# Chiral Restoration and Electric Conductivity: Opportunities with Precision Dileptons at the LHC

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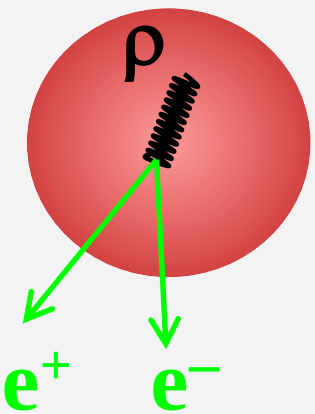
**ALICE-3 Meeting**
**CERN / hybrid, 18.-19.10.21**

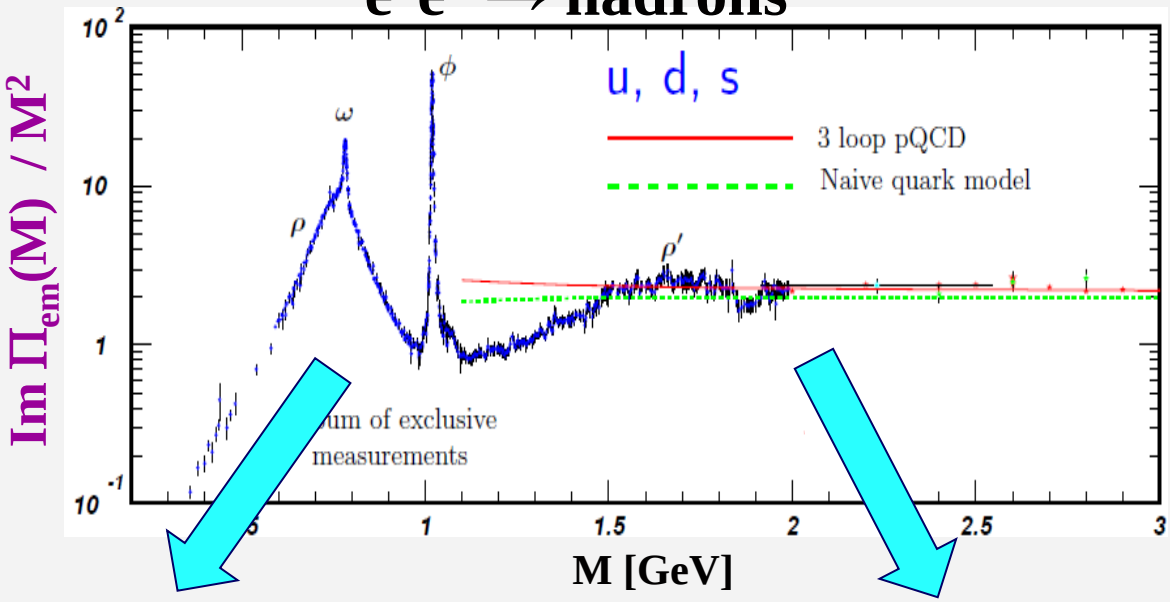
# 1.) Intro: EM Spectral Function to Probe Fireball

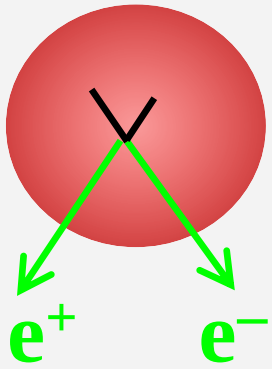
- **Thermal Dilepton Rate**

$$\frac{dR}{d^4q} = \frac{-\alpha^2}{\pi^3 M^2} f^B(q_0, T)\ \mathrm{Im}\,\Pi_{em}(M,q;\mu_B,T)$$




$e^+e^- \rightarrow$ hadrons

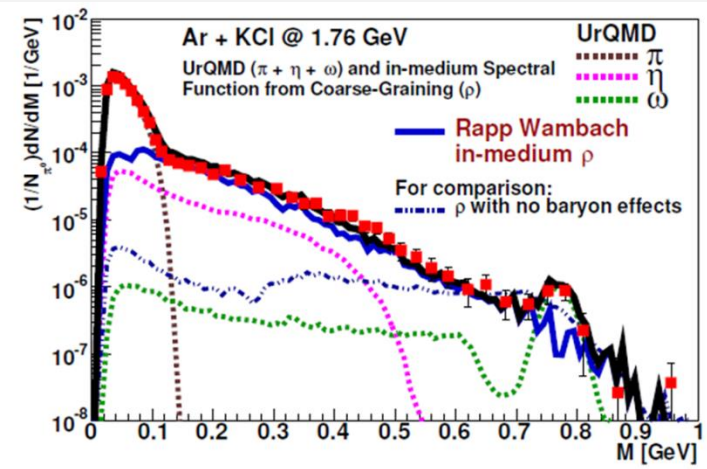


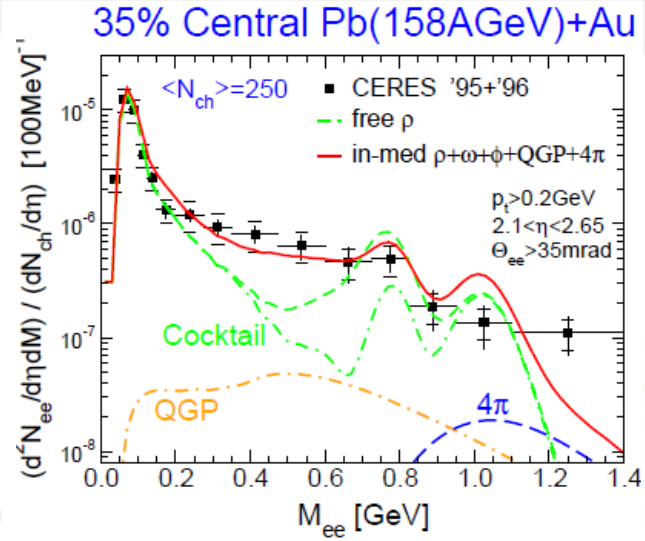



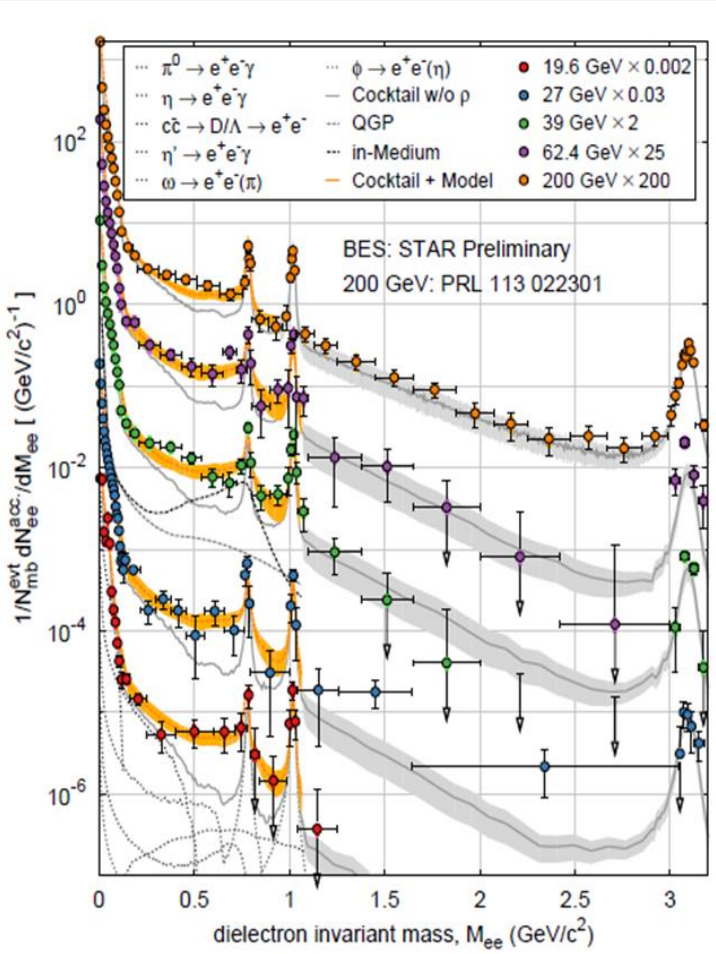

- **Hadronic Resonances**
  - **change in degrees of freedom?**
  - **restoration of chiral symmetry?**
- **Continuum**
  - **temperature?**

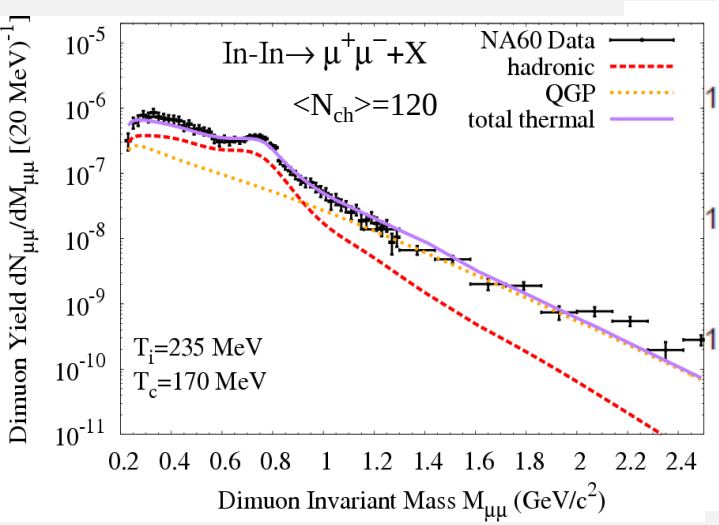
- **Low-$q_0$,q limit: transport coefficient (charge)?**
- **Total yields: fireball lifetime?**

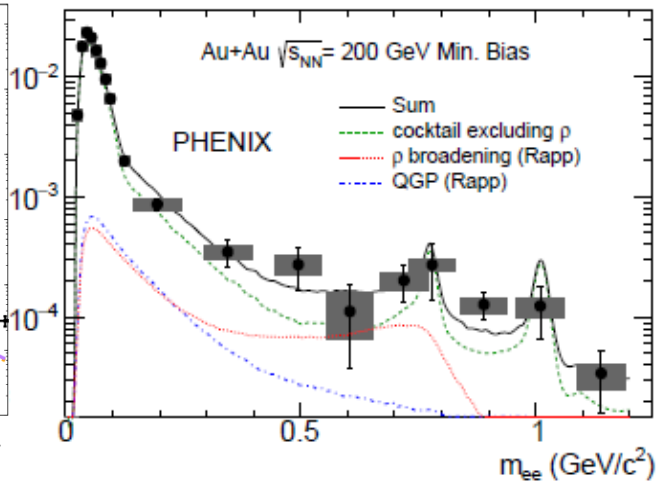
# 1.2 35 Years of Dileptons in Heavy-Ion Collisions




- **Current understanding:**
  **QGP + hadronic radiation with melting ρ resonance; $T > T_c$**

# 1.3 Precision Physics with Thermal Dileptons

- **Spectral Information: M~ 0.2-1.5 GeV**
  - Change in **degrees of freedom**: $\rho$ melts into partons?
  - **How** is **chiral restoration** realized? ($\rho$-$a_1$ degeneracy; "chiral mixing")

- **Electric Conductivity: very low M, q**

  $$\sigma_{el}(T) = - e^2 \lim_{q_0 \to 0} [ \mathrm{Im}\, \Pi_{em}(q_0, q=0; T) / q_0 ]$$

  as **fundamental** as $\eta/s$ and $\mathcal{D}_s^{HF}$

- **Fireball Diagnostics**
  - Early **temperatures** (**M ≥ 1.5 GeV**; no blue-shift distortion)
  - **Lifetime** of radiating phase (low-mass yield **M ~ 0.5 GeV**)
  - **Flow** ($p_T$ spectra and $v_2$ for **any** mass)

# Outline

1.) **Introduction**

2.) **Chiral Restoration and sQGP**

- **QCD + Weinberg Sum Rules**
- **Resonances above $T_c$?**
- **Pre-equilibrium Radiation**

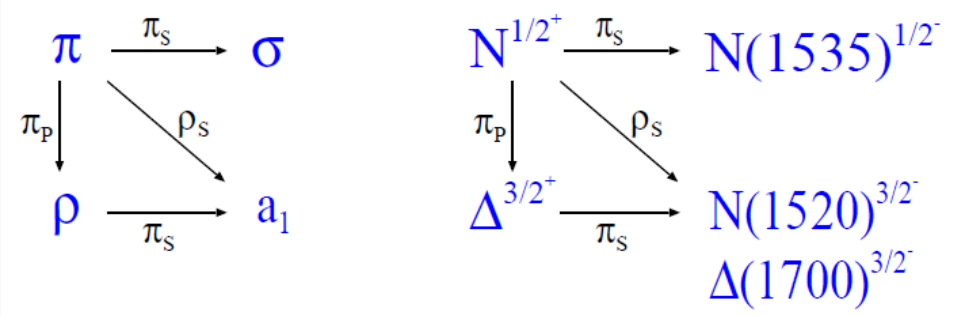
3.) **Transport Properties**

- **Electric Conductivity**

4.) **Conclusions**

# 2.1 Chiral Symmetry Breaking in Vacuum

- Mass **splitting** within chiral multiplets




- Quantitative: Sum Rules

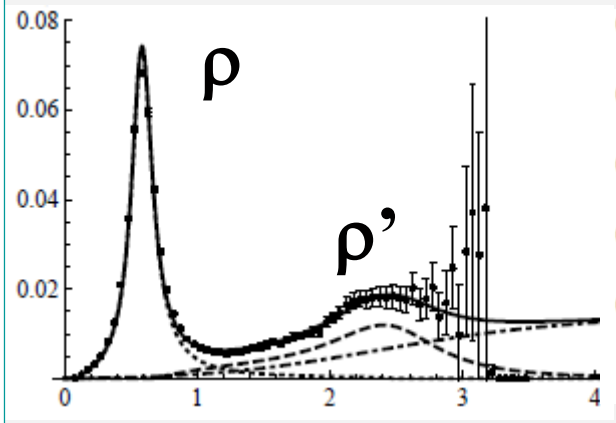
$$\int_0^\infty ds\,\frac{\Delta\rho(s)}{s^2} = \frac{1}{3} f_\pi^2 \langle r_\pi^2 \rangle - F_A$$

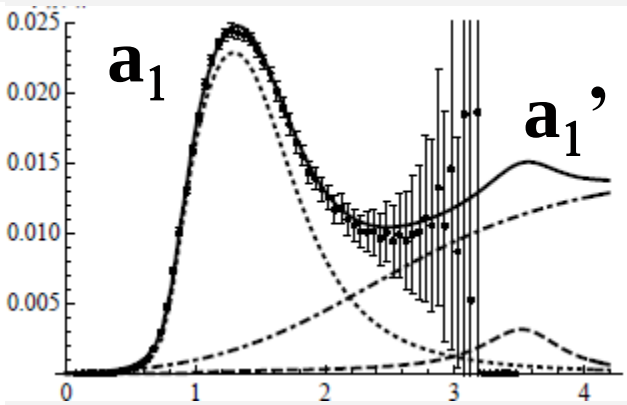
$$\int_0^\infty ds\,\frac{\Delta\rho(s)}{s} = f_\pi^2\ ,$$

$$\int_0^\infty ds\,\Delta\rho(s) = f_\pi^2 m_\pi^2 = -2 m_q \langle \bar{q} q \rangle$$

$$\int_0^\infty ds\, s\,\Delta\rho(s) = -2\pi\alpha_s \langle \mathcal{O}_4^{SB} \rangle$$

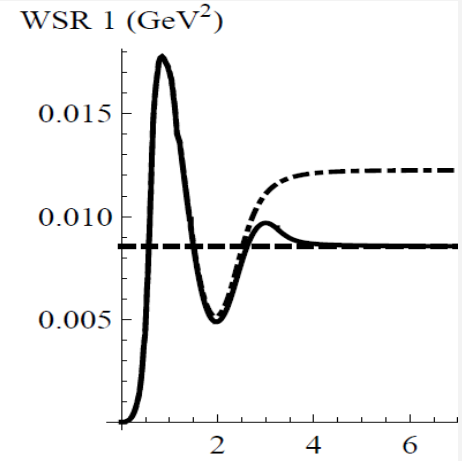
$\Delta\rho = \rho_V - \rho_A$ **[Weinberg '67, Das et al '67; Kapusta+Shuryak '94]**

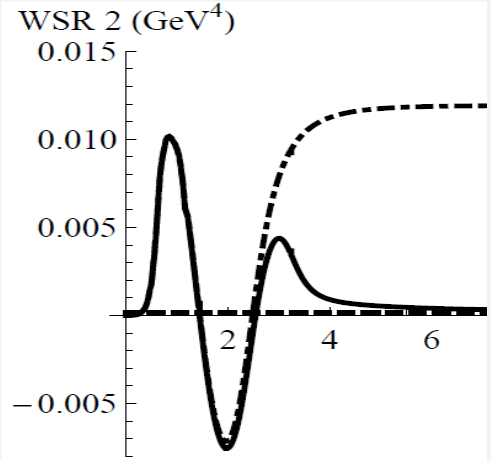



- Sensitive to excited states: predict **$a_1$(1950)** state

**[Hohler+RR '12]**

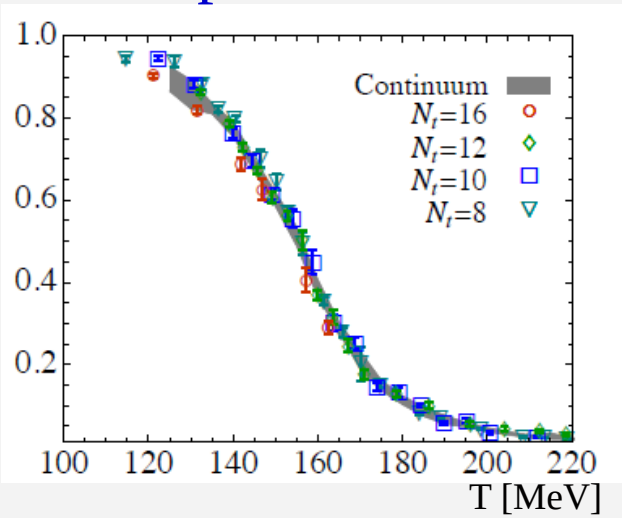


# 2.2 Chiral Restoration in the Axial-/Vector Channels

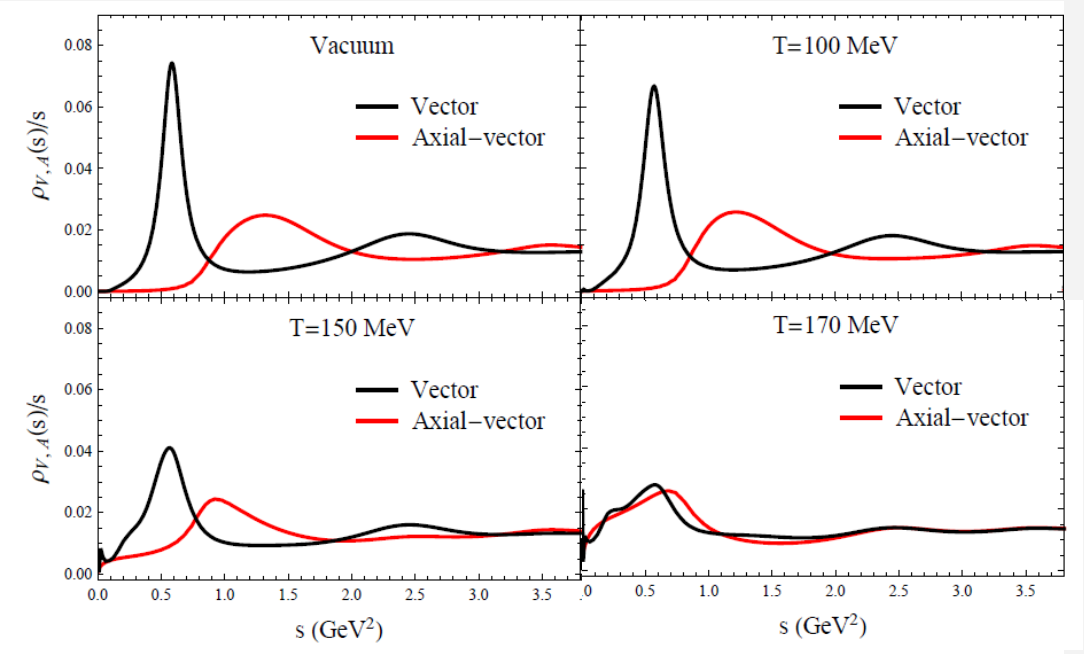
**Evaluate sum rules at finite T:**

- In-medium ρ spectral fct.
- Lattice-QCD for chiral order parameters




⇒

**In-Medium Spectral Functions**



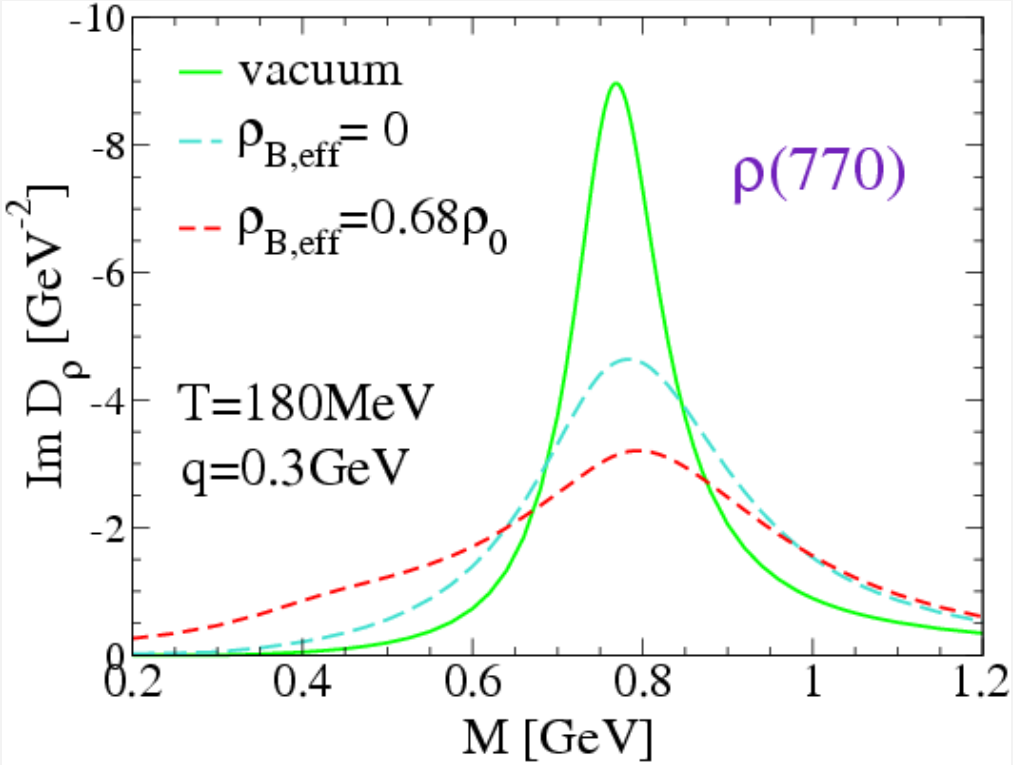

**[Hohler+RR '13]**

Mechanism of chiral restoration:

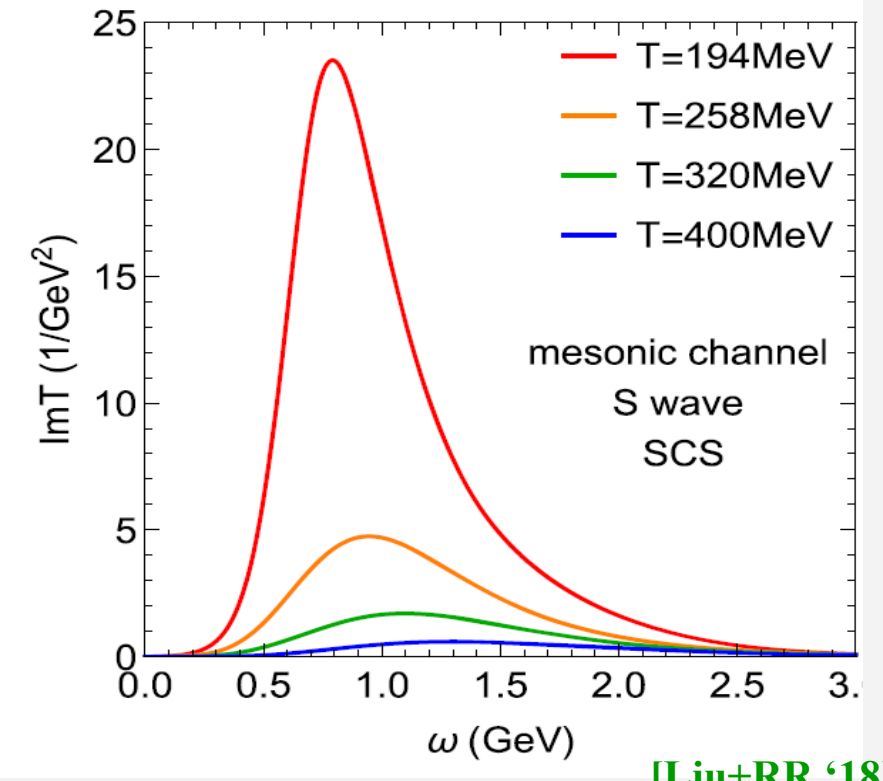
- **ρ-a$_1$ mass splitting "burns off"** [also for **π-σ, N-N*(1535)** **[Aarts et al '17]**]
- "chiral mixing" for **M=1-1.5 GeV**: **π-a$_1$** annihilation or ρ' broadening…?

# 2.3 Where Does the ρ Melt?

## Hadronic Many-Body




## QGP: $q\bar{q}$ T-Matrix

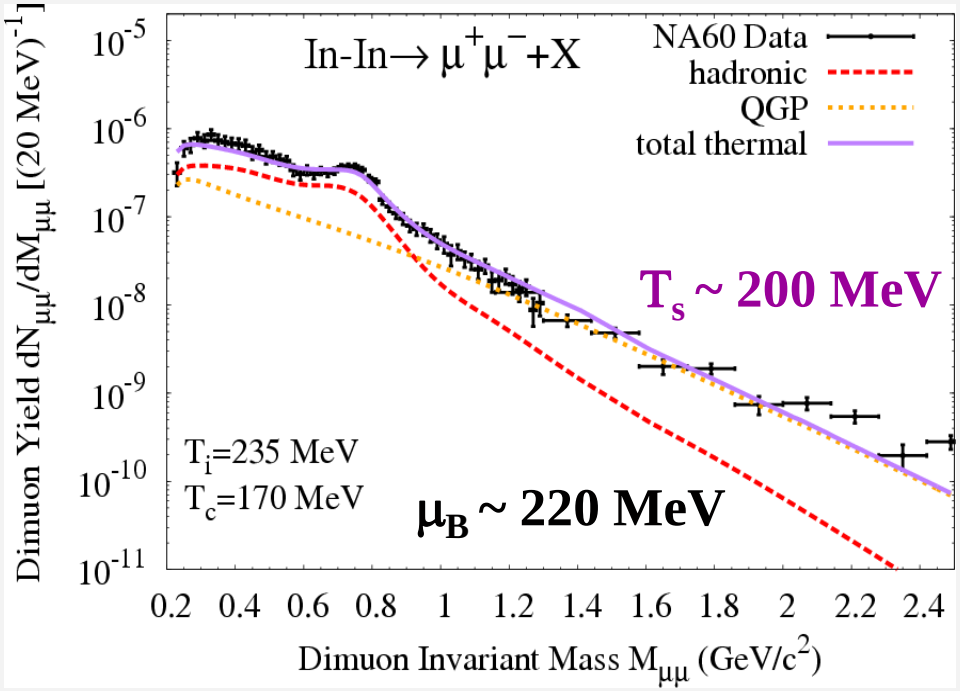



[Liu+RR '18]

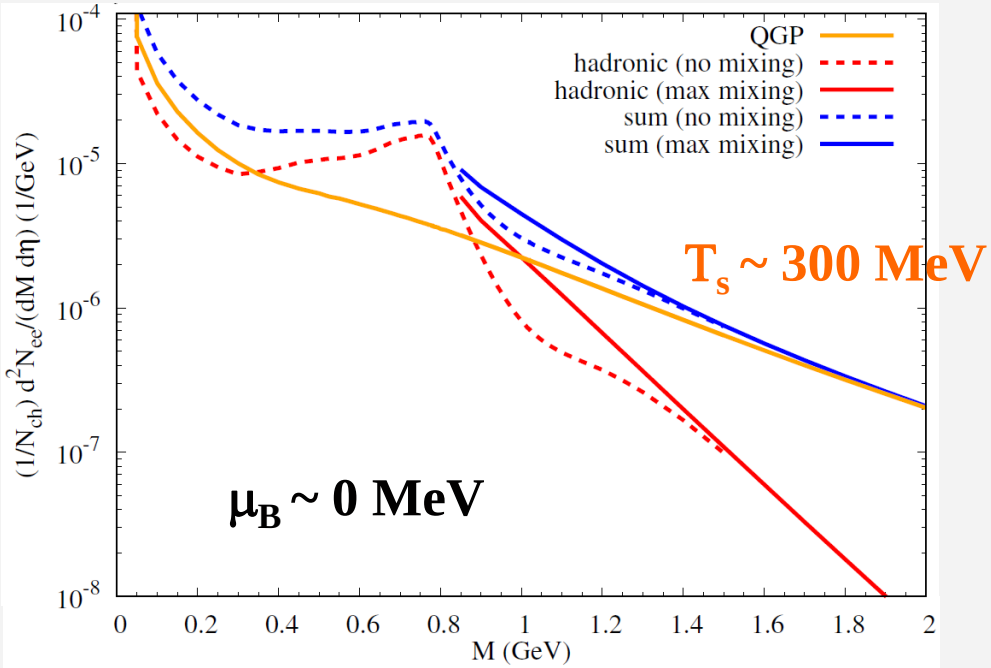
- Hadronic + partonic calculations match near $T_{pc}$ via broad ρ-resonance
- Nature of the medium (**sQGP**) above $T_{pc}$ ($\mathcal{D}_s$, η/s, ...)?

# 2.3 Dilepton Spectra and Chiral Restoration

**SPS**



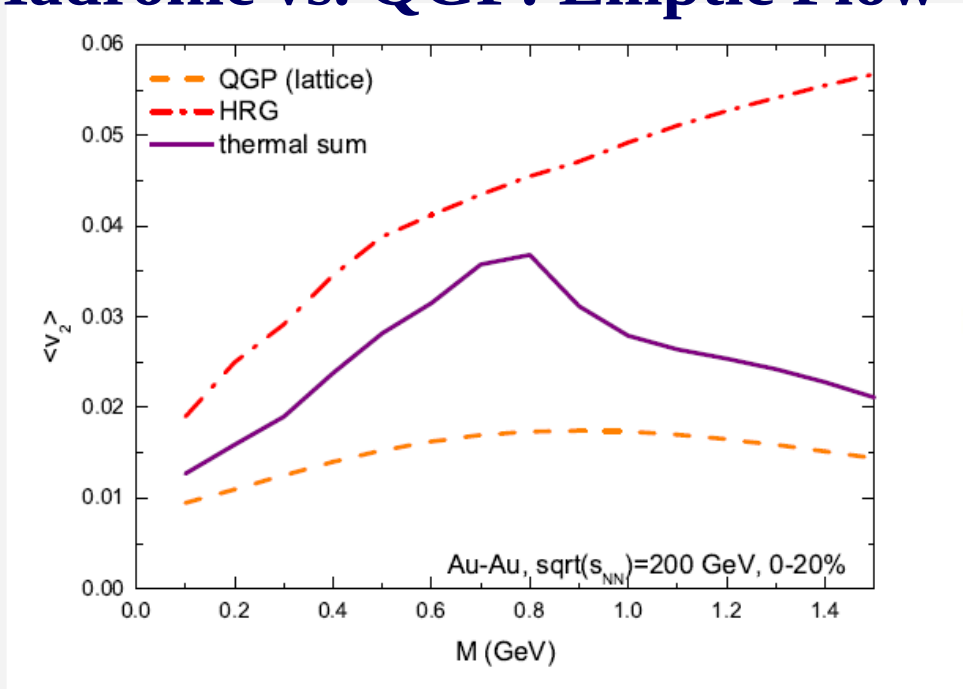

**LHC**



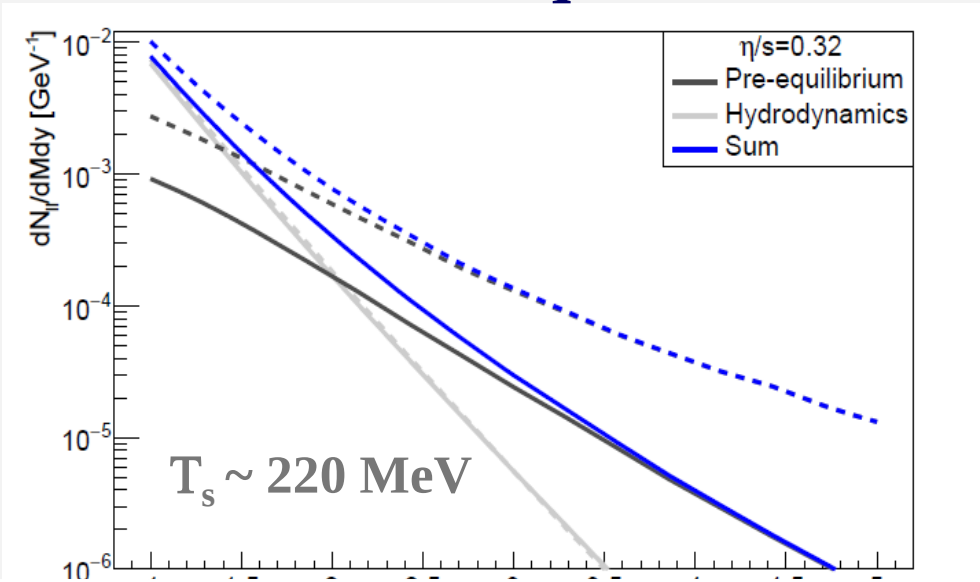

- precision data sensitive to ρ-meson spectral shape
- Is the ρ-meson really melted above $T_{pc}$ at the **LHC?**
- "chiral mixing" discernible at **M ~ 0.9-1.5 GeV**

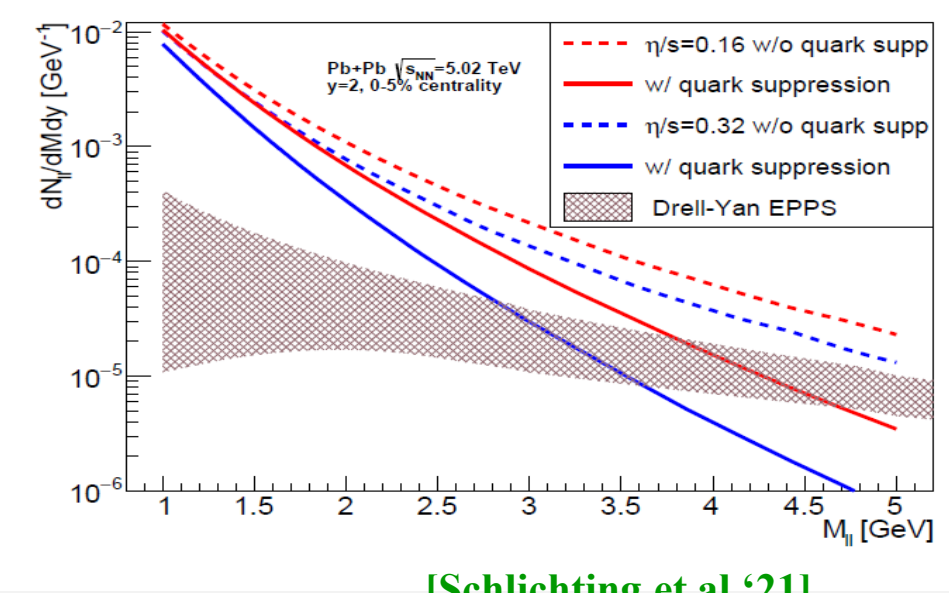
# 4.1 QGP Radiation and Pre-Equilibrium

## Hadronic vs. QGP: Elliptic Flow




## QGP vs. Pre-equilibrium




[Schlichting et al '21]

- Transition hadronic → QGP in **M**-dep. of radial + elliptic flow
- Pre-equilibrium radiation: **M>2 GeV**, sensitive to viscosity + quark chemistry

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- **QCD + Weinberg Sum Rules**
- **Resonances above $T_c$?**
- **Pre-equilibrium Radiation**

3.) **Transport Properties**

- **Electric Conductivity**

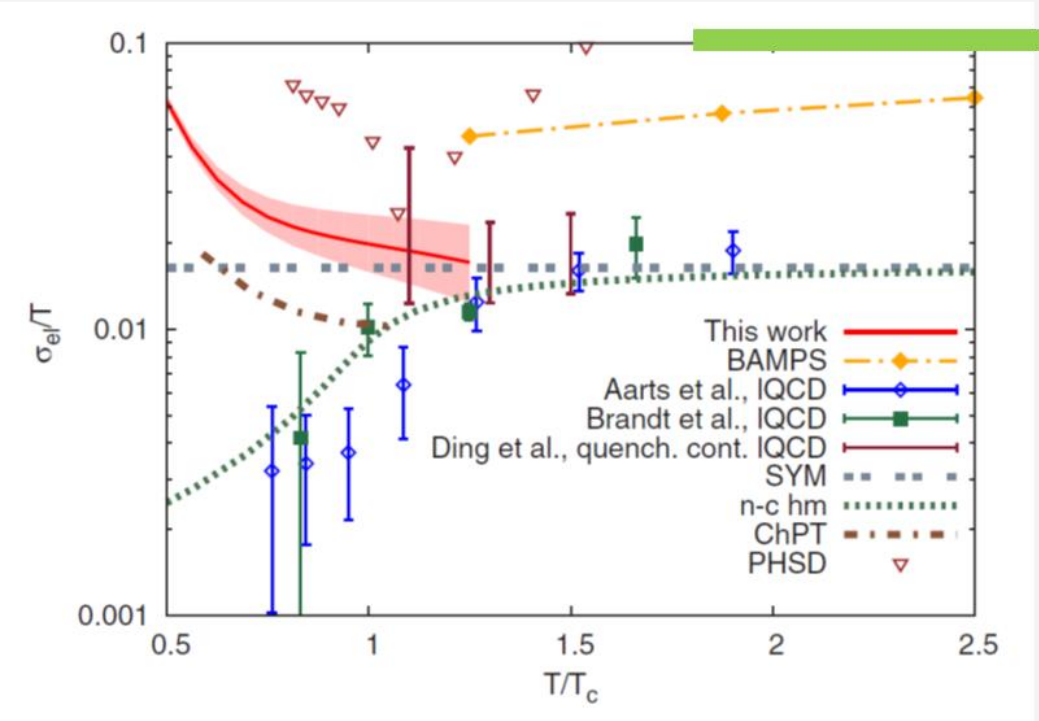
4.) **Conclusions**

# 3.) Electric Conductivity

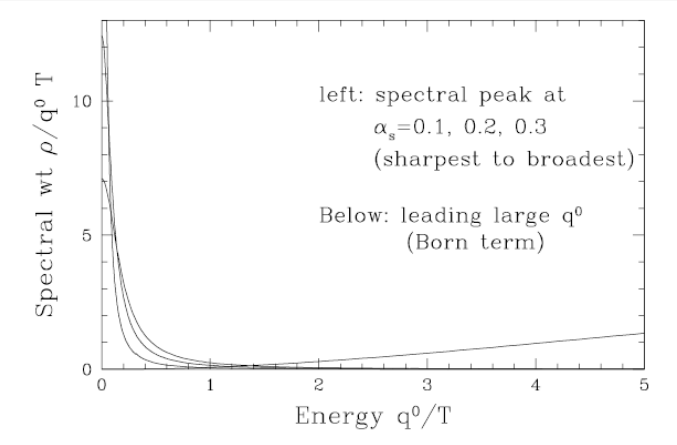
- Generic transport coefficient (charge): $\sigma_{el}/T \sim 4\pi\, \eta/s \sim 2\pi T\, \mathcal{D}_s^{HF}$
- Probes timelike long-wavelength limit of EM spectral function:

$$\sigma_{el}(T) = -\, e^2 \lim_{q_0 \to 0} [\mathrm{Im}\, \Pi_{em}(q_0, q=0; T)/q_0\,]$$

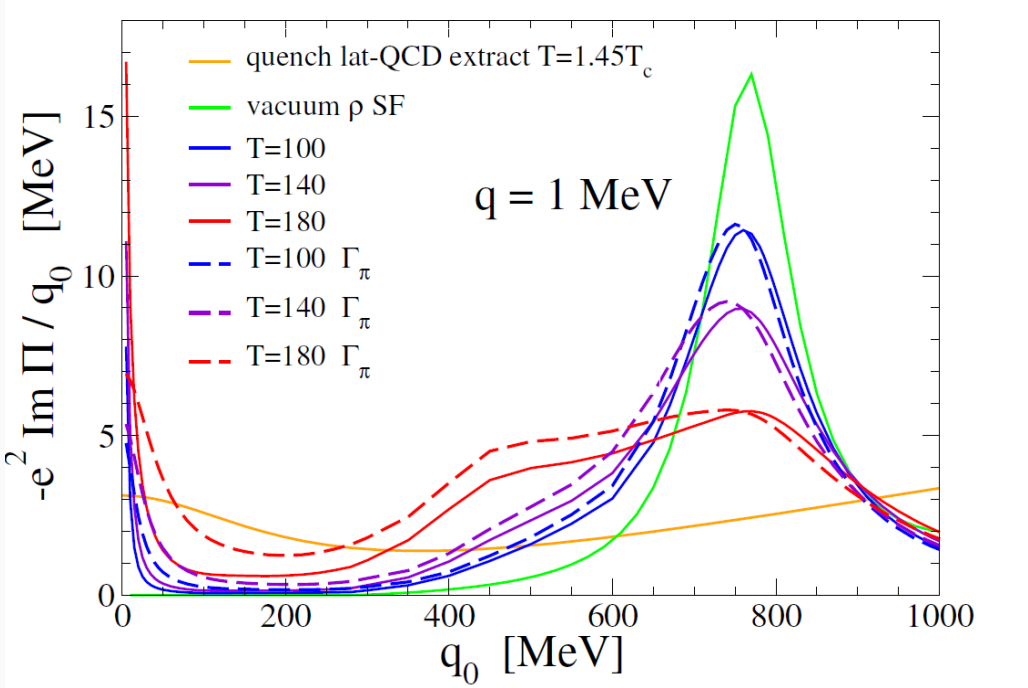
- Kinetic theory: $\sigma_{\rm el} = \frac{1}{3T} \sum_{i=1}^{N_{\rm species}} q_i^2 n_i \tau$




**pQCD**
**[Moore+Robert '06]**

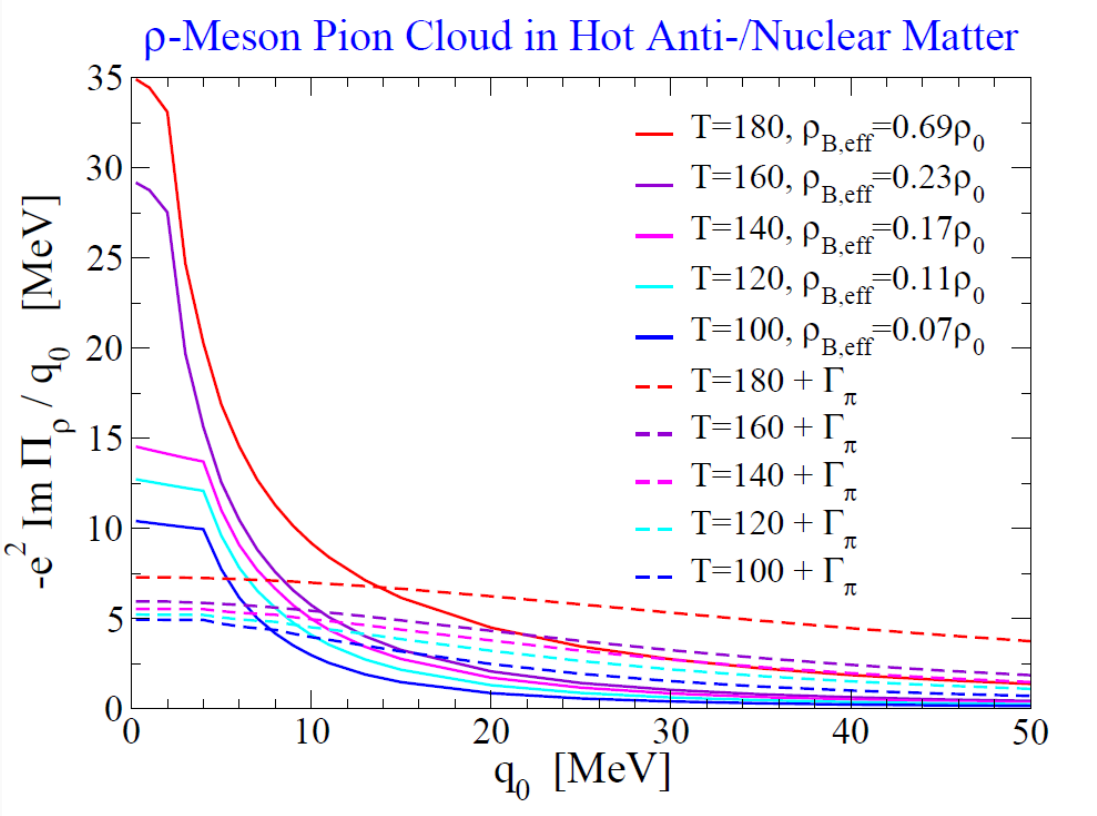


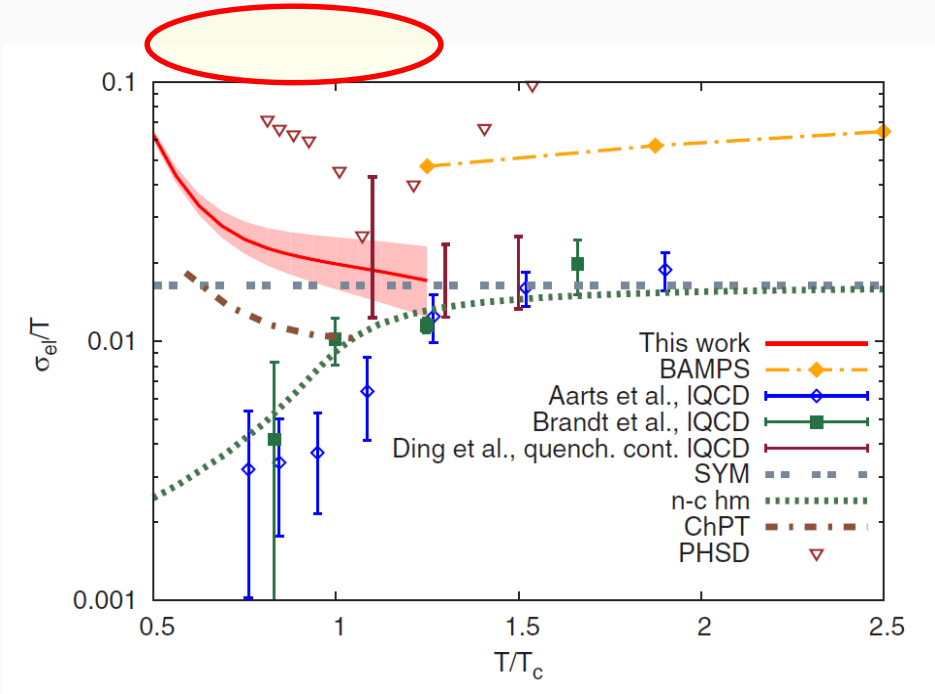
# 3.1 Conductivity Peak in Hadronic Matter




- Conductivity peak at zero energy
  stronger interaction $\rightarrow$ broadening reduces peak + enhances shoulder
- Peak quickly disappears at finite 3-momentum (non-zero energies)

# 3.2 Sensitivity to Conductivity Peak

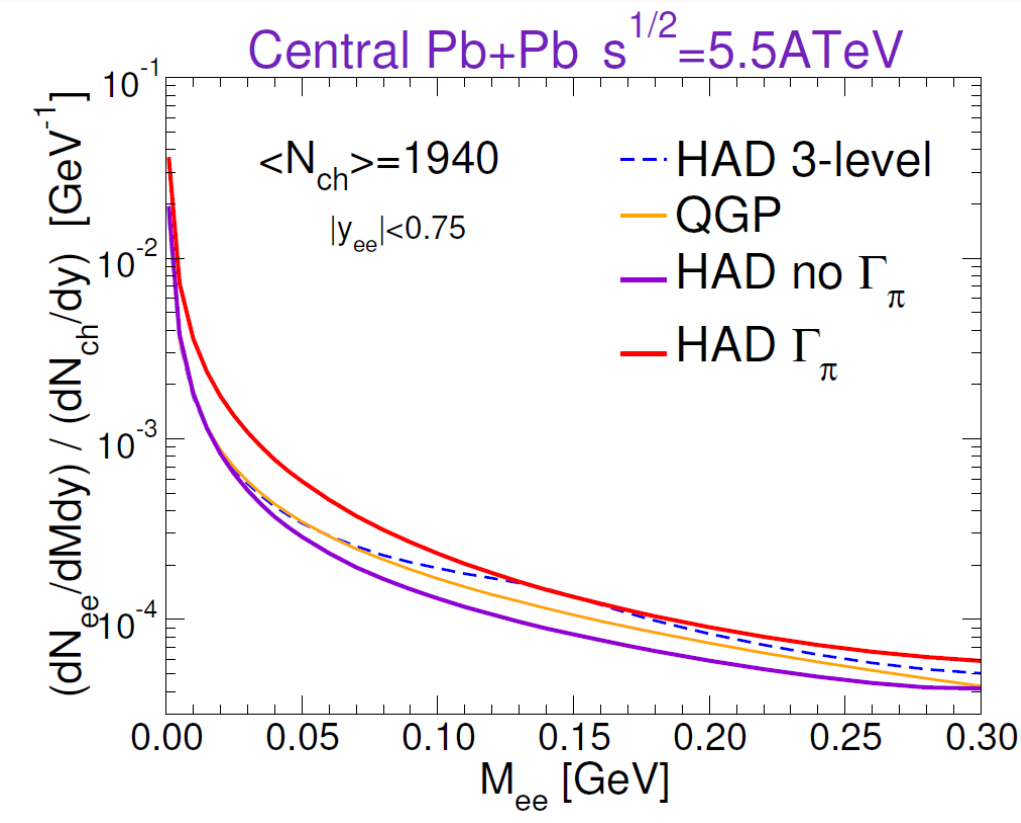


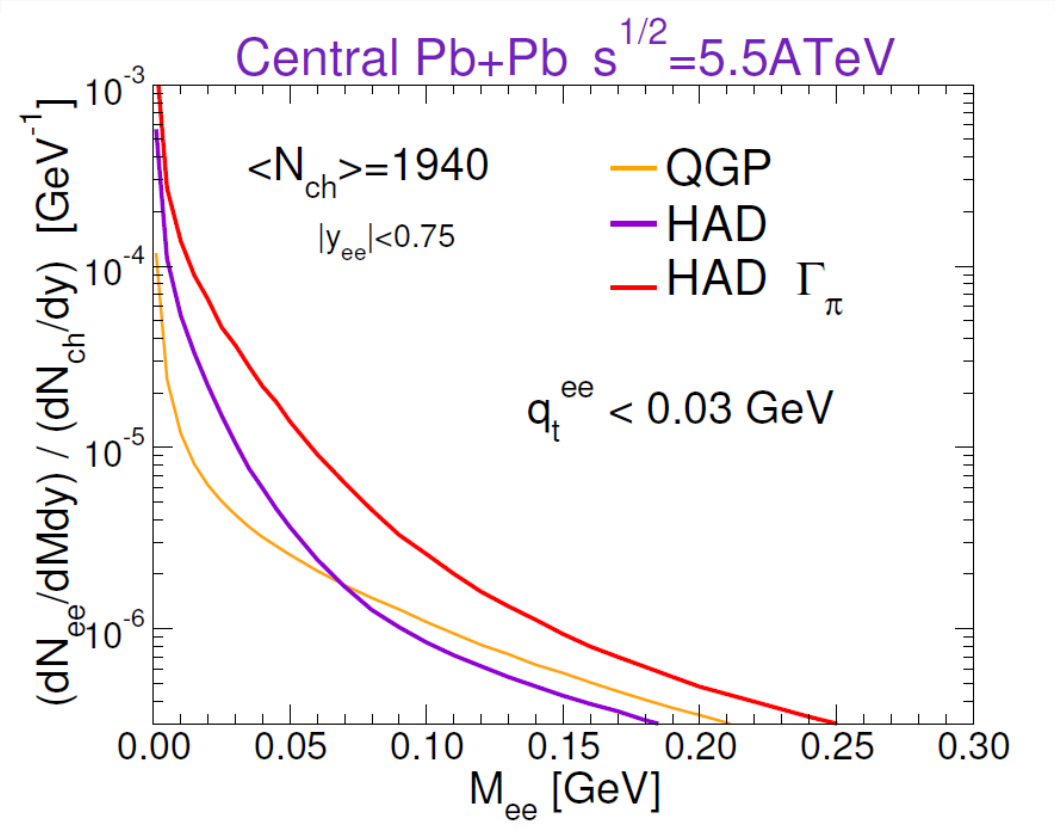




[Greif et al '16]

- conductivity with **π**-baryon interactions: **$\sigma_{el}$ ~ 10-40 MeV** or **$\sigma_{el}/T$ ~ 0.1-0.2**
  ⇒ inefficient in reducing **$\sigma_{el}$**
- much reduced upon inclusion of thermal-pion interactions

# 3.3 Thermal Dileptons: No Single-e$^{\pm}$ Cuts



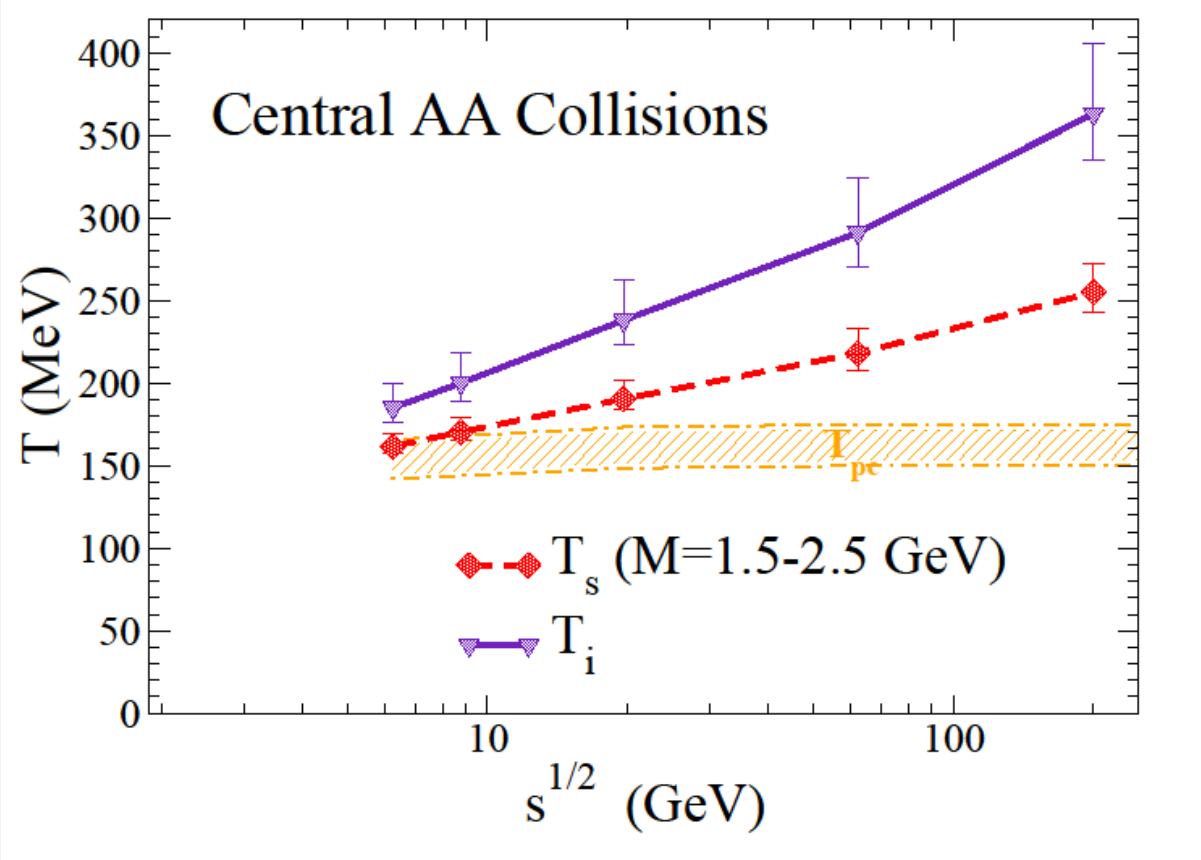

- Factor ~2 increase due to reduced $\sigma_{el}$
- Factor ~3 for $q_t^{ee}$ < 200 MeV
- Factor ~4 for $q_t^{ee}$ < 30 MeV

# 4.) Conclusions

- **Precise measurement of dilepton spectral shape**
  - Chiral restoration of hadron masses and "chiral mixing"
  - $\rho$ spectral shape above $\mathbf{T_{pc}}$ and nature of sQGP?
- **Very-low-mass dileptons**
  - probe electric conductivity consistent with low-mass dileptons
- **Dilepton radiation at intermediate mass**
  - mass dependent $\mathbf{v_0}$ and $\mathbf{v_2}$: transition hadronic $\rightarrow$ QGP
  - early temperature vs. pre-equilibrium: $\boldsymbol{\eta/s}$, quark chemistry

# 5.2 Fireball Temperature

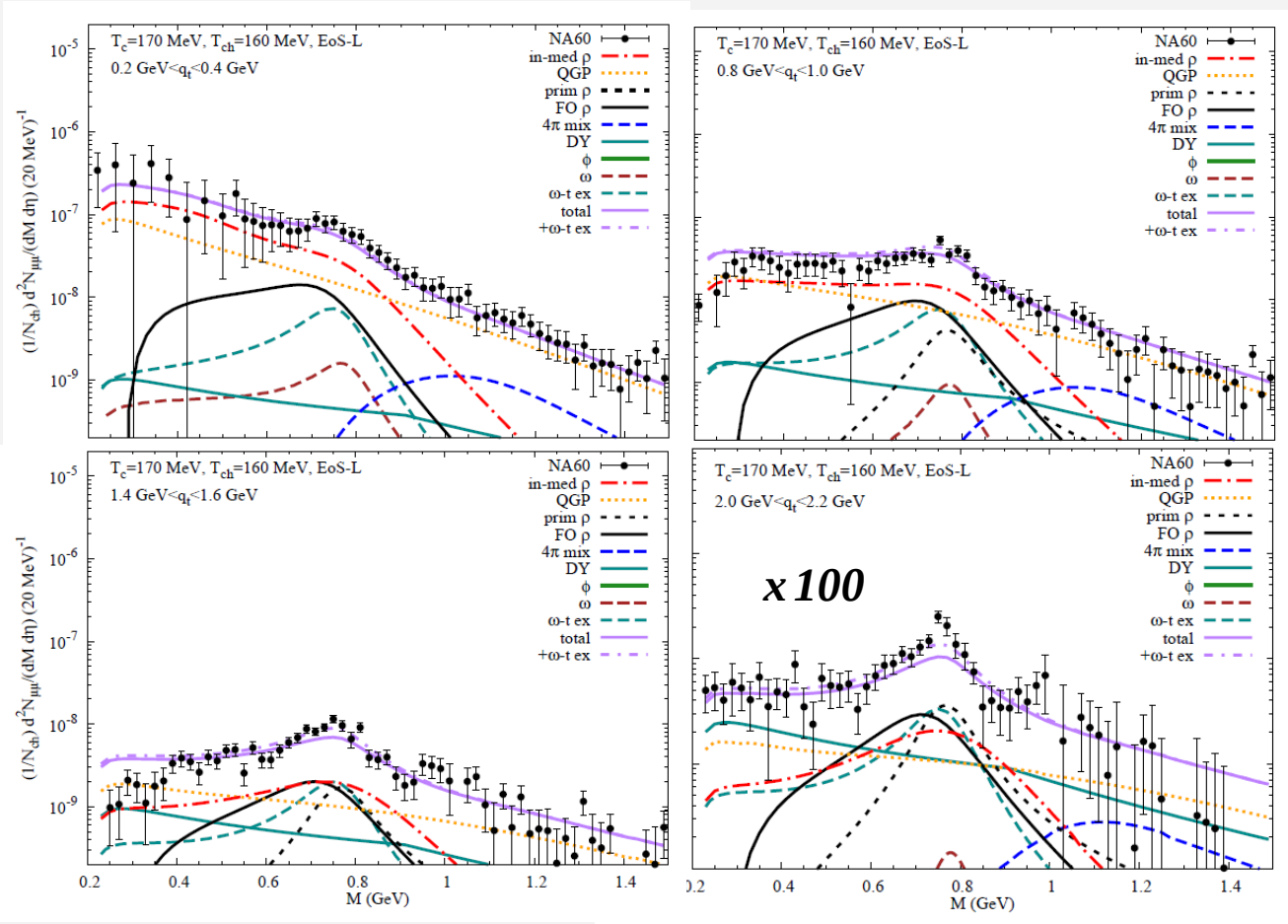
## Slope of Intermediate-Mass Excess Dileptons



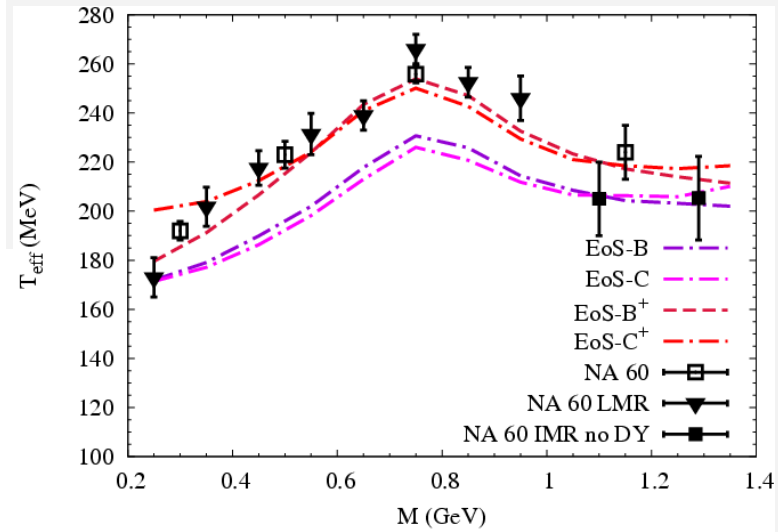

- unique ``**early" temperature** measurement (no blue-shift!)
- $\mathbf{T_s}$ approaches $\mathbf{T_i}$ toward lower energies
- first-order "plateau" at **BES-II/CBM?**

# 2.2 Transverse-Momentum Dependence

## $p_T$ -Sliced Mass Spectra



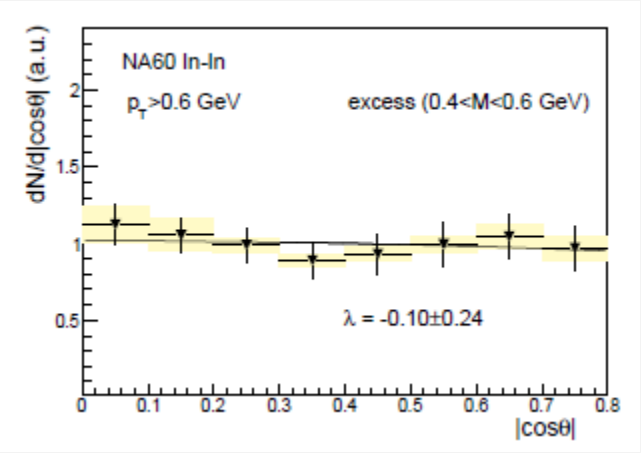

## $m_T$ -Slopes




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

# 3.) Polarization Observables

- little explored for thermal radiation
- Non-trivial even for isotropic medium: depend on **transverse** vs. **longitudinal** modes of spectral function




$$\frac{dR_{l^+l^-}}{d^4q} = -\frac{\alpha^2}{\pi^3 M^2} f^B(q_0;T) \; \tfrac{1}{3}\,[2\,\mathrm{Im}\,\Pi_T + \mathrm{Im}\,\Pi_L]$$

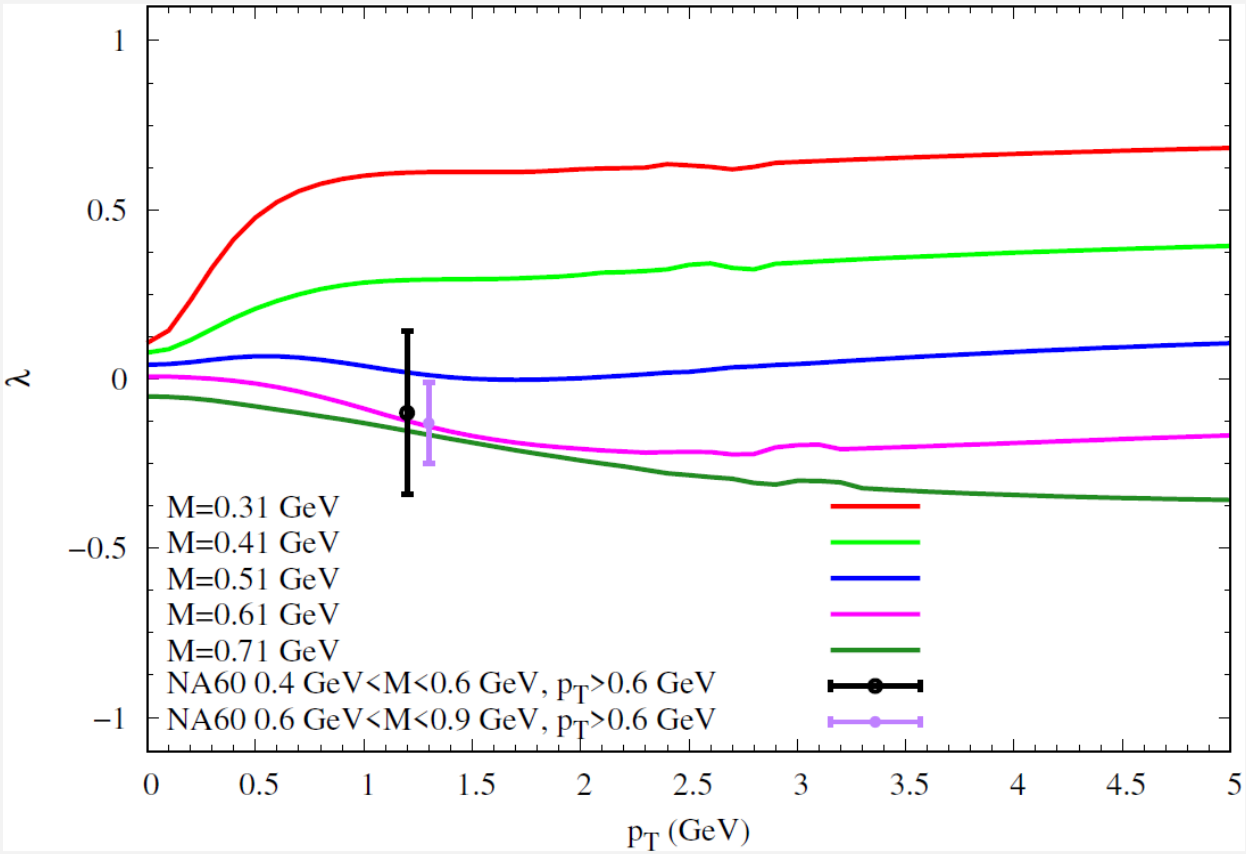
$$\propto (1 + \lambda cos^2\theta + \mu sin2\theta cos\phi + \frac{\nu}{2} sin^2\theta cos2\phi)$$

**[Hoyer '87, Baym et al '18, Speranza+Friman '18]**

- angle between electron and photon momentum

$$\lambda_\theta = \frac{\mathrm{Im}\,\Pi_T - \mathrm{Im}\,\Pi_L}{\mathrm{Im}\,\Pi_T + \mathrm{Im}\,\Pi_L}$$

# 3.2 Polarization Coefficients from ρ Spectral Fct.

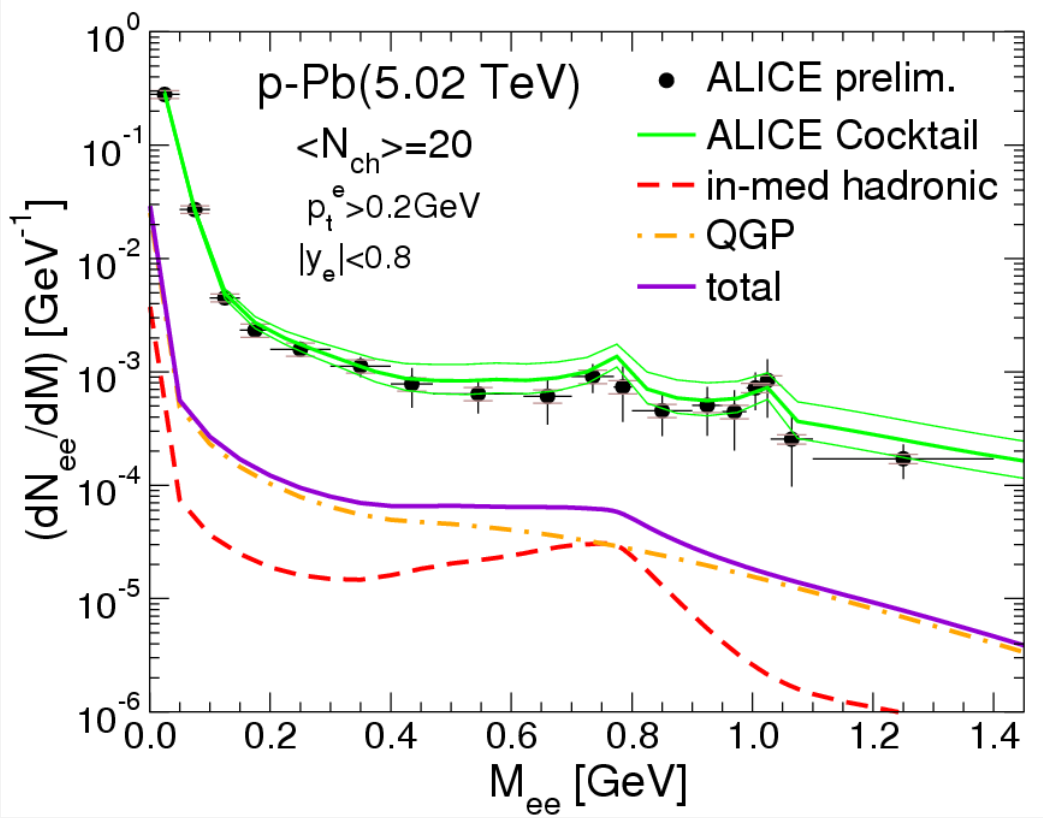



[Speranza et al in prog]

- very sensitive to production process:

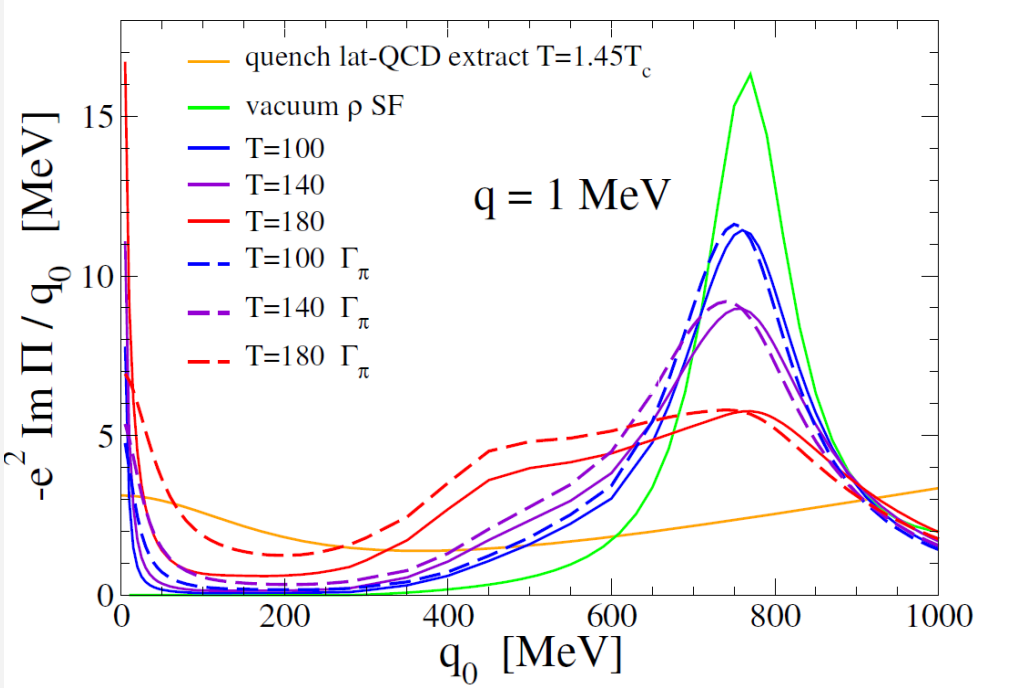
  **$q\bar{q}$** vs. **ππ** annihilation vs. Dalitz decay vs. partial wave

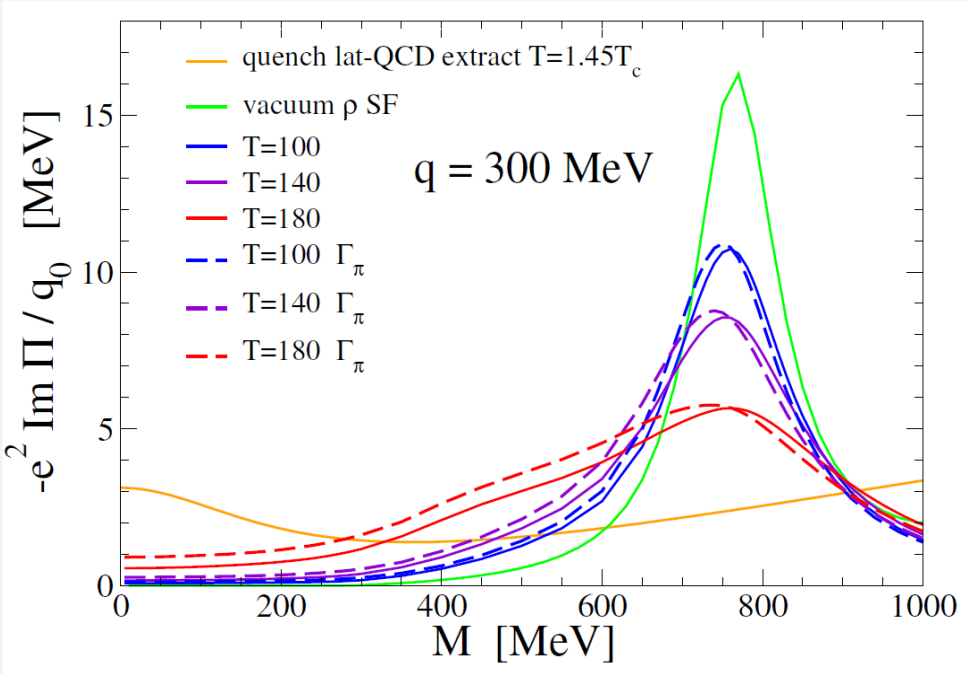
# 5.3 Low-Mass Dileptons in p-Pb (5.02GeV)




- Thermal radiation at **~10%** of cocktail
- follows excess-lifetime systematics
- photons **[Shen et al '15]**

# 3.1 Conductivity Peak in Hadronic Matter

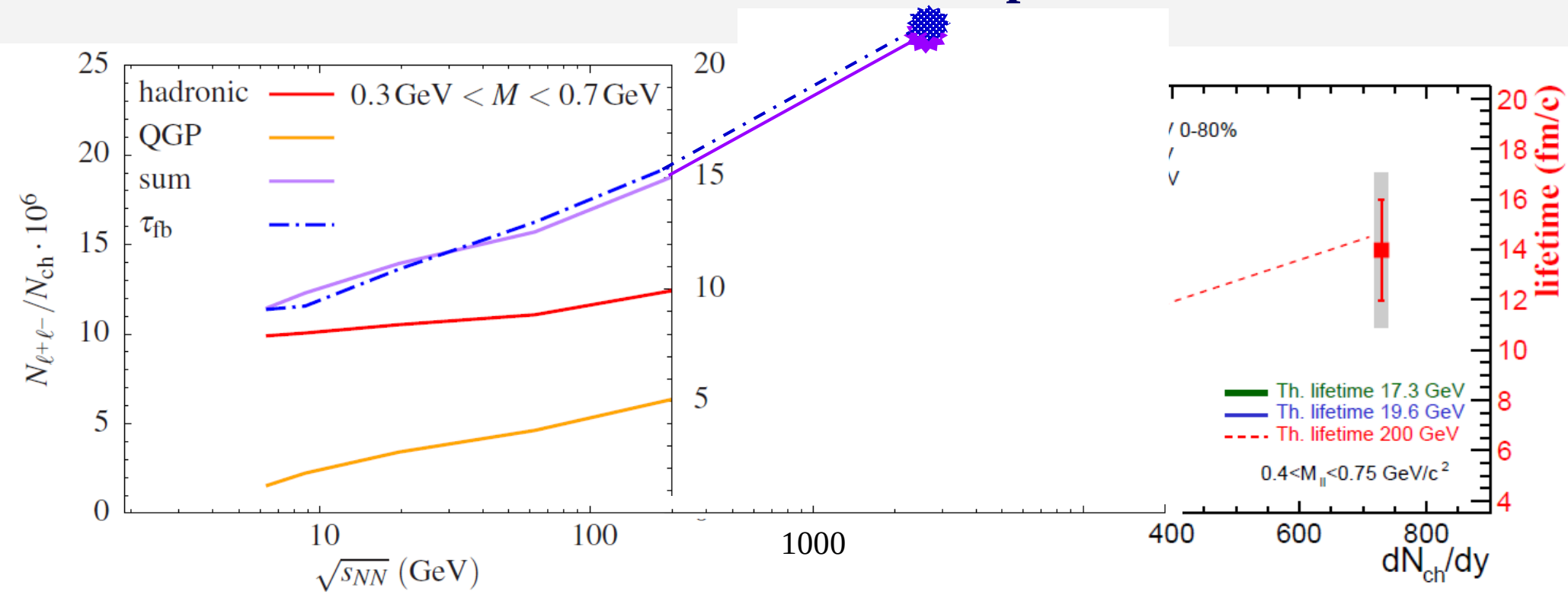



- Conductivity peak at zero energy
  stronger interaction $\rightarrow$ broadening reduces peak + enhances shoulder
- Peak quickly disappears at finite 3-momentum (non-zero energies)

# 5.1 Fireball Lifetime

## Excitation Function of Low-Mass Dilepton Excess Yield

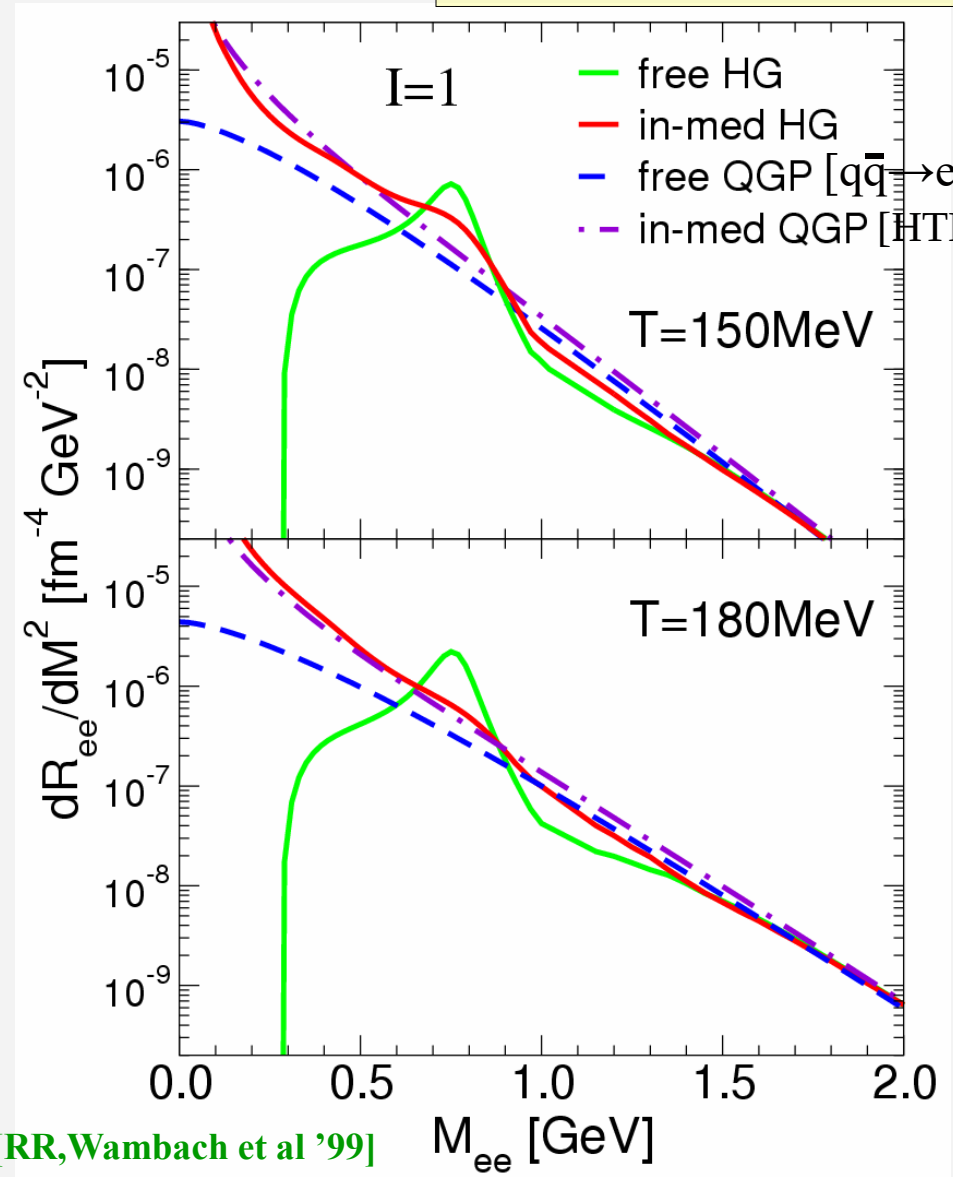



[RR+van Hees '14] [STAR '15]

- Low-mass excess tracks lifetime well (medium effects!)
- Tool for critical point search?

# 2.) Dilepton Rates and Degrees of Freedom

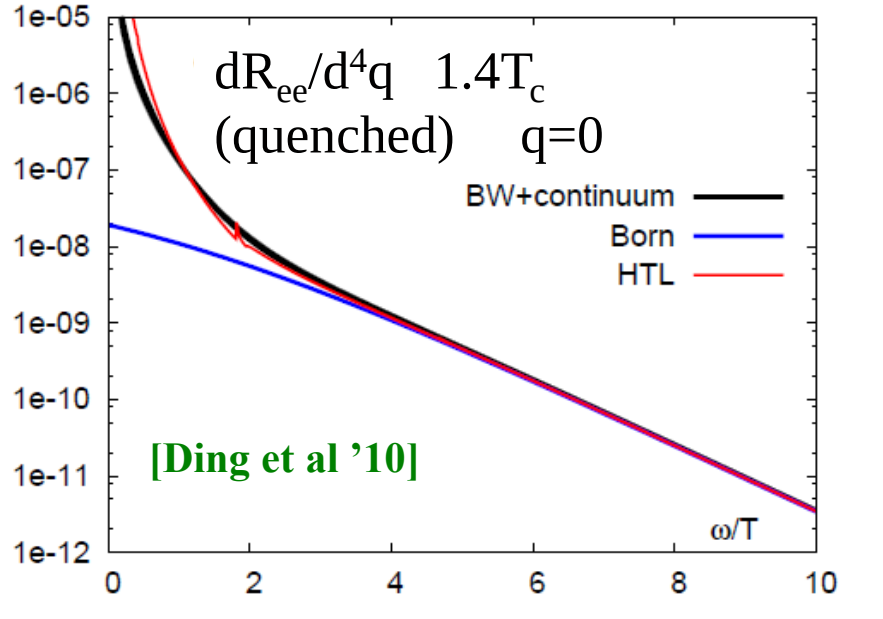
$$dR_{ee}/dM^2 \sim \int d^3q/q_0\ f^B(q_0;T)\ \mathrm{Im}\,\Pi_{em}/M^2$$




[RR,Wambach et al '99]

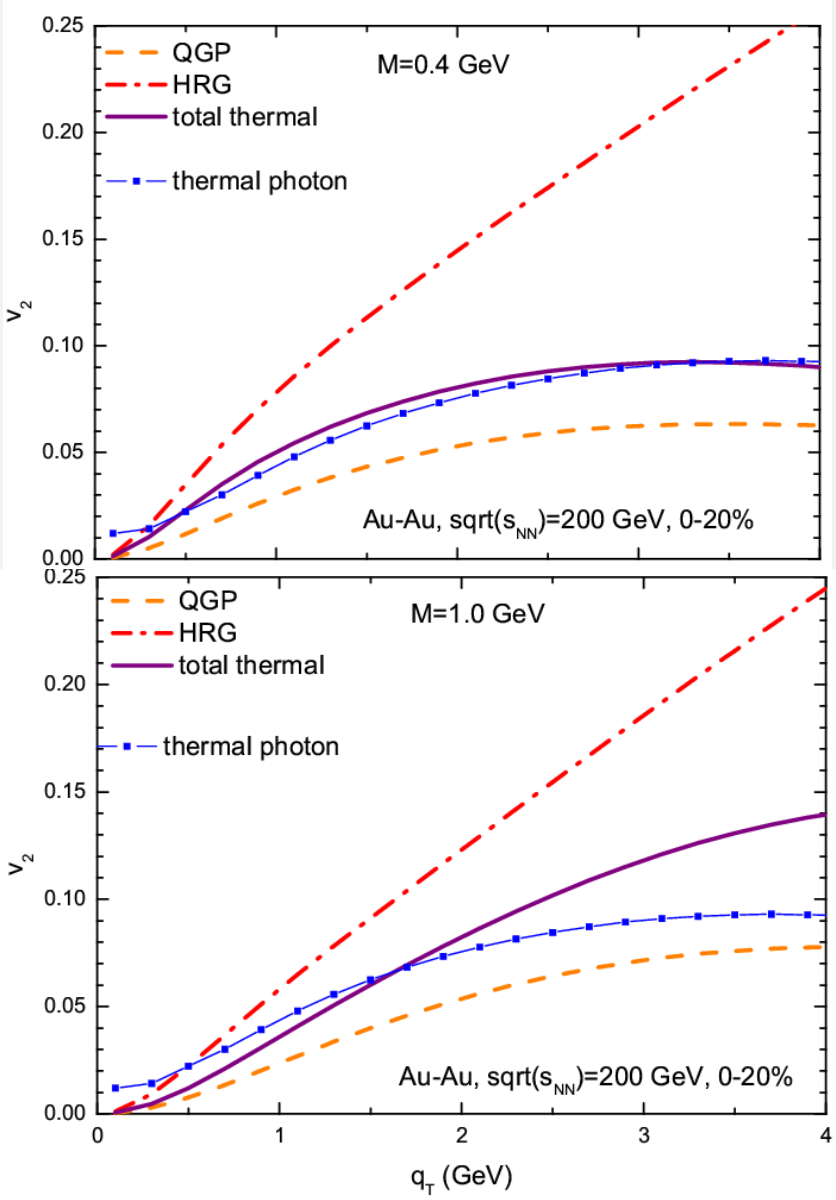
- ρ-meson resonance "melts"
- spectral function merges into QGP description

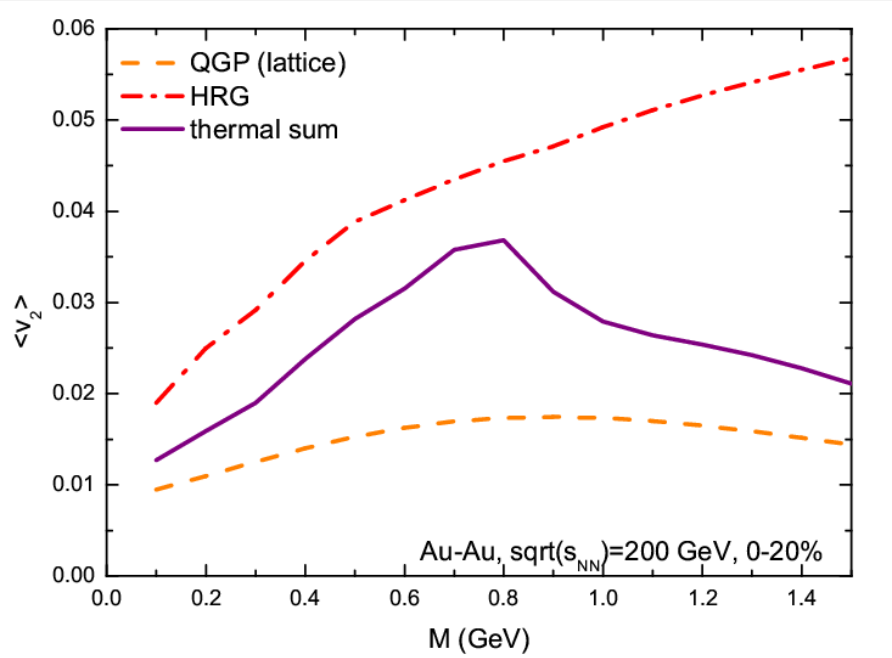
⇒ Direct evidence for transition hadrons → quarks + gluons




[Ding et al '10]

# 4.4 Elliptic Flow of Dileptons at RHIC



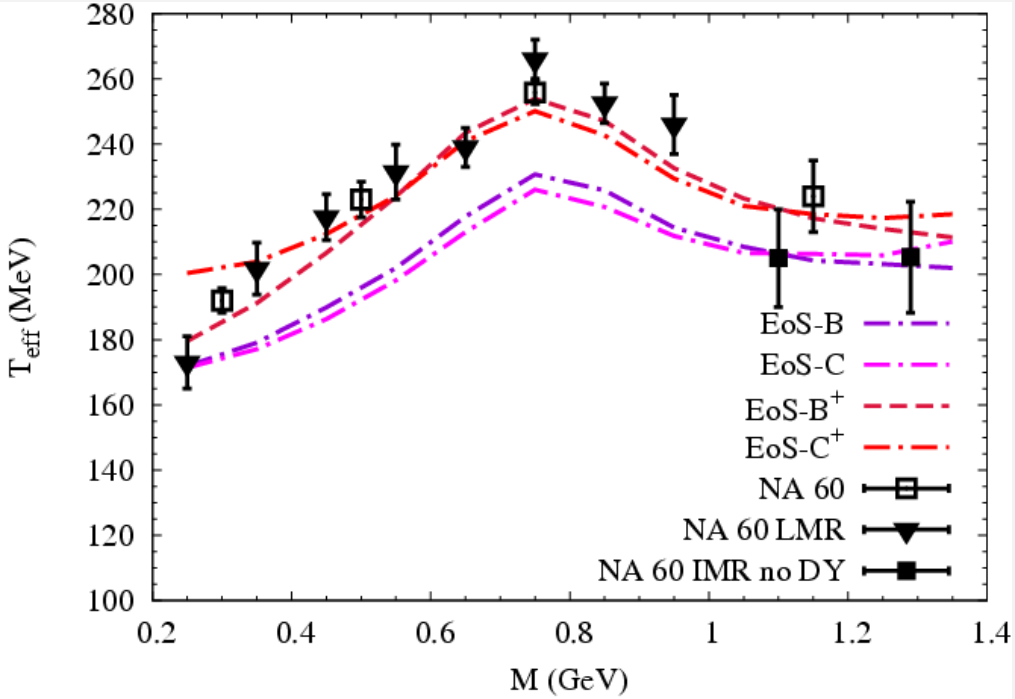

- maximum structure due to late ρ decays

[He et al '12]

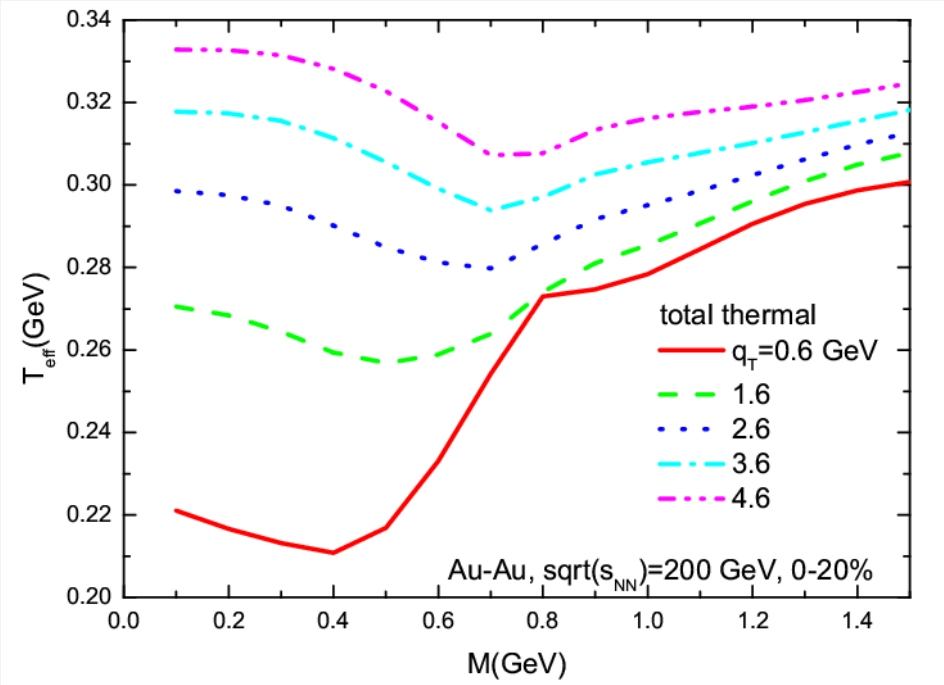
[Chatterjee et al '07, Zhuang et al '09]

# 4.5 QGP Barometer: Blue Shift vs. Temperature

**SPS**

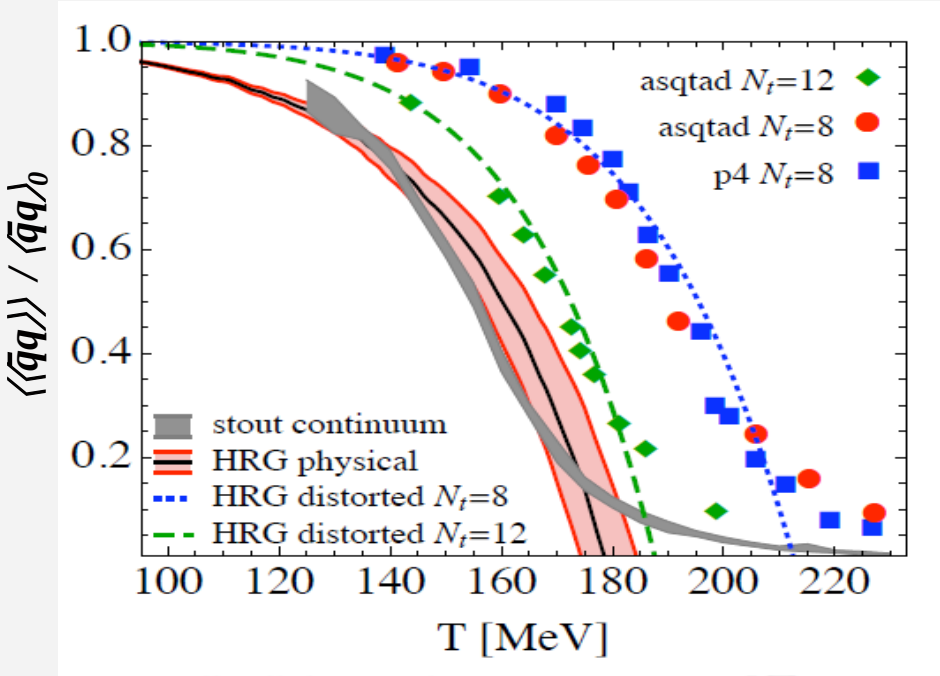


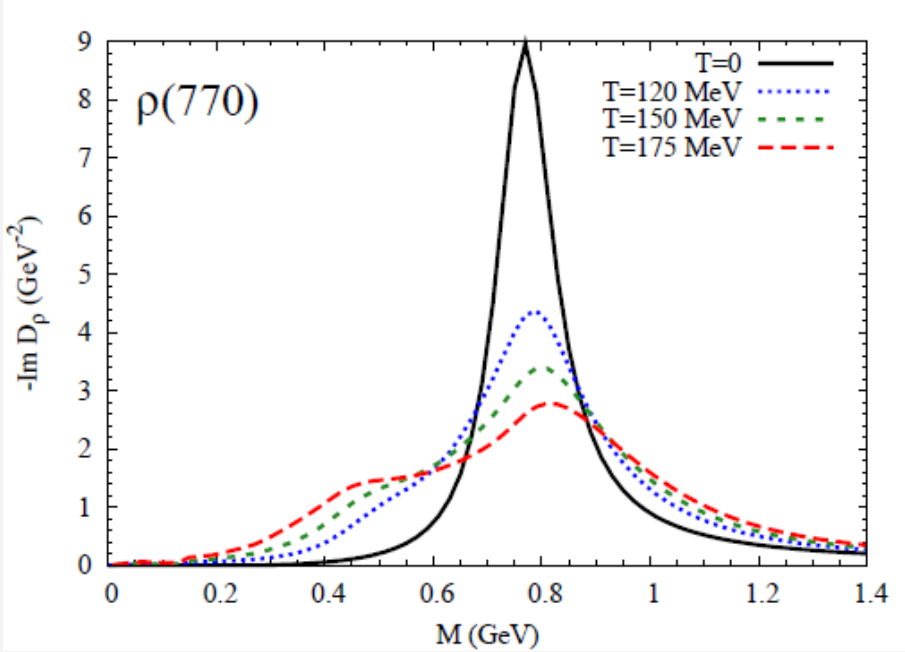

**RHIC**




- 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)

# 2.2 Chiral Condensate + ρ-Meson Broadening



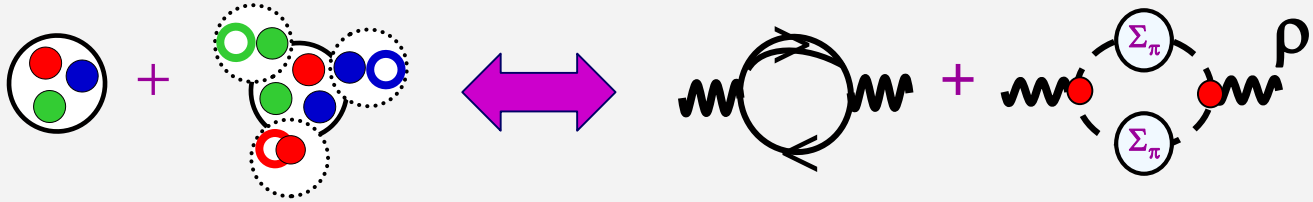




$$\frac{\langle\langle\bar{q}q\rangle\rangle(T,\mu_B)}{\langle\bar{q}q\rangle} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$$

⟺ effective hadronic theory

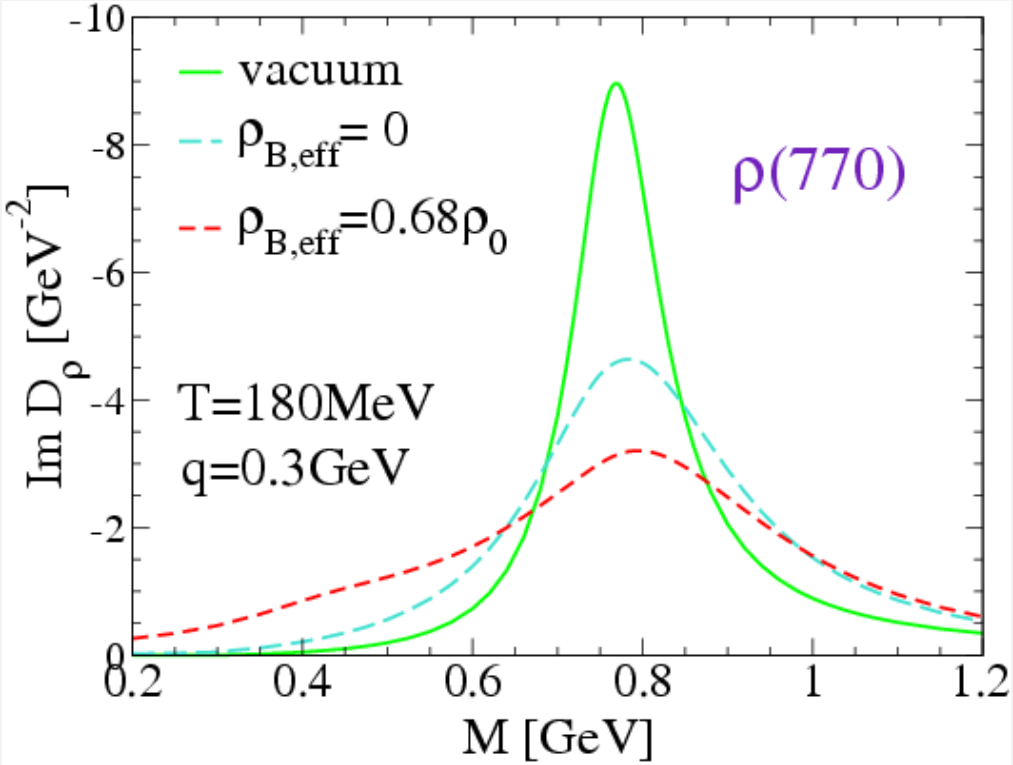
- $\Sigma_h = m_q \langle h|\bar{q}q|h\rangle > 0$ contains quark core + pion cloud

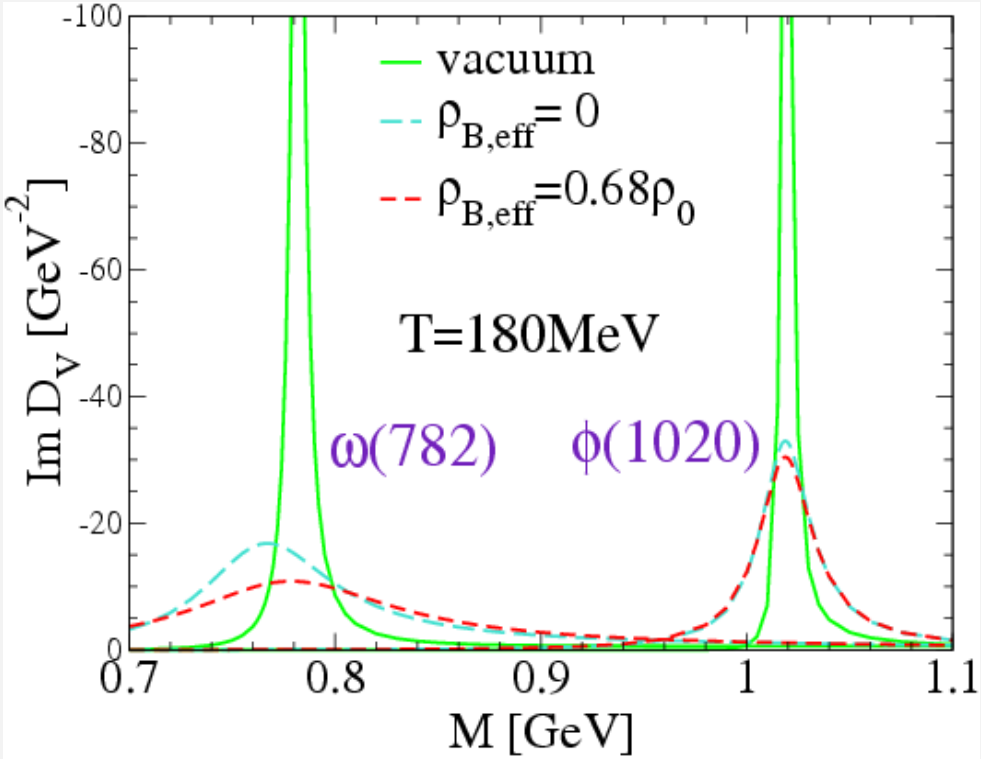
$= \Sigma_h^{core} + \Sigma_h^{cloud} \sim$




- **matches spectral medium effects: resonances + pion cloud**
- **resonances + chiral mixing drive ρ-SF toward chiral restoration**

# 4.7.2 Light Vector Mesons at RHIC + LHC

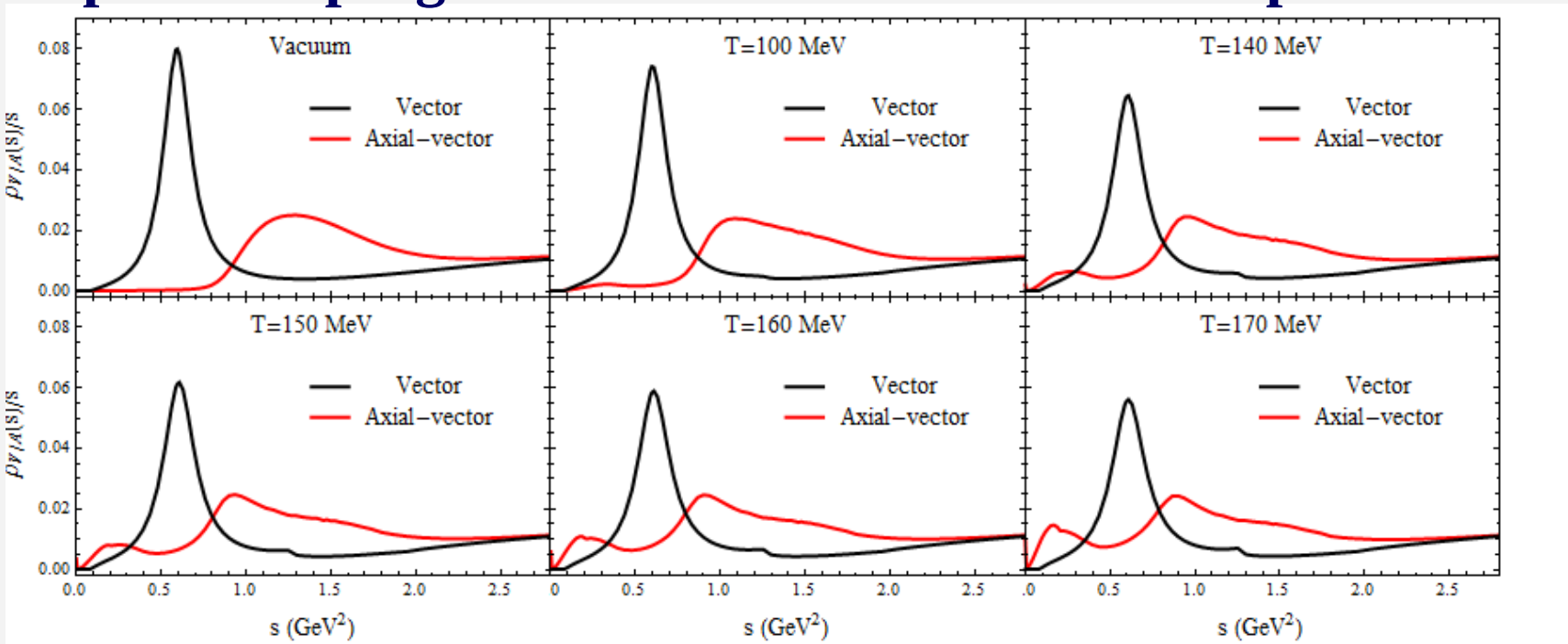


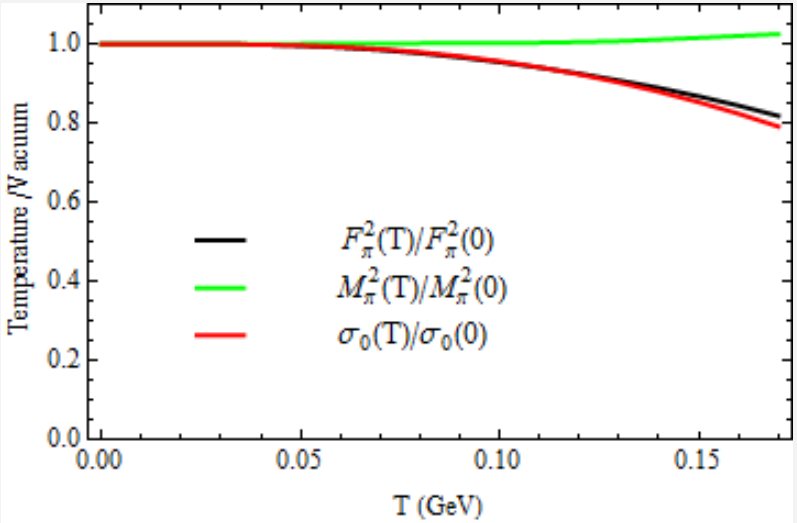

- **baryon effects important even at $\rho_{B,tot}$= 0 :**
  **sensitive to $\rho_{Btot}$= $\rho_B$ + $\rho_{\bar{B}}$ (ρ-N and ρ-$\bar{N}$ interactions identical)**
- **ω also melts, ϕ more robust ↔ OZI**

# 3.2 Massive Yang-Mills in Hot Pion Gas

## Temperature progression of vector + axialvector spectral functions




- supports "burning" of chiral-mass splitting as mechanism for chiral restoration [as found in sum rule analysis]



# 3.2 Massive Yang-Mills Approach in Vaccum

- Gauge **ρ** + **a$_1$** into chiral pion lagrangian:

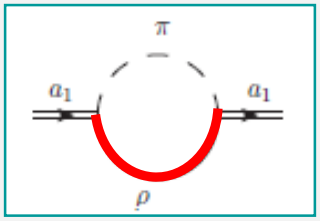
$$\mathcal{L}_{\rm MYM} = \frac{\tilde{f}_\pi^2}{8}(\mathrm{Tr}[D_\mu U^\dagger D^\mu U] + \tilde{m}_\pi^2 \mathrm{Tr}[U + U^\dagger - 2]) - \frac{1}{2}\mathrm{Tr}[F_L^2 + F_R^2] + m_0^2 \mathrm{Tr}[A_L^2 + A_R^2] - i\xi\ \mathrm{Tr}[D_\mu U D_\nu U^\dagger F_L + D_\mu U^\dagger D_\nu U F_R] + \gamma\ \mathrm{Tr}[F_L U F_R U^\dagger]\ ,$$

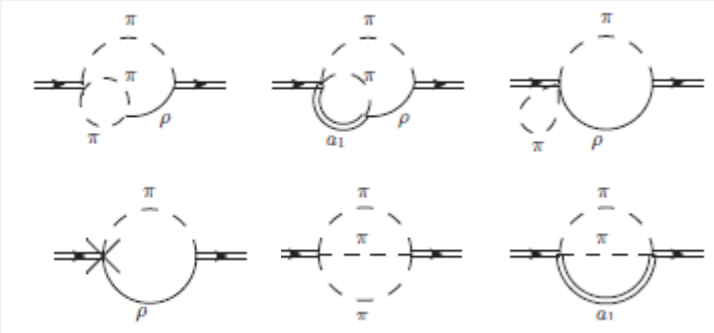
- problems with vacuum phenomenology

  → global gauge? **[Urban et al '02, Rischke et al '10]**

- Recent progress:
  - **full ρ** propagator in **a$_1$** selfenergy
  - **vertex corrections** to preserve **PCAC:**

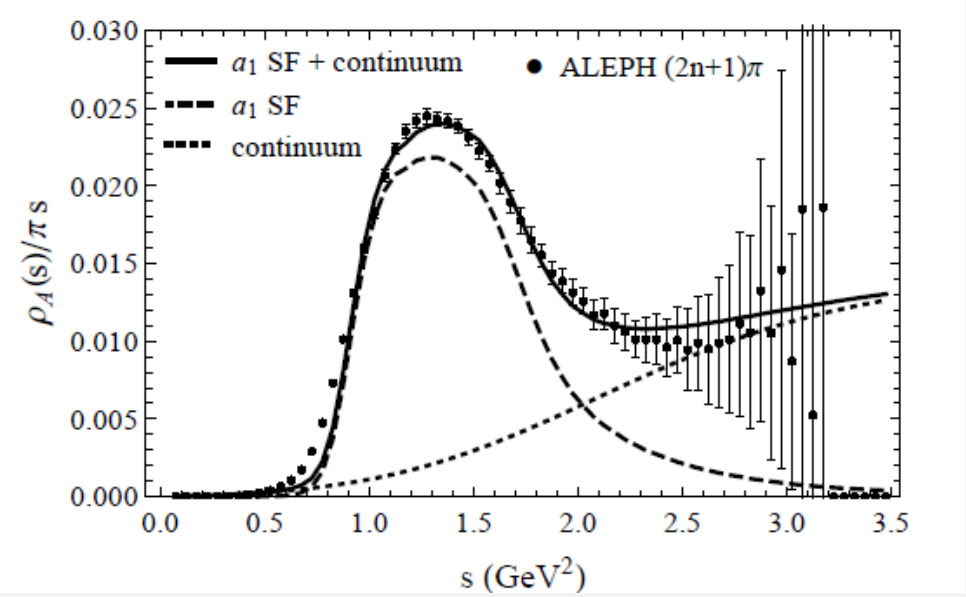
$$\int \frac{(-\mathrm{Im}\Pi_A^L)}{\pi s} ds = \frac{F_\pi^2}{2}$$



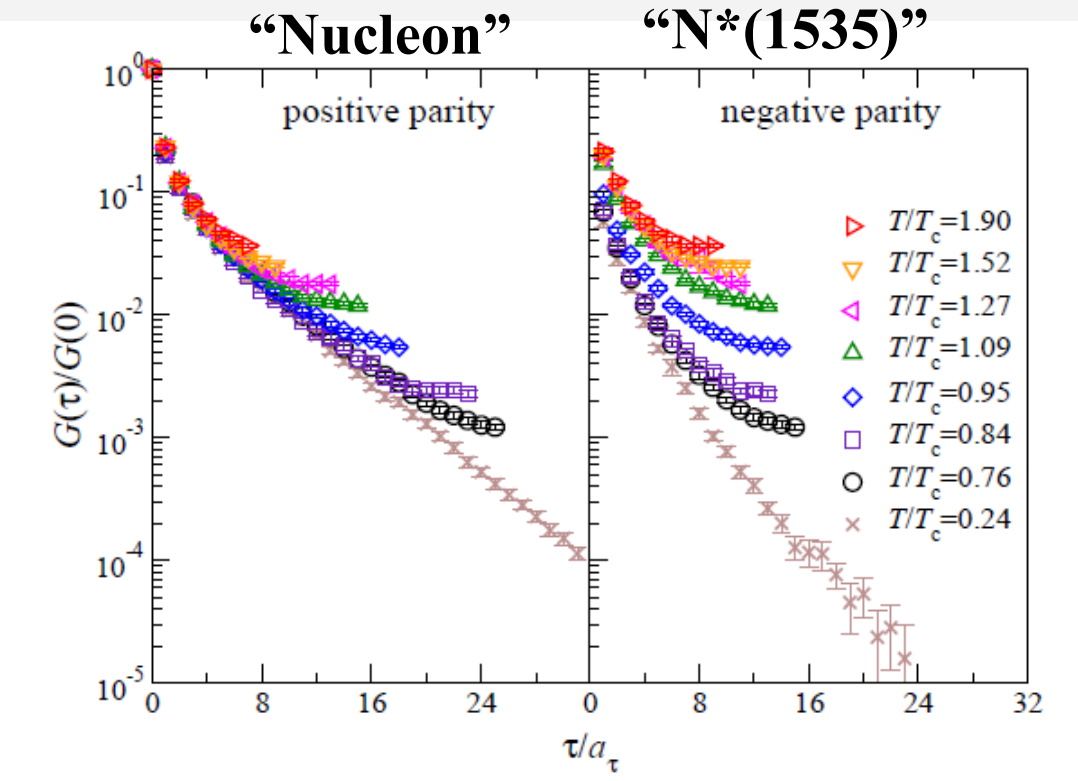
**[Hohler +RR '14]**

- enables fit to **τ**-decay data!
- local-gauge approach viable
- starting point for addressing **chiral restoration in medium**



# 3.2 Lattice-QCD Results for N(940)-N*(1535)

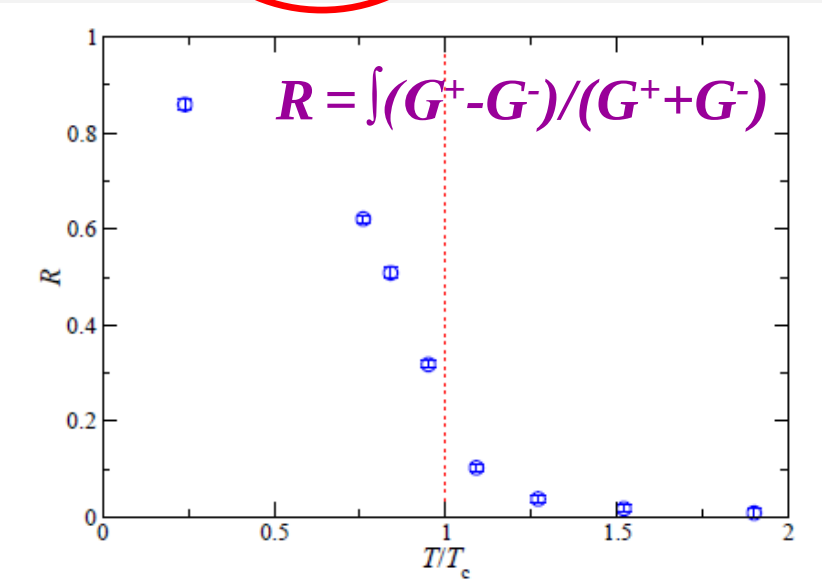
## Euclidean Correlator Ratios




[Aarts et al '15]

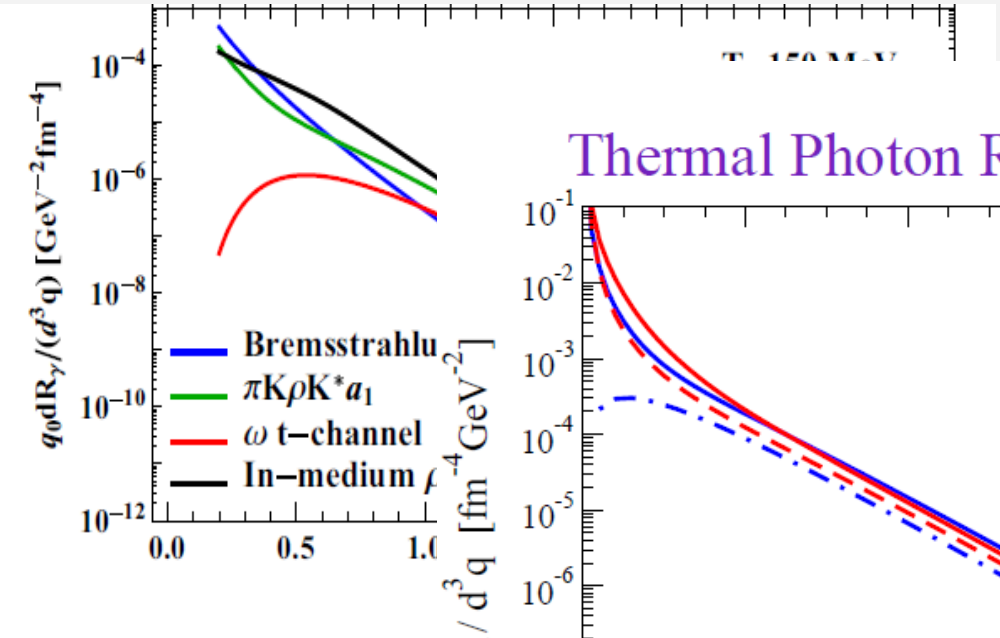
## Exponential Mass Extraction

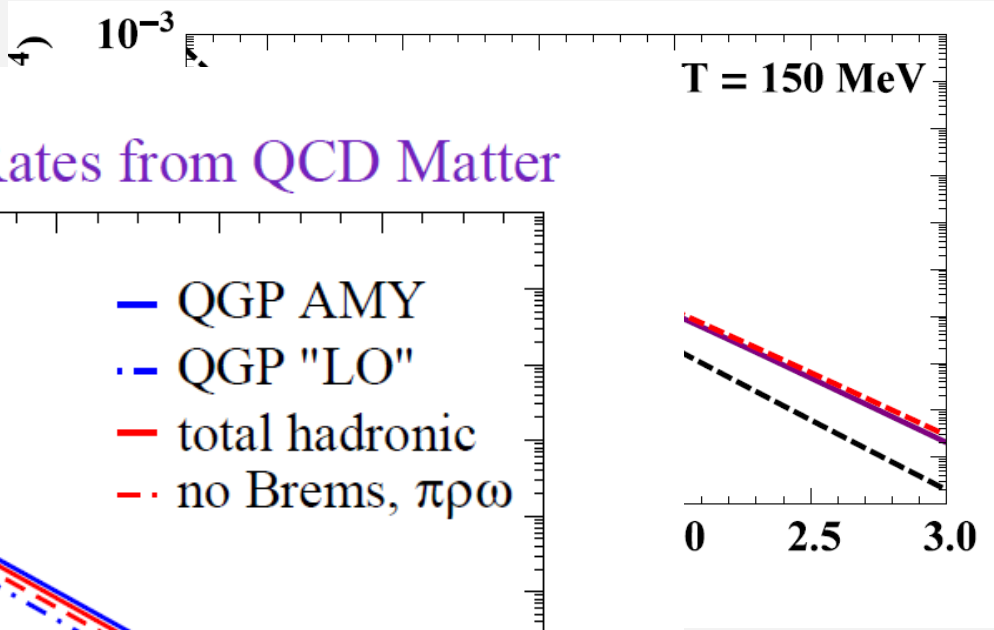
| $T/T_c$ | $m_+$ [GeV] | $m_-$ [GeV] | $\Delta$ |
|---|---|---|---|
| 0.24 | 1.20(3) | 1.9(3) | 0.209(28)(082) |
| 0.76 | 1.18(9) | 1.6(2) | 0.138(29)(130) |
| 0.84 | 1.08(9) | 1.6(1) | 0.197(39)(054) |
| 0.95 | 1.12(14) | 1.3(2) | 0.052(35)(190) |

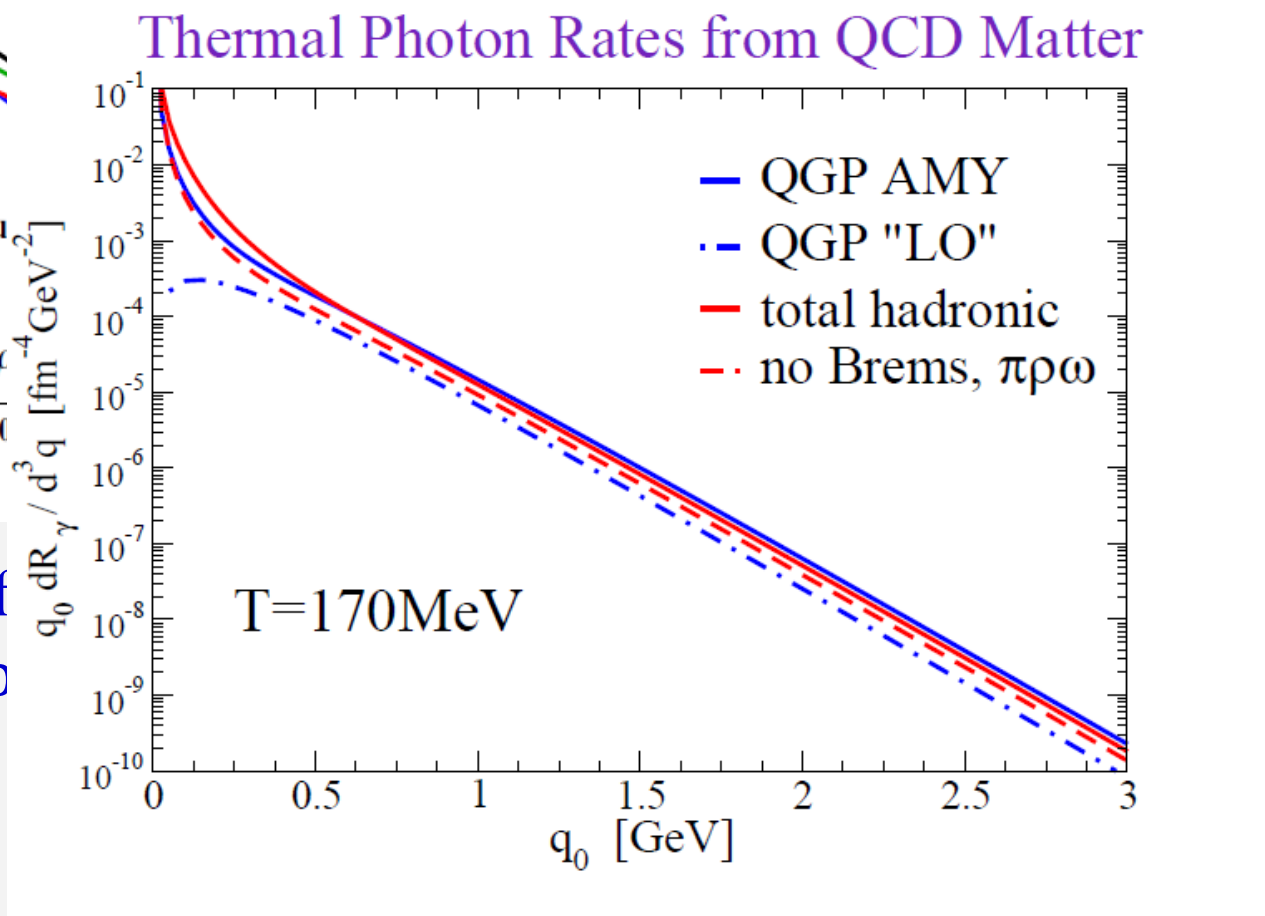



- also indicates $M_{N^*}(T) \rightarrow M_N(T) \approx M_N^{vac}$
- see also talk by **R.-A. Tripolt**

# 4.2 Thermal Photon Rates



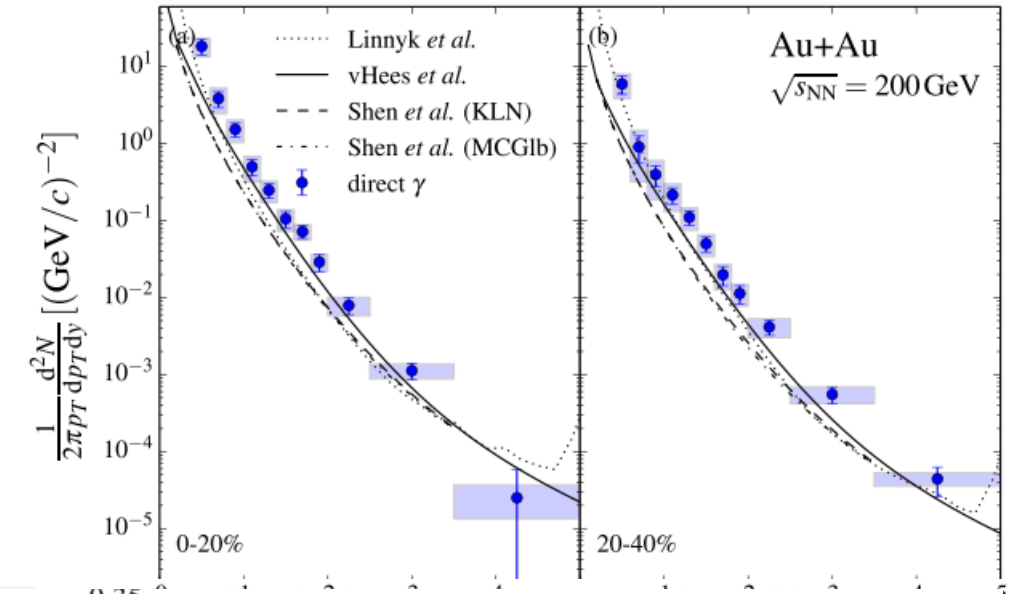



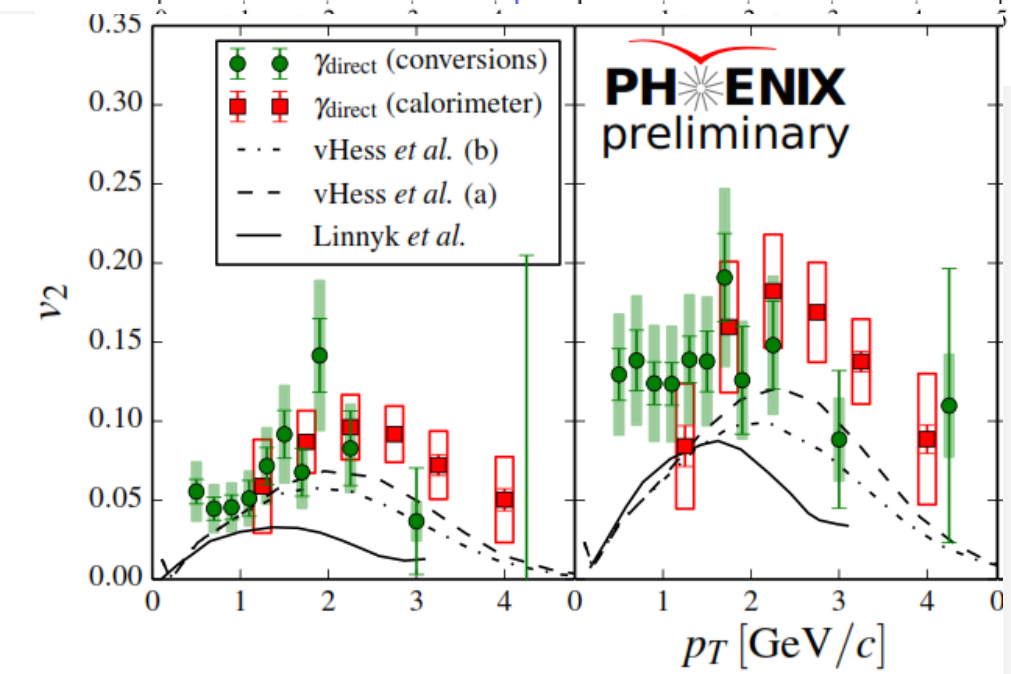

- ``Cocktail" of ... ources:
  (available in p... $\rho\omega \rightarrow \gamma\pi$

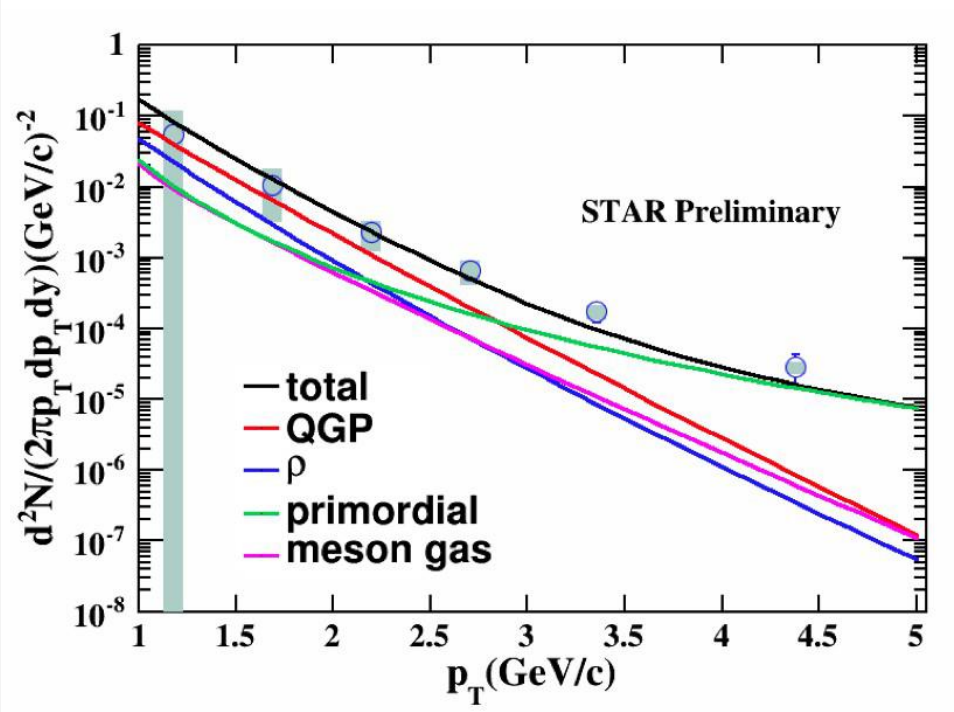
[Heffernan ... Iohler+RR in prep]

- Hadronic emission rate close to QGP-**AMY**
- semi-QGP much more suppressed [Pisarski et al '14]

# 4.3.2 Photon Puzzle!?



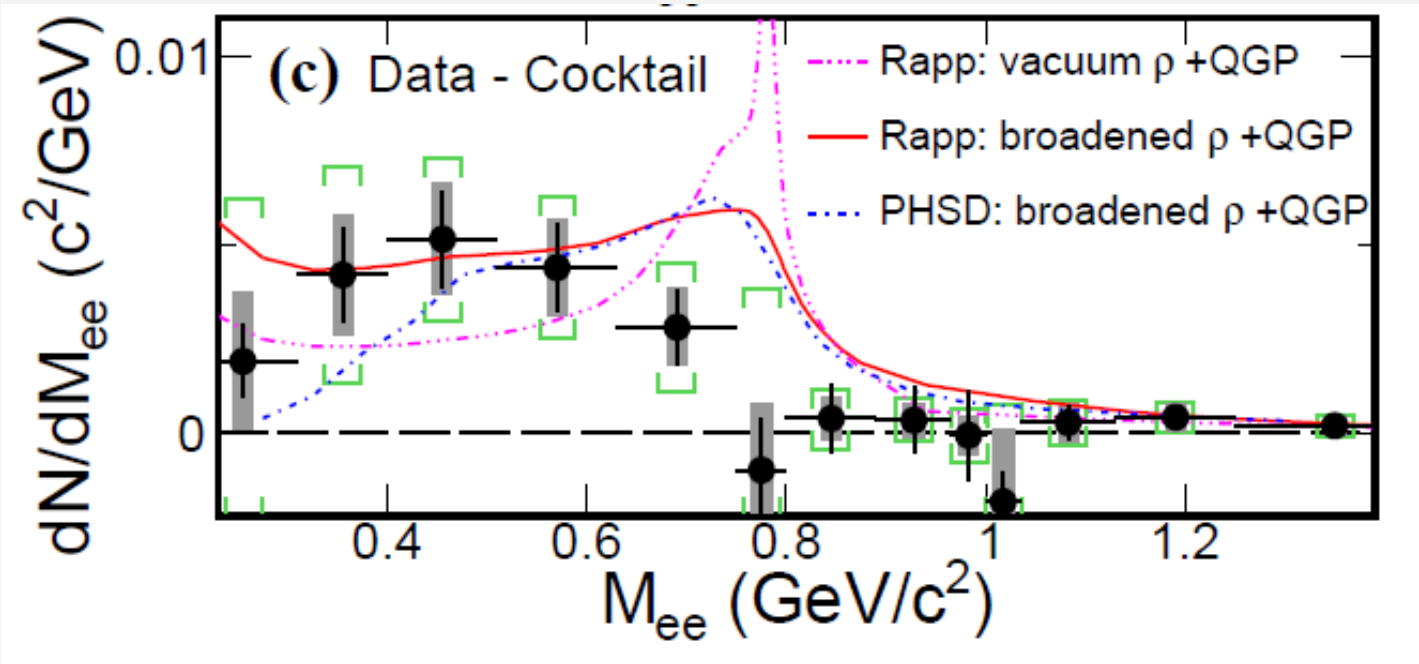




- $T_{slope}^{excess} \sim 240$ MeV
- blue-shift: $T_{slope} \sim T\sqrt{(1+\beta)/(1-\beta)}$

  $\Rightarrow T \sim 240/1.4 \sim 170$ MeV

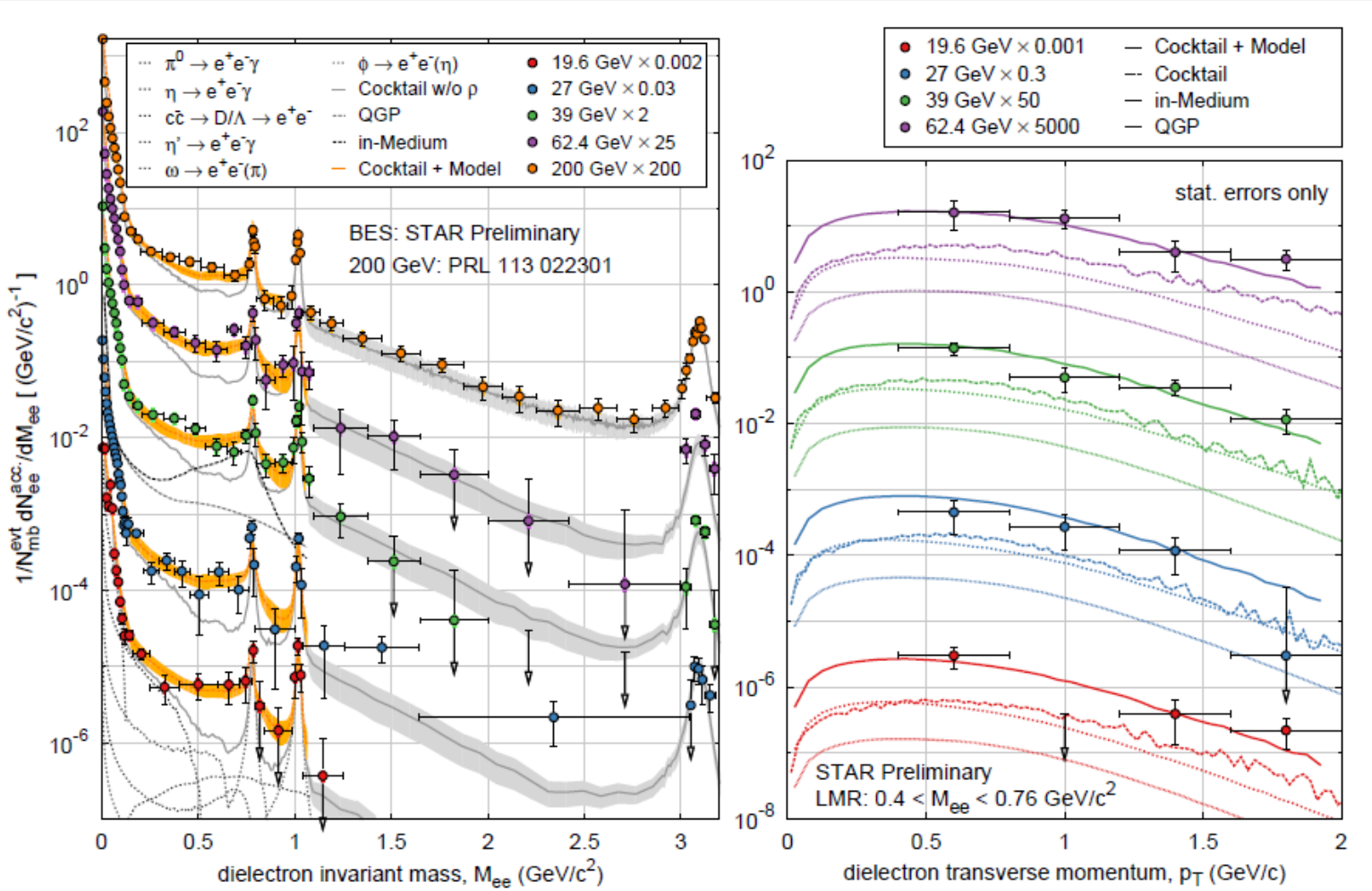
# 4.1 Prospects I: Spectral Shape at $\mu_B \sim 0$

**STAR Excess Dileptons** [STAR '14]




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

# 2.3 Low-Mass $e^+e^-$ Excitation Function: 20-200 GeV

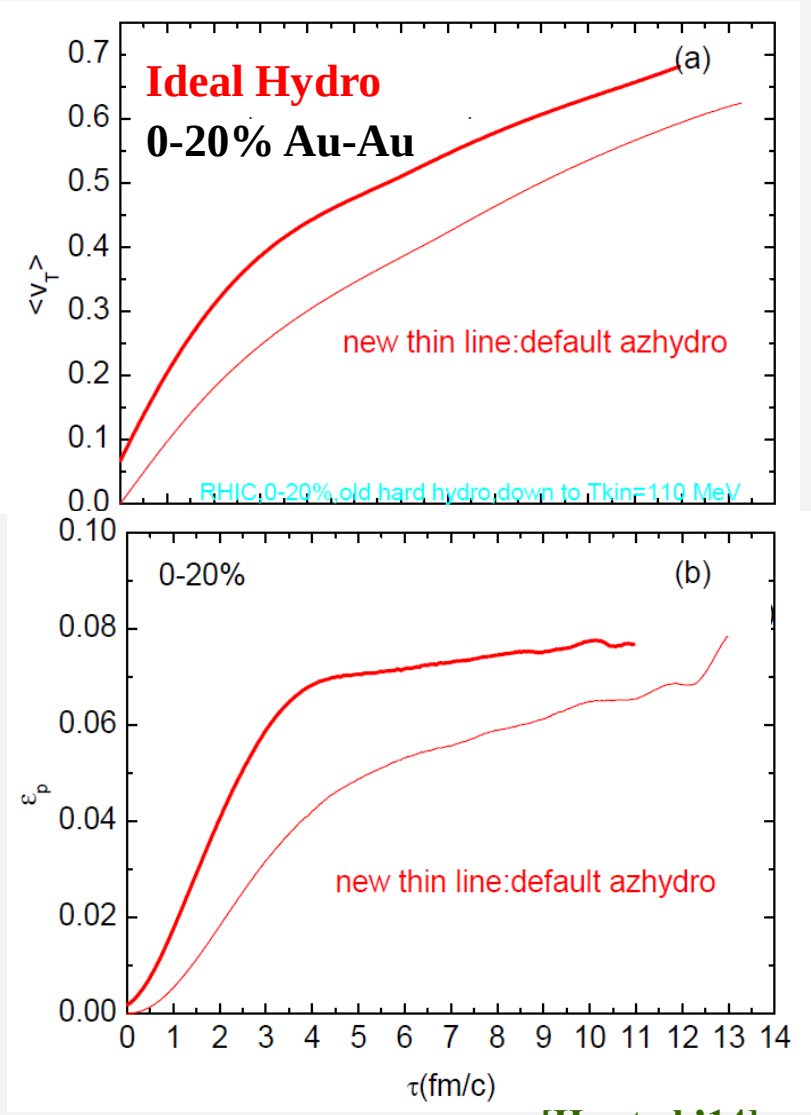



P. Huck et al. [STAR], QM14

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

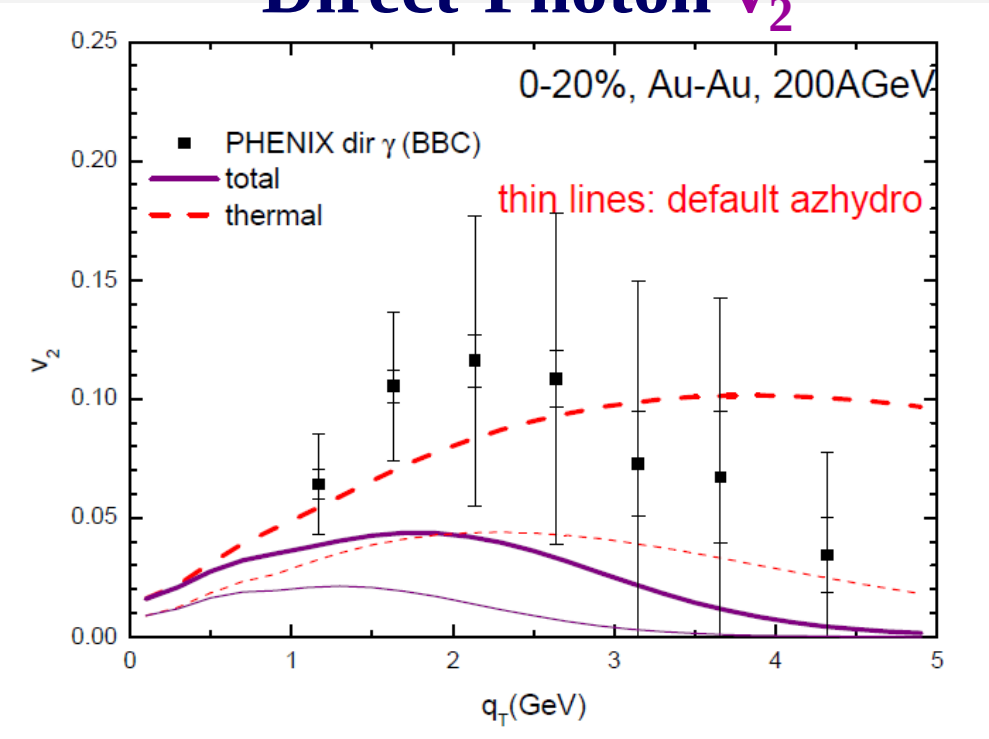
# 4.1 Initial Flow + Thermal Photon-$v_2$

## Bulk-Flow Evolution




[He et al '14]

## Direct-Photon $v_2$



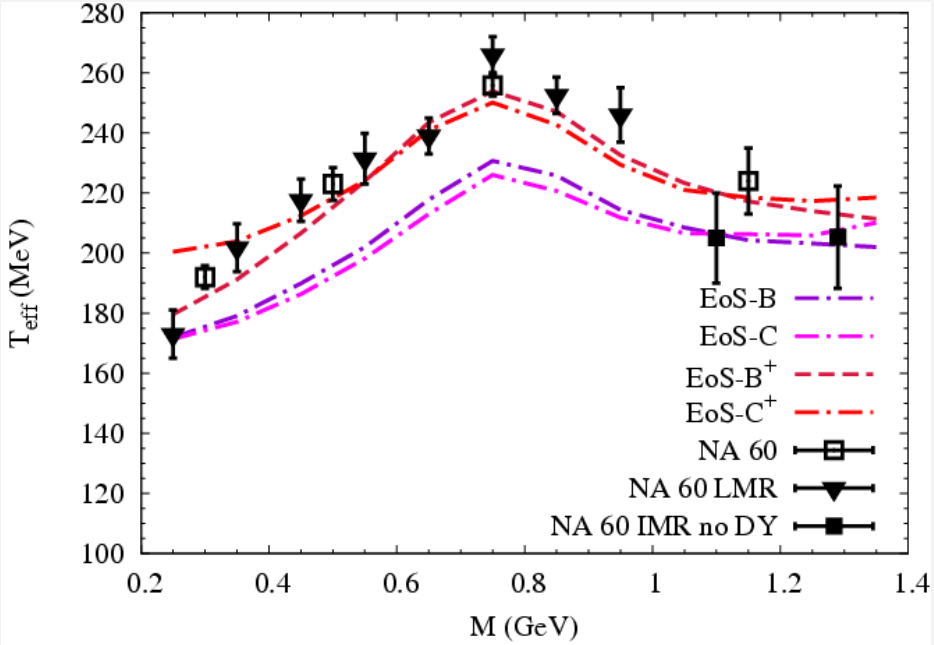

- initial radial flow: - accelerates bulk $v_2$
  - harder radiation spectra

  (pheno.: coalescence, multi-strange f.o.)
- much enhances thermal-photon $v_2$

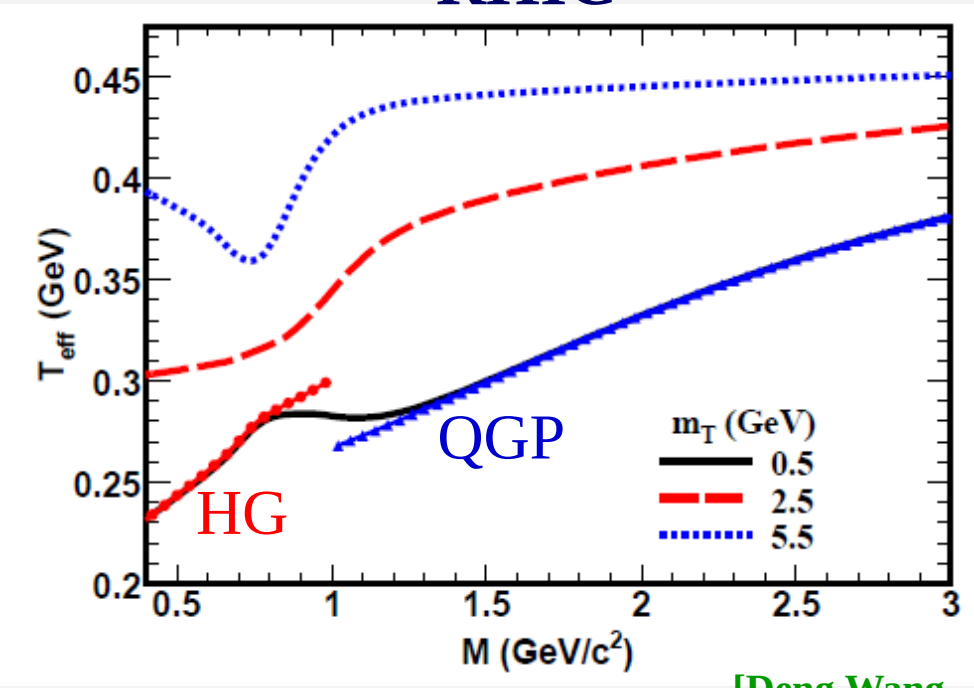
# 3.1.2 Transverse-Momentum Spectra: Baro-meter

## Effective Slope Parameters

**SPS**



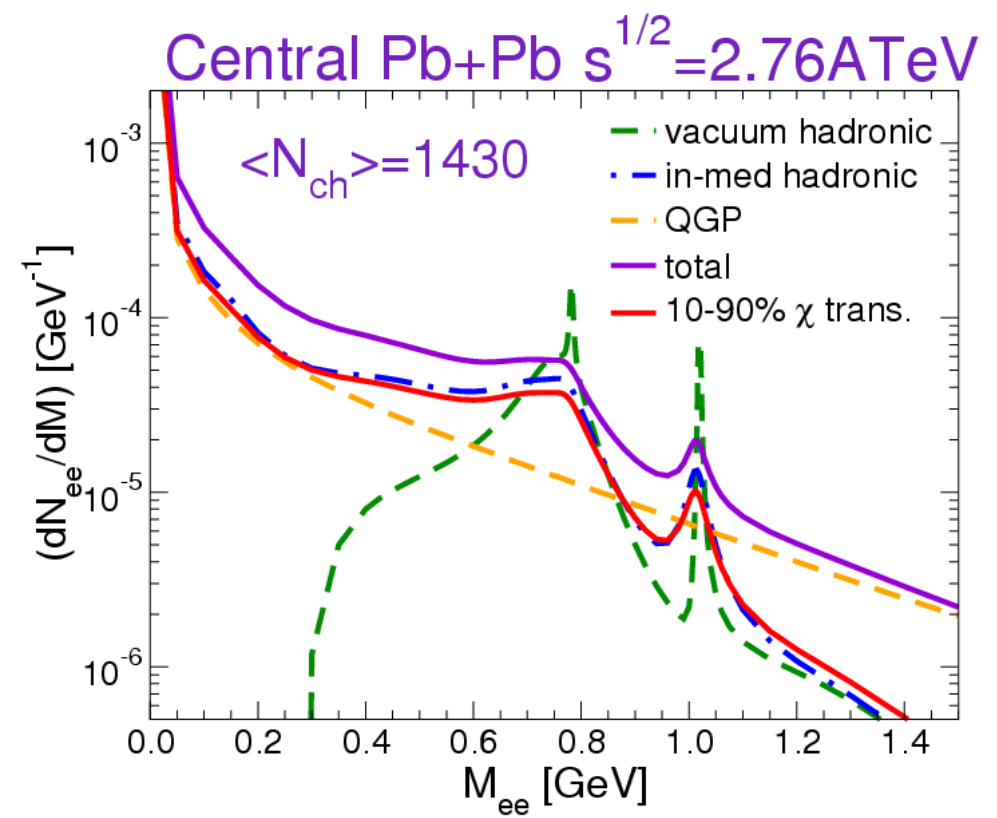

**RHIC**

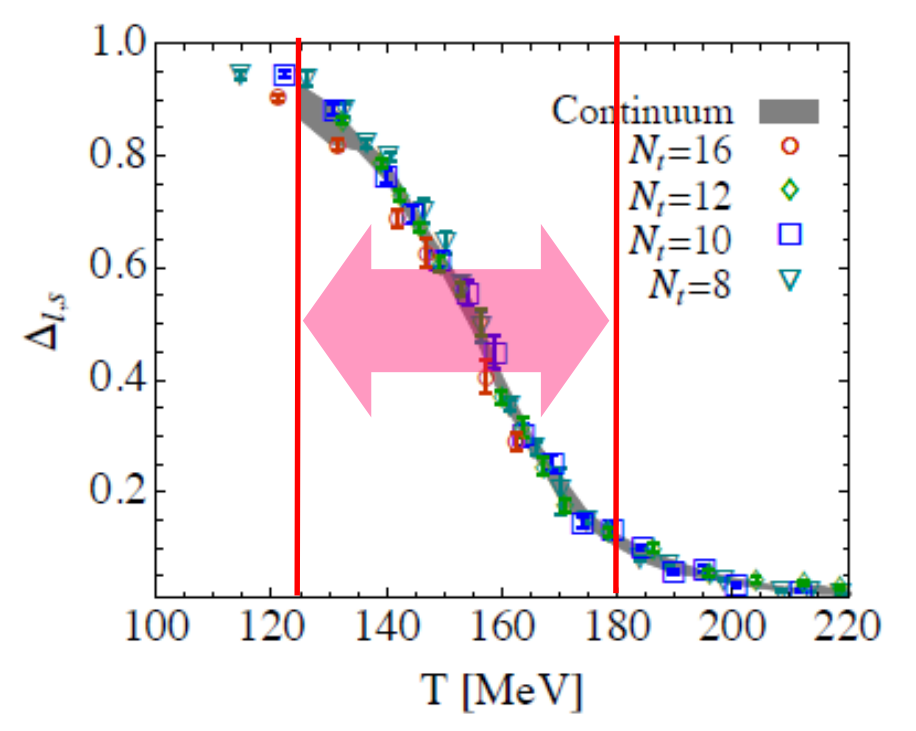



[Deng,Wang, Xu+Zhuang '11]

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

# 5.2 Chiral Restoration Window at LHC



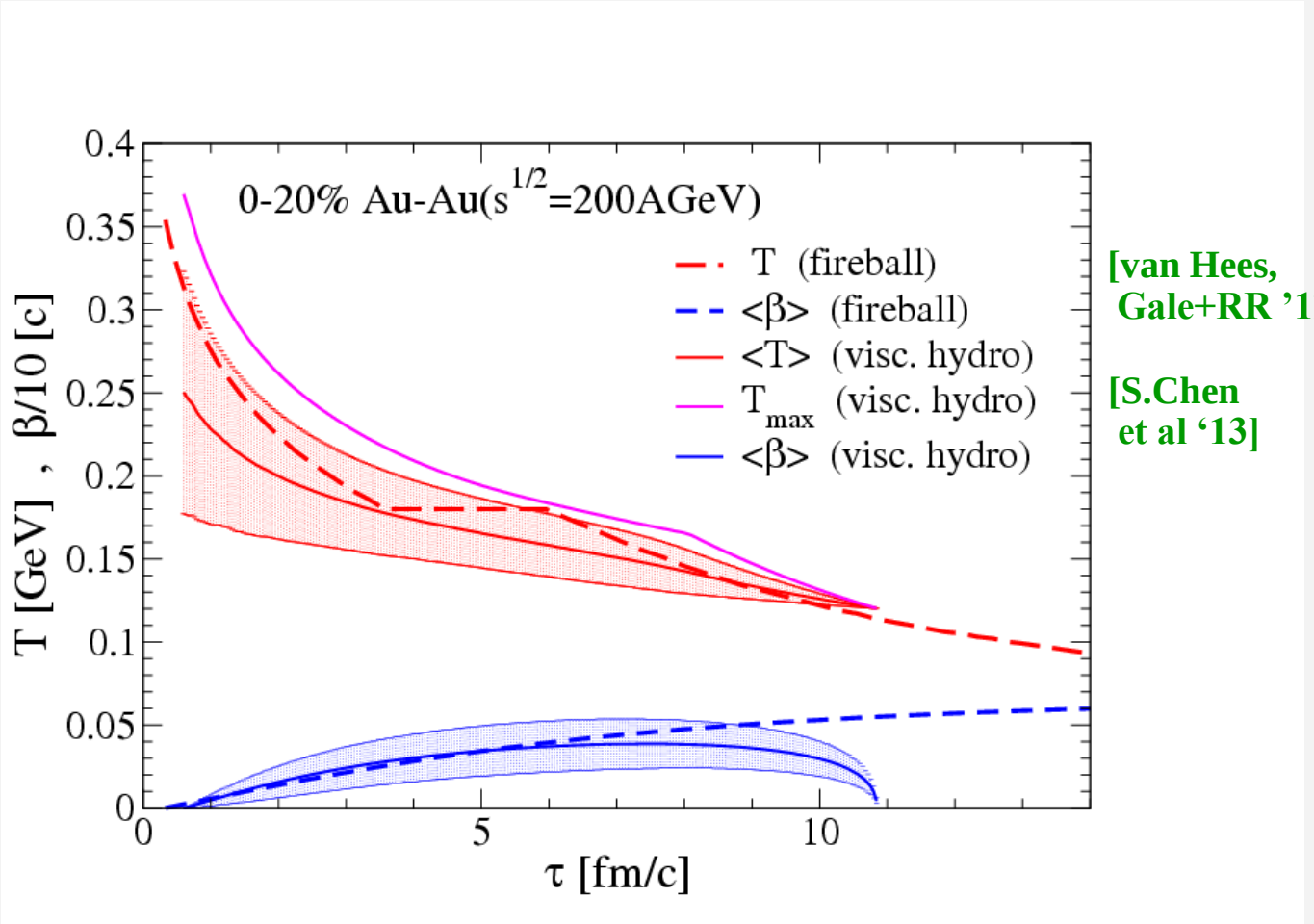

- low-mass spectral shape in chiral restoration window:

  **~60%** of thermal low-mass yield in "chiral transition region"

  **(T=125-180MeV)**

- enrich with (low-) $\mathbf{p_t}$ cuts

# 3.3.2 Fireball vs. Viscous Hydro Evolution



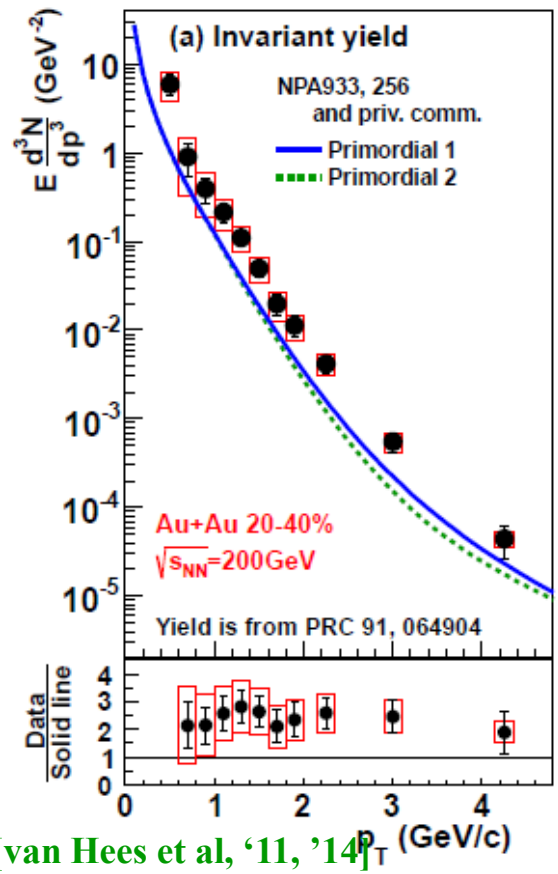

[van Hees, Gale+RR '11]

[S.Chen et al '13]

- very similar!

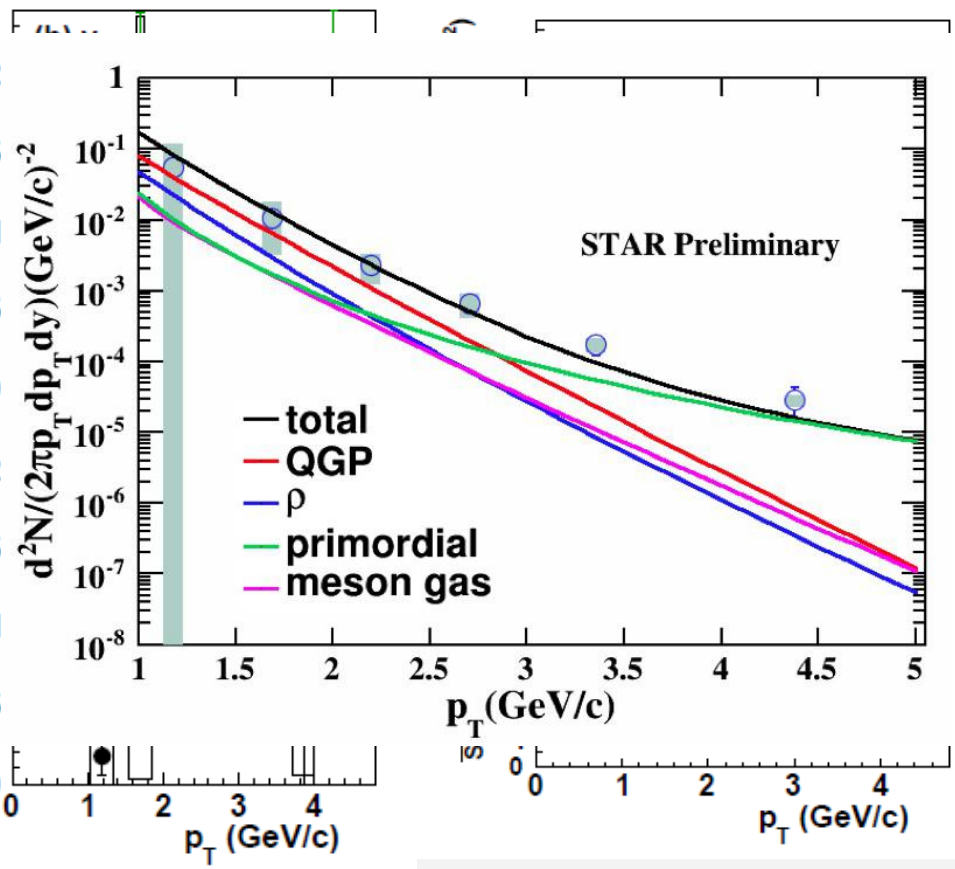
# 4.3 Comparison to Data: RHIC

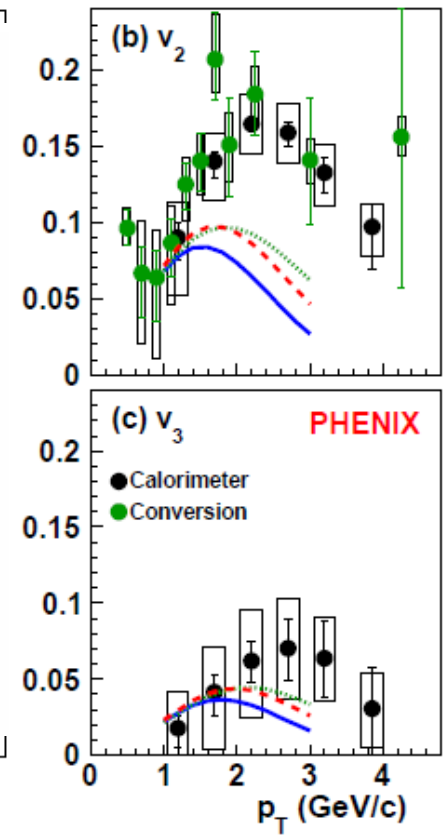
## Ideal Hydro




[van Hees et al, '11, '14]

## Viscous Hydro

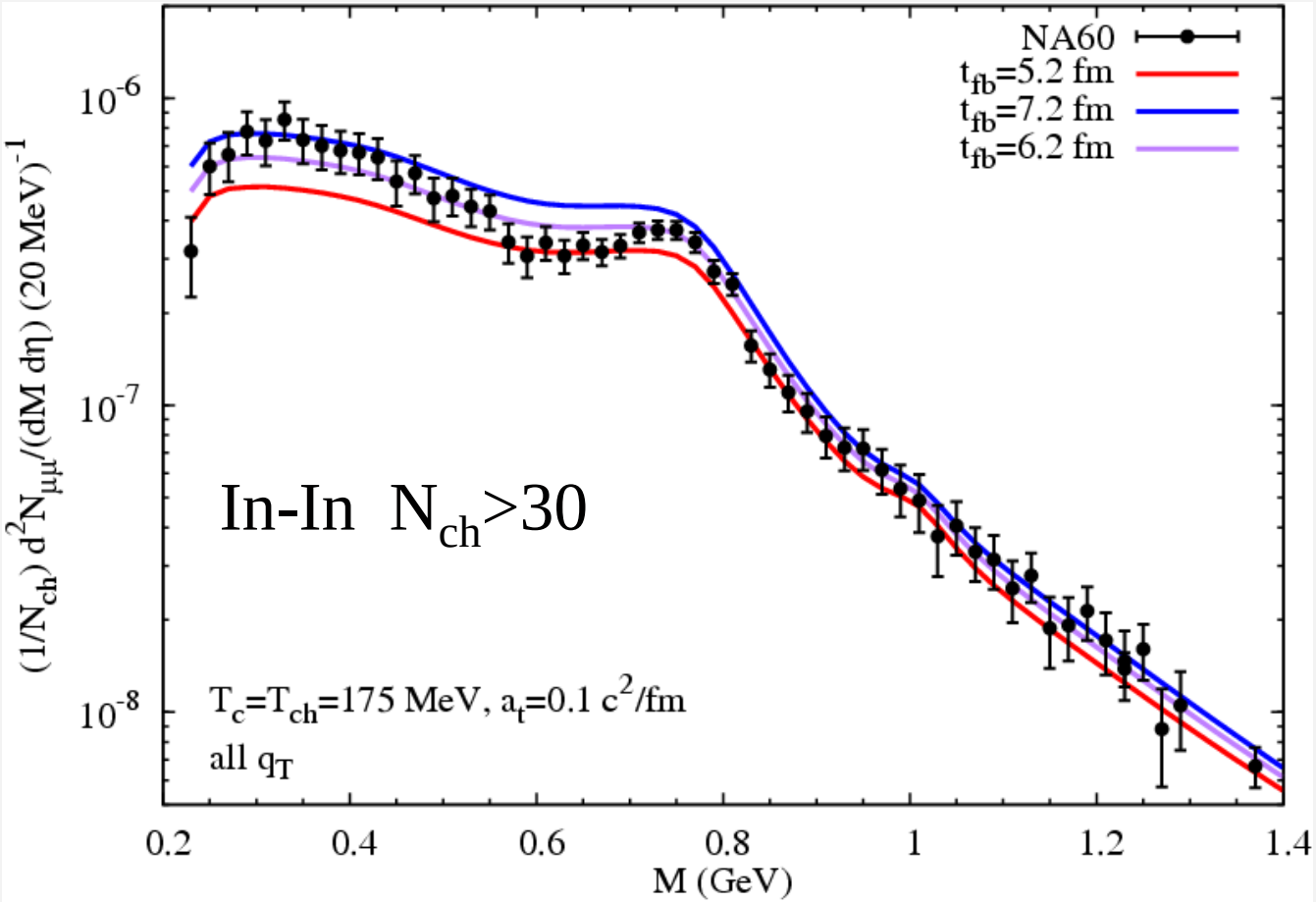



[Paquet et al '16]

- same rates + intial flow ⇒ similar results from various evolution models

# 4.2 Low-Mass Dileptons: Chronometer




- first "explicit" measurement of interacting-fireball **lifetime**:

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