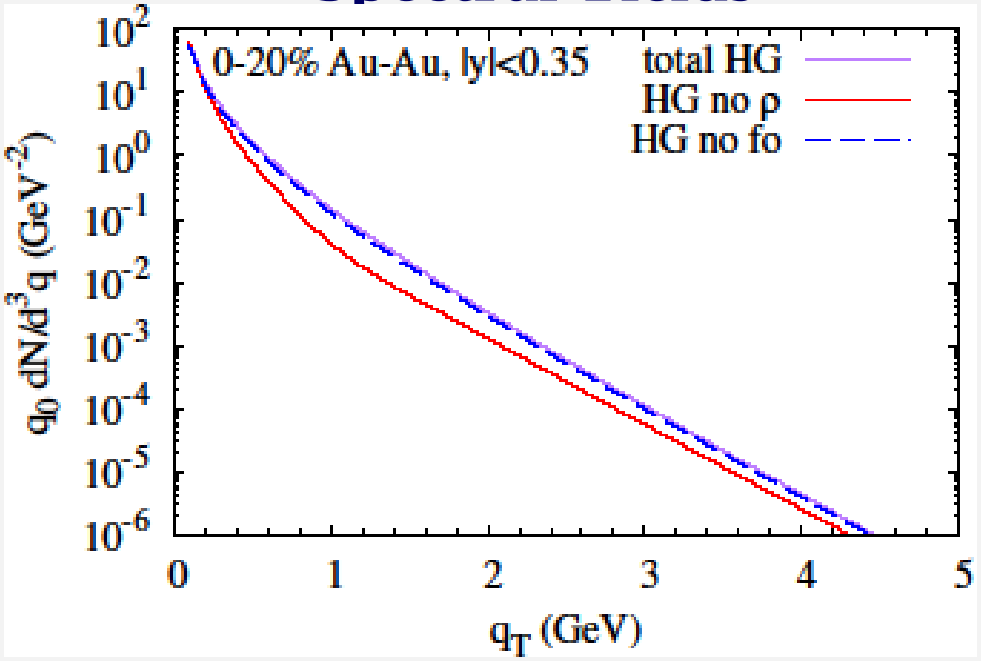


[van Hees,He+RR '14]

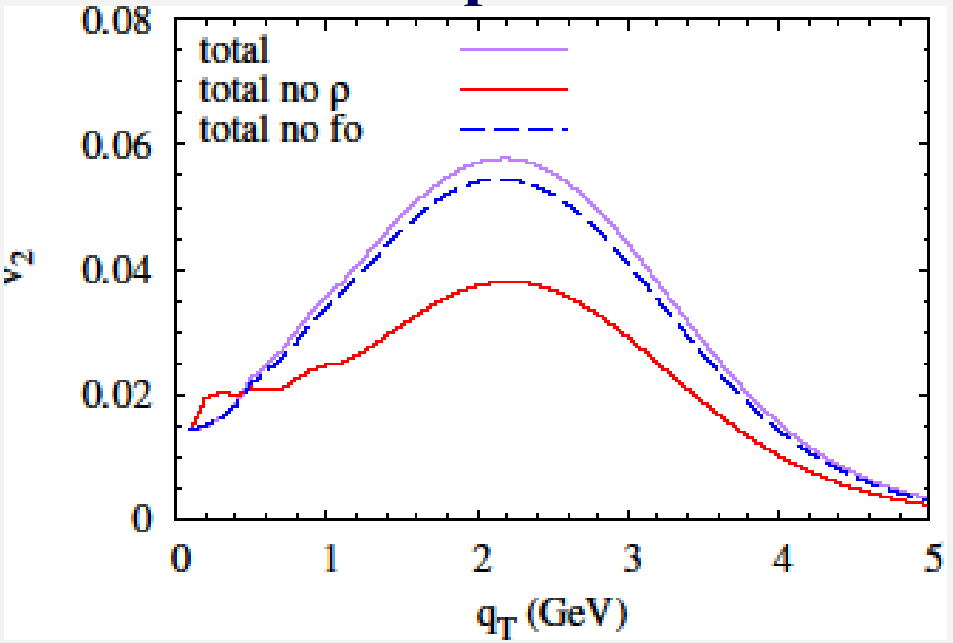
- local temperatures **T≤ 200MeV**

4.x Decomposition of Hadronic Contribution

Spectral Yields



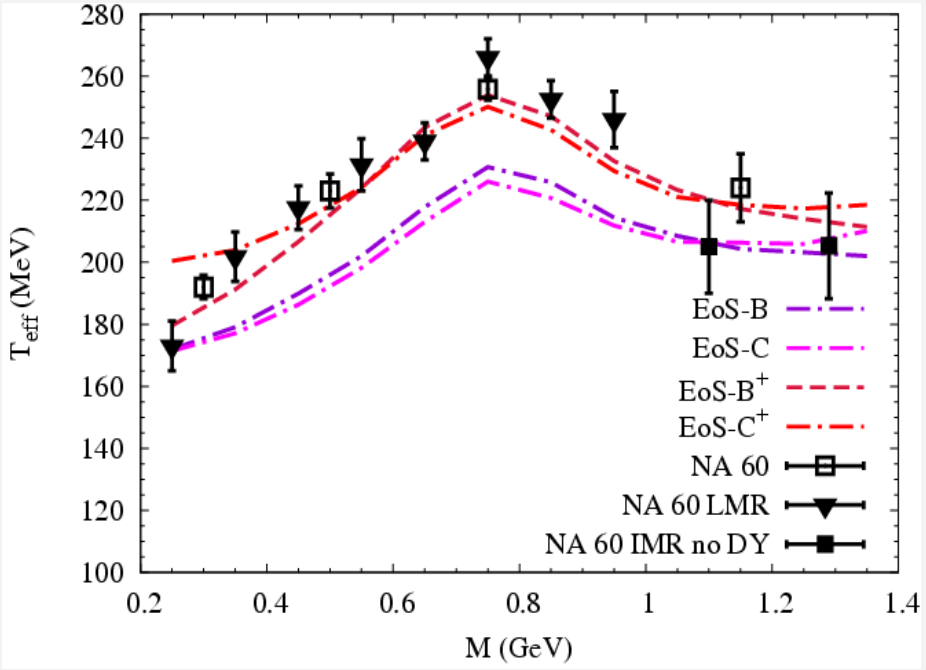
Elliptic Flow



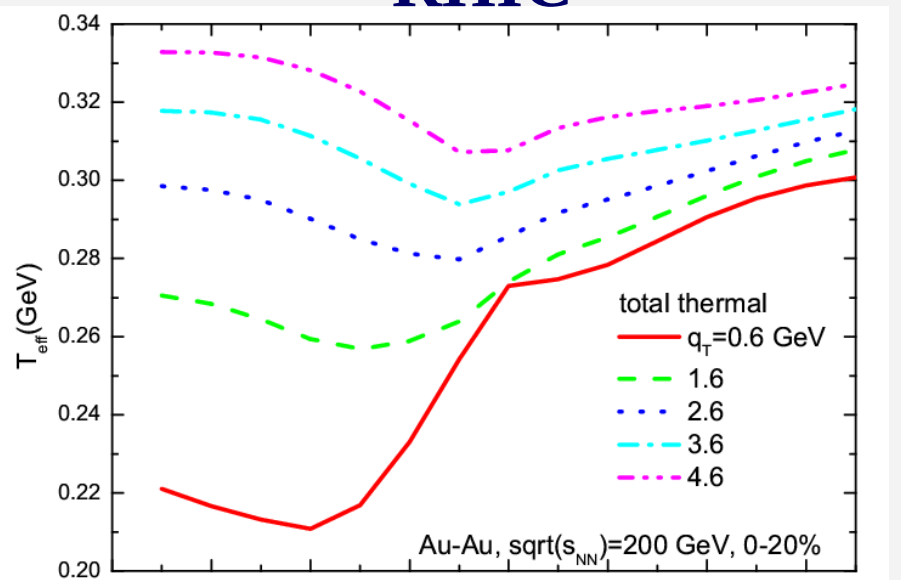
- ρ spectral function contribution appreciable

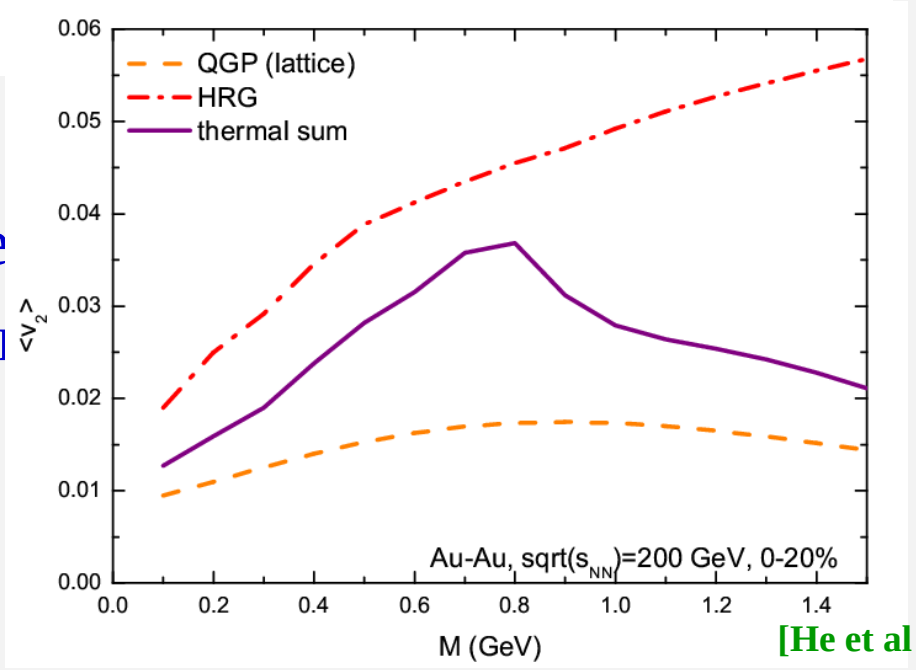
3.5 Collectivity of Dileptons: Blue Shift and v_2

SPS



RHIC



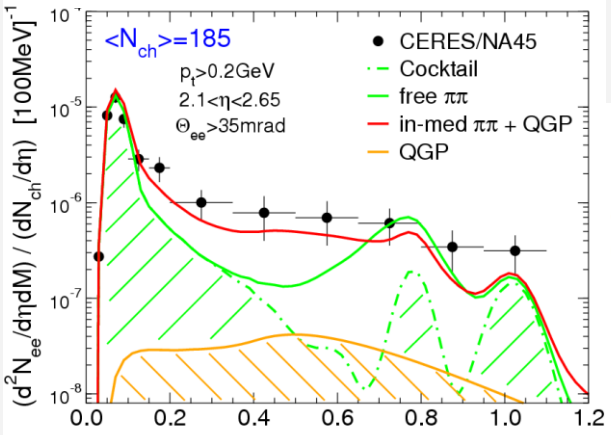


- QGP-flow "arm" (**M > 1GeV**) rise
- high p_t: slope saturates at initial te
- v_2 develops maximum at ρ mass!

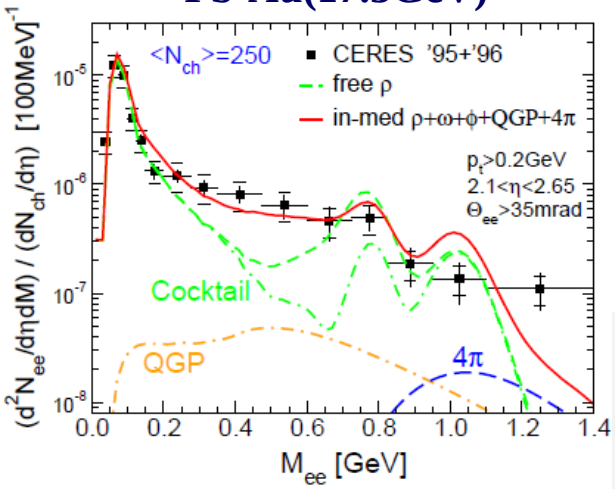
[He et al in prep]

3.2 Excitation Function: SPS - RHIC

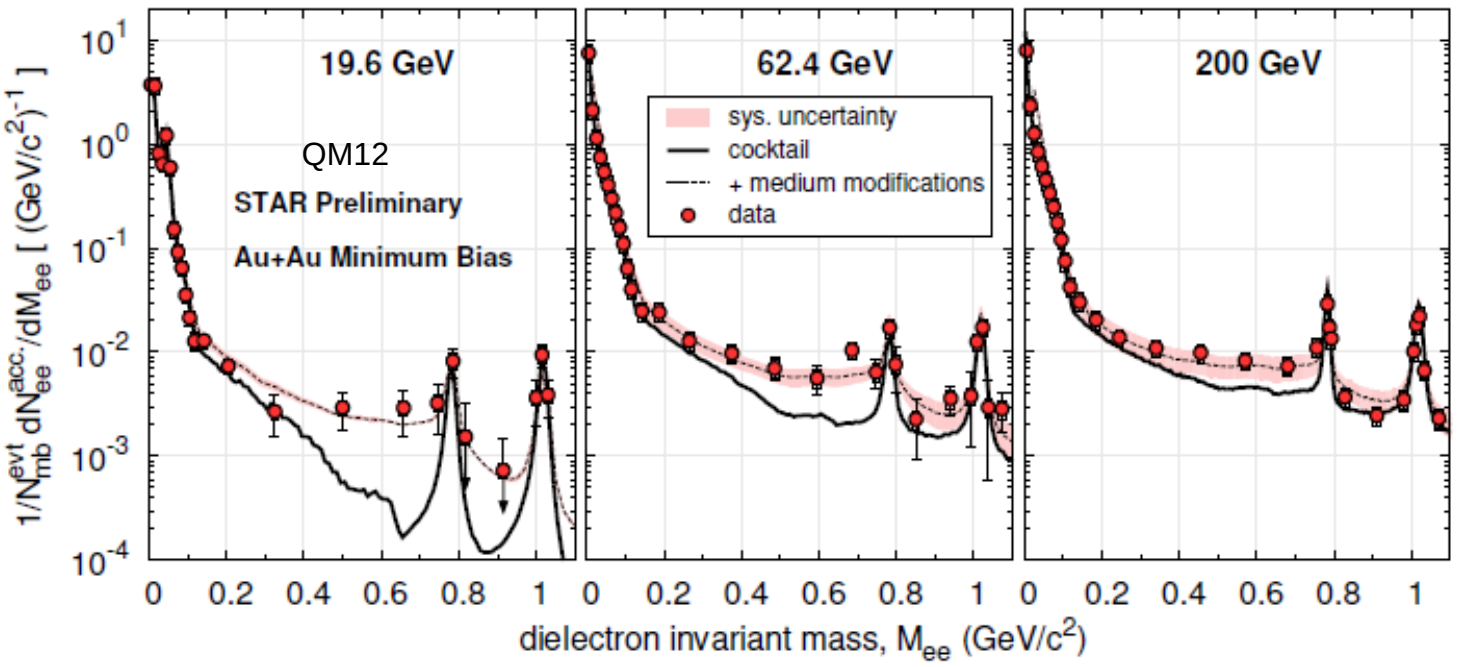
Pb-Au(8.8GeV)



Pb-Au(17.3GeV)



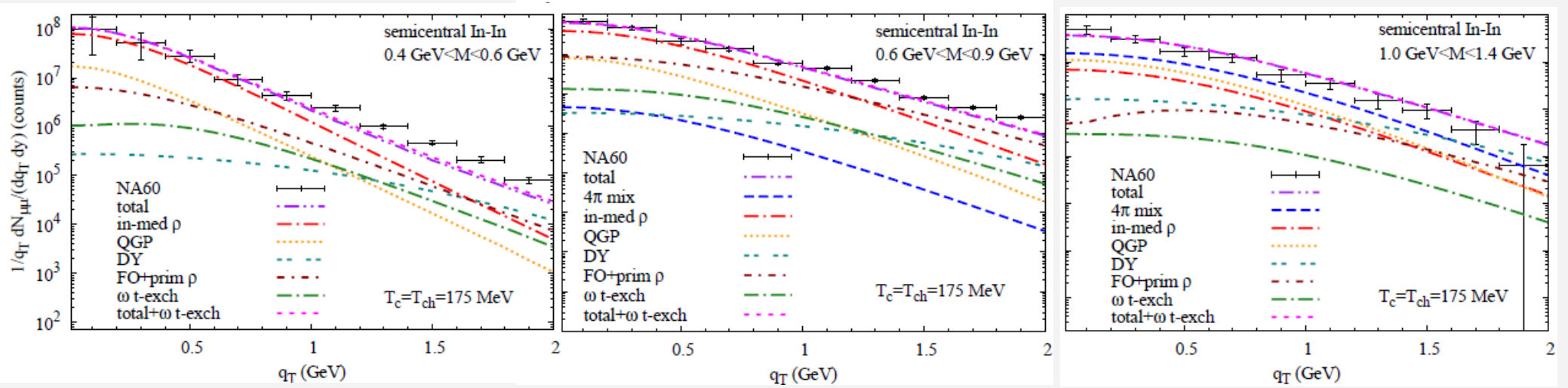
Au-Au (20-200GeV)



- consistent excess emission source
- suggests "universal" medium effect around T_{pc}
- **FAIR, LHC?**

[cf. also Bratkovskaya et al, Alam et al, Bleicher et al, Wang et al …]

4.3 Dimuon p_t-Spectra and Slopes: Barometer



- theo. slopes originally too soft
- increase fireball acceleration,
  e.g. $\mathbf{a_\perp = 0.085/fm \rightarrow 0.1/fm}$
- insensitive to $\mathbf{T_c}$=160-190MeV

Effective Slopes T_{eff}