Thermal EM Radiation in AA and pA

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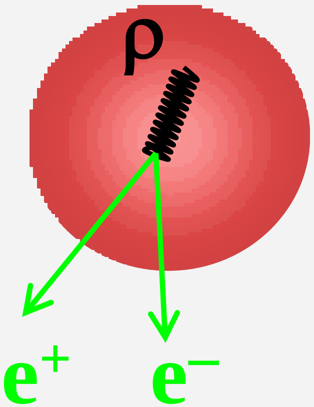
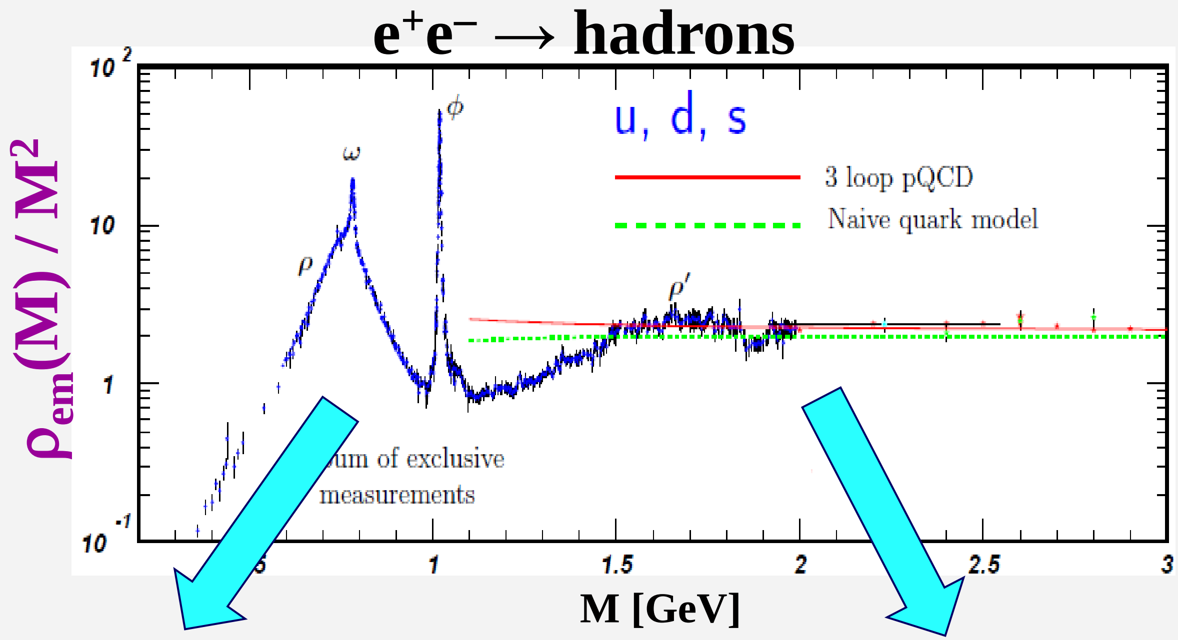
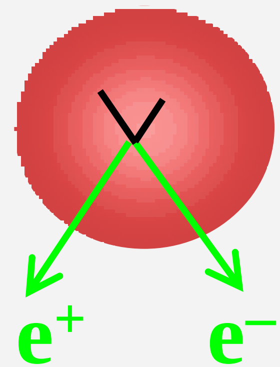
1.) Intro: EM Spectral Function Probing Fireballs

- **Thermal Dilepton Rate**

$$\frac{dN_{ee}}{d^4x d^4q} = \frac{\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T)\ \rho_{em}(M,q;\mu_B,T)$$







- **Hadrons:** $\rho_{em} \sim \mathrm{Im}\, D_{\rho,\omega,\phi}$
  - change in **degrees of freedom,** **chiral restoration**

- **$q\bar{q}$ Continuum:** $\rho_{em} / M^2 \sim 1 + \mathcal{O}(T^2/M^2)$
  - **temperature**

- **Total yields** $\sim V_{FB} \cdot \tau_{FB}$: **fireball lifetime**

Outline

1.) **Introduction**

2.) **Dilepton Spectra in AA**

   2.1 In-Medium Spectral Functions

   2.2 Medium Evolution in URHICs

   2.3 Spectra

3.) **“Initial-Stage” Effects**

   3.1 Dilepton Radiation in p-Pb

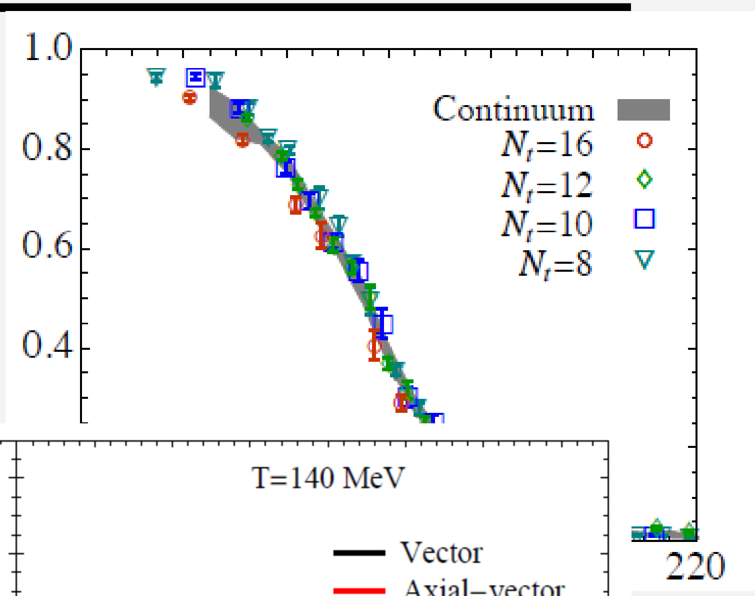
   3.2 Direct Photons

4.) **Conclusions**

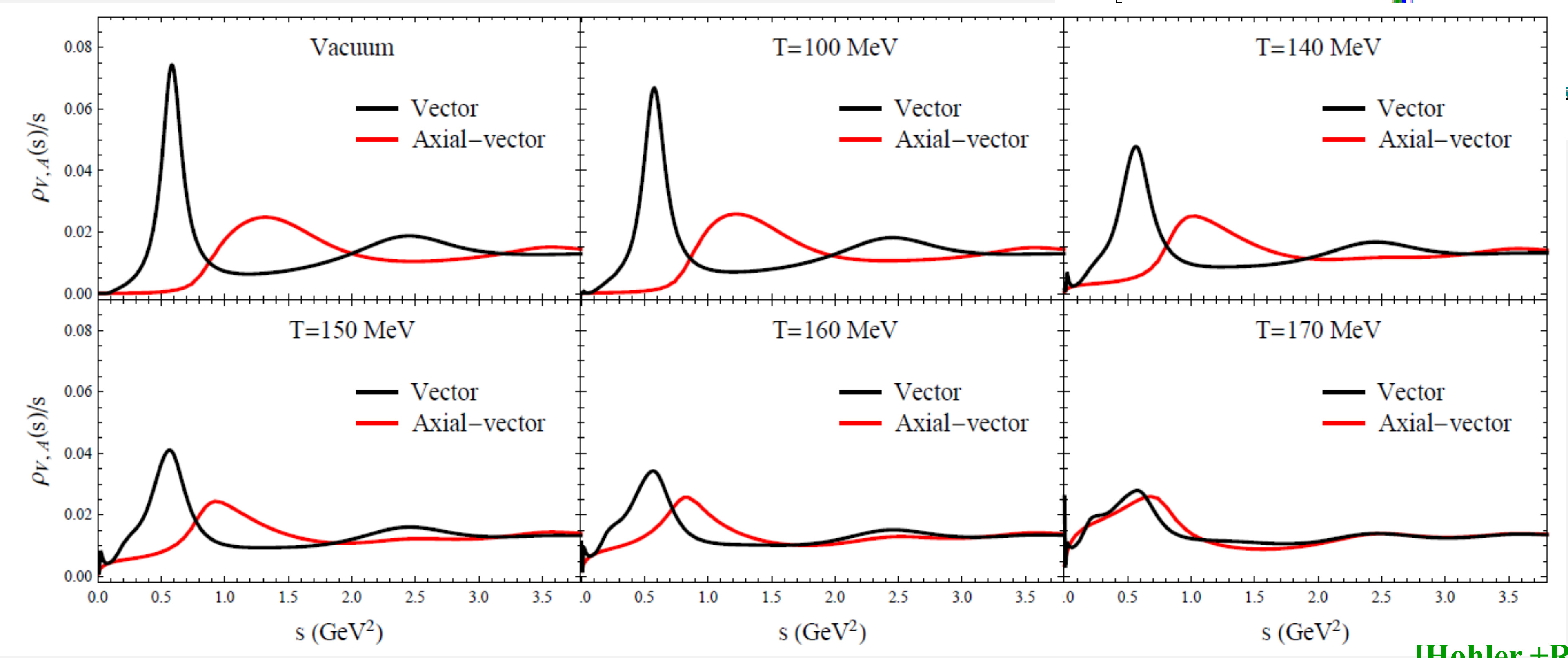
2.1 Spectral Functions + Sum Rules in Medium

2.1.1 Weinberg + QCD Sum Rules

$$\int \frac{ds}{\pi}\frac{1}{s}(\rho_V-\rho_A)=f_\pi^2 \quad , \quad \int \frac{ds}{\pi}(\rho_V-\rho_A)=-m_q\langle\bar{q}q\rangle$$



- Input: - condensates from lattice QCD

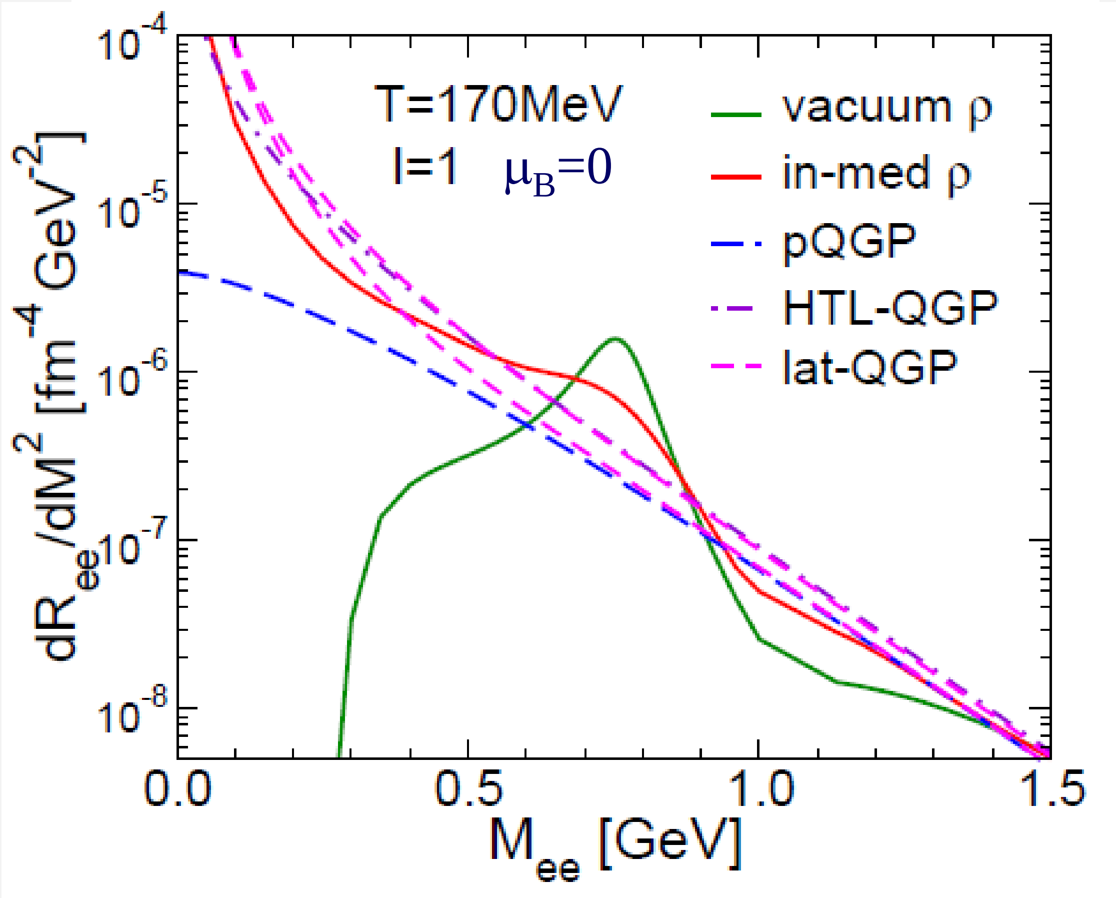


[Hohler +RR '13]

- **Compatible with approach to chiral restoration**

2.1.2 Dilepton Rates: Hadronic, QGP, Lattice

$$dR_{ee}/dM^2 \sim \int d^3q/q_0 \; f^B(q_0;T) \; \rho_{em}(M,q;\mu_B,T)$$



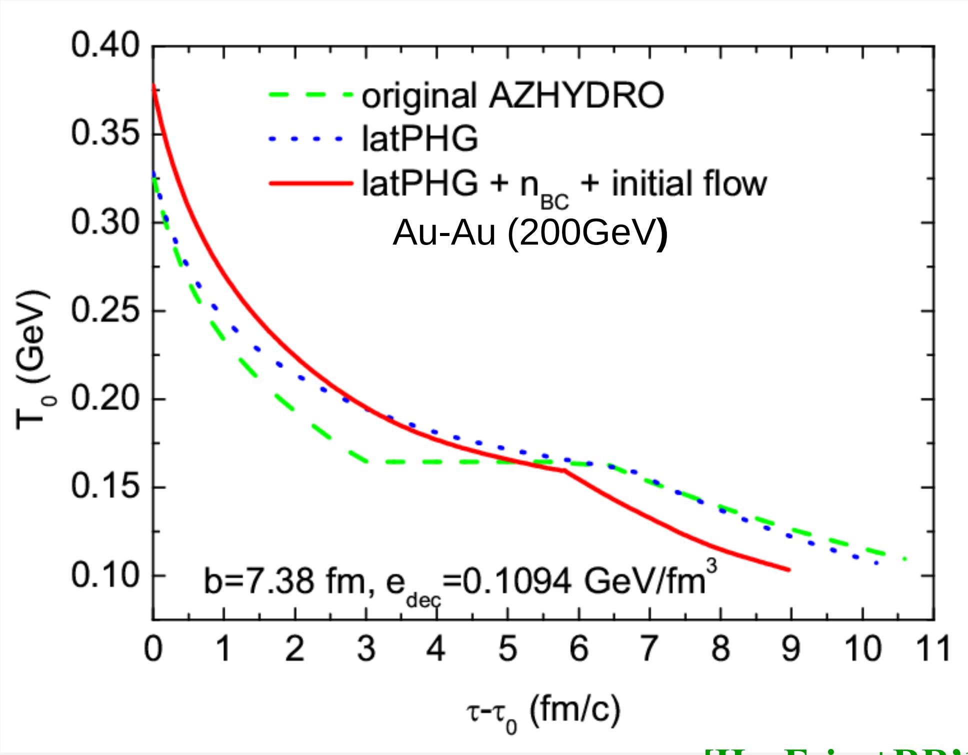
• **Resonance melting:** transition **hadronic → QGP** toward T_{pc}

2.2 Medium Evolution in Heavy-Ion Collisions

- Evolve rates over fireball:

$$\frac{dN_{ll}^{therm}}{dM^2} = \int_{\tau_0}^{\tau_{fo}} d\tau V_{FB}(\tau) \int \frac{d^3q}{2q_0} \frac{dR_{ll}^{therm}}{d^4q}$$

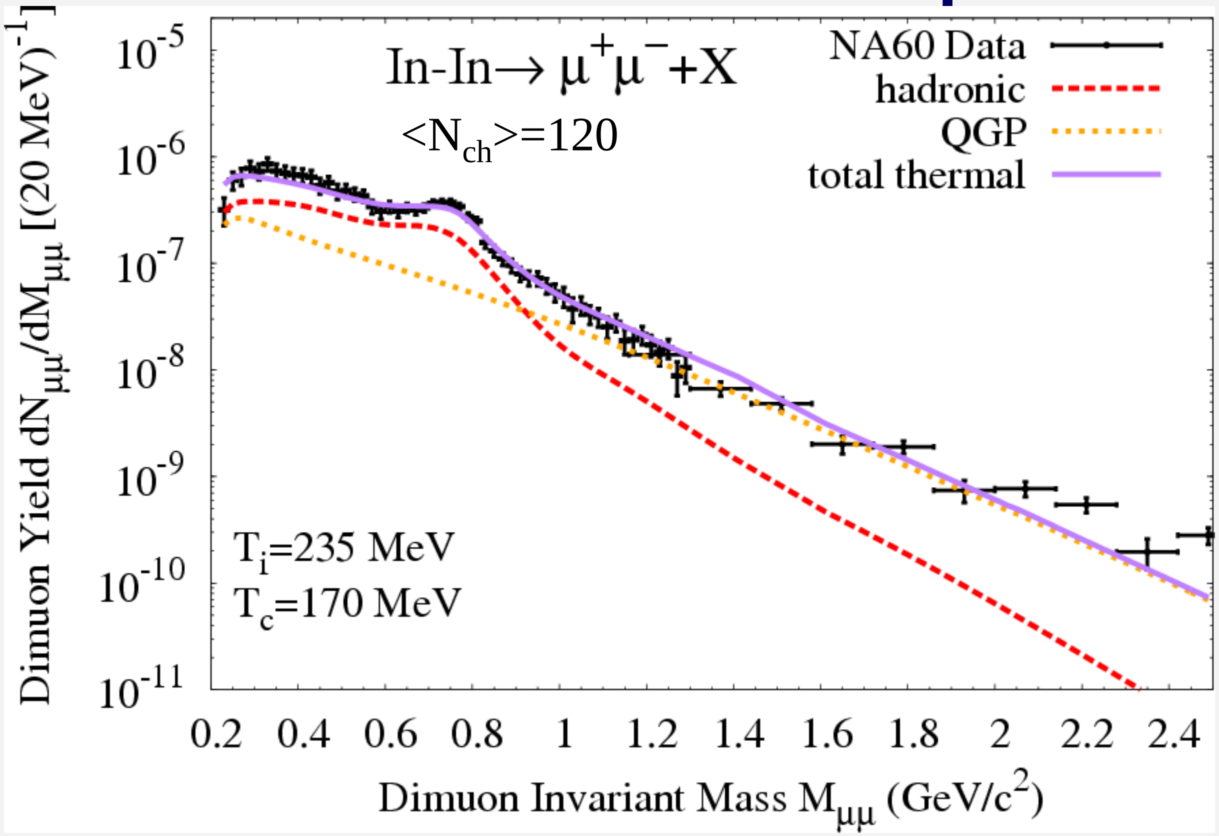
- **Bulk Medium Evolution**
  - lattice EoS + HRG, $\mathbf{T_{pc}=170}$ **MeV**
  - $\mathbf{T_{ch}}$ **= 160MeV**
  - $\mathbf{T_{fo}}$ **~ 100 MeV**
  - initial profile, radial flow, … ?!
  - fit hadron spectra + $\mathbf{v_2}$



[He ,Fries+RR'12]

2.3.1 Precision Dileptons at SPS (17.3 GeV)

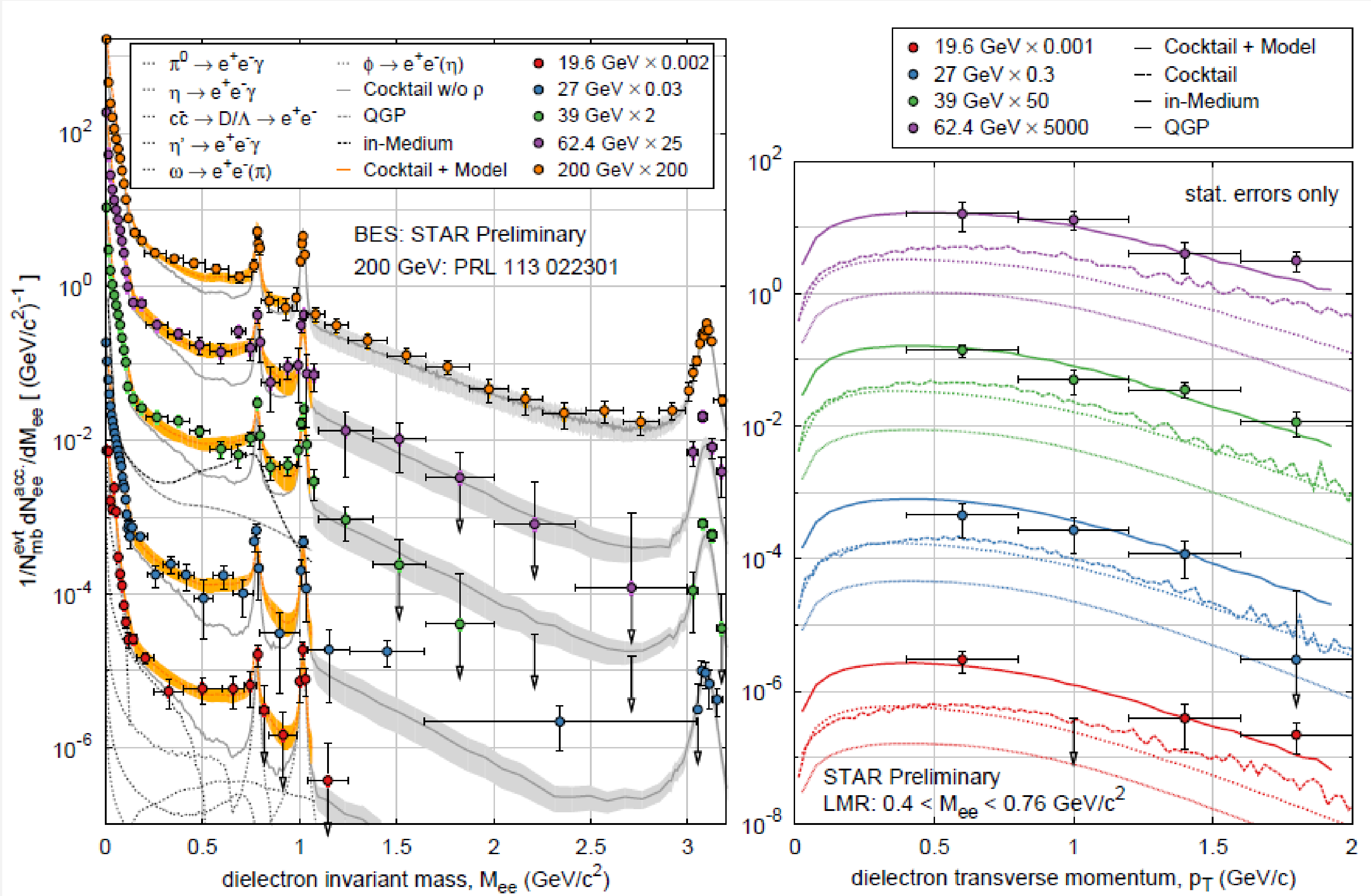
Invariant-Mass Excess Spectrum



[van Hees+RR '13]

- **Low mass**: radiation from **$T \sim T_{pc}^{\chi} \sim 150$MeV** - **spectrometer**
- **Intermediate mass**: **$T \sim 180$-200 MeV** - **thermometer**
- **Total yield:** fireball lifetime **$\tau_{FB} = 7 \pm 1$ fm/c** - **chronometer**

2.3.2 Low-Mass Excitation Function: 20-200 GeV

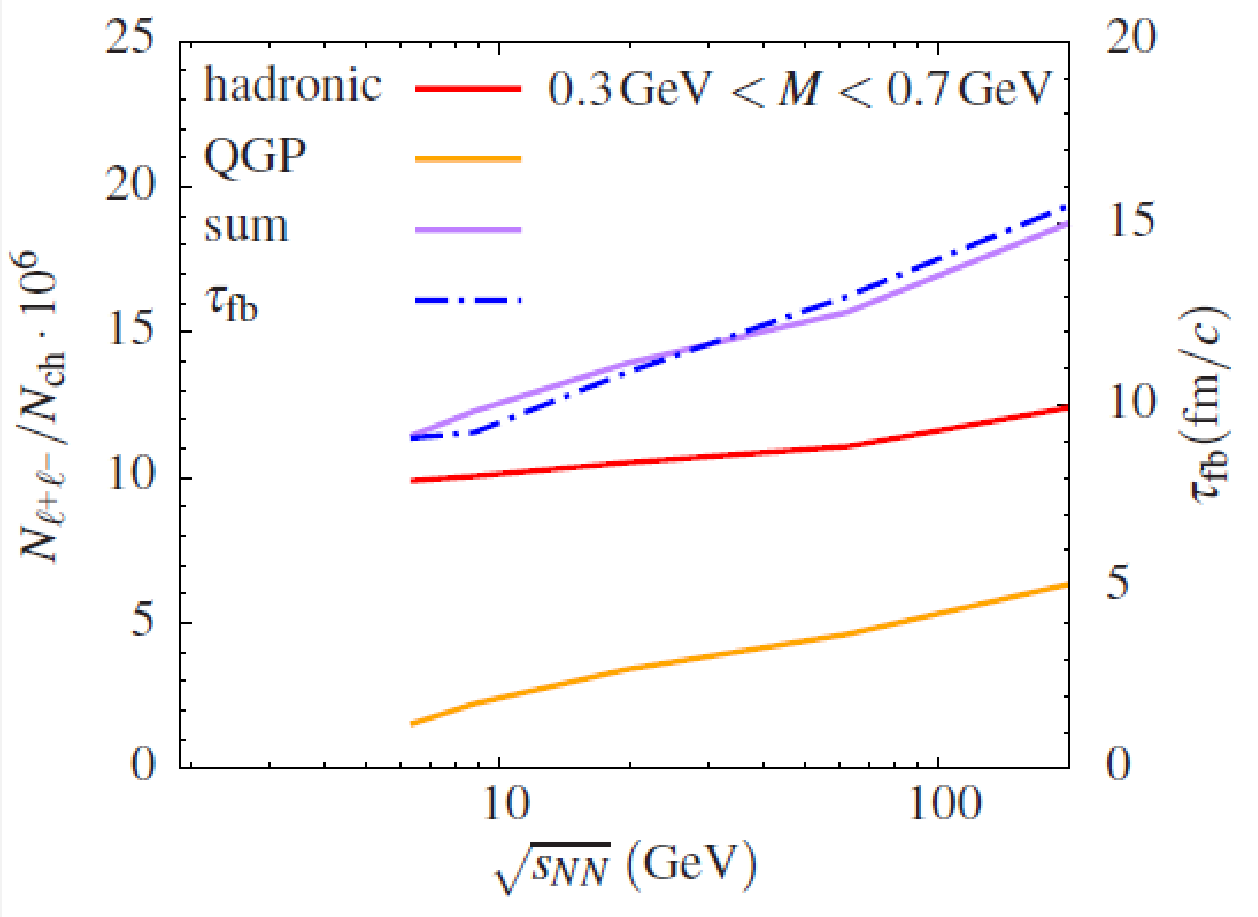


[STAR '14]

- compatible with predictions from melting ρ meson
- "universal" source around T_{pc}

2.3.3 Dilepton Excitation Function

Low-Mass Excess Radiation



• tracks **fireball lifetime**! (interacting/radiating medium)

[RR+van Hees '14]

Outline

1.) **Introduction**

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2.3 Spectra

3.) **"Initial-Stage" Effects**

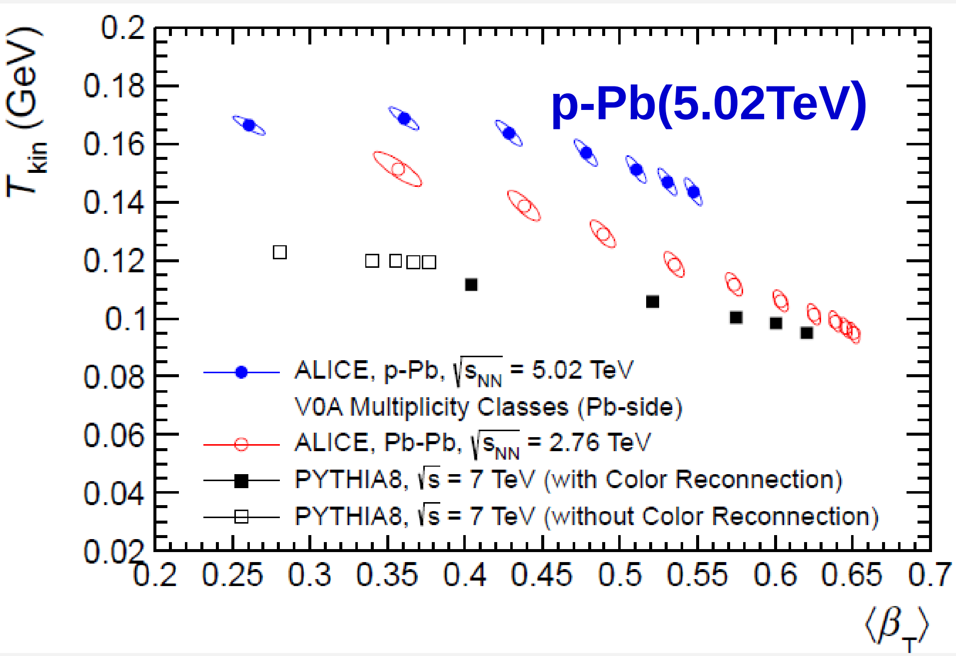
3.1 Dilepton Radiation in p-Pb

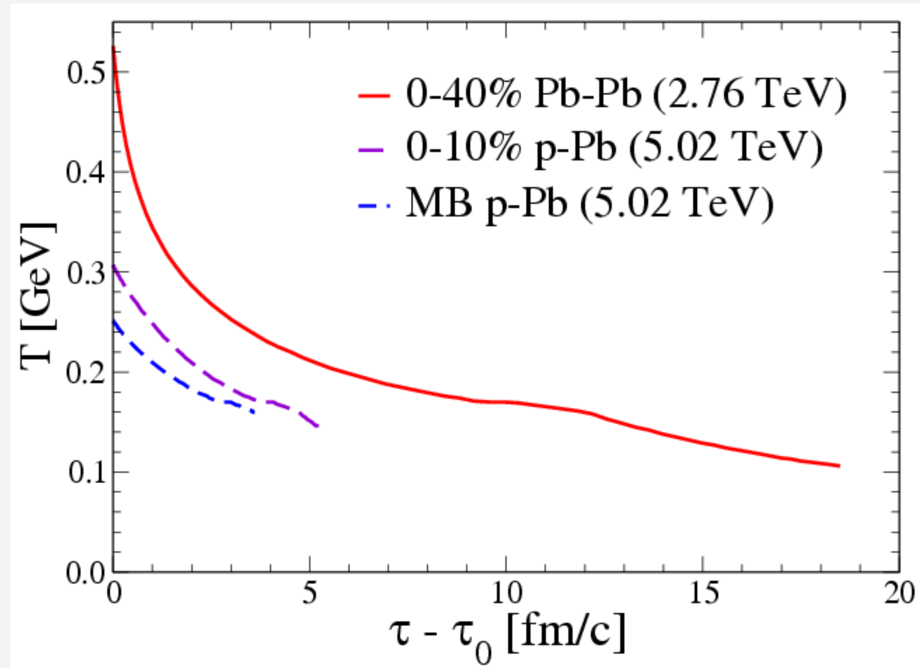
3.2 Direct Photons

4.) **Conclusions**

3.1 Dilepton Radiation in p-Pb at LHC

3.1.1 Bulk Medium Evolution

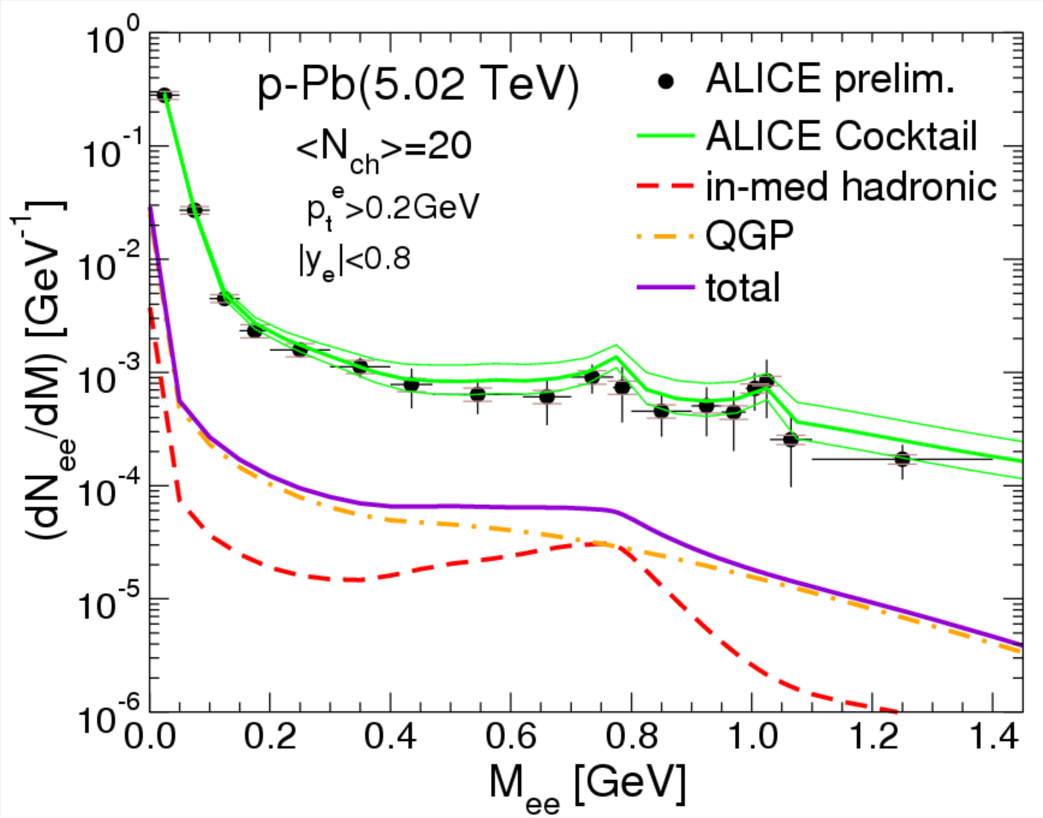




- assume fireball with
  $(\langle\beta_\perp\rangle, T_{kin}) \approx (0.4, 160\text{MeV})$
  $(dN_{ch}/dy)_{MB} \approx 20$
  $\tau_0 \sim 0.65$ fm/c $\Rightarrow T_0 \approx 250$ MeV

- interacting medium in **p-Pb**
  for $\tau_{FB} \approx$ **3.5 fm/c** (MB)
  $\approx$ **5 fm/c** (central)

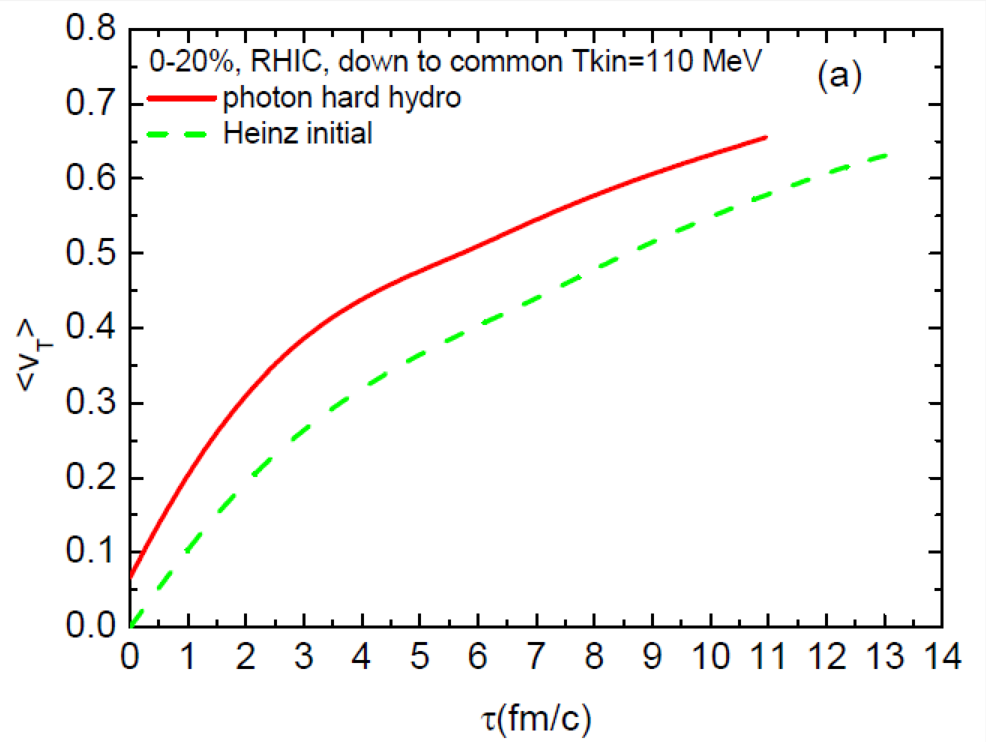
3.1.2 Low-Mass Dileptons in p-Pb (5.02GeV)



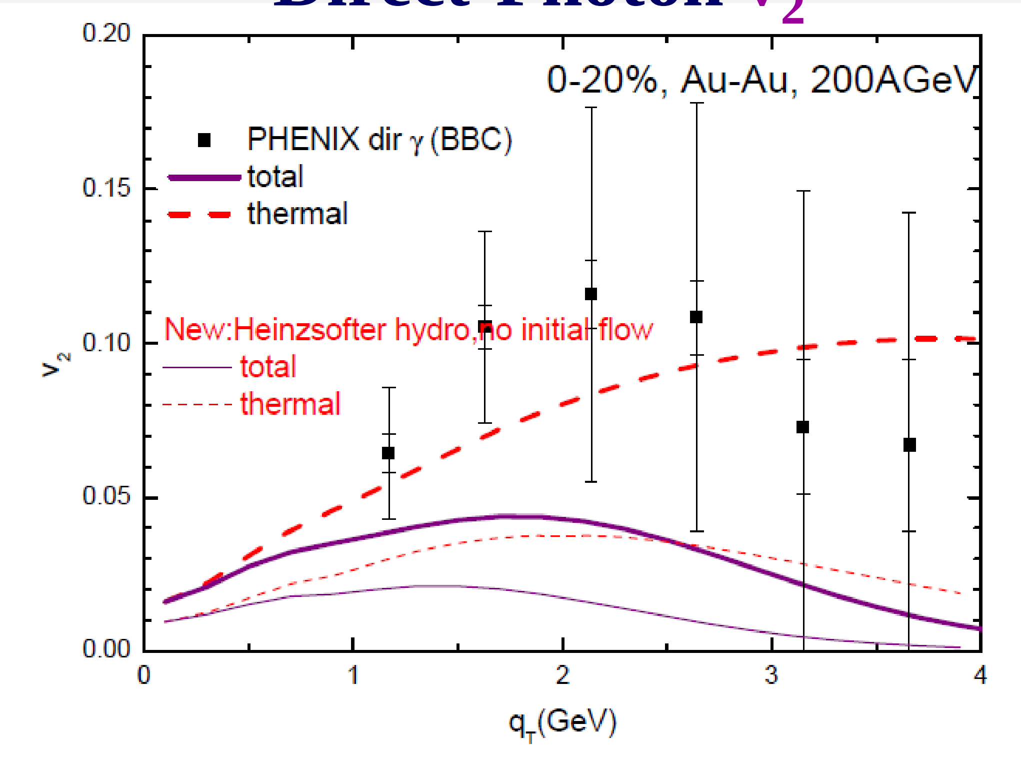
- Thermal radiation at **~ 10%** of cocktail
- fits excess vs. lifetime relation
- large QGP component probe of initial stages?!

3.2 Initial Flow and Thermal Photon-v_2

Bulk Flow Evolution



Direct-Photon v_2

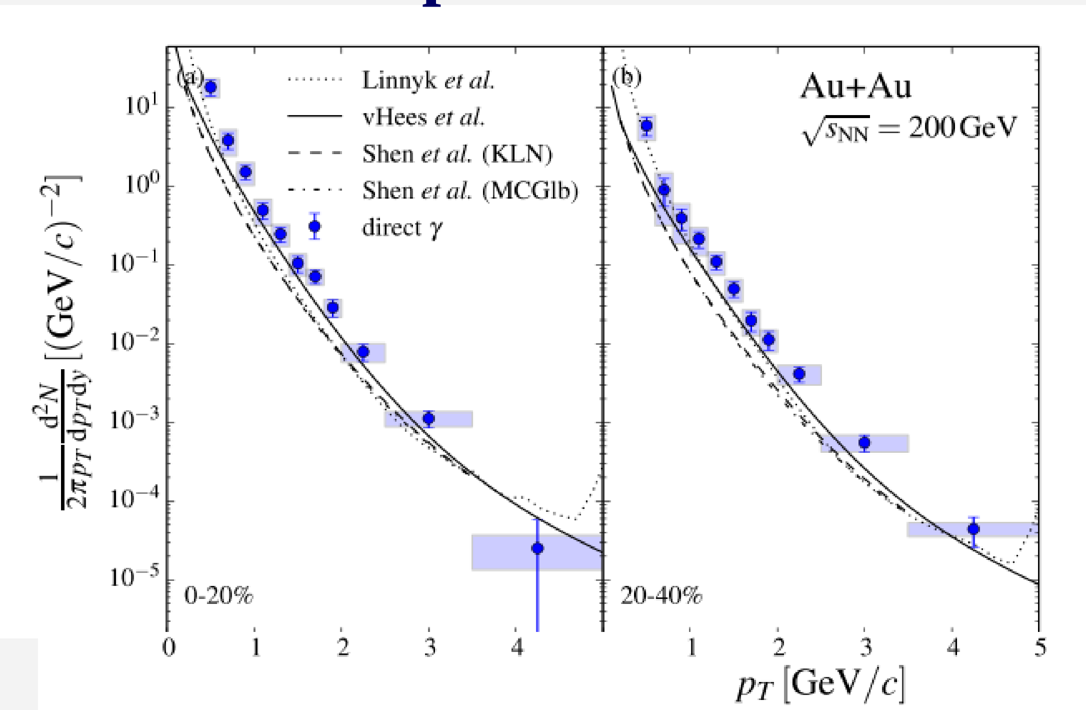


- initial radial flow: - accelerates build-up of bulk v_2
  - produces harder radiation spectra
- largely enhances QGP photon v_2 toward higher q_t

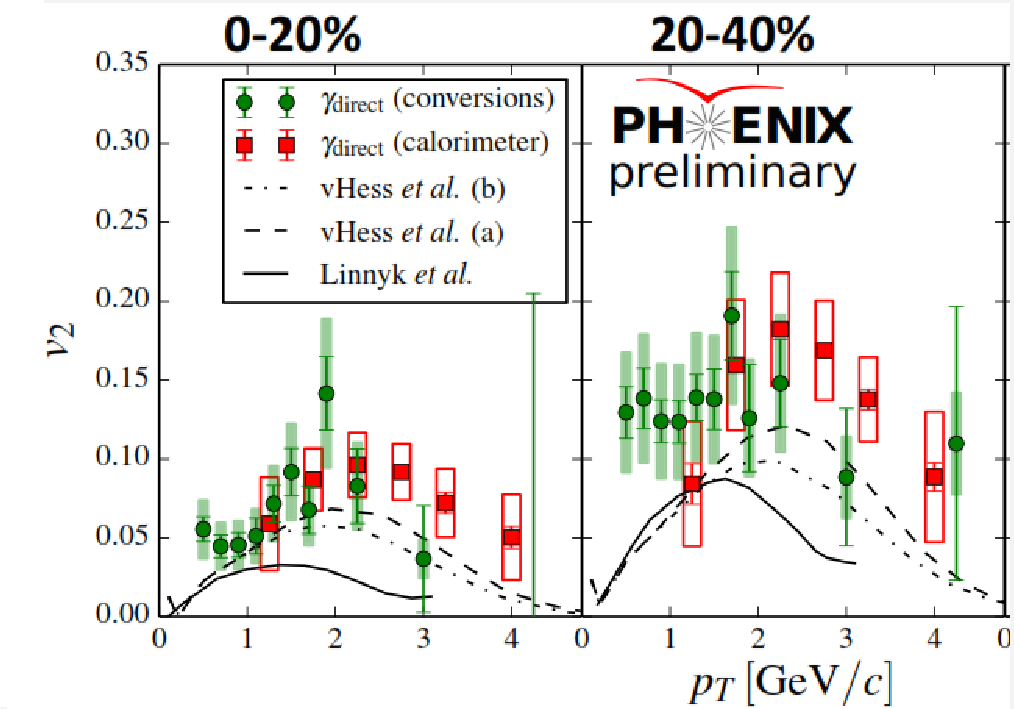
[He et al '14]

3.2.2 Photon "Puzzle"

Spectra



Elliptic Flow



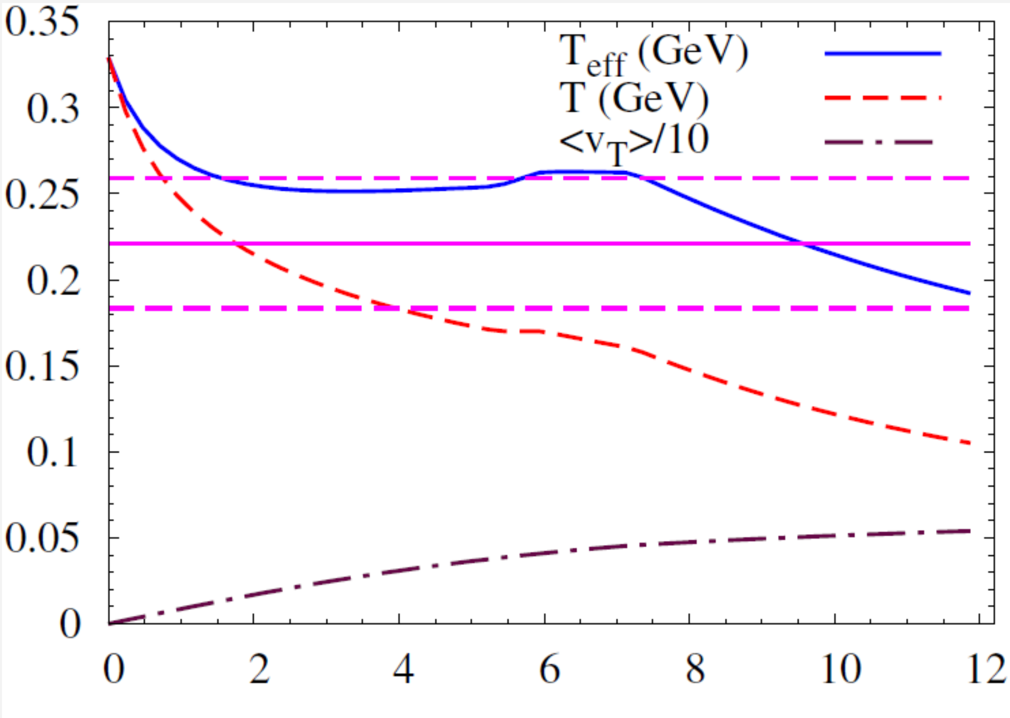
- T_{eff}^{excess} = (220±25) MeV
- flow blue-shift: $T_{eff} \sim T \sqrt{(1+\beta)/(1-\beta)}$ ⇒ T ~ 220/1.35 ~ 160 MeV
- "small" slope + large v_2 suggest **main emission around T_{pc}** [van Hees et al '11]
- other effects …?

4.) Conclusions

- **Versatility of Thermal Dileptons**
  - spectral shape: chiral restoration, degrees of freedom
  - inv.-mass slope: (early) temperature (no blue shift)
  - total yields: fireball lifetime
- **Phenomenology**
  - compatible with chiral restoration (sum rules)
  - probe presence of interacting medium (quarks) in **pA**
  - initial flow impacts photon-/dilepton-$\mathbf{v_2}$

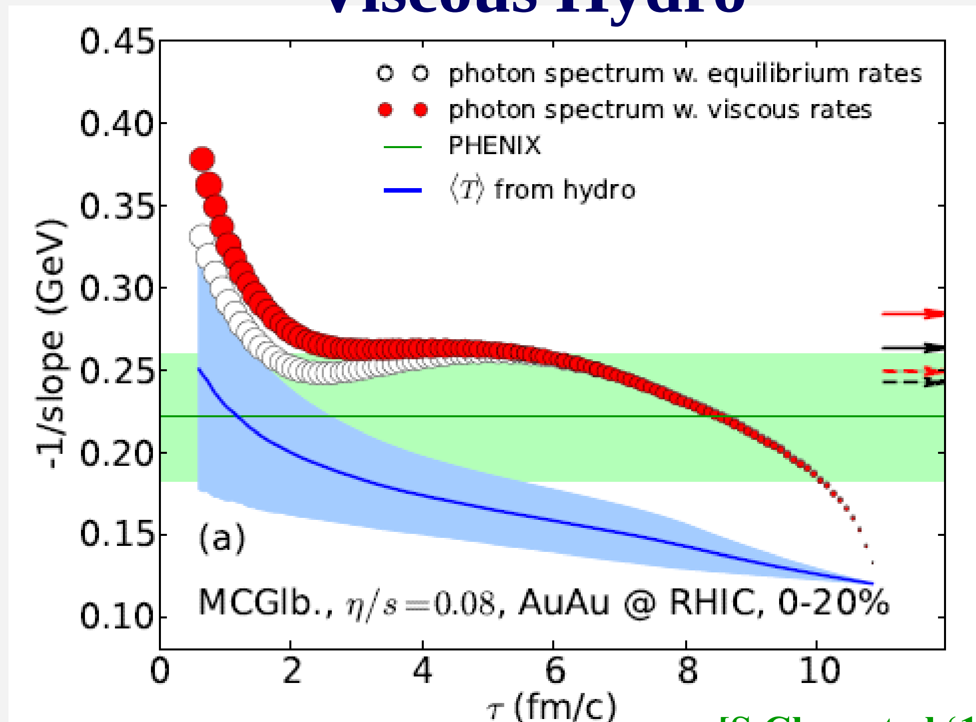
3.2.3 Effective Slopes of Thermal Photons

Thermal Fireball



[van Hees et al '11, '14]

Viscous Hydro



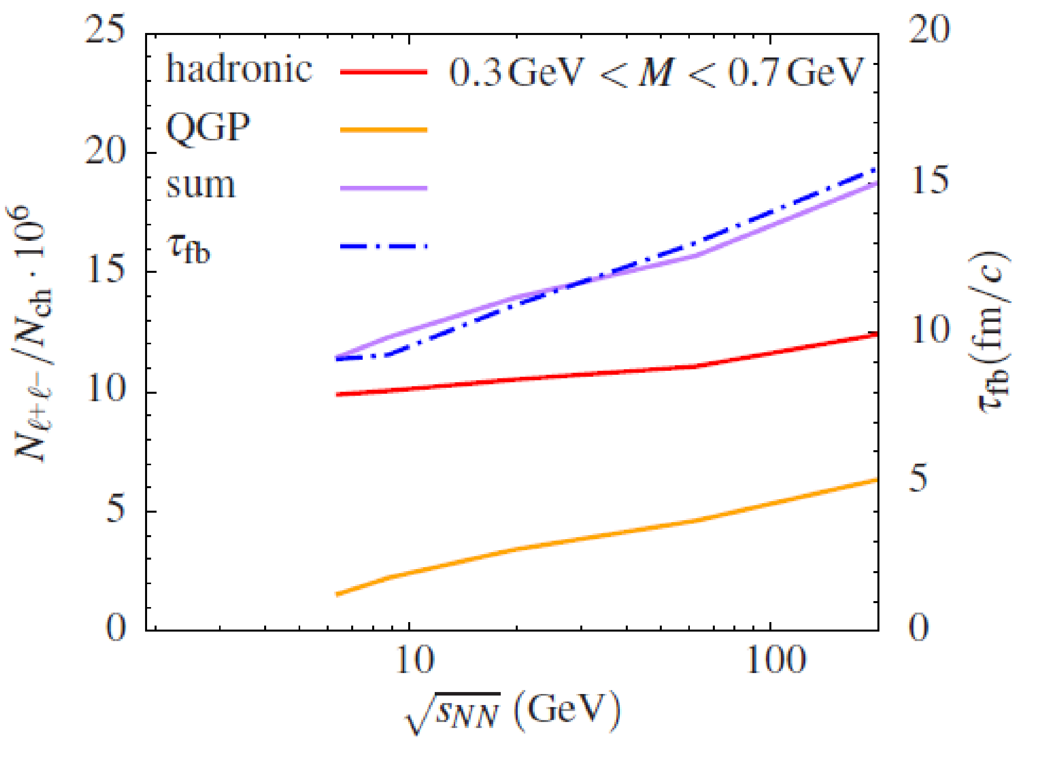
[S.Chen et al '13]

- thermal slope mostly arises from $\mathbf{T \leq T_c}$
- confirmed by hydro
- other mechanisms: glasma BE? Magnetic fields + $\mathbf{U_A(1)}$?

[Liao at al '12, Skokov et al '12,,…]

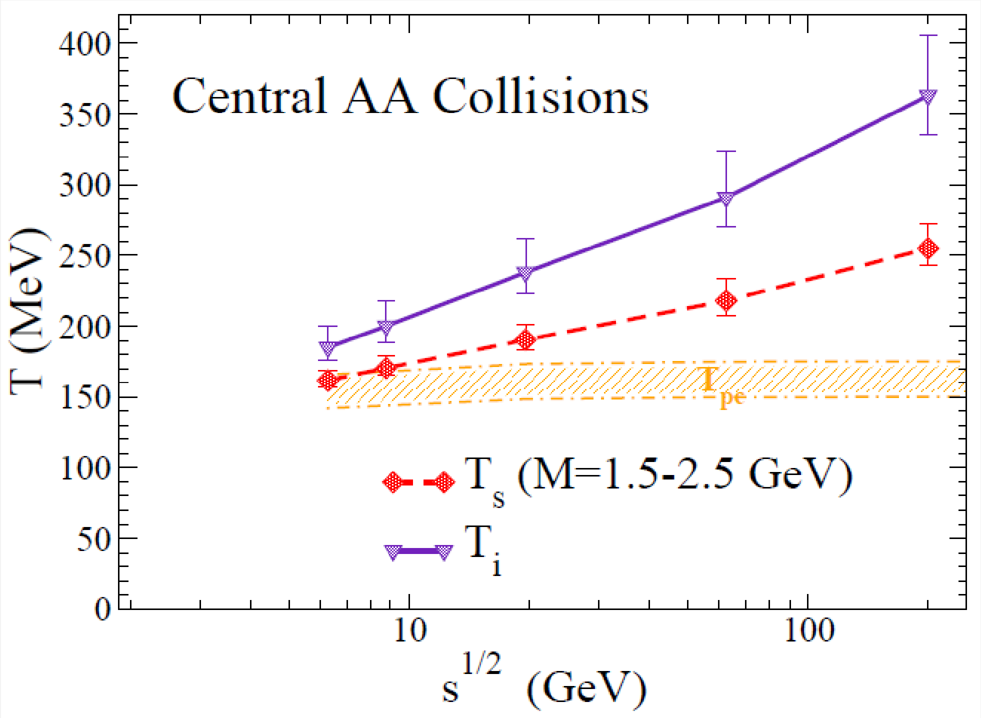
2.3.4 Dilepton Excitation Functions

Low-Mass Excess



- tracks **fireball lifetime**!
  (interacting/radiating medium)

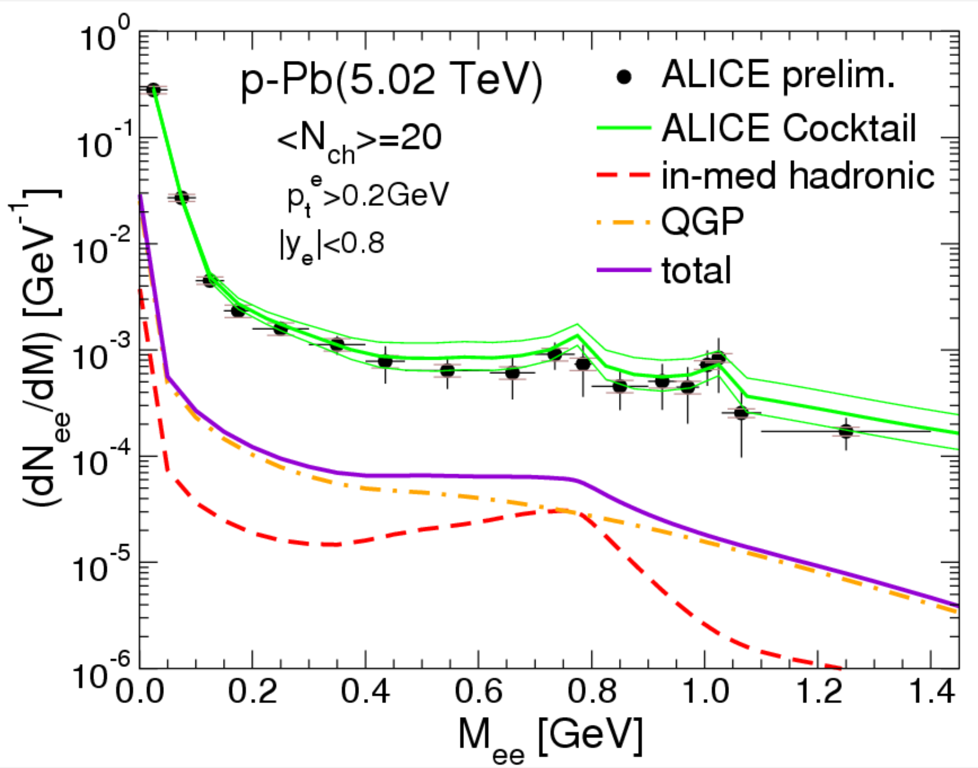
Intermediate-Mass Slope

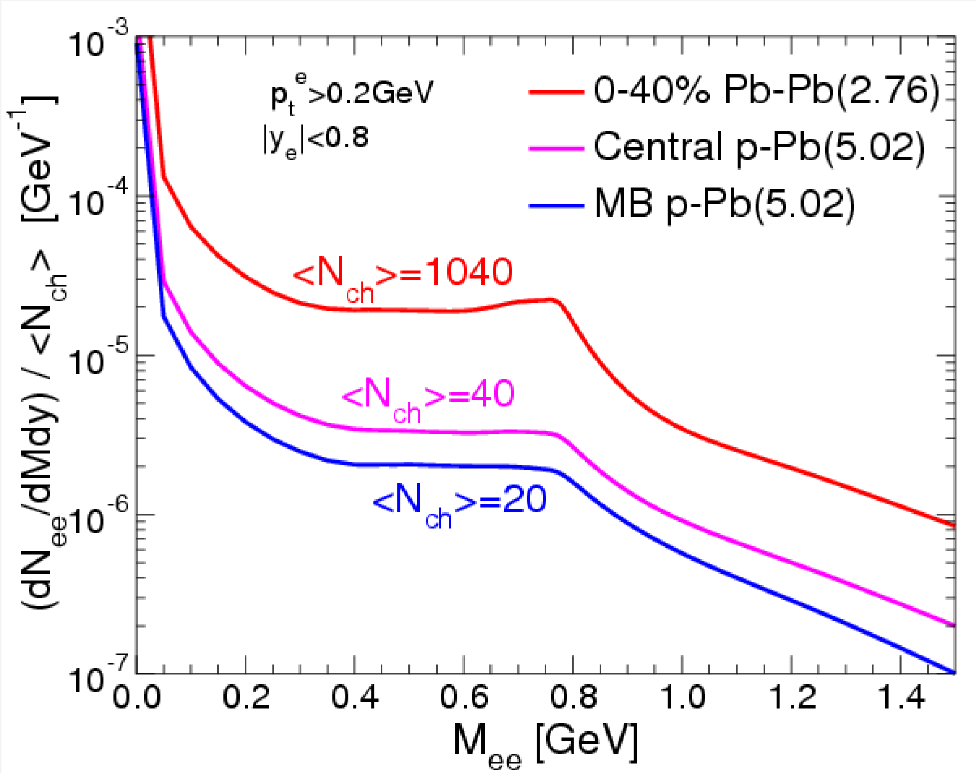


- unique **temperature** measurement

[RR+van Hees '14]

3.1.3 Dilepton Spectra in p-Pb (5.02GeV)

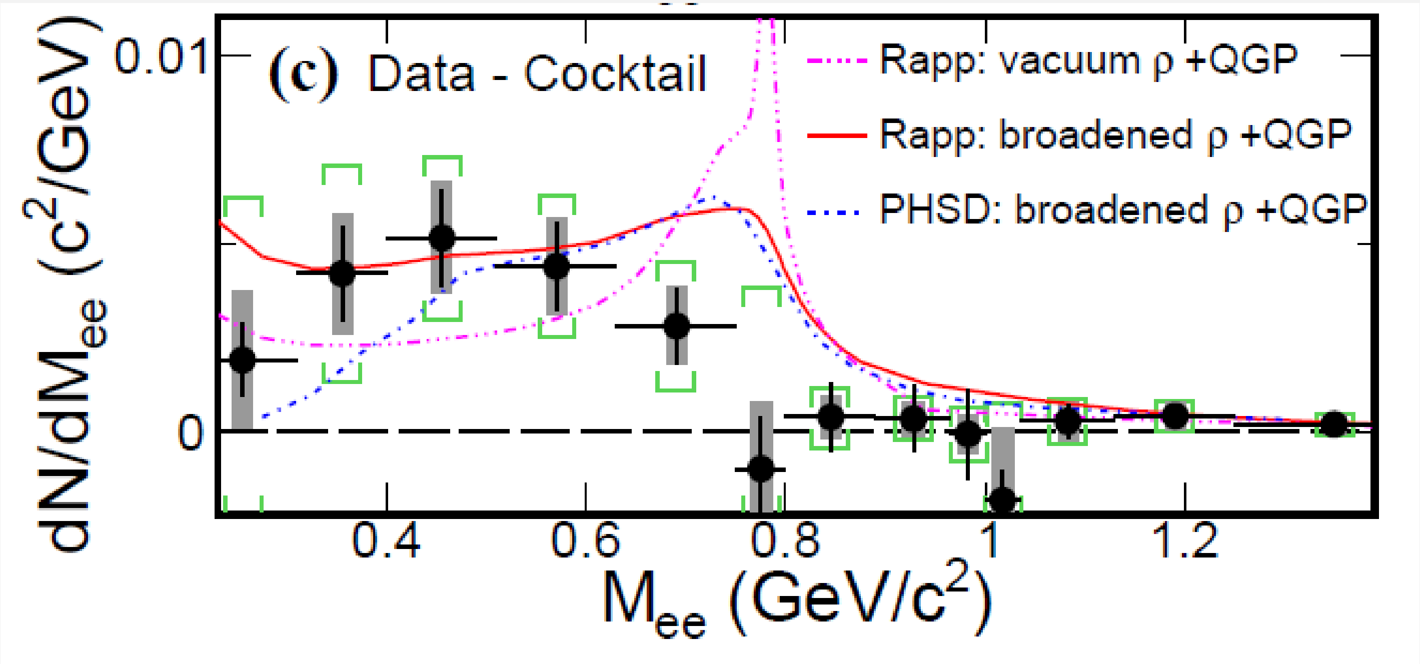




- Thermal radiation at **<10%** of cocktail
- factor **~10** increase in **Pb-Pb**
- fits systematics of excess vs. lifetime relation

4.1 Prospects I: Spectral Shape at $\mu_B \sim 0$

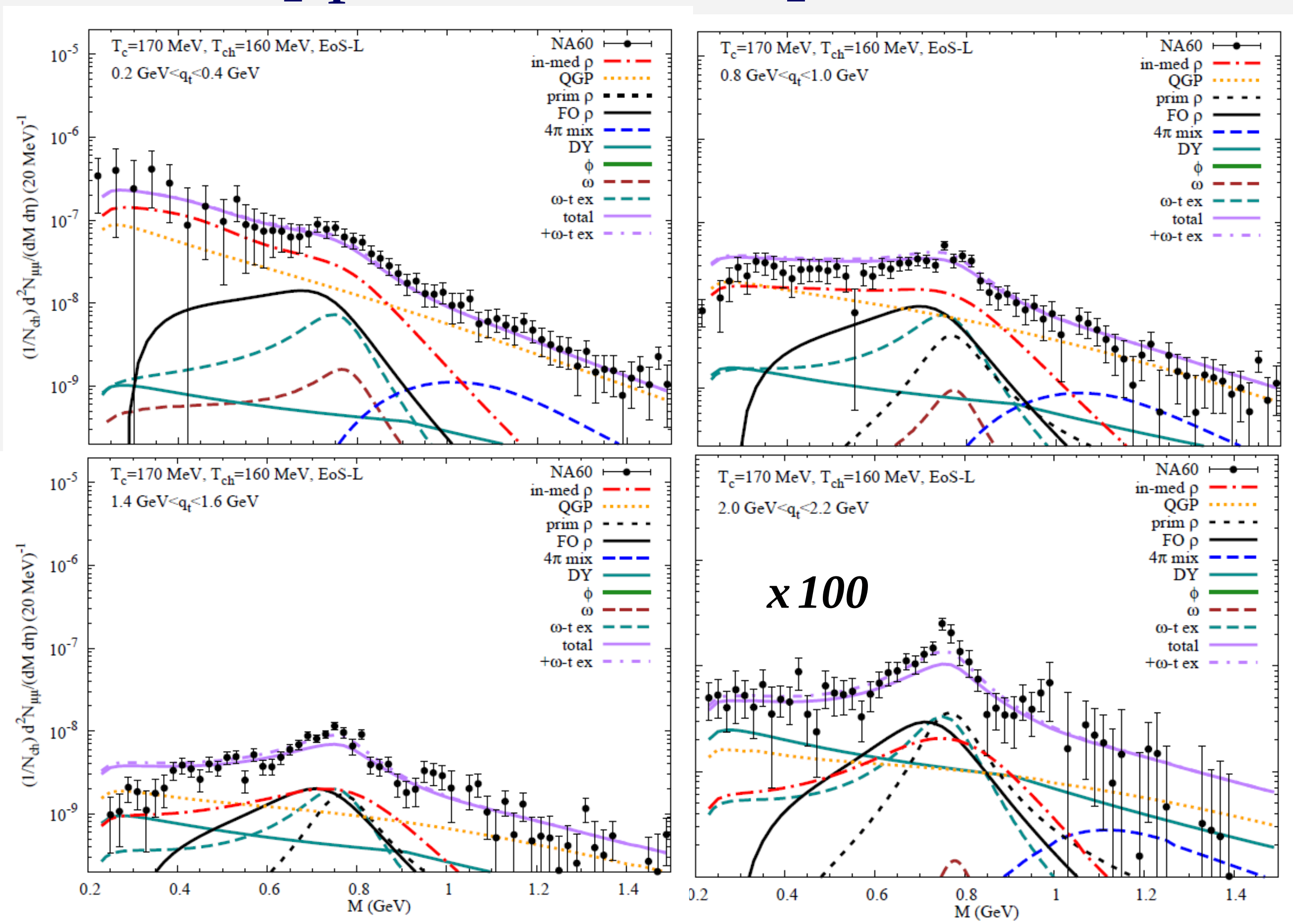
STAR Excess Dileptons [STAR '14]



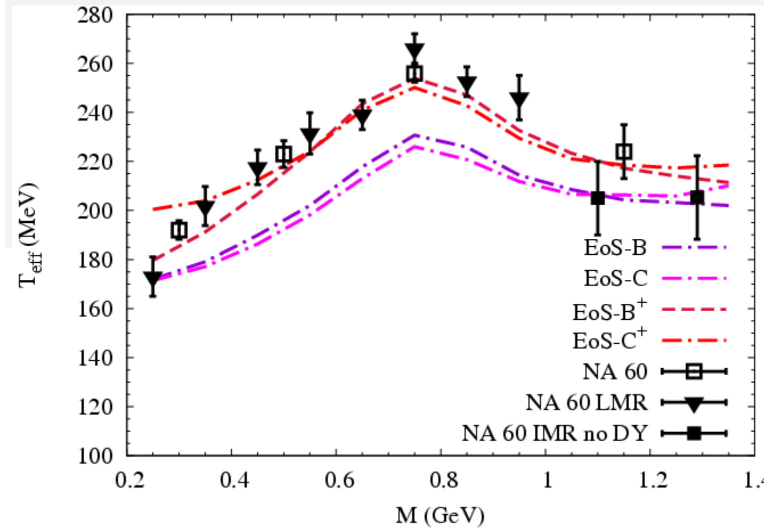
- rather different spectral shapes compatible with data
- QGP contribution?

2.2 Transverse-Momentum Dependence

p_T -Sliced Mass Spectra



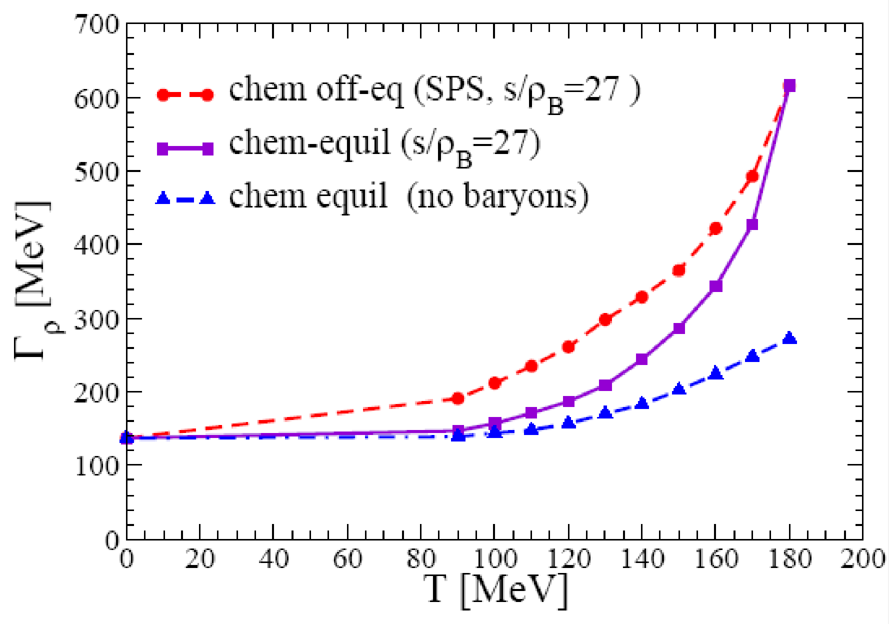
m_T -Slopes

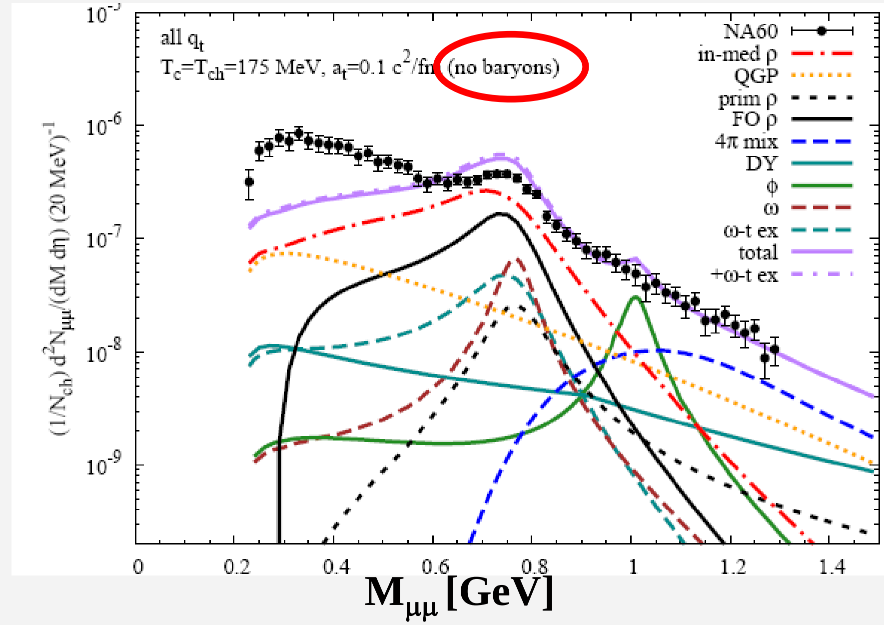


- spectral shape as function of pair-p_T
- entangled with transverse flow (**barometer**)

4.1.2 Sensitivity to Spectral Function

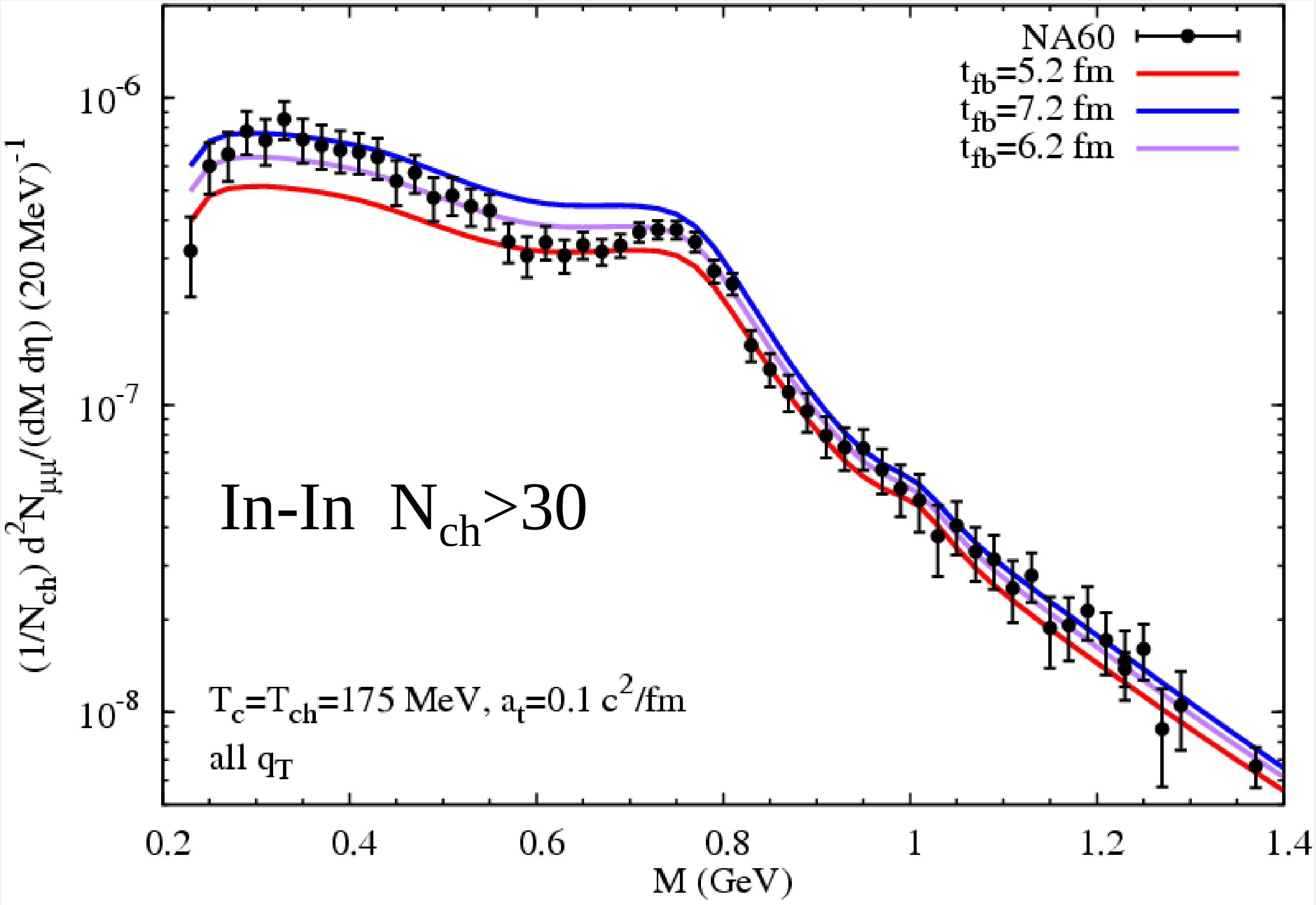
In-Medium ρ-Meson Width





- avg. Γ_ρ(T~150MeV) ~ 370 MeV ⇒ Γ_ρ (T~T_c) ≈ 600 MeV → m_ρ
- driven by (anti-) baryons

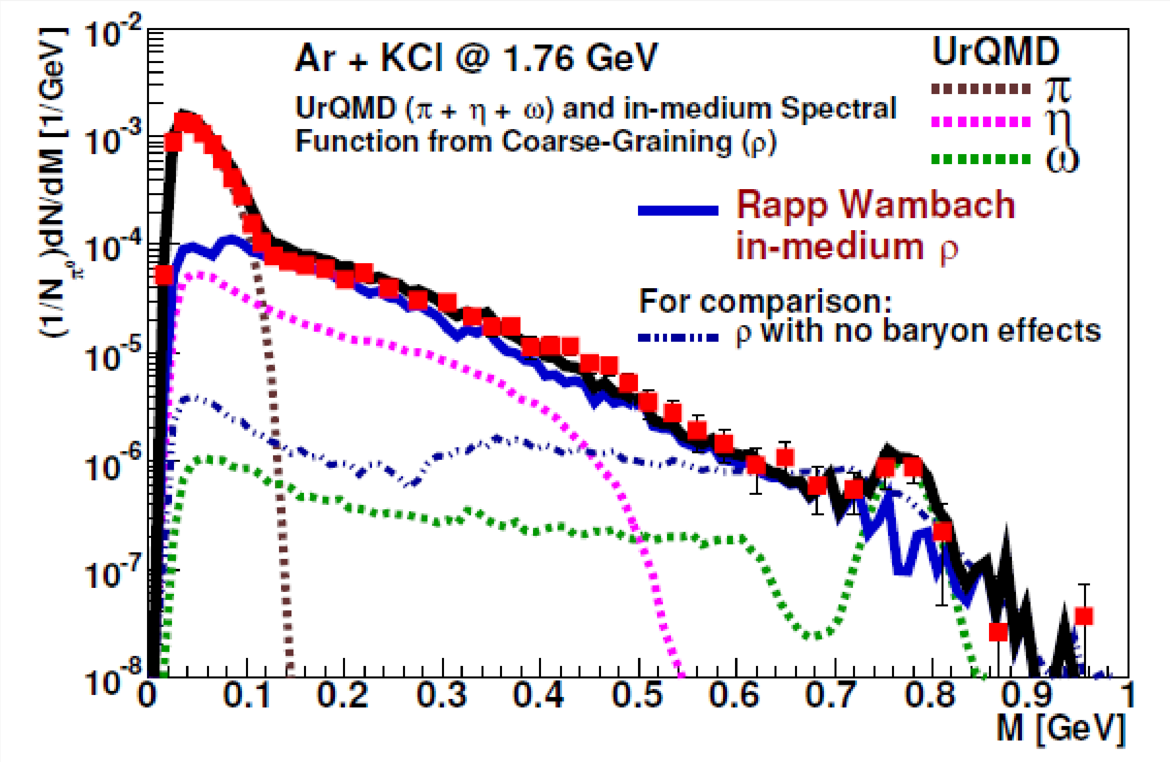
4.2 Low-Mass Dileptons: Chronometer

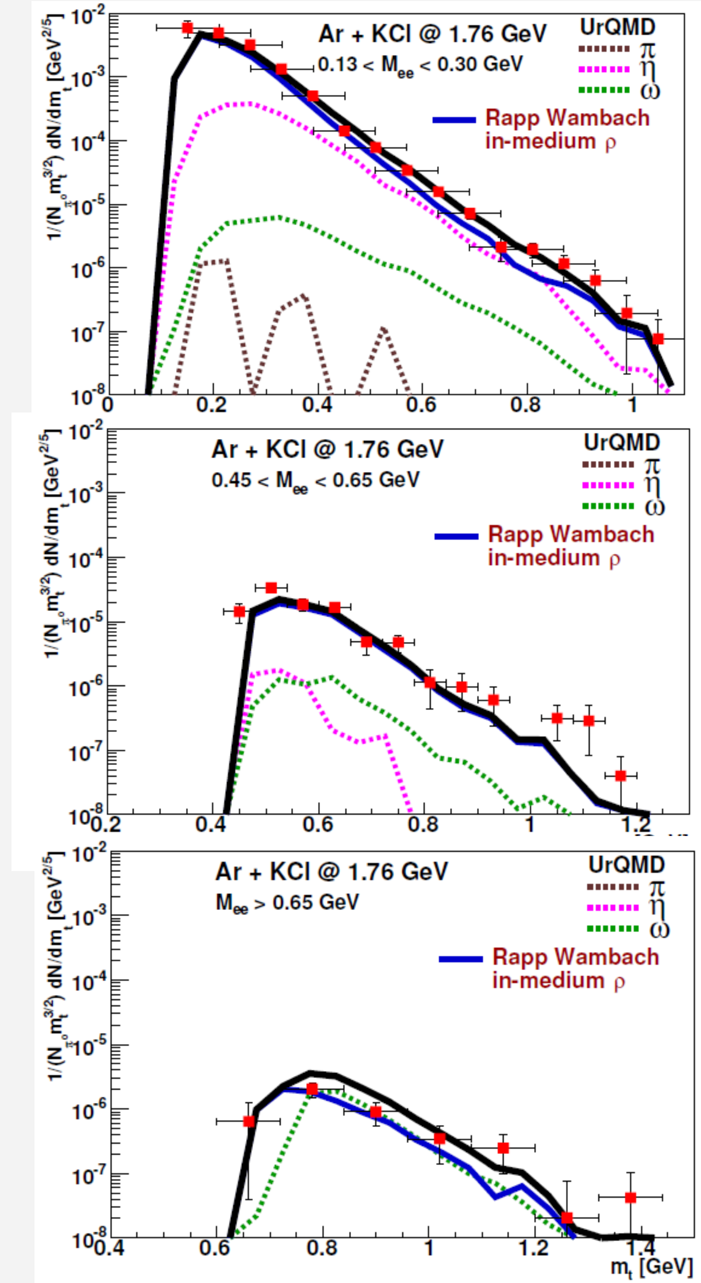


- first “explicit” measurement of interacting-fireball **lifetime**:

  $\tau_{FB} \approx (7\pm1)$ **fm/c**

2.4 Low-Mass e^+e^- at HADES (2.63 GeV)



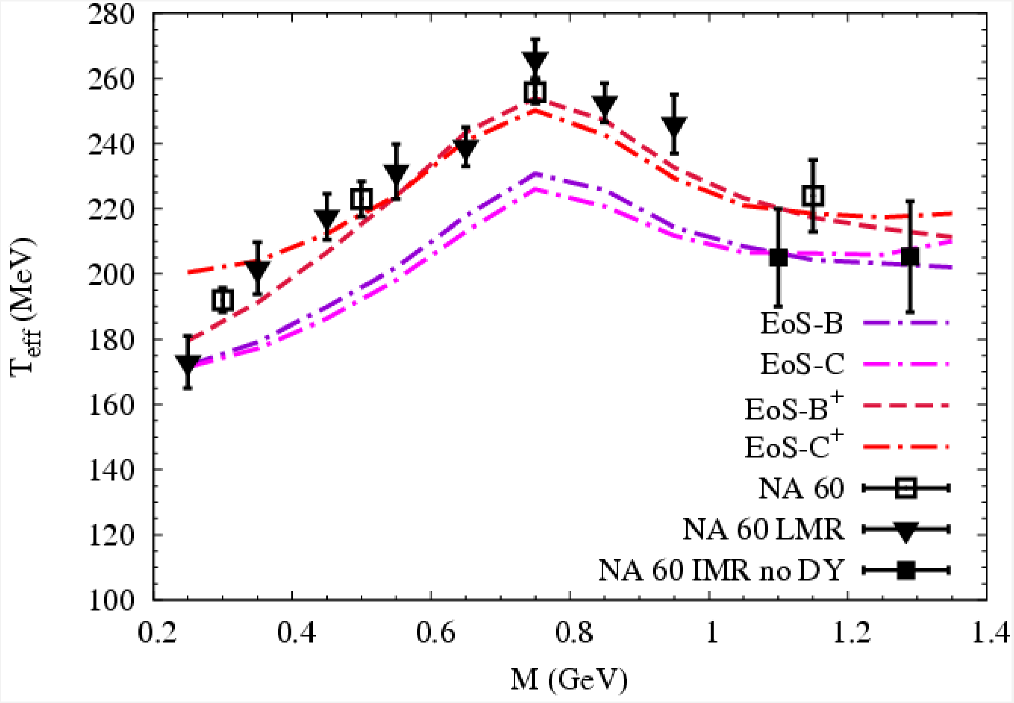


[Endres,van Hees+Bleicher, in prep]

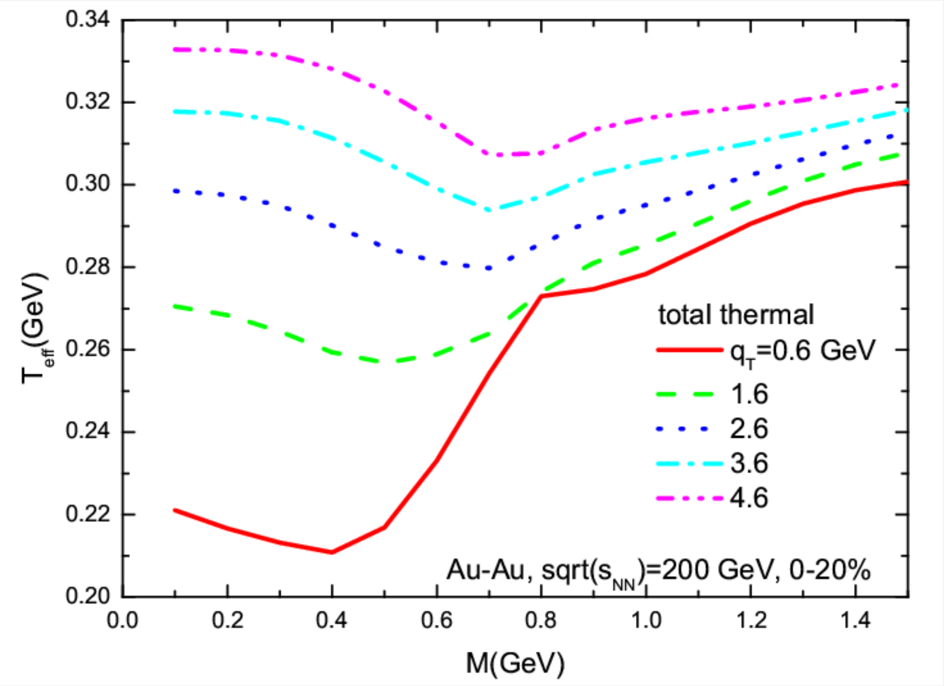
- Thermal rates folded over **coarse-grained UrQMD** medium evolution
- good description in **(M,q_t)**
- data well beyond kinematic limit (**0.75GeV**)!

4.5 QGP Barometer: Blue Shift vs. Temperature

SPS



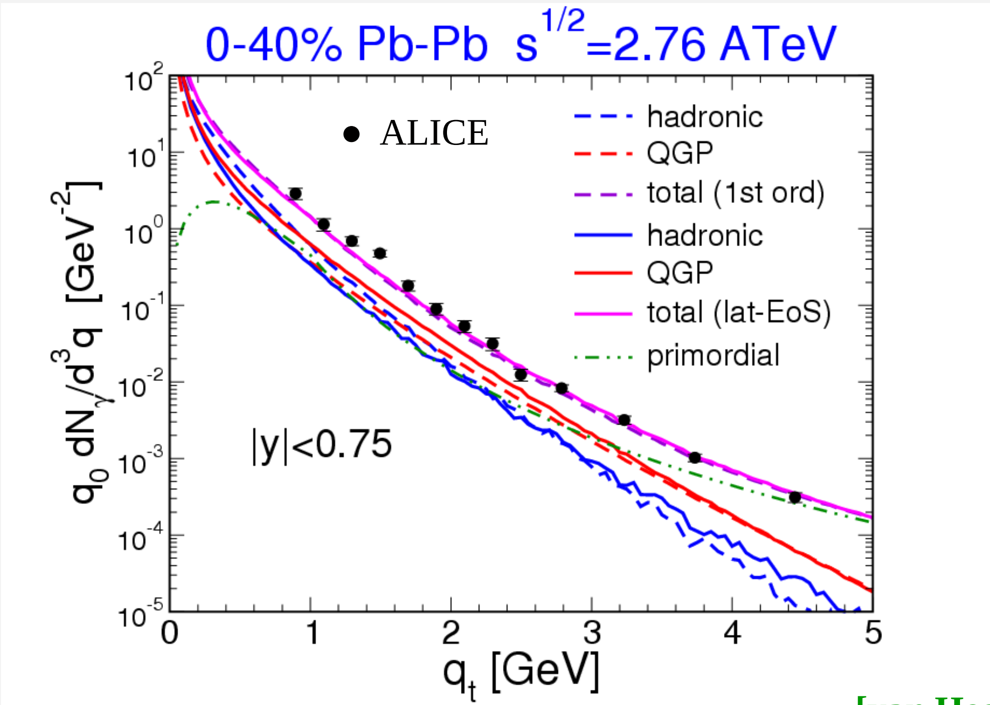
RHIC



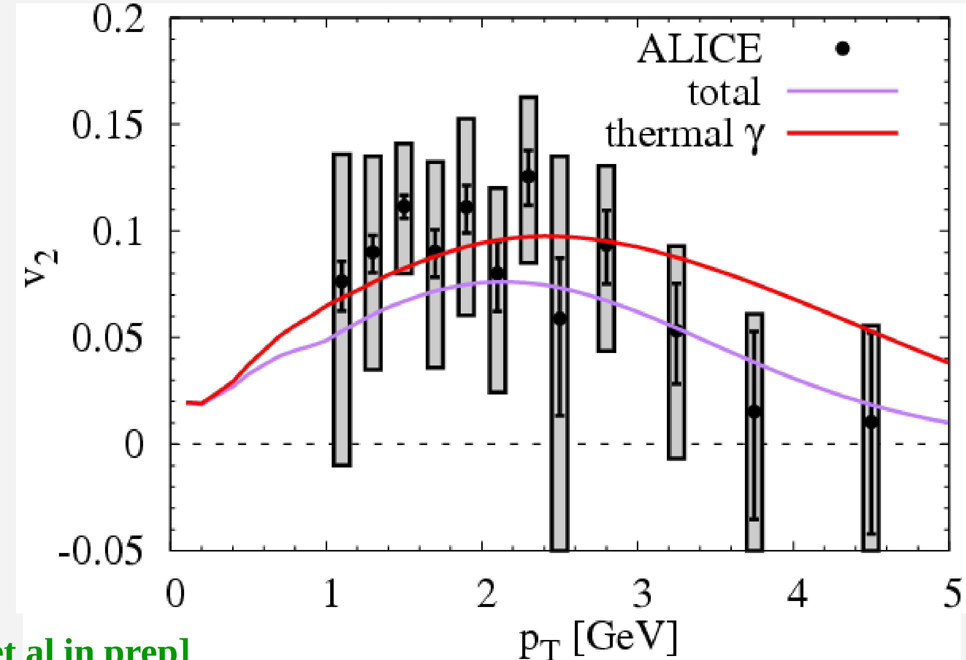
- QGP-flow driven increase of **$T_{eff} \sim T + M\,(\beta_{flow})^2$** at **RHIC**
- high **p_t**: high **T** wins over high-flow ρ's → minimum (opposite to **SPS**!)
- saturates at "true" early temperature **T_0** (no flow)

3.3.3 Direct Photons at LHC

Spectra



Elliptic Flow



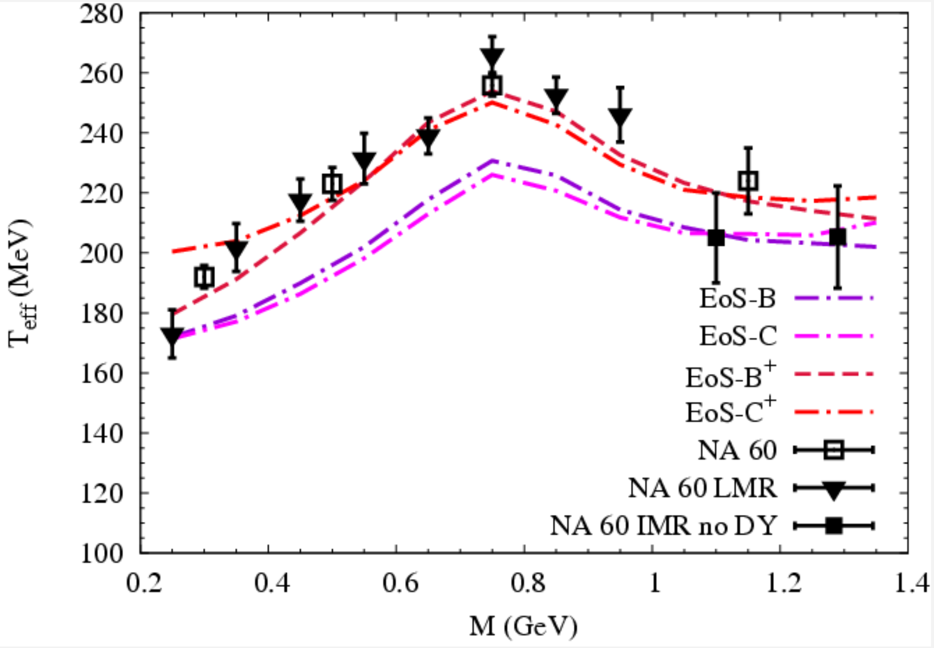
[van Hees et al in prep]

- similar to RHIC results
- non-perturbative photon emission rates around T_{pc}?

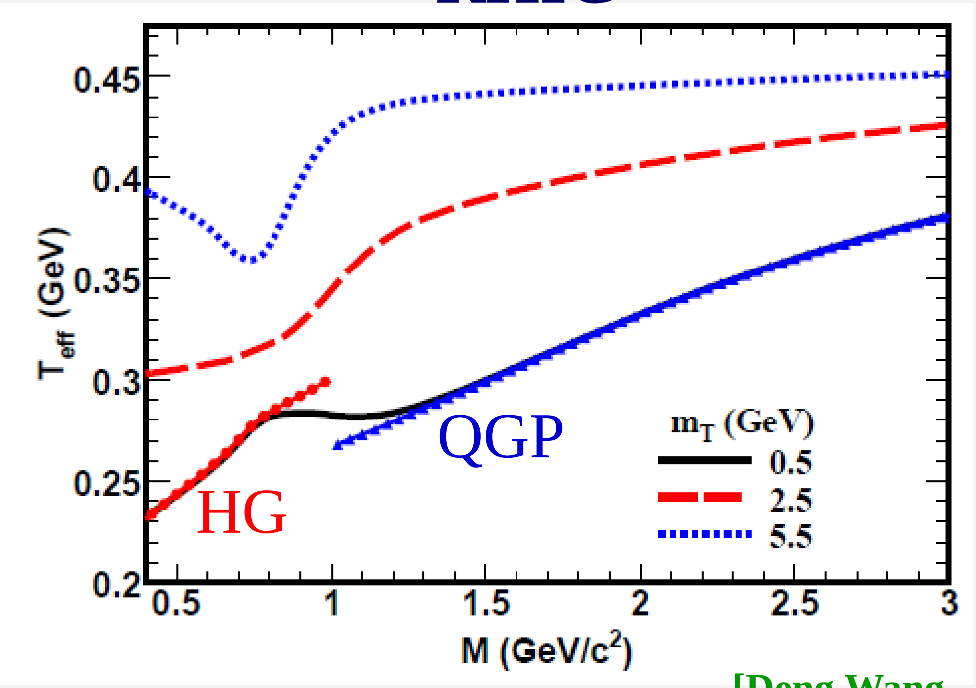
3.1.2 Transverse-Momentum Spectra: Baro-meter

Effective Slope Parameters

SPS



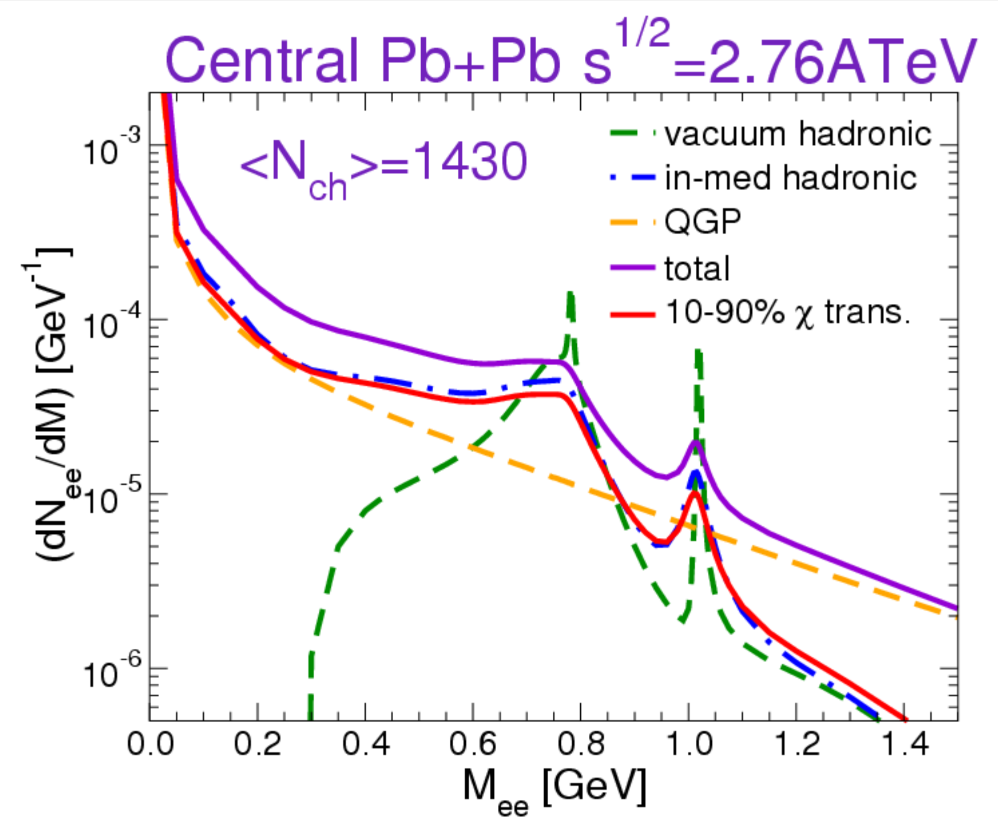
RHIC

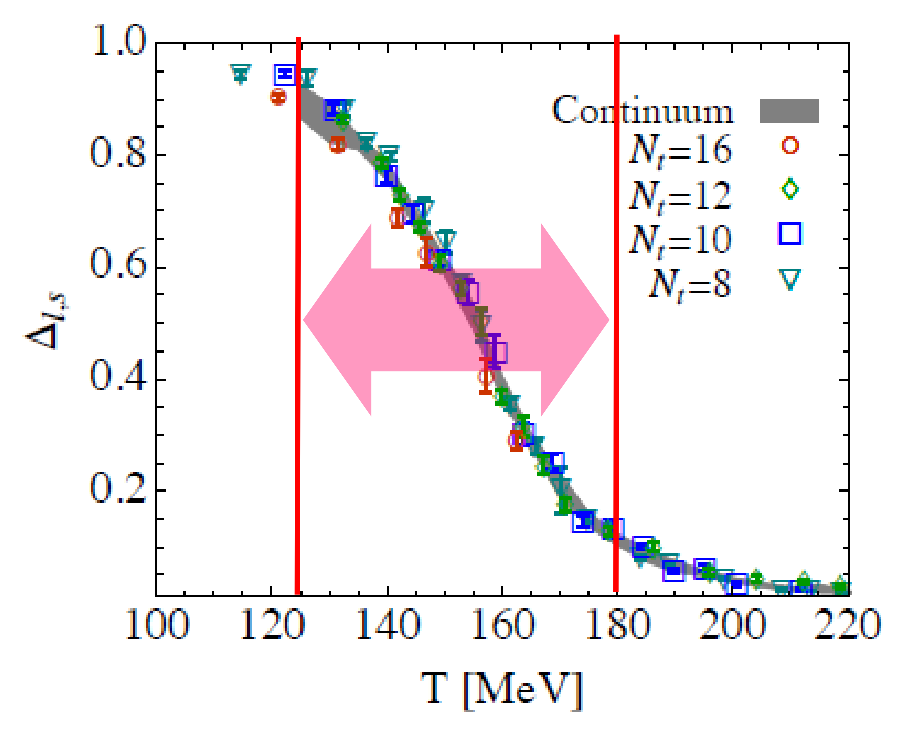


[Deng,Wang, Xu+Zhuang '11]

- qualitative change from SPS to RHIC: flowing QGP
- true temperature "shines" at large $\mathbf{m_T}$

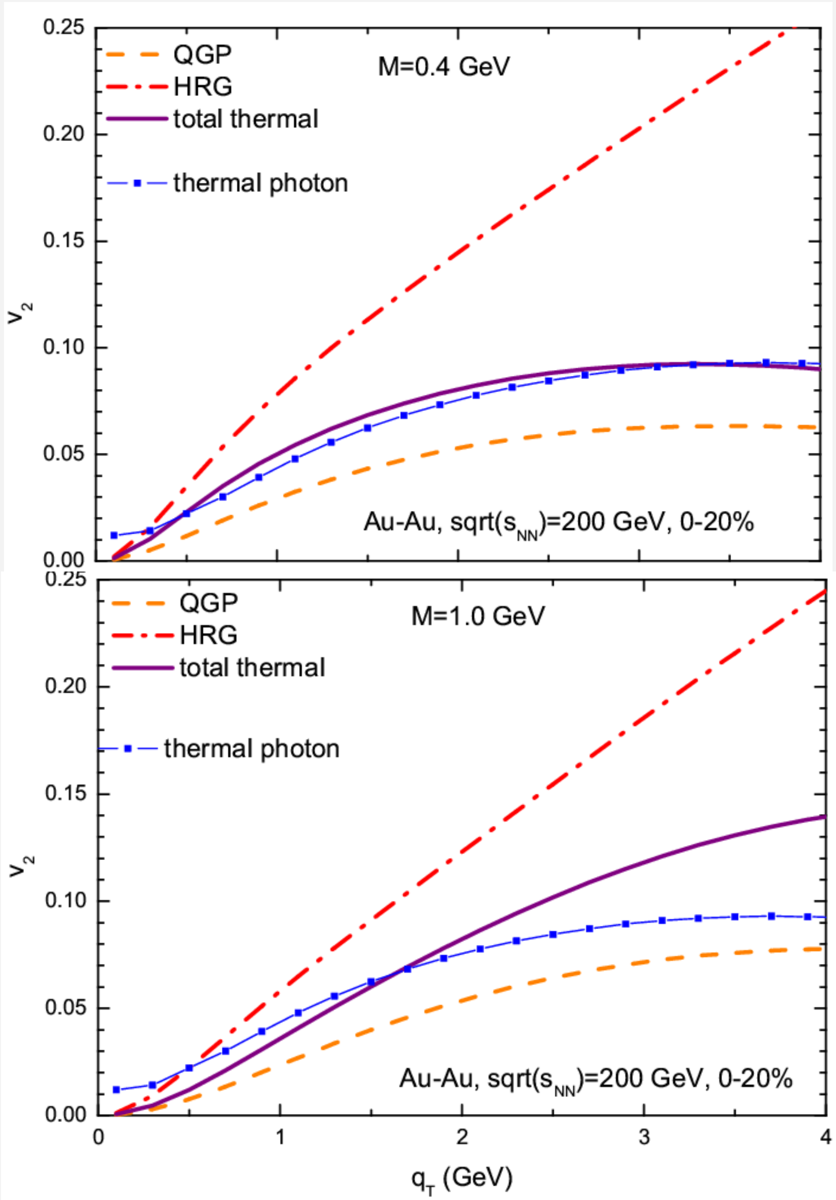
5.2 Chiral Restoration Window at LHC

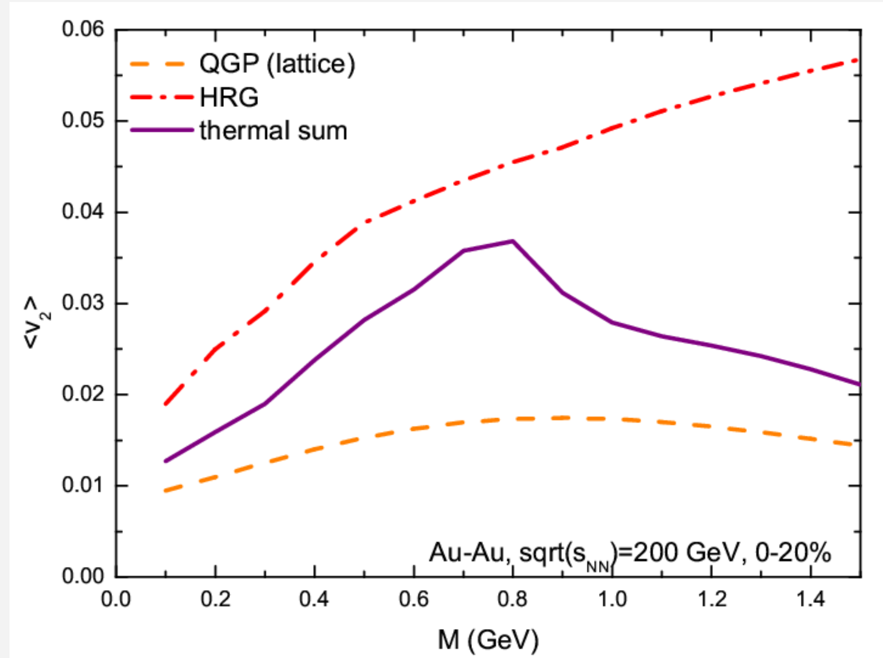




- low-mass spectral shape in chiral restoration window:
  ~60% of thermal low-mass yield in "chiral transition region"
  (T=125-180MeV)
- enrich with (low-) $\mathbf{p_t}$ cuts

4.4 Elliptic Flow of Dileptons at RHIC



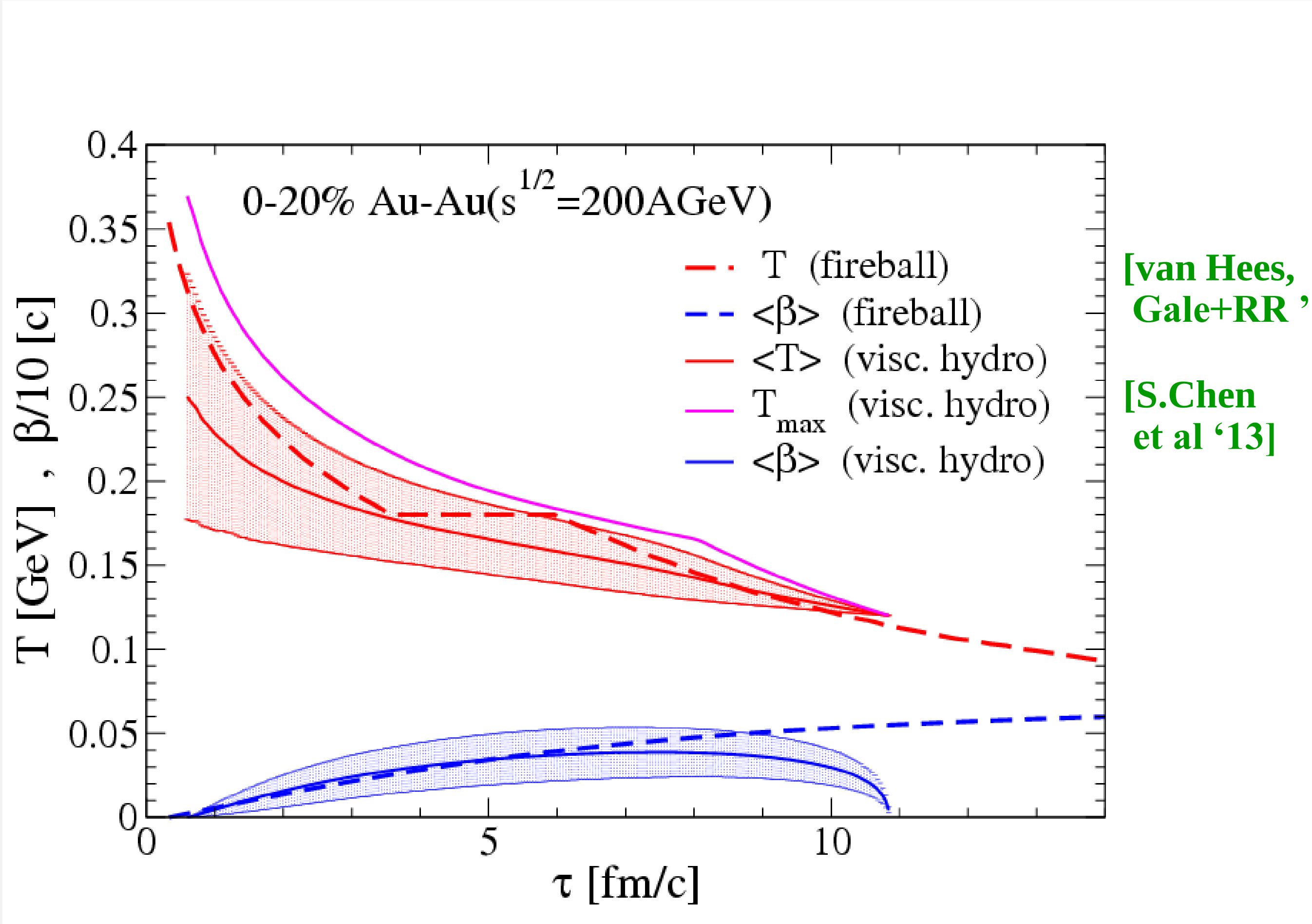


- maximum structure due to late ρ decays

[He et al '12]

[Chatterjee et al '07, Zhuang et al '09]

3.3.2 Fireball vs. Viscous Hydro Evolution



[van Hees, Gale+RR '11]

[S.Chen et al '13]

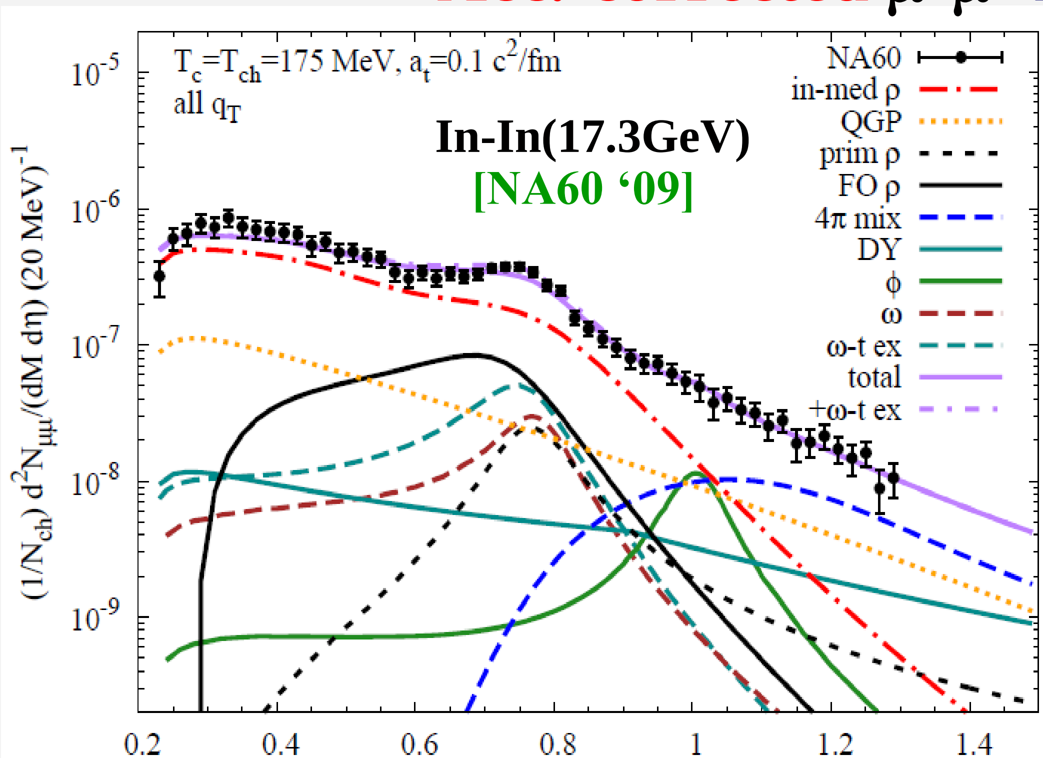
- very similar!

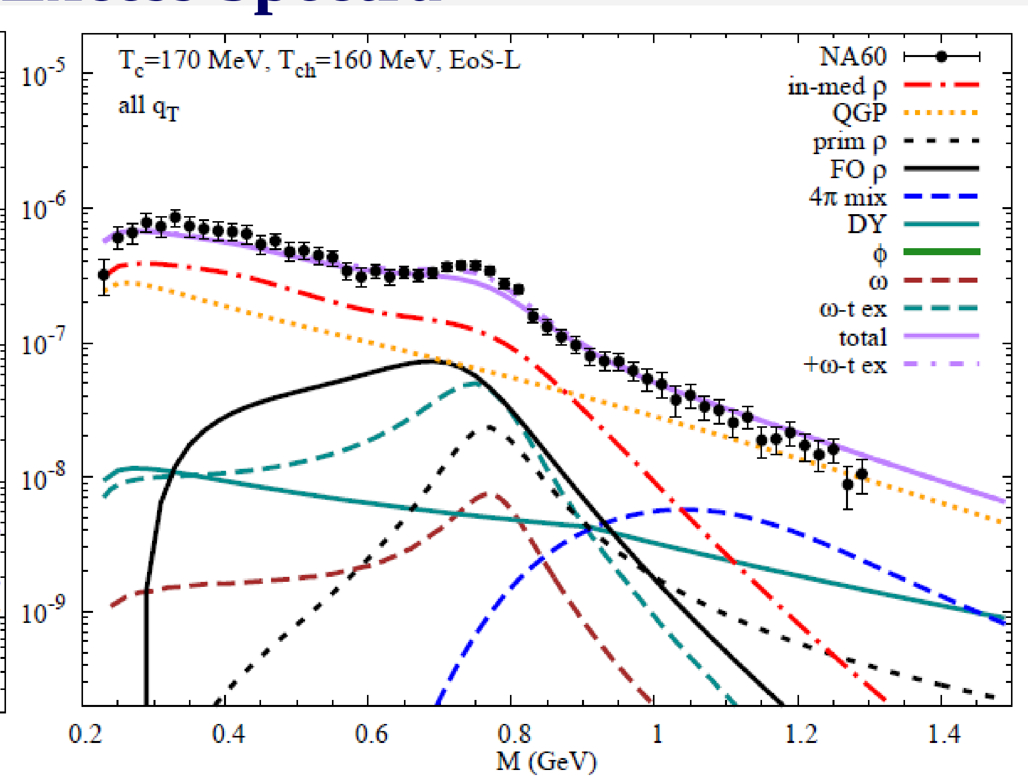
2.3 Dilepton Rates vs. Exp.: NA60 “Spectrometer”

• **Evolve rates over fireball expansion:**

$$\frac{dN^{therm}_{\mu\mu}}{dM} = \int_{\tau_0}^{\tau_{fo}} d\tau V_{FB}(\tau) \int \frac{M\, d^3q}{q_0} \frac{dR^{therm}_{\mu\mu}}{d^4q}$$

Acc.-corrected $\mu^+\mu^-$ Excess Spectra





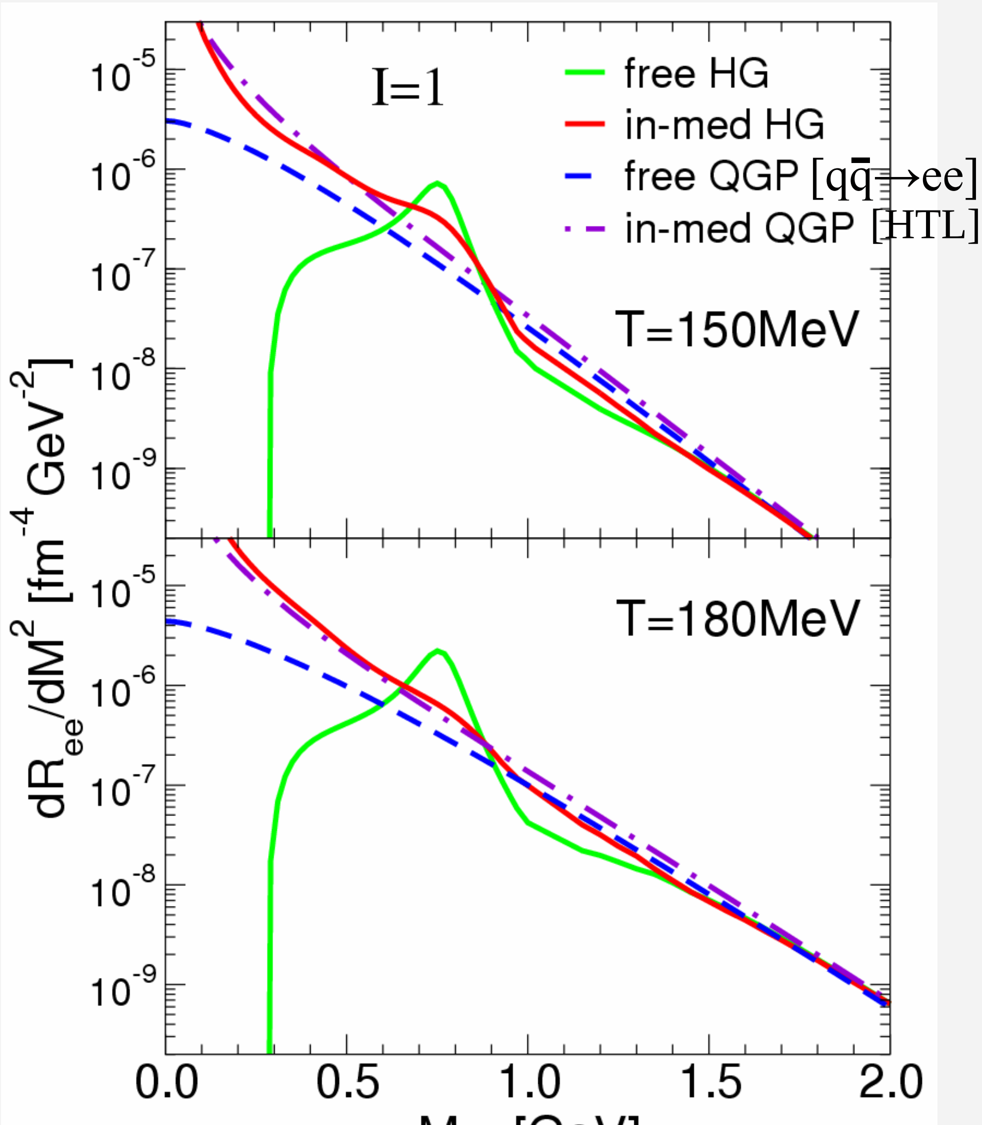
[van Hees+RR ’08]

$M_{\mu\mu}$ [GeV]

• **invariant-mass spectrum directly reflects thermal emission rate!**

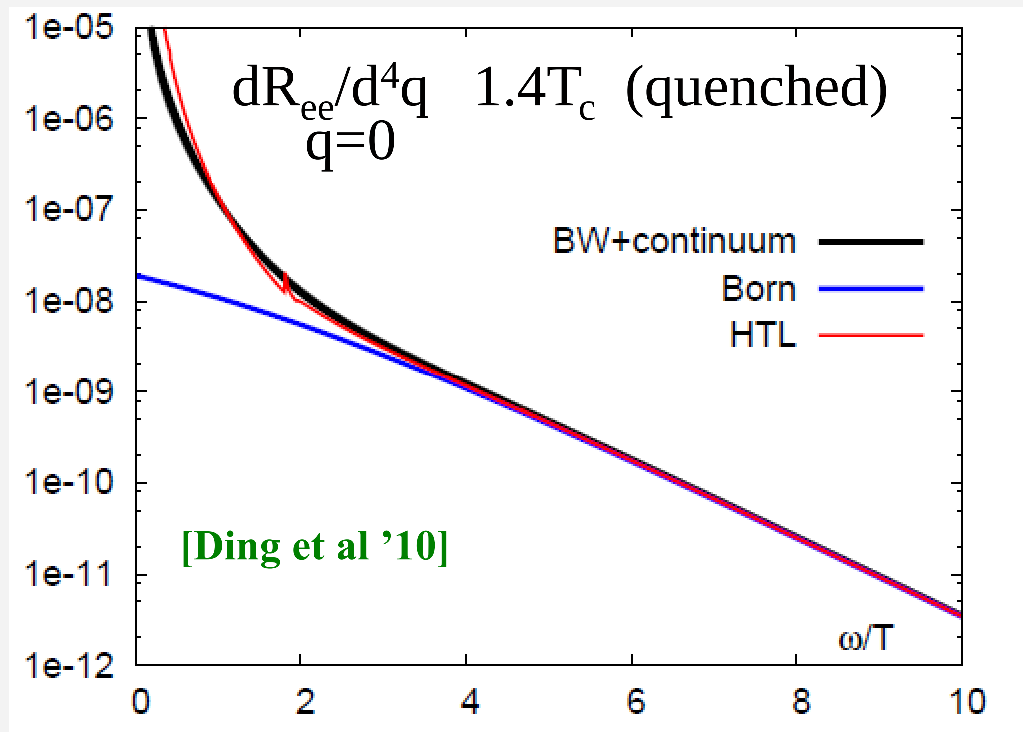
2.2 Dilepton Rates: Hadronic - Lattice - Perturbative

$dR_{ee}/dM^2 \sim \int d^3q \;\; f^B(q_0;T)$ **Im Π_{em}**

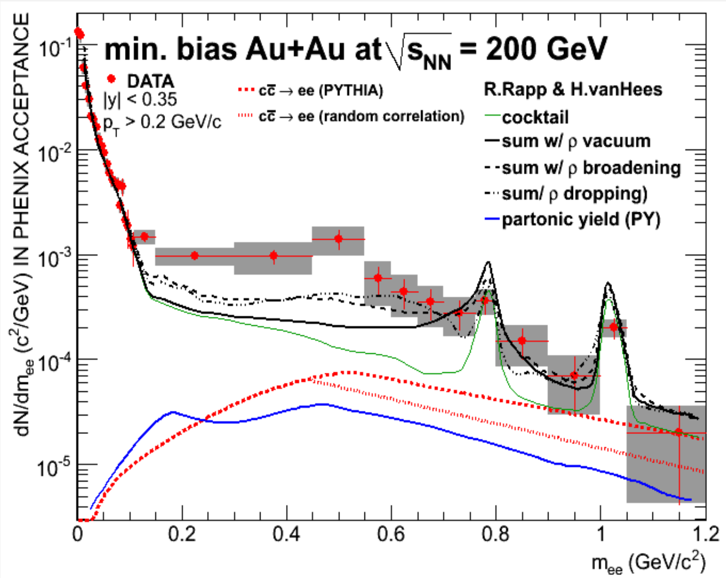


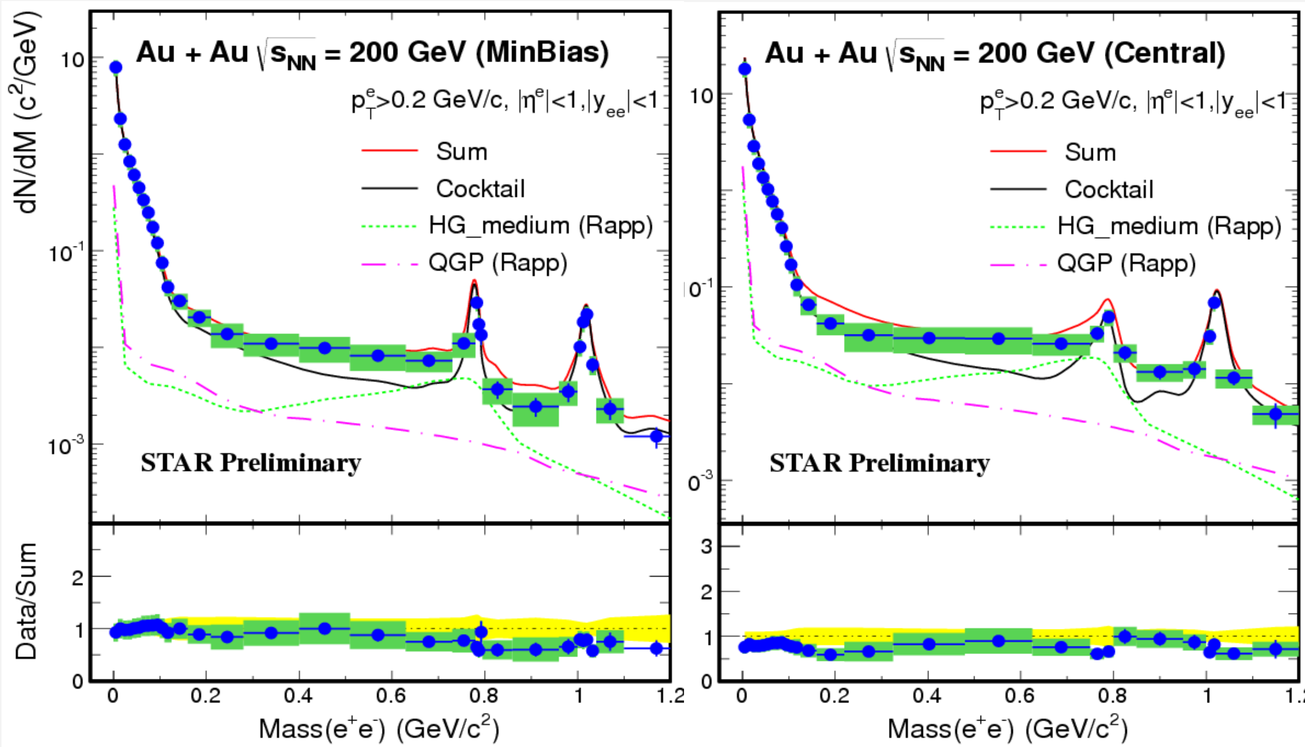
[RR,Wambach et al '99]

- **continuous rate through T_{pc}**
- **3-fold "degeneracy" toward ~T_{pc}**



4.2 Low-Mass e^+e^- at RHIC: PHENIX vs. STAR

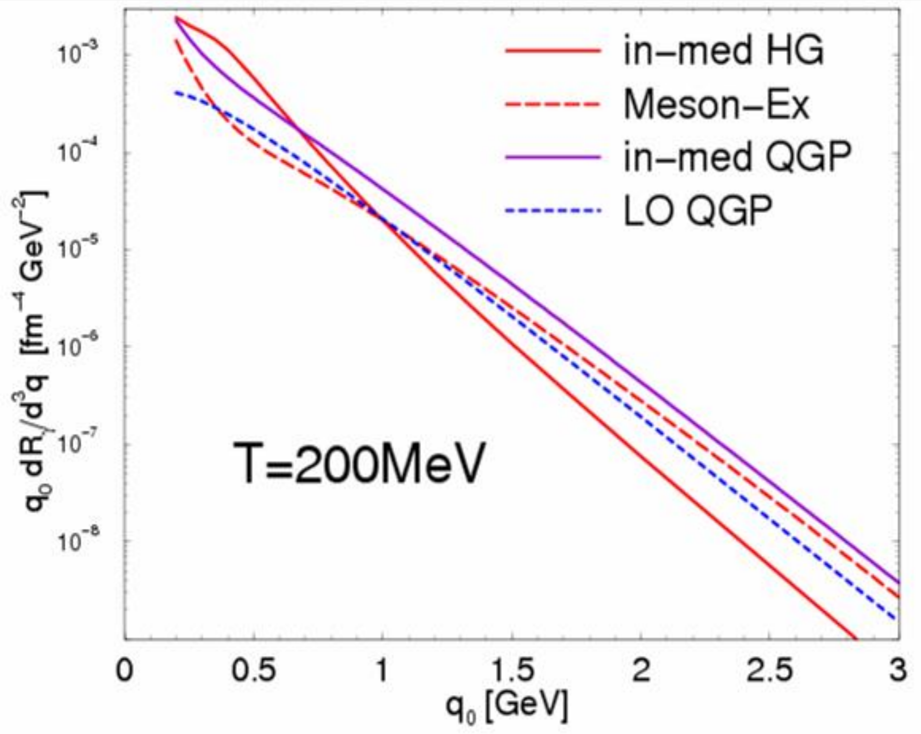




- **PHENIX** enhancement (central!) not accounted for by theory
- **STAR** data ok with theory (charm?!)

4.3.2 Revisit Ingredients

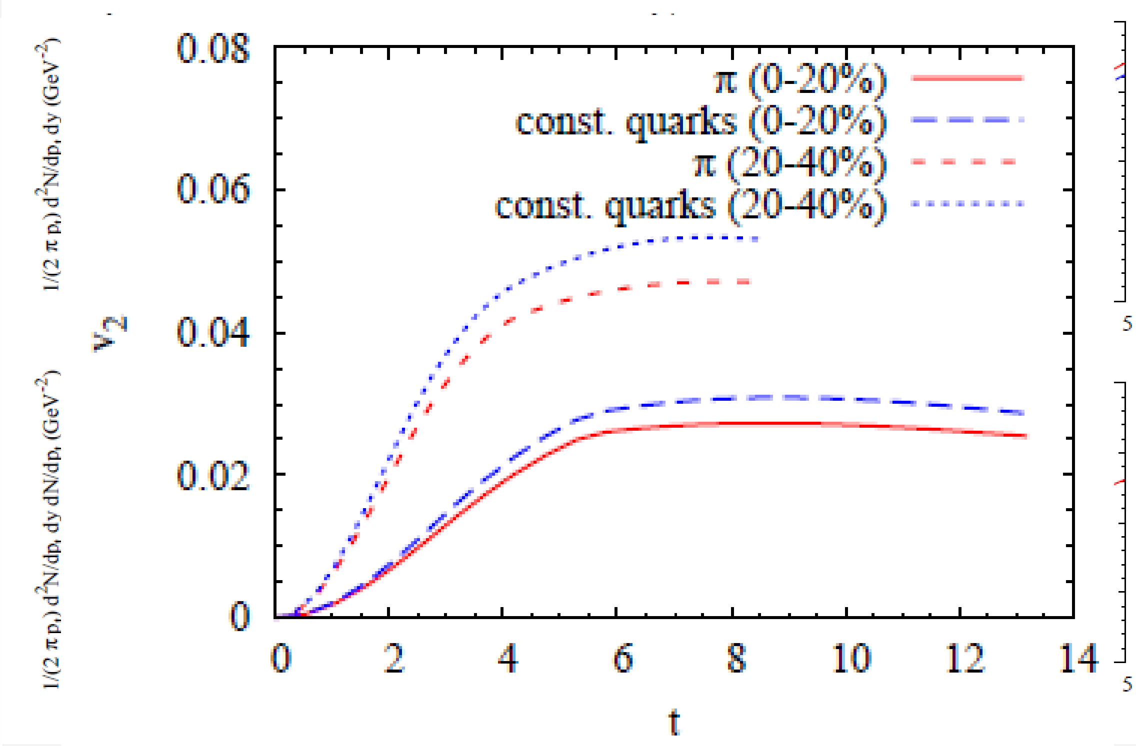
Emission Rates



- Hadron - QGP continuity!
- conservative estimates…

[Turbide et al ’04]

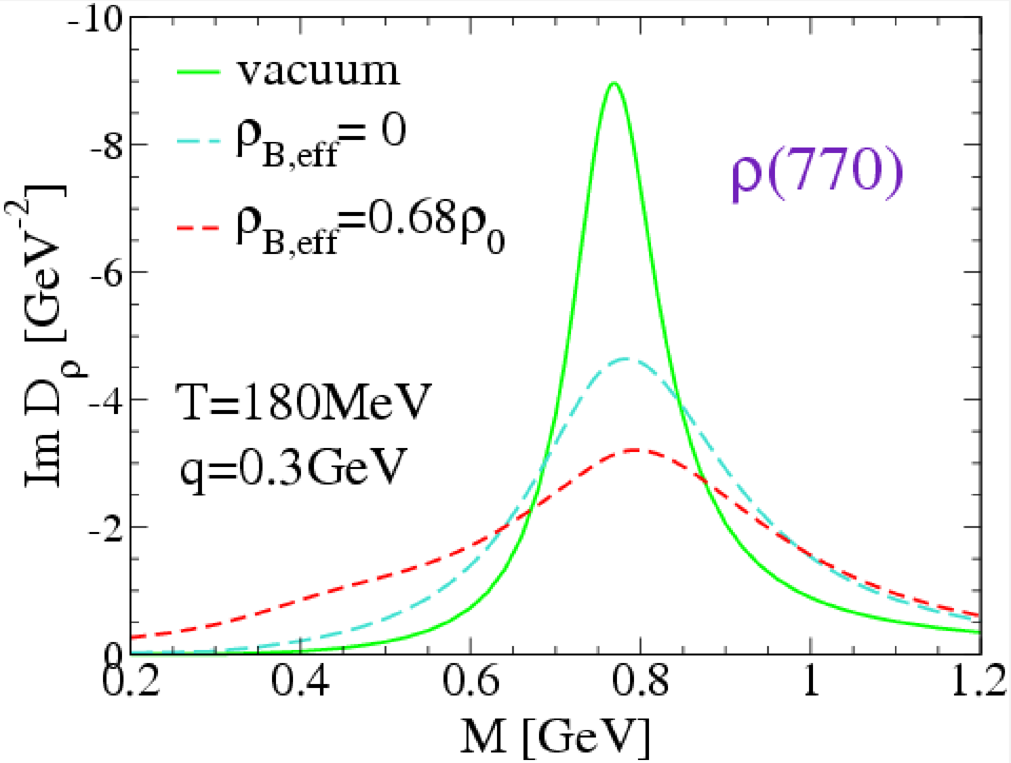
Fireball Evolution

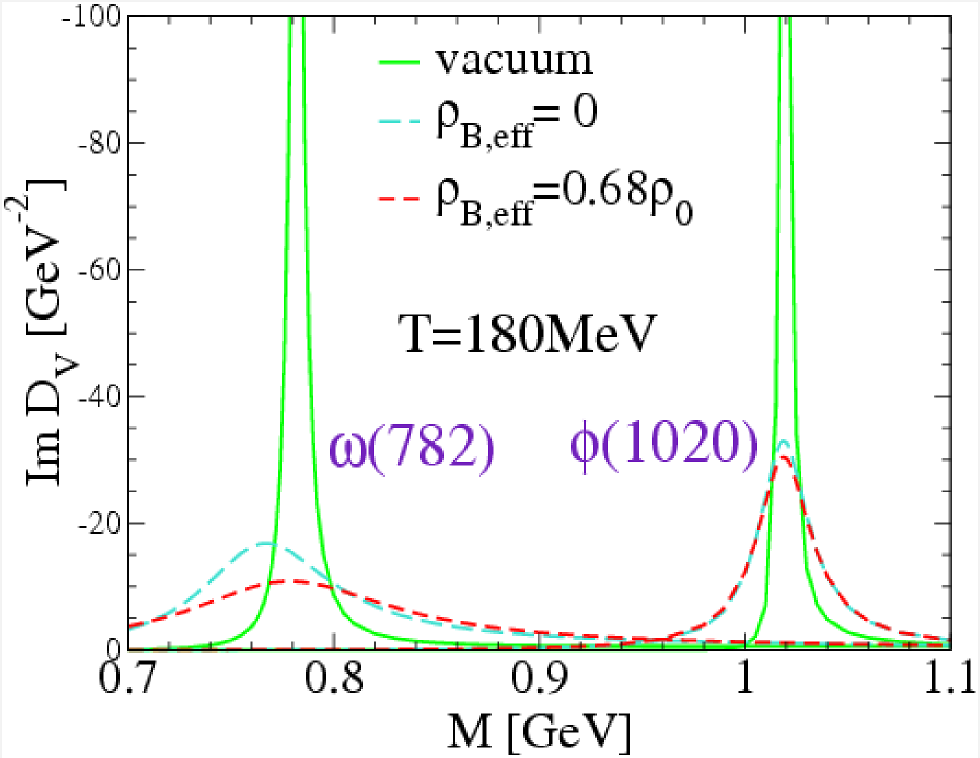


- multi-strange hadrons at “T_c”
- v_2^{bulk} fully built up at hadronization
- chemical potentials for π, K, …

[van Hees et al ’11]

4.7.2 Light Vector Mesons at RHIC + LHC

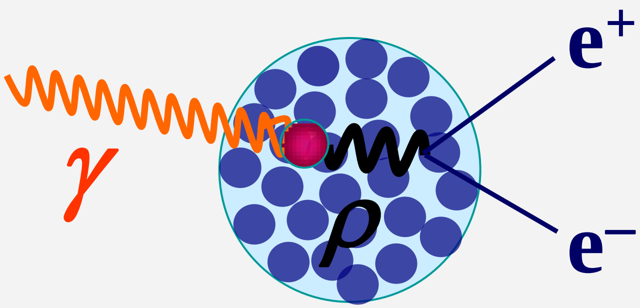


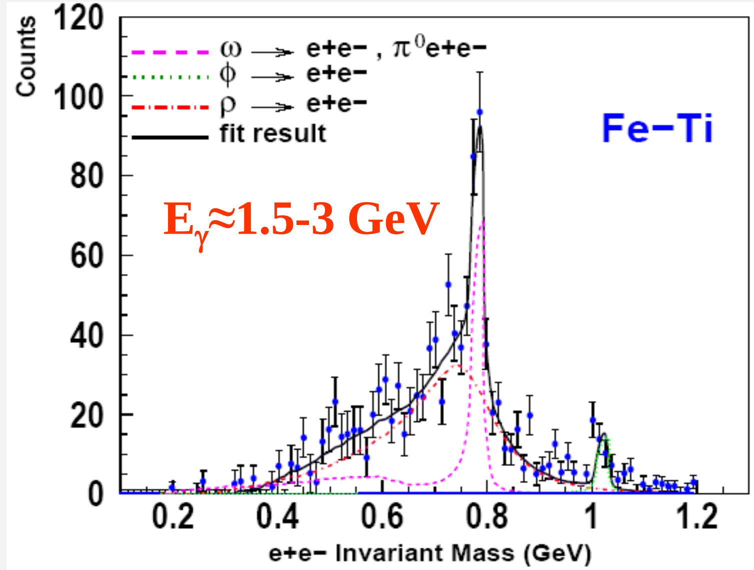


- **baryon effects important even at $\rho_{B,tot}= 0$:**
  sensitive to $\rho_{Btot}= \rho_B + \rho_{\bar{B}}$ (ρ-N and ρ-$\bar{N}$ interactions identical)
- **ω also melts, ϕ more robust ↔ OZI**

4.1 Nuclear Photoproduction: ρ Meson in Cold Matter

$\gamma + A \rightarrow e^+e^- X$



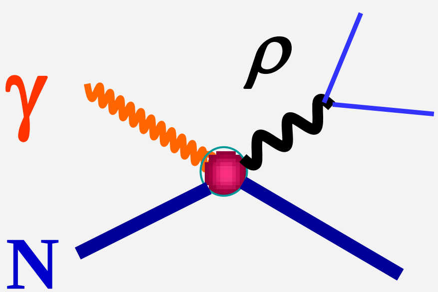


- extracted "in-med" ρ-width $\Gamma_\rho \approx 220$ MeV

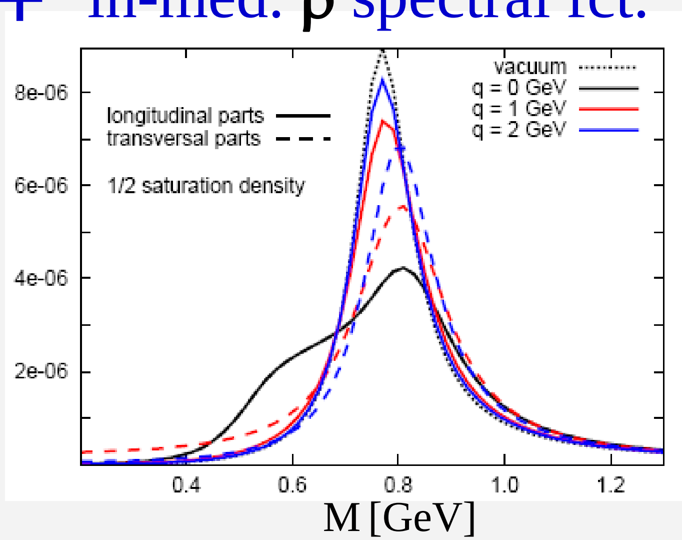
[CLAS+GiBUU '08]

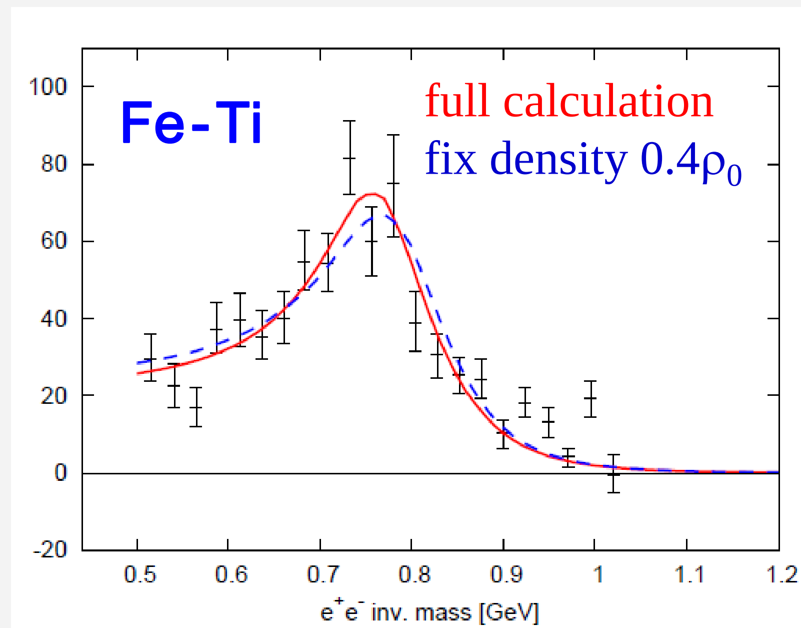
- **Microscopic Approach:**

product. amplitude + in-med. ρ spectral fct.



[Riek et al '08, '10]





- ρ-broadening reduced at high 3-momentum; **need low momentum cut!**