Dileptons at Low Mass and Low Momentum

Ralf Rapp
Cyclotron Institute +
Dept of Phys & Astro
Texas A&M University
College Station, USA

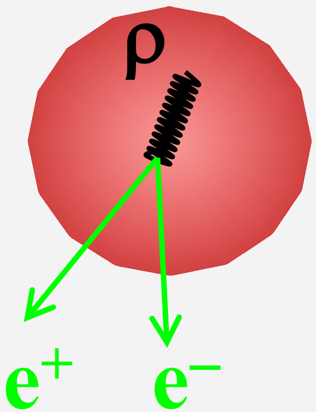
CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

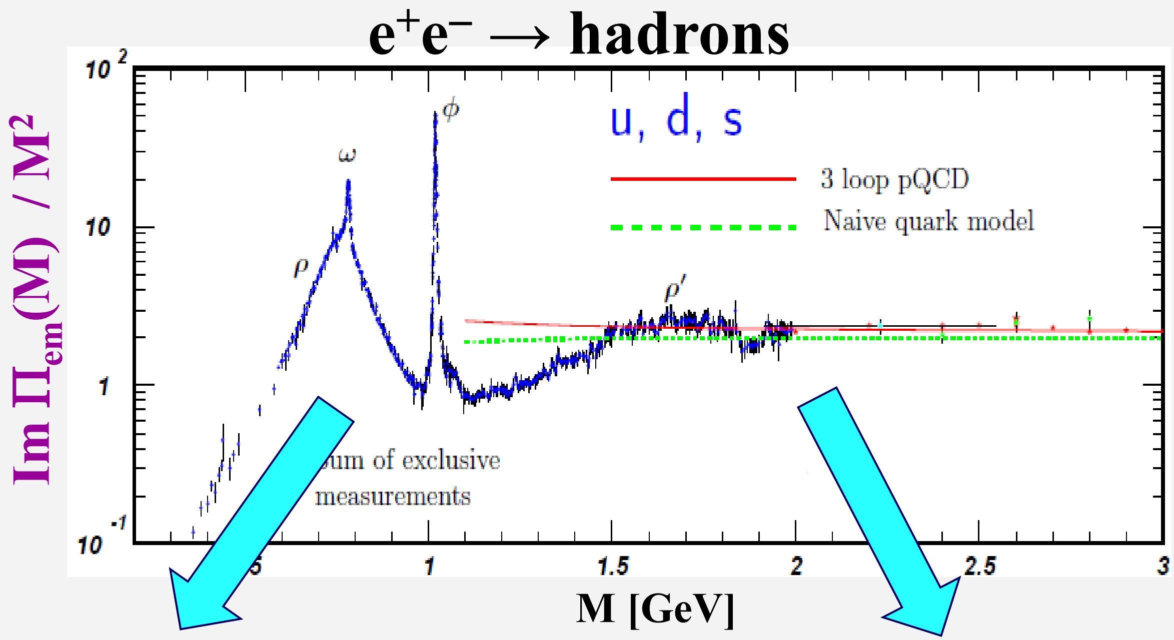
Alexander von Humboldt
Stiftung/Foundation

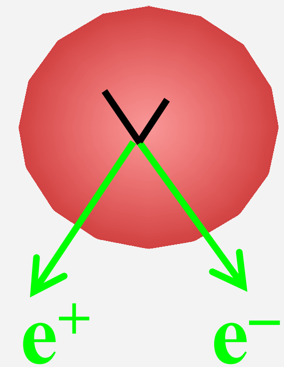
ECT* Workshop on
"Electromagnetic Probes of Hot and Dense Matter"
ECT* (Trento, Italy), 26.-30.11.18

1.) Intro: EM Spectral Function to Probe Fireball

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







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

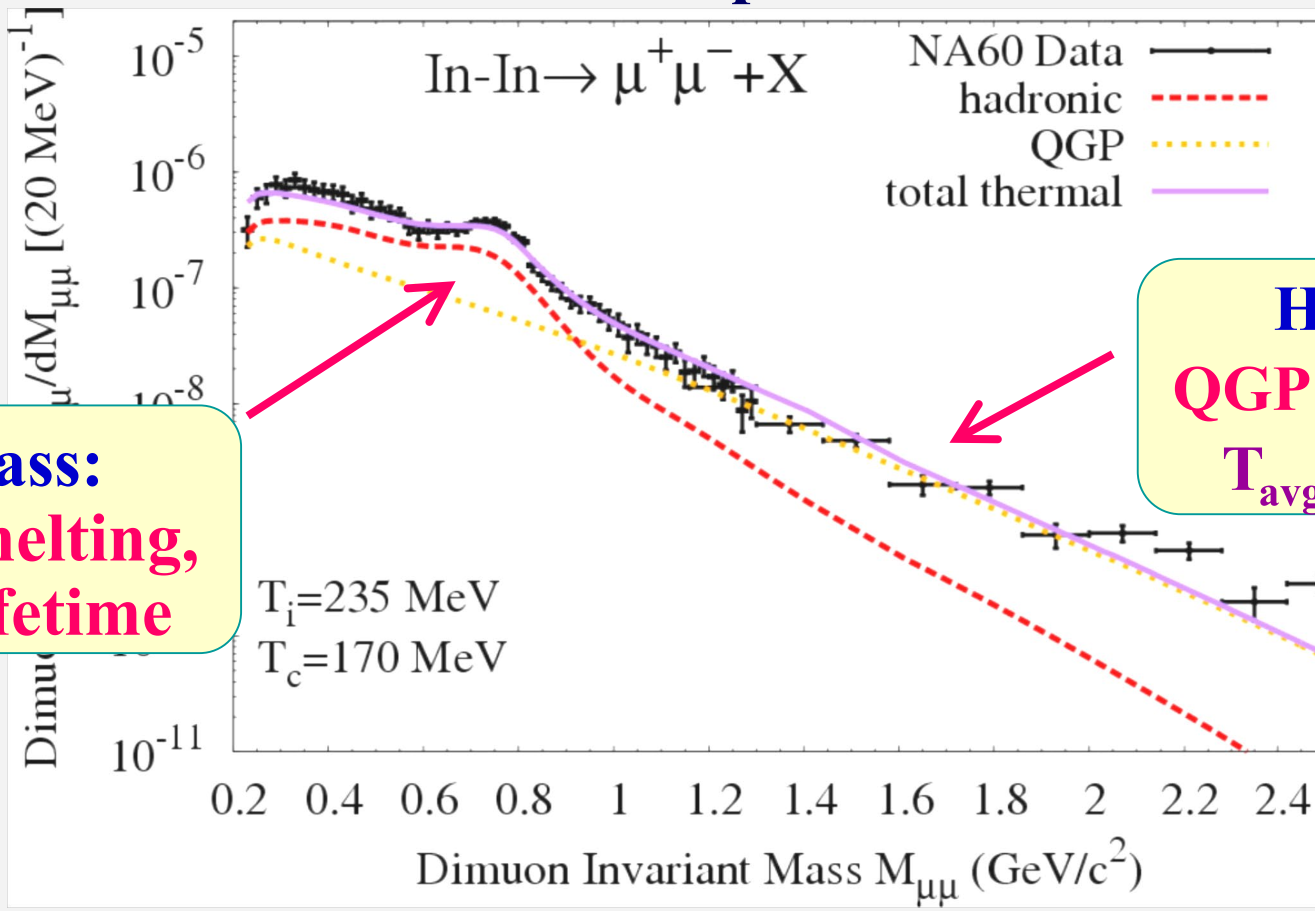
- **Low-q_0,q limit: transport coefficient (EM conductivity)**
- **Total yields: fireball lifetime**

1.2 NA60 Dimuons at SPS ($\sqrt{s}$=17.3 GeV)

- Integrate rates over thermal fireball:

$$\frac{dN_{ll}}{dM} = \int d^4x \, \frac{M d^3q}{q_0} \, \frac{dN_{ll}}{d^4x d^4q}$$

Radiation Spectrum

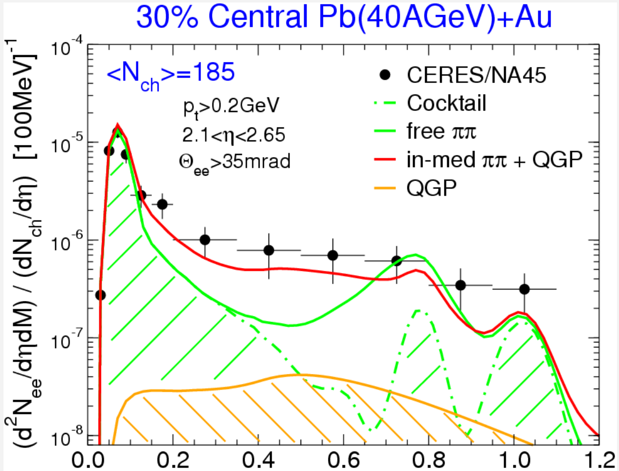


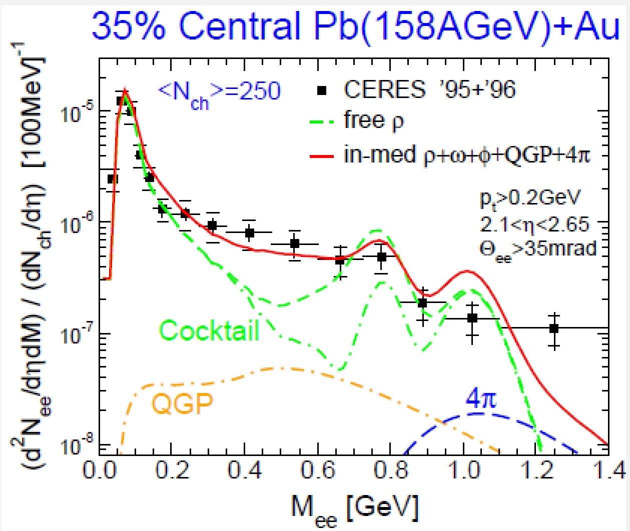
Low mass:
ρ-meson melting, fireball lifetime

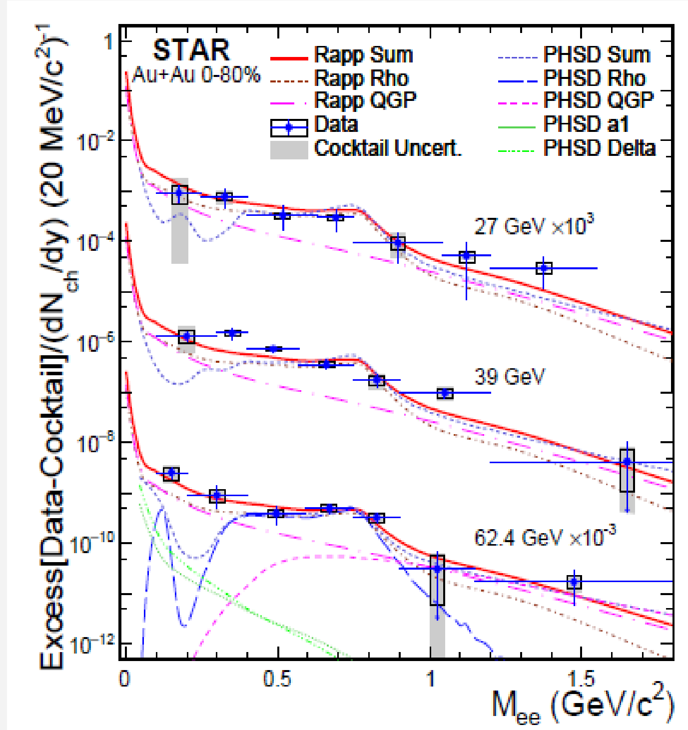
High mass:
QGP thermometer
T_{avg} ~ 200 MeV

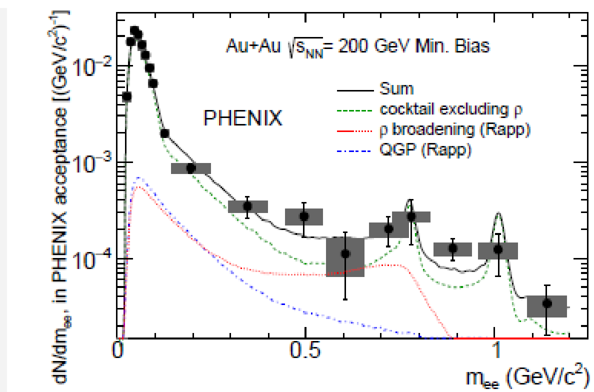
[van Hees+RR '14]

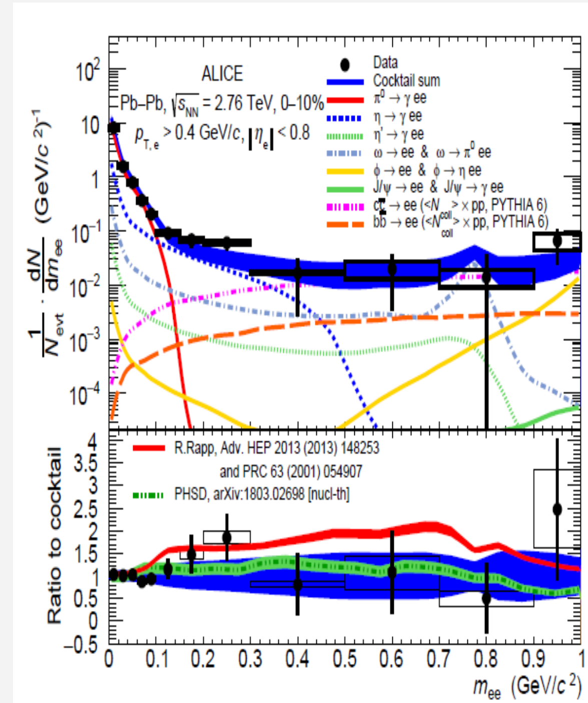
1.3 Dilepton Radiation from SPS via RHIC to LHC











- **Robust understanding across QCD phase diagram: QGP + hadronic radiation with melting ρ resonance**

Outline

1.) **Introduction**

2.) **Thermal Radiation**

- Quark-Hadron Transition
- Chiral Symmetry Restoration

3.) **Very-Low Momentum + Mass**

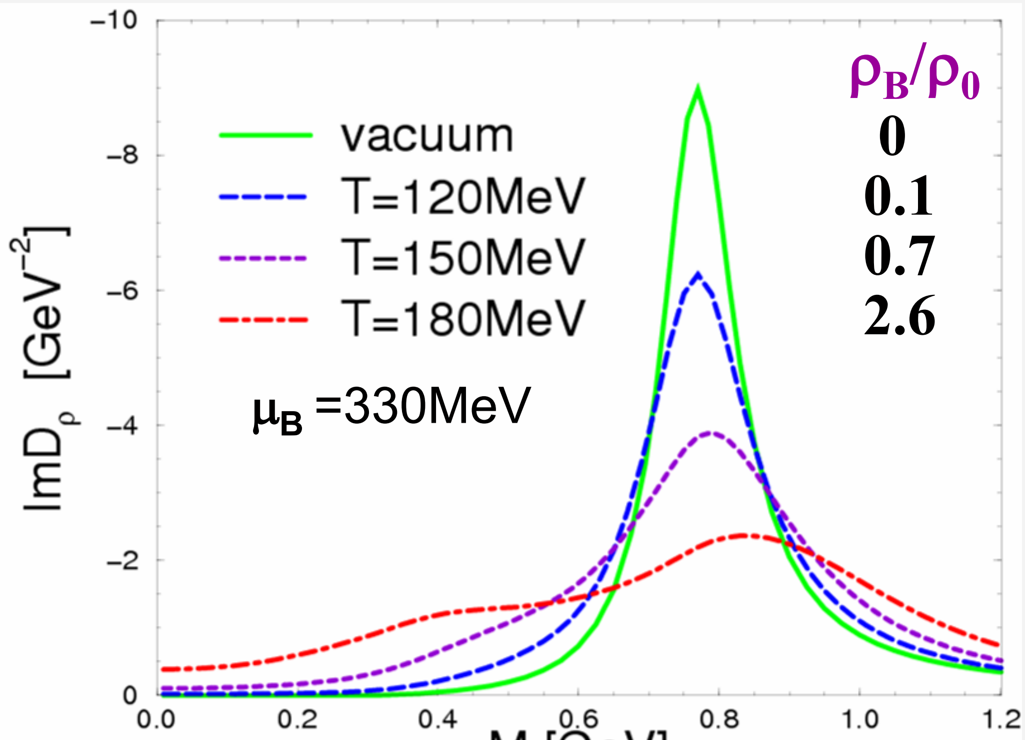
- EM Conductivity
- Coherent Radiation

4.) **Conclusions**

2.1 In-Medium ρ-Meson Spectral Functions

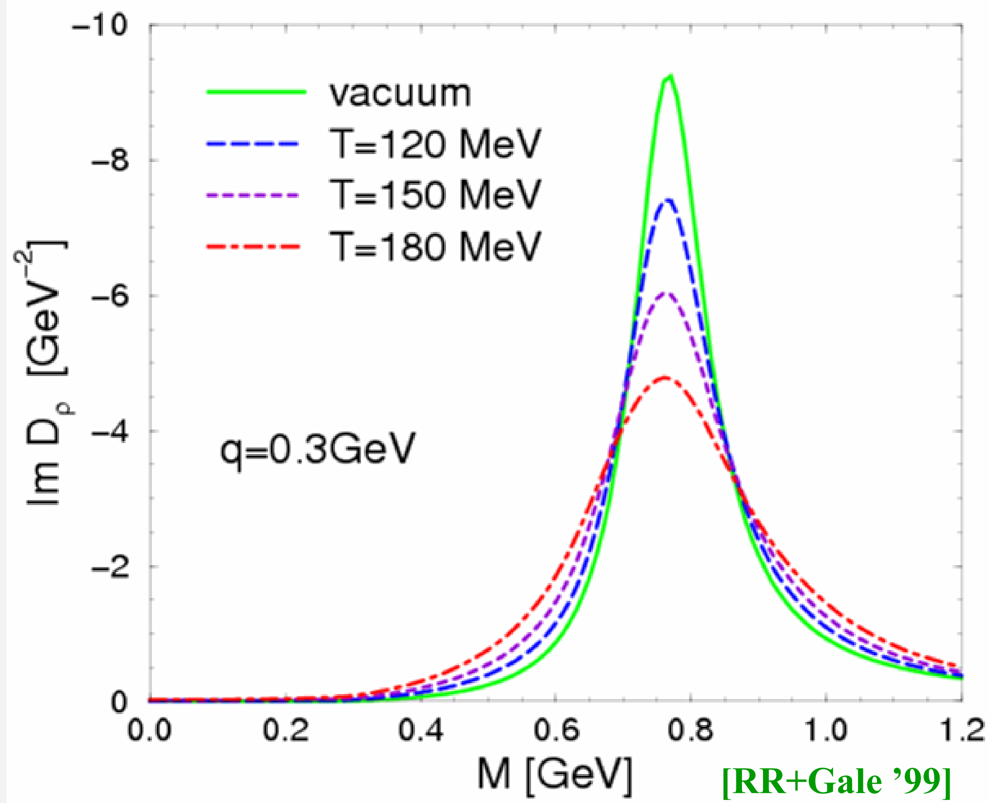
$$D_\rho(M,q;\mu_B,T) = 1 / [M^2 - (m_\rho^{(0)})^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]$$

Hot + Dense Matter



[RR+Wambach '99]

Hot Meson Gas

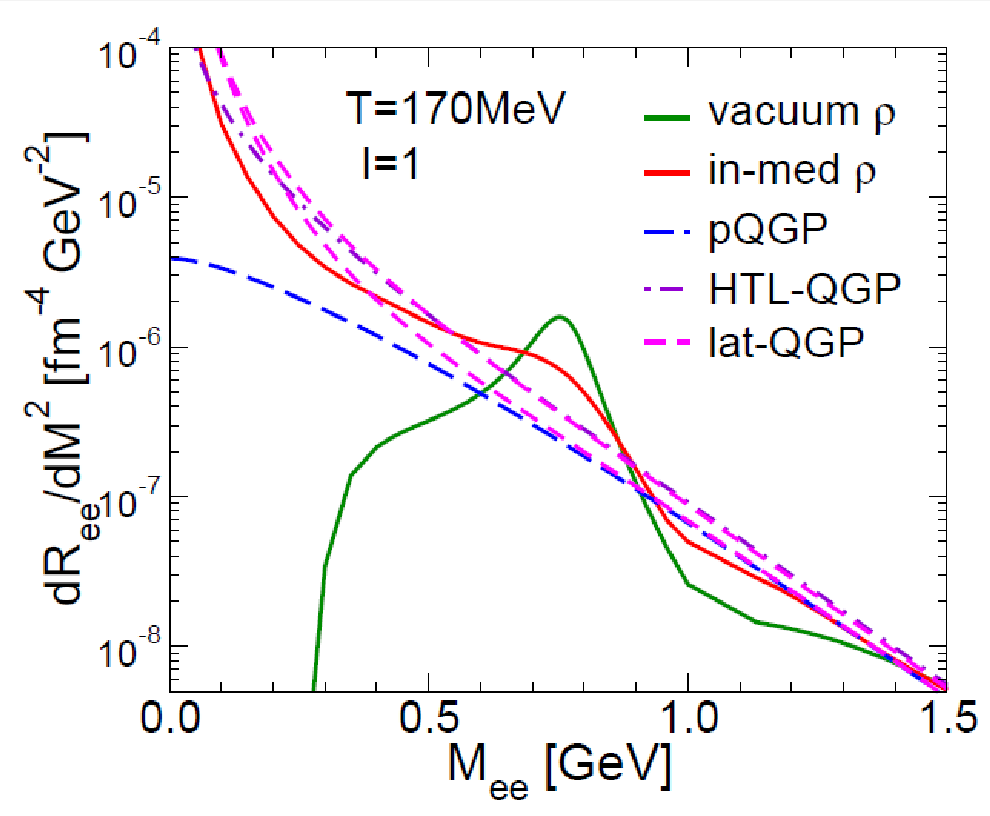


[RR+Gale '99]

- ρ-meson "melts" in hot/dense matter
- baryon density ρ_B more important than temperature

2.2 Dilepton Rates and Degrees of Freedom

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



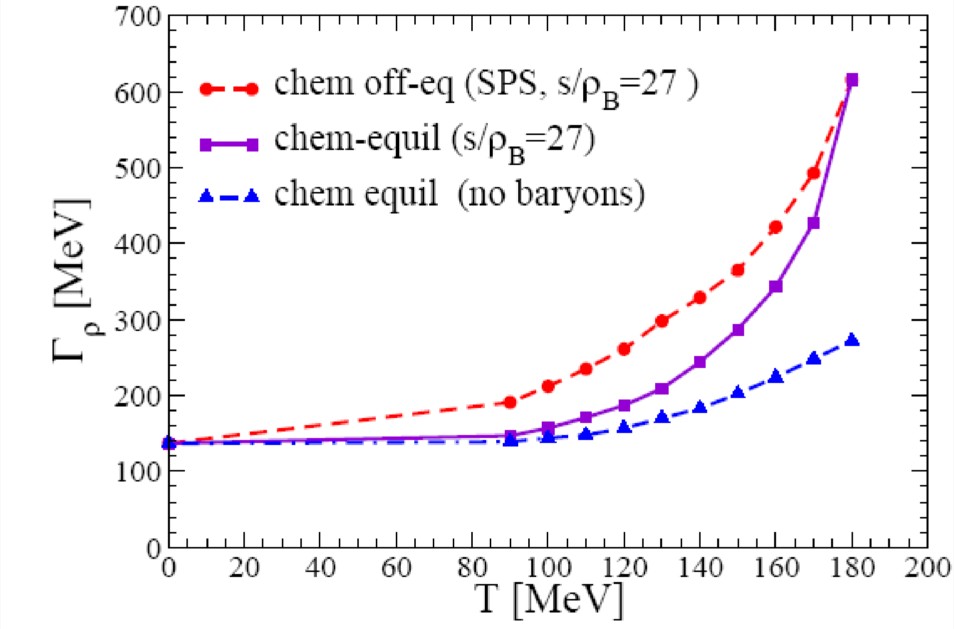
[RR,Wambach et al '99]

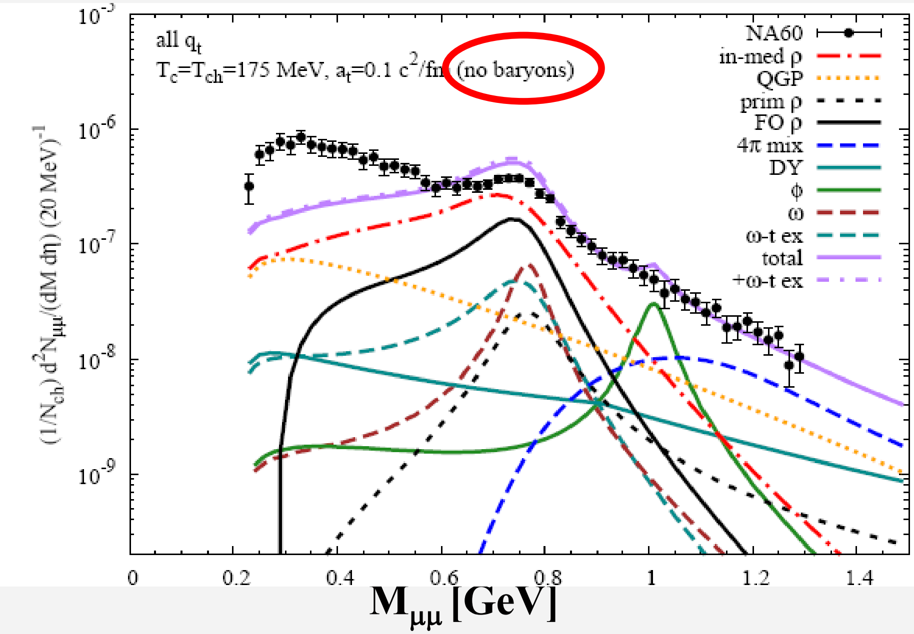
- **ρ-meson melting:** **spectral function merges into QGP description**

⇒ **Direct evidence for transition hadrons → quarks + gluons**

2.3 Sensitivity to Spectral Function

In-Medium ρ-Meson Width





- avg. Γ_ρ(T~150MeV)~370 MeV $\Rightarrow$ Γ_ρ (T~T_c) ≈ 600 MeV → m_ρ
- driven by (anti-) baryons
- **hadronic matter is a liquid, too: Γ ≥ KE ~ 3/2 T**

2.4 QCD + Weinberg Sum Rules

$$\frac{1}{M^2}\int_0^\infty ds \frac{\rho_V(s)}{s} e^{-s/M^2} = \frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right) + \frac{m_q\langle\bar{q}q\rangle}{M^4} + \frac{1}{24M^4}\langle\frac{\alpha_s}{\pi}G^2_{\mu\nu}\rangle - \frac{56\pi\alpha_s}{81M^6}\langle\mathcal{O}_4^V\rangle \ldots$$

[Hatsuda+Lee'91, Asakawa+Ko '93, Leupold et al '98, …]

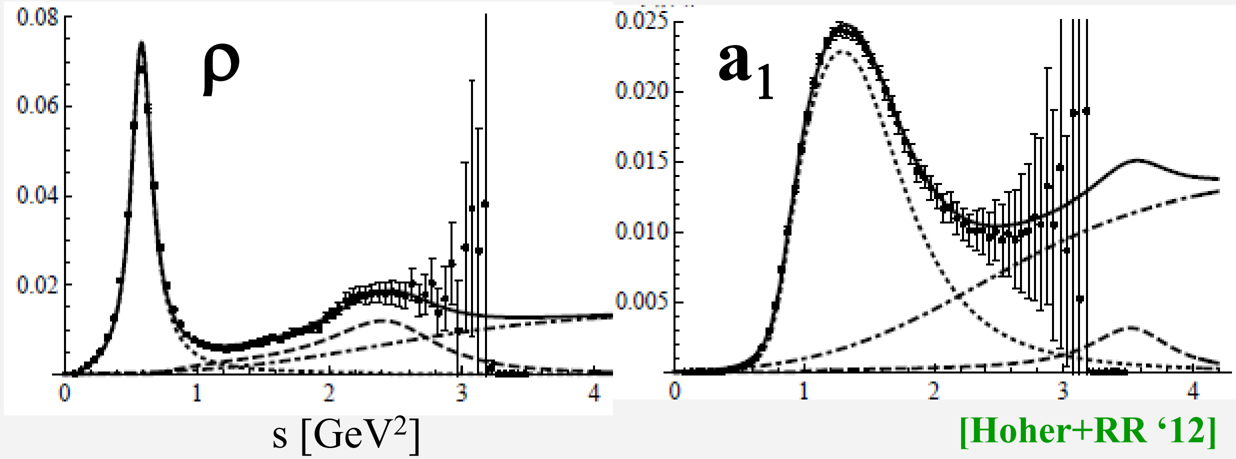
$$\int_0^\infty ds \, \frac{\Delta\rho(s)}{s} = f_\pi^2 \; ,$$

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

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

$$\Delta\rho = \rho_V - \rho_A$$

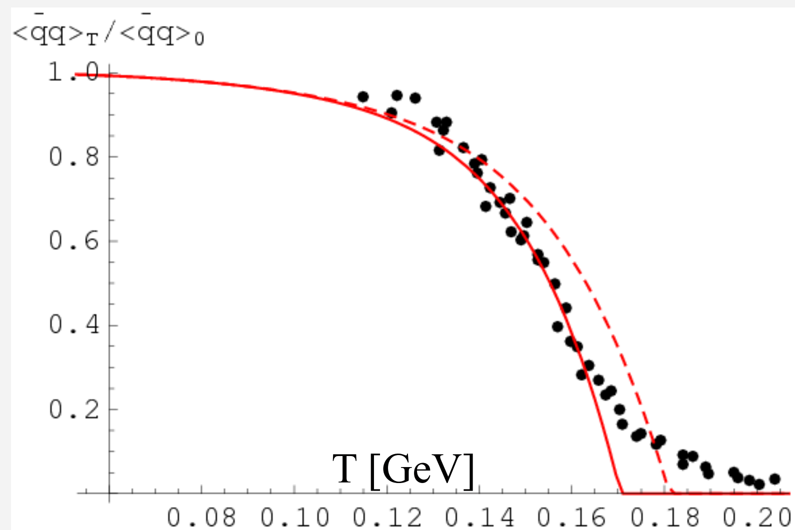
[Weinberg '67, Das et al '67; Kapusta+Shuryak '94]



[Hoher+RR '12]

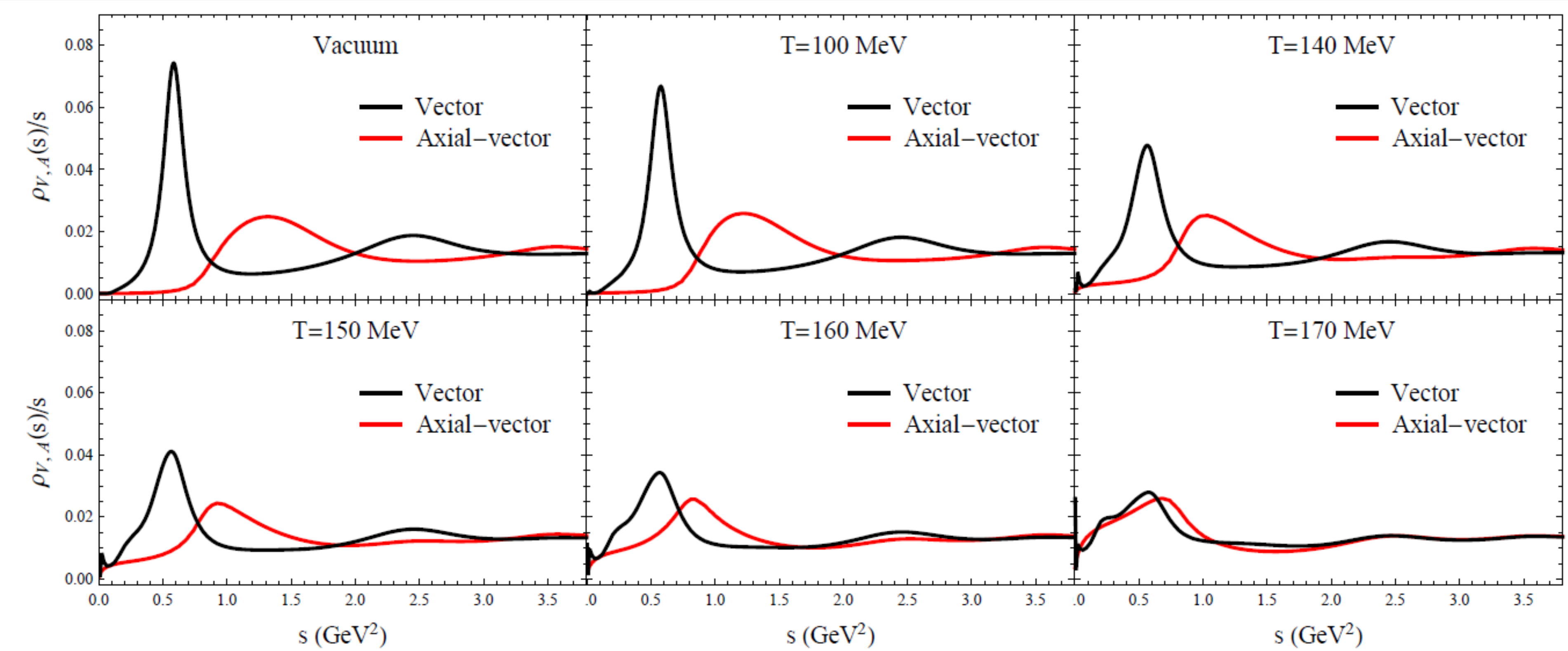
- accurately satisfied in **vacuum**
- **In Medium**:
  condensates from hadron resonance gas,
  constrained by lattice-QCD

$$\langle\mathcal{O}\rangle_T \simeq \langle\mathcal{O}\rangle_0 + \sum_h d_h \int \frac{d^3k}{(2\pi)^3\, 2E_h}\langle h(\vec{k})|\mathcal{O}|h(\vec{k})\rangle n_h(E_h)$$



2.4.2 QCD + Weinberg Sum Rules in Medium

→ Search for solution for axial-vector spectral function



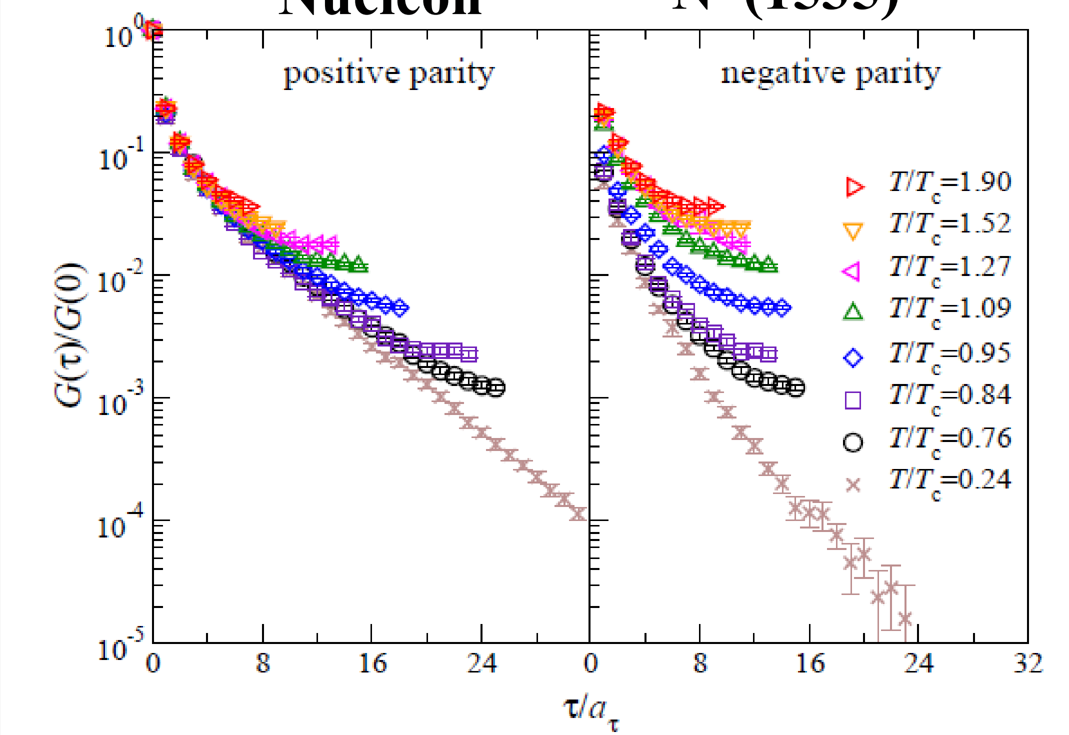
[Hohler +RR '13]

- quantitatively compatible with (approach to) chiral restoration
- strong constraints by combining SRs
- **Chiral mass splitting "burns off", resonances melt**

2.5 Lattice-QCD Results for N(940)-N*(1535)

Euclidean Correlator Ratios

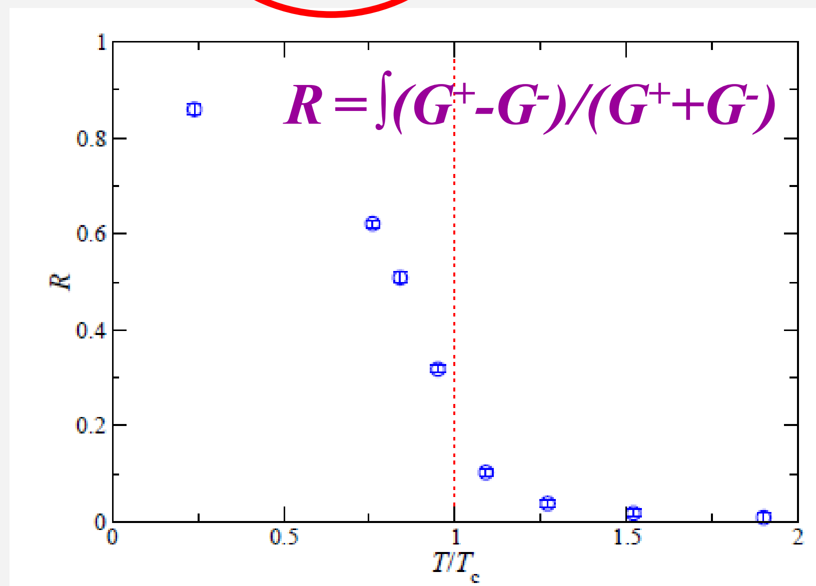
"Nucleon" "N*(1535)"



[Aarts et al '15]

Exponential Mass Extraction

T/T_c	m_+ [GeV]	m_- [GeV]	Δ
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 $M_{N*}(T) \rightarrow M_N(T) \approx M_N^{vac}$

Outline

1.) Introduction

2.) Thermal Radiation

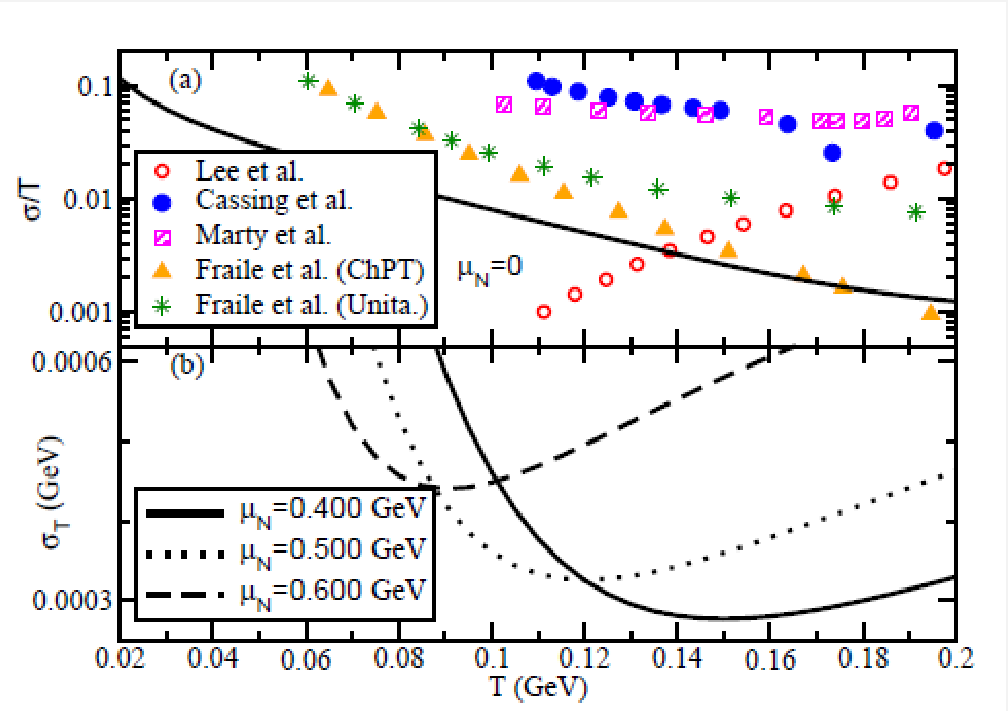
- Quark-Hadron Transition
- Chiral Symmetry Restoration

3.) Very-Low Mass + Momentum

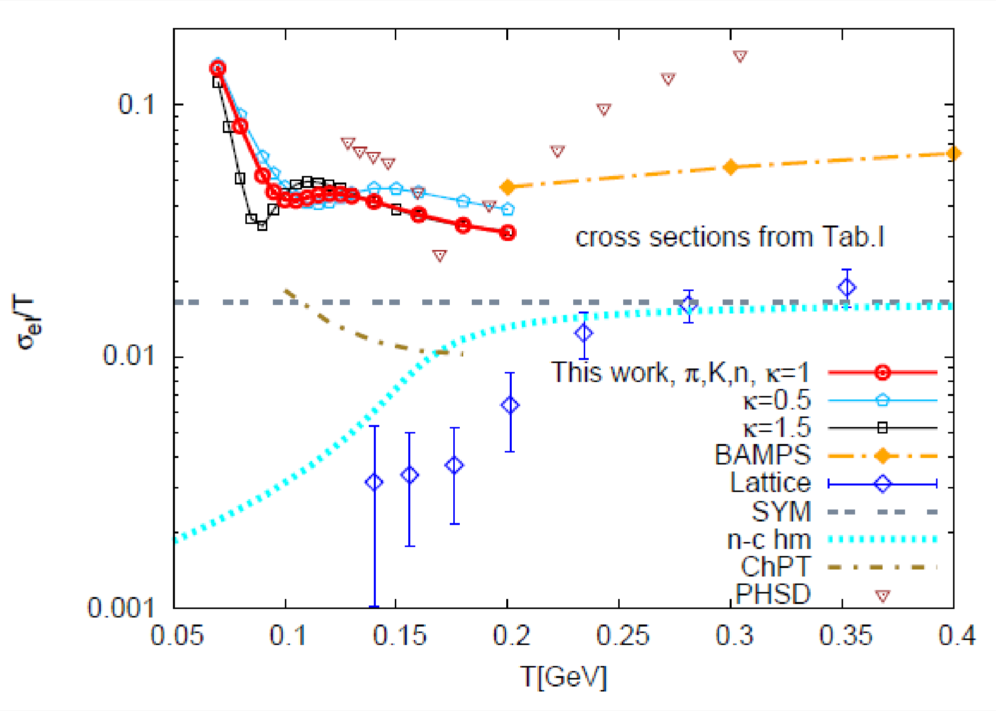
- EM Conductivity
- Coherent Radiation

4.) Conclusions

3.1 EM Conductivity: Overview



[S. Ghosh '17]



[Greif '17]

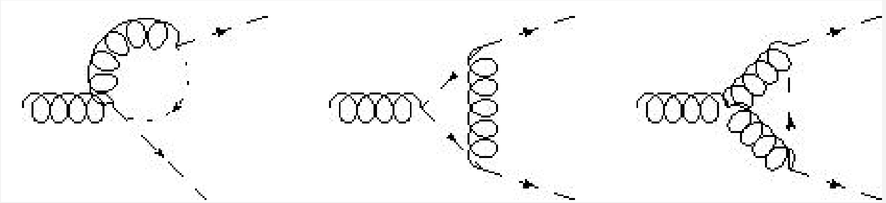
- Large spread in the literature (kinetic theory, EM SF)
- Large baryon effects not unexpected

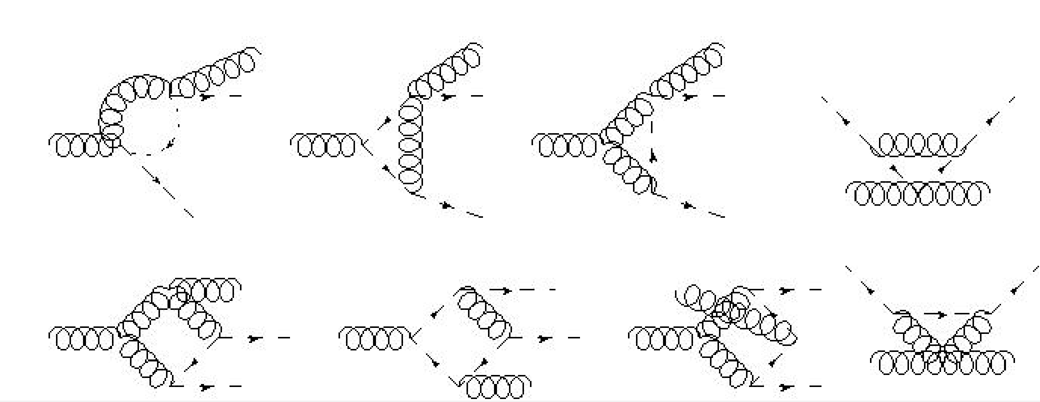
3.2 Hadronic Many-Body Theory (HMBT)

- Connect dilepton production to EM conductivity
- Probes soft limit of EM spectral function

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

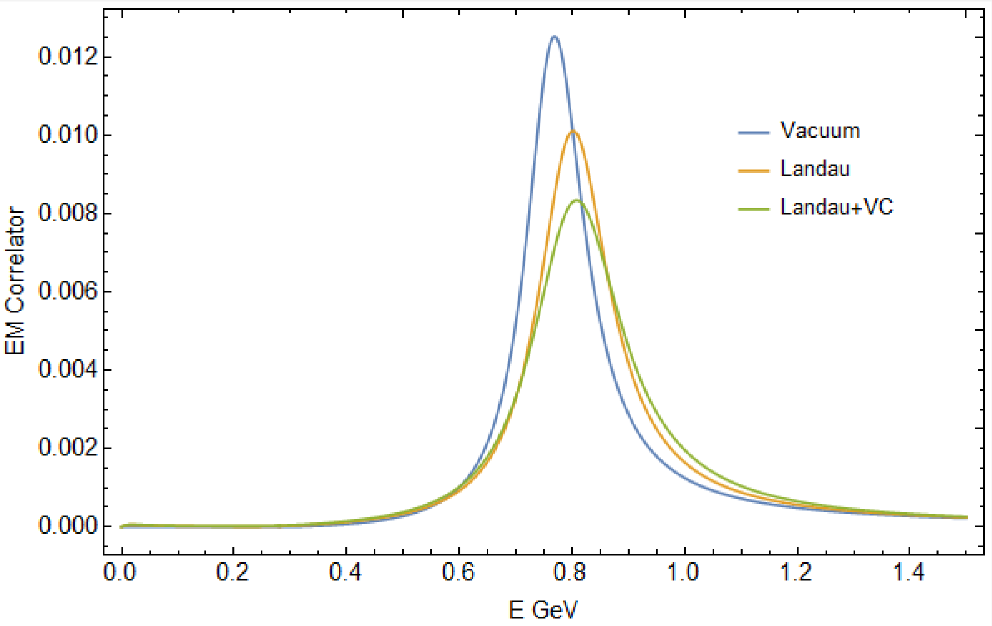
- Need density-squared contributions
- Non-trivial for vertex corrections
  (usually evaluated with vacuum propagators)
- Start out with pion gas: dress pions in ρ -cloud + vertex corrections

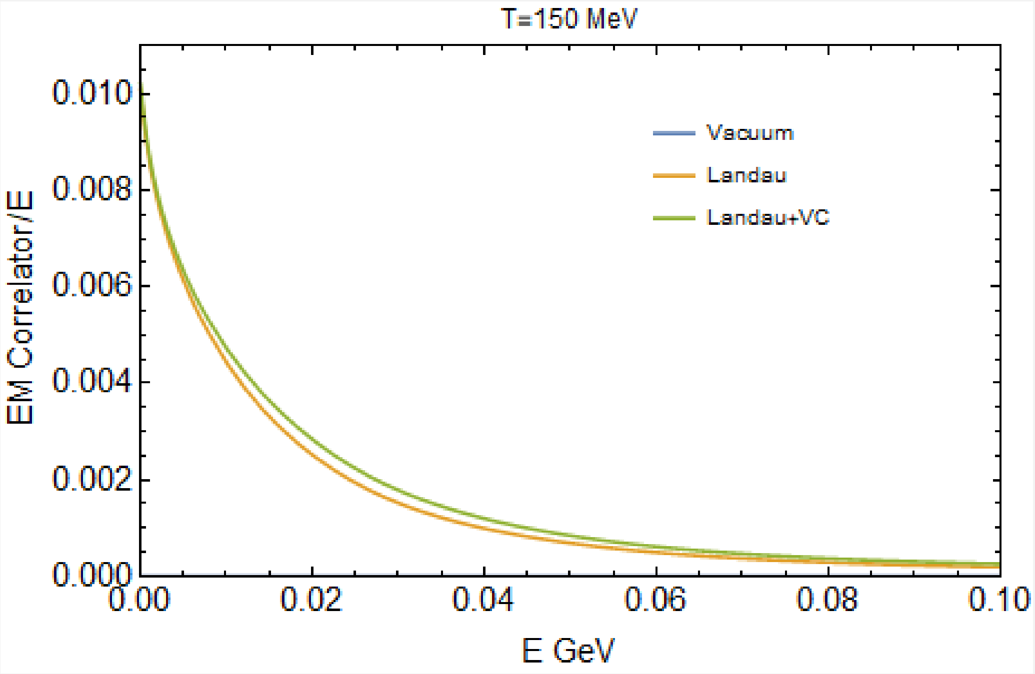




[Atchison+RR in prog.]

3.2.1 EM Spectral Function Pion Gas (HMBT)

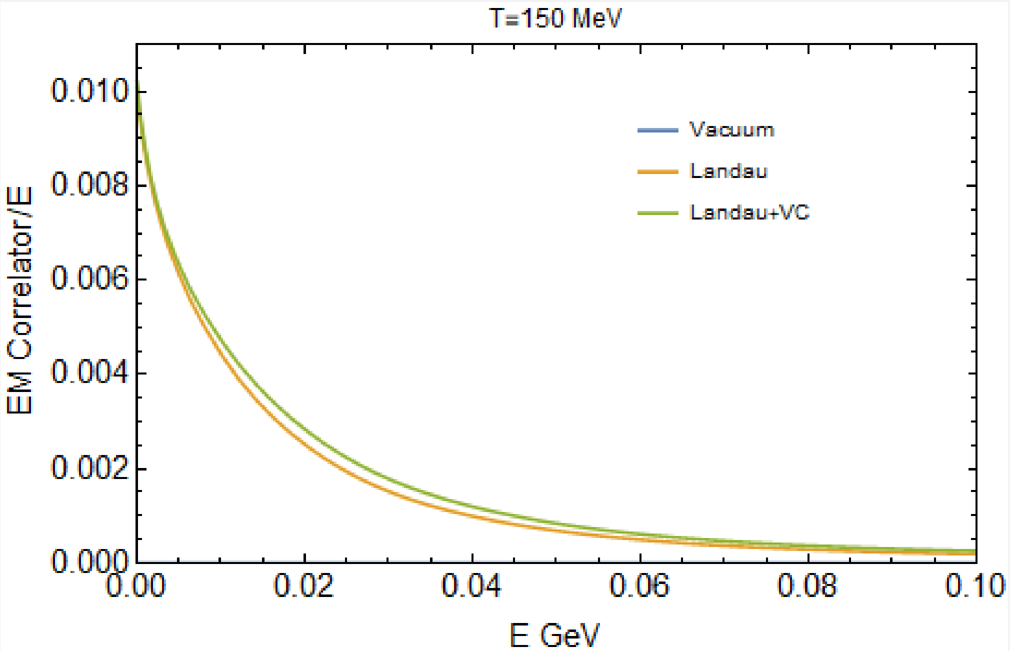




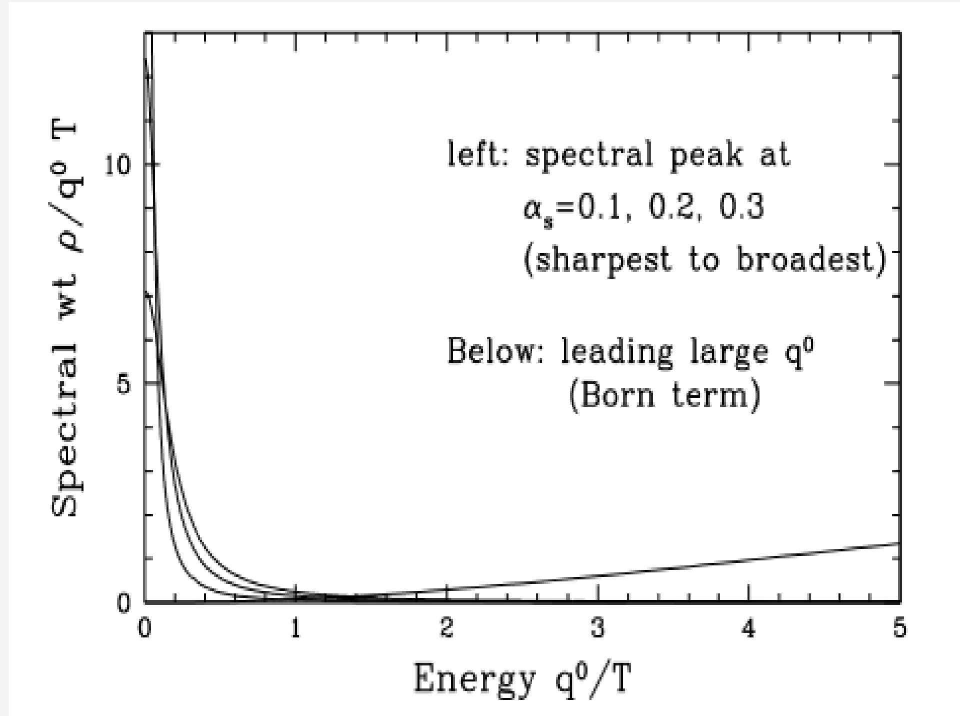
- modest modifications of ρ spectral function (as expected)
- rather narrow conductivity peak
- suggestive for relatively weakly coupled system

3.2.2 Low-Energy Limit of Spectral Function

Pion Gas



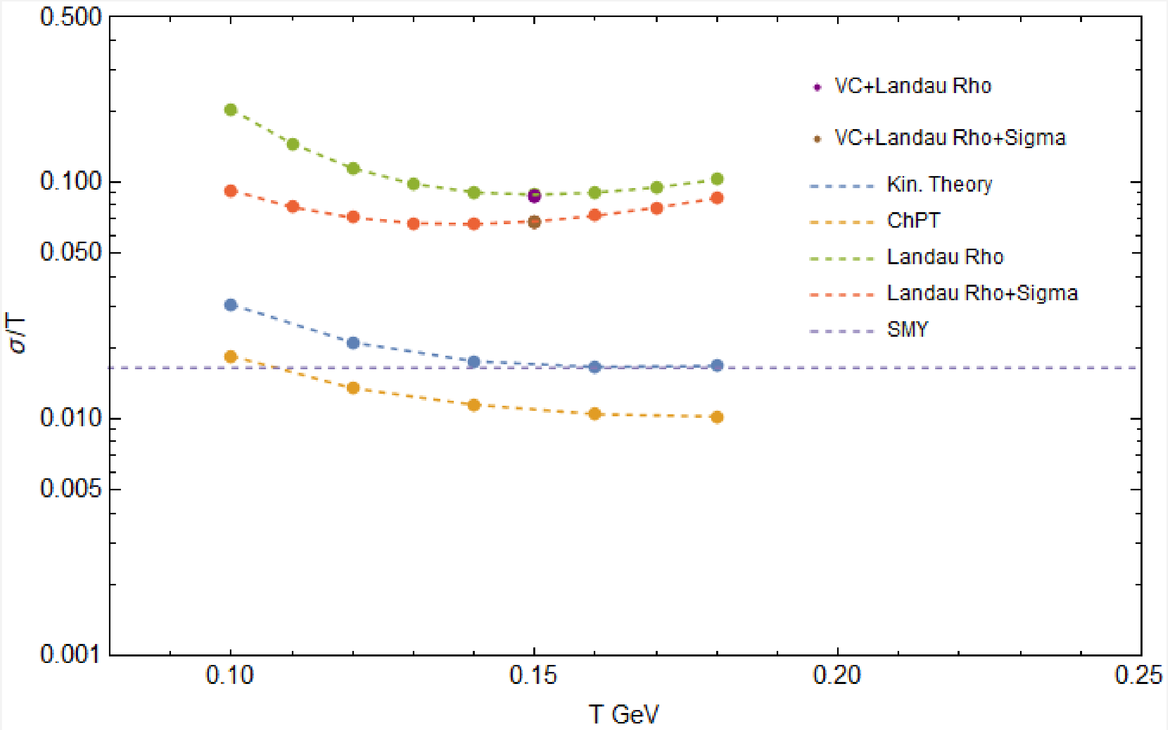
Perturbative QGP



[Moore+Robert '06]

- pion gas and quark-gluon gas comparable, with $\Gamma_{cond} \sim 0.1\ q_0/T$

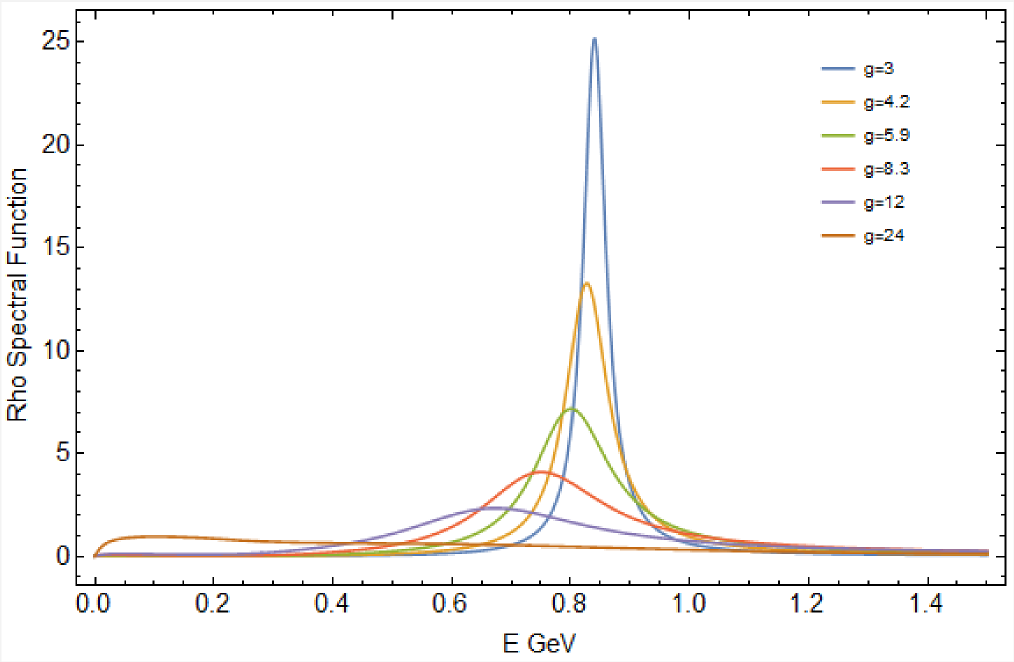
3.3 EM Conductivity in Pion Gas: Comparisons

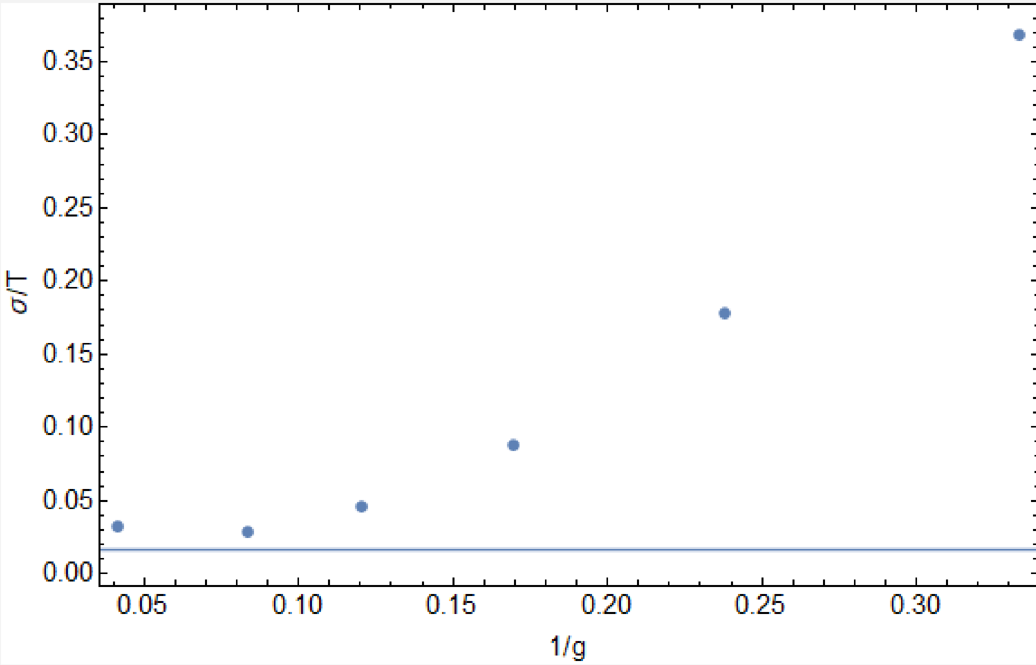


- larger values than in the literature
- sigma meson relevant (more so at low T)

3.4 Strong Coupling Limit in HMBT

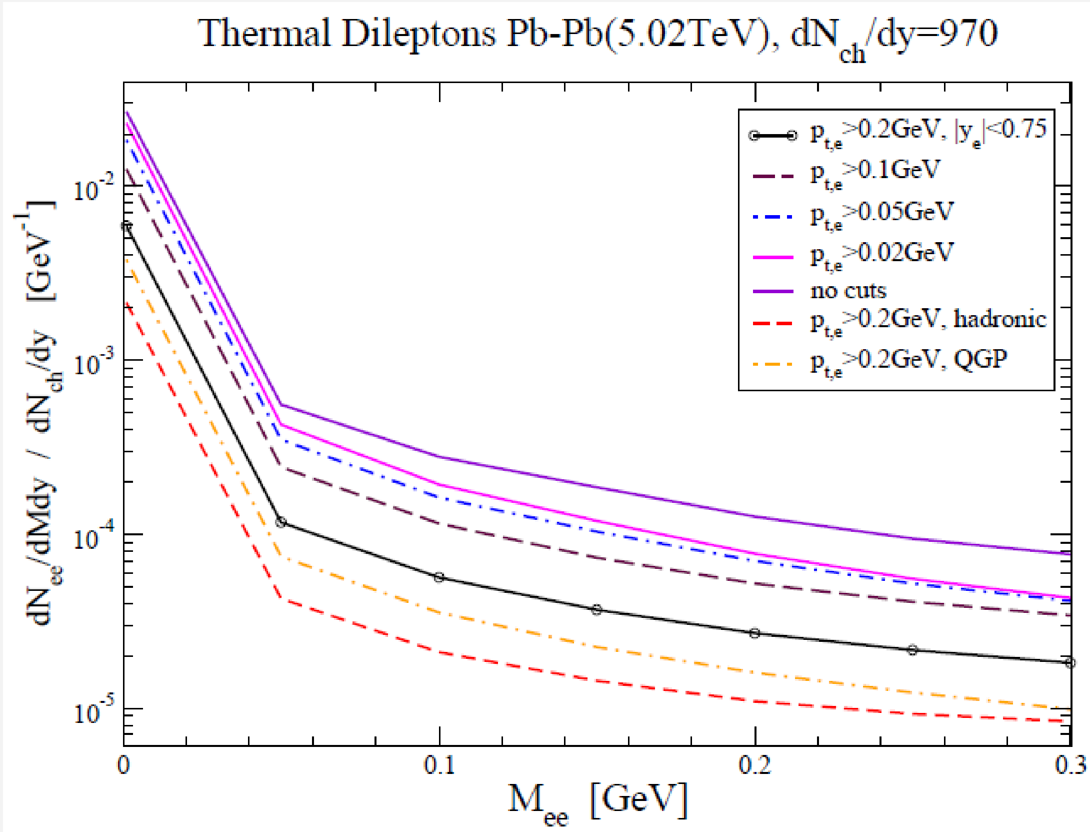
- vary gauge coupling $\mathbf{g=g_{\rho\pi\pi}}$ in pion gas





- spectral function strongly smeared
- approaches strong coupling "limit" (does not violate it!)

3.5 Test Conductvity in Very-Low-Mass Spectrum



- Conductivity peak?!
- another source will come in…

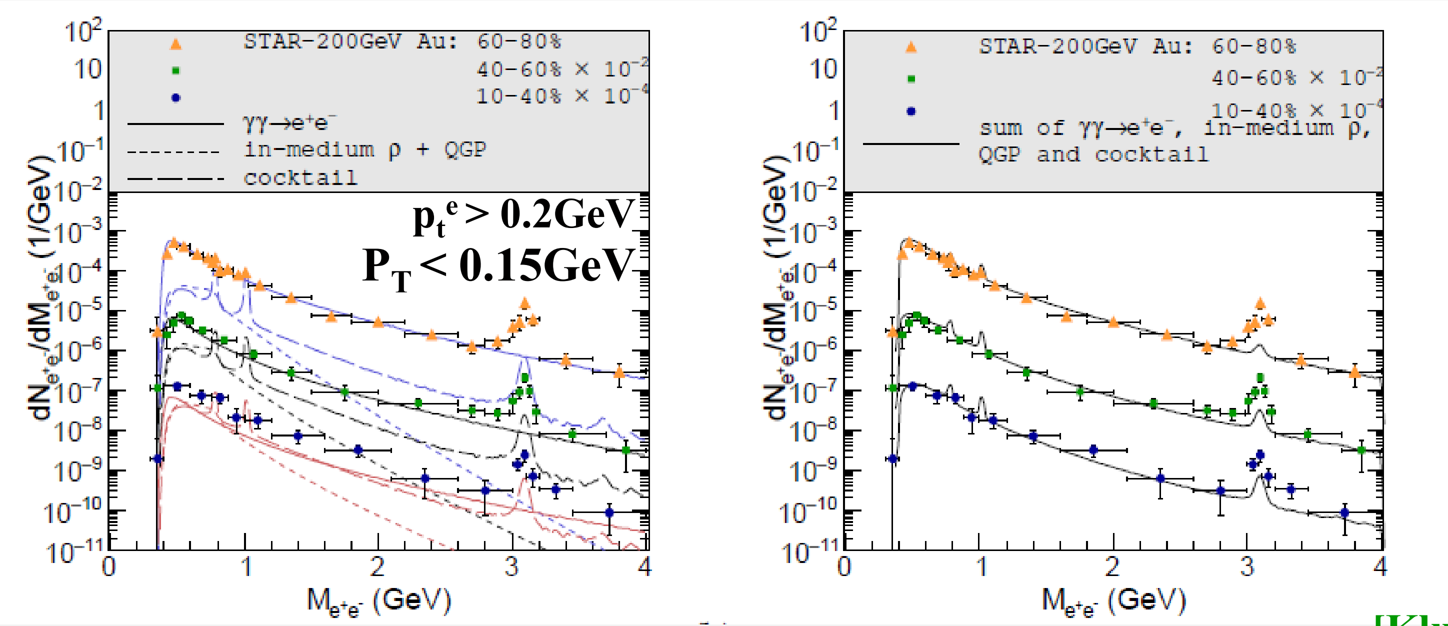
3.6 Coherent Radiation

- Photon fusion $\gamma\gamma \to l^+l^-$ in the EM field of incoming nuclei

$$\frac{d\sigma_{ll}}{d\xi d^2\boldsymbol{b}} = \int d^2\boldsymbol{b}_1 d^2\boldsymbol{b}_2\, \delta^{(2)}(\boldsymbol{b} - \boldsymbol{b}_1 - \boldsymbol{b}_2) N(\omega_1, b_1) N(\omega_2, b_2) \frac{d\sigma(\gamma\gamma \to l^+l^-; \hat{s})}{d(-\hat{t})}$$

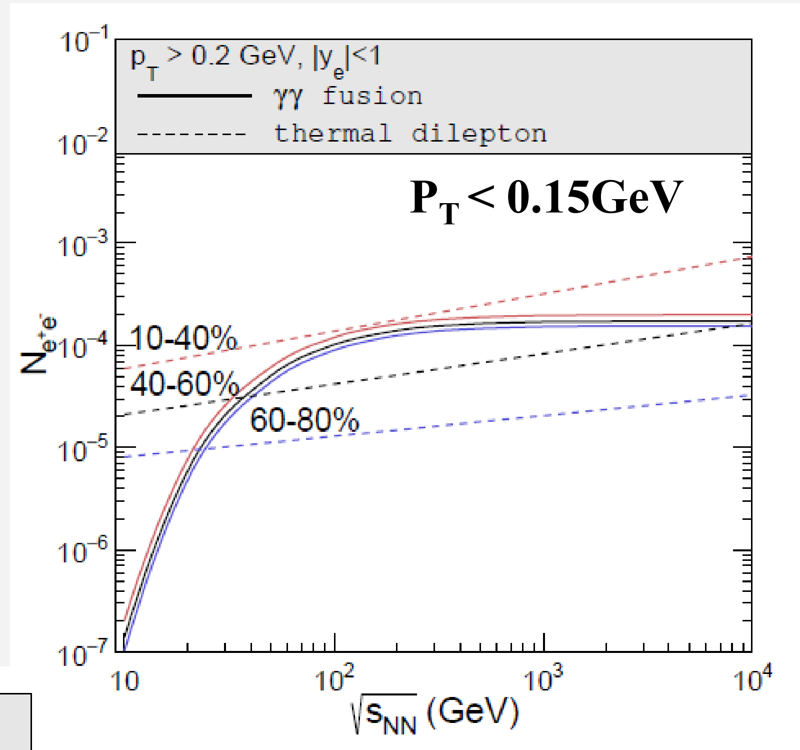
- Any mass but very limited in pair-P_T
- Well established in "ultra-peripheral" **AA** collisions (UPCs)
- Competition with Strong sources at finite nuclear overlap

[Klein '18; Zha et al '18]

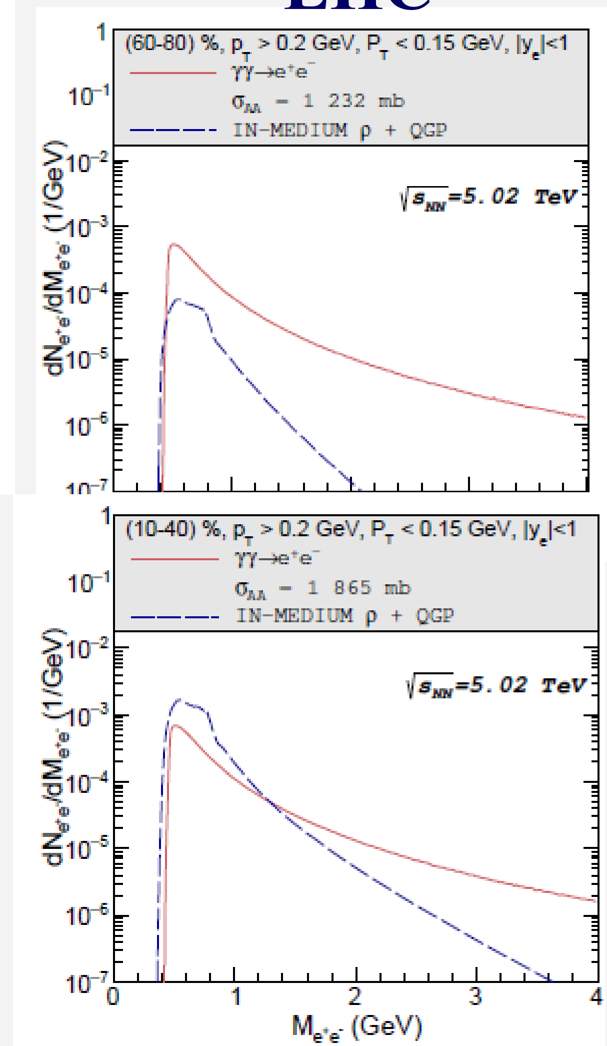


[Klusek-Gawenda, RR, Schaefer+Szczurek '18]

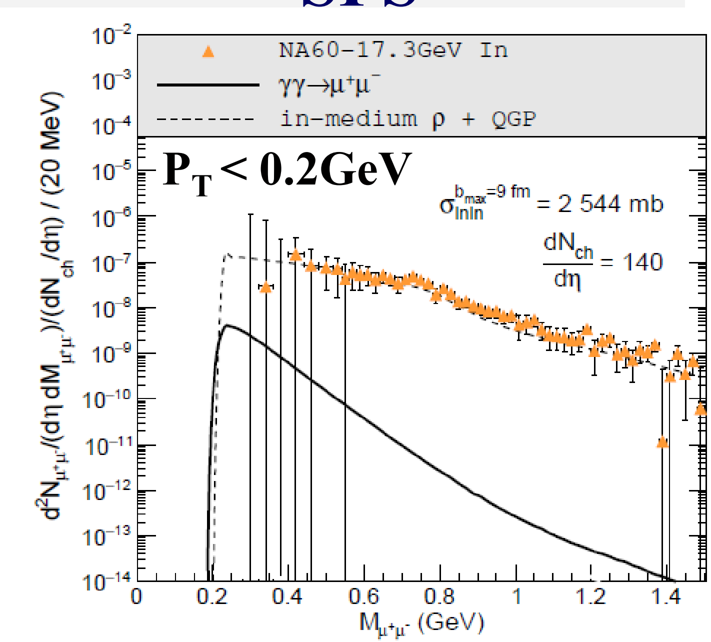
3.6.1 Excitation Function



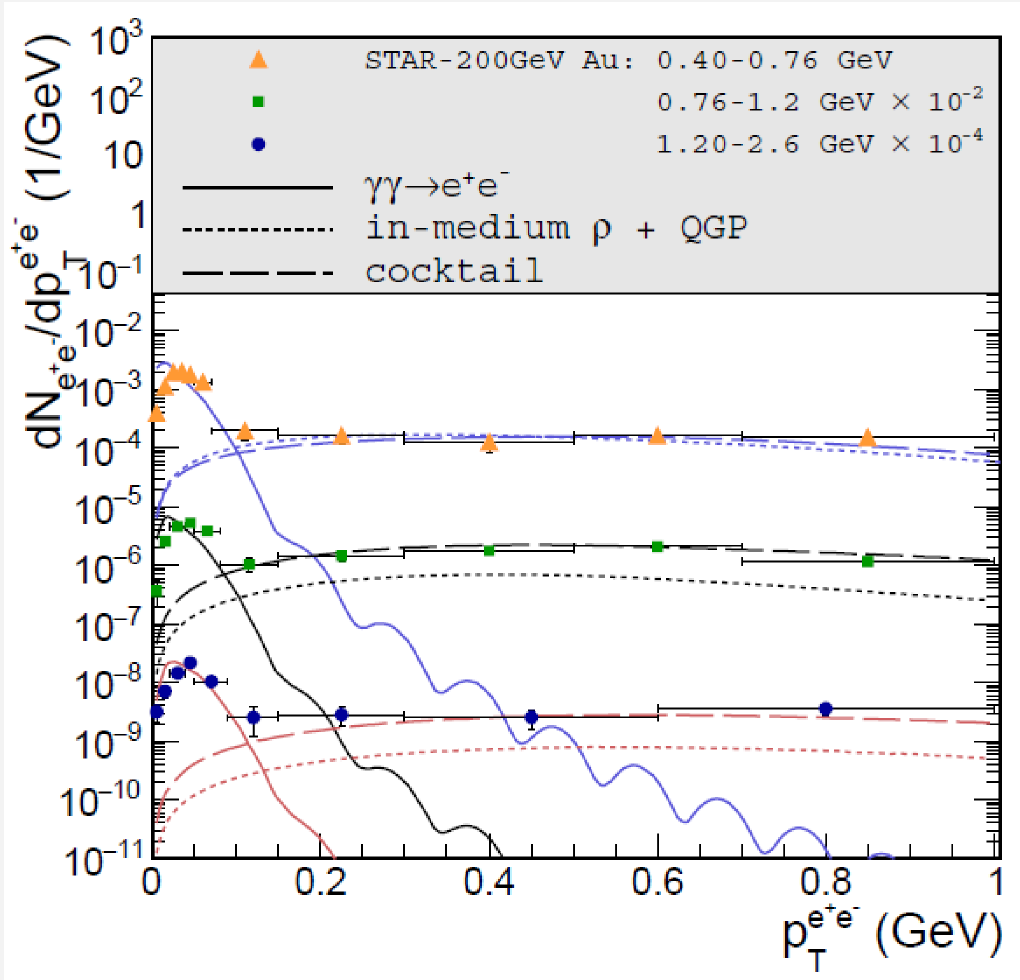
LHC



SPS



3.6.2 P_T Dependence



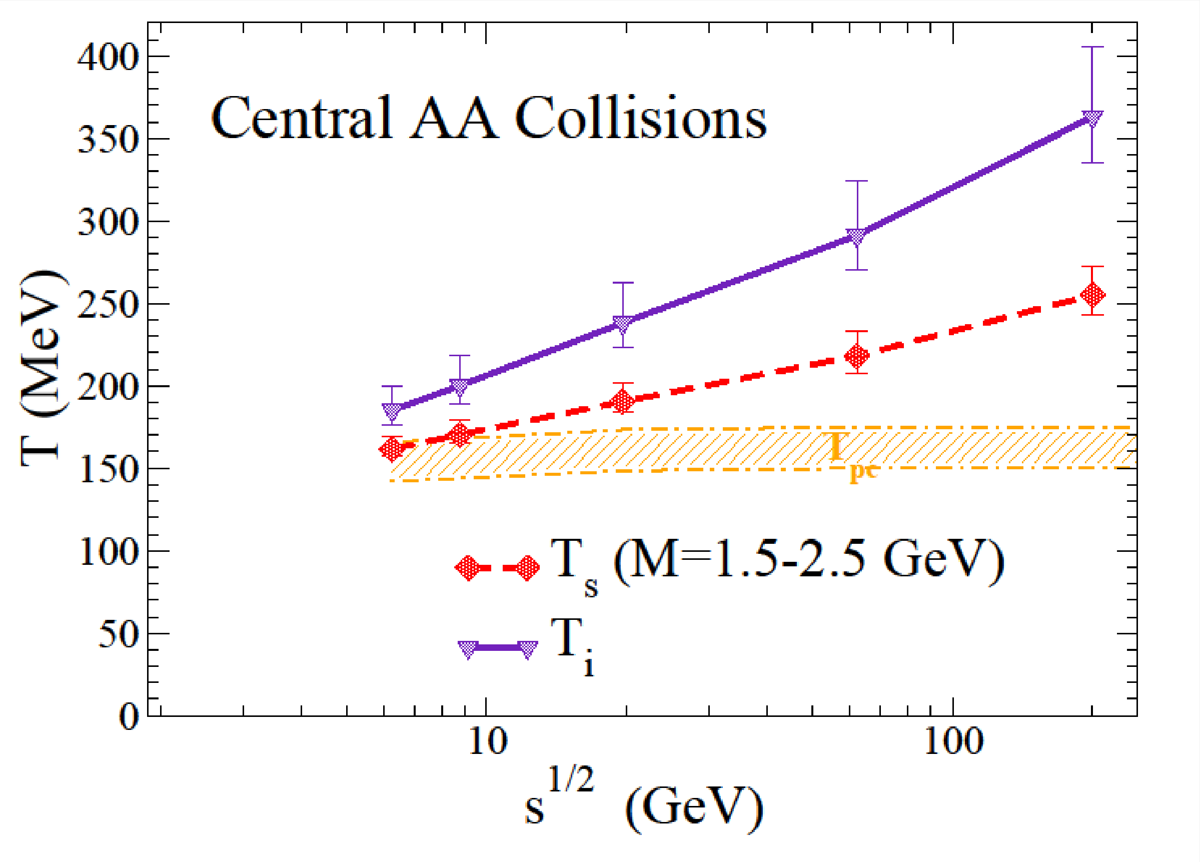
- Indication of nuclear broadening… (also: **[ATLAS, ALICE]**)

4.) Conclusions

- **Explicit evidence for parton-hadron transition: ρ melting**
- **Progress in understanding mechanisms of chiral restoration**
  - evaporation of chiral mass **ρ-a_1** splitting (sum rules, MYM)
  - also found for baryon correlators from QCD
- **Very-low mass dileptons to extract EM conductivity**
  - uncomfortable spread in model calculations, even for pion gas
  - coherent emission probably relevant (broadening?!)

4.2 Fireball Temperature

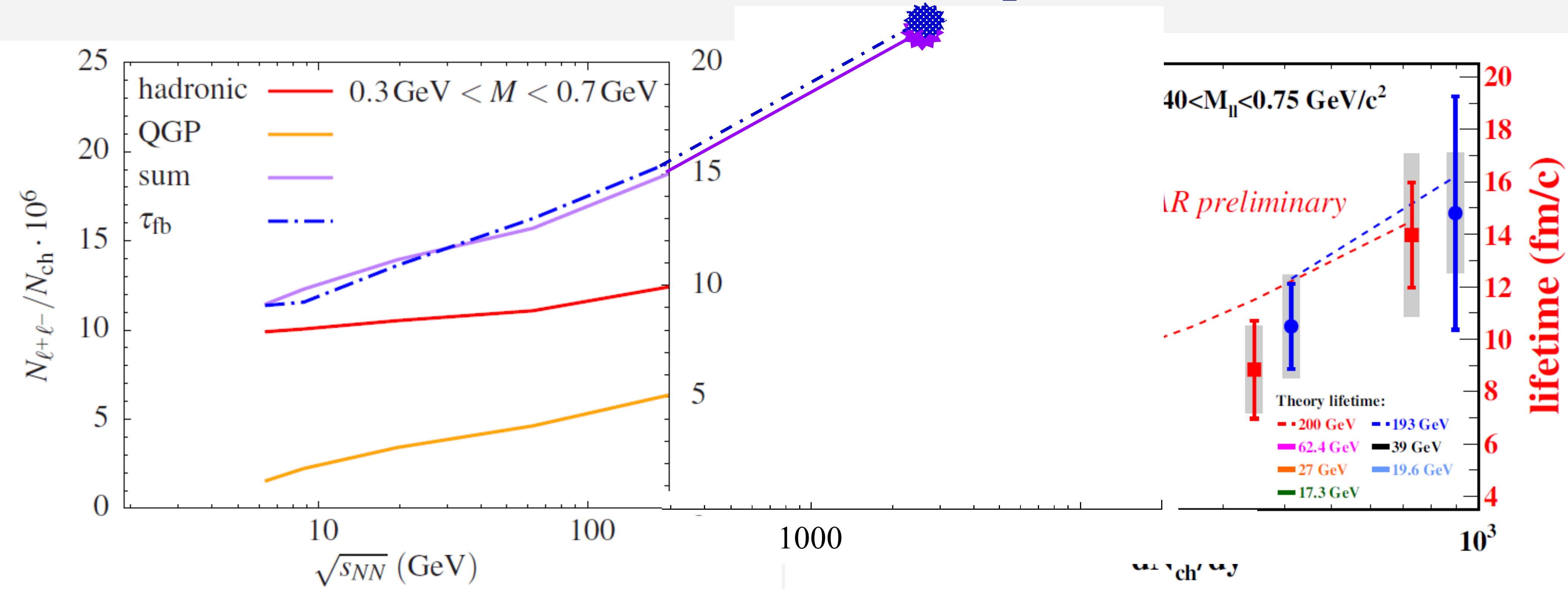
Slope of Intermediate-Mass Excess Dileptons



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

4.3 Fireball Lifetime

Excitation Function of Low-Mass Dilepton Excess Yield

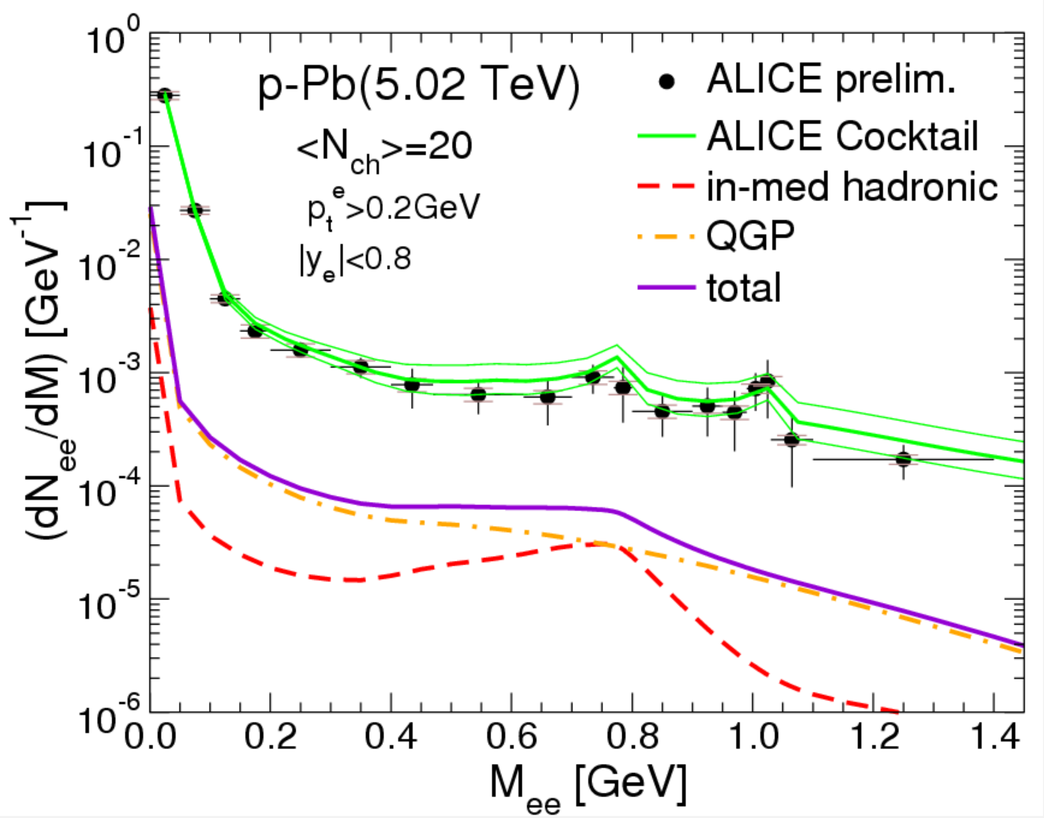


[RR+van Hees '14]

[STAR '15]

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

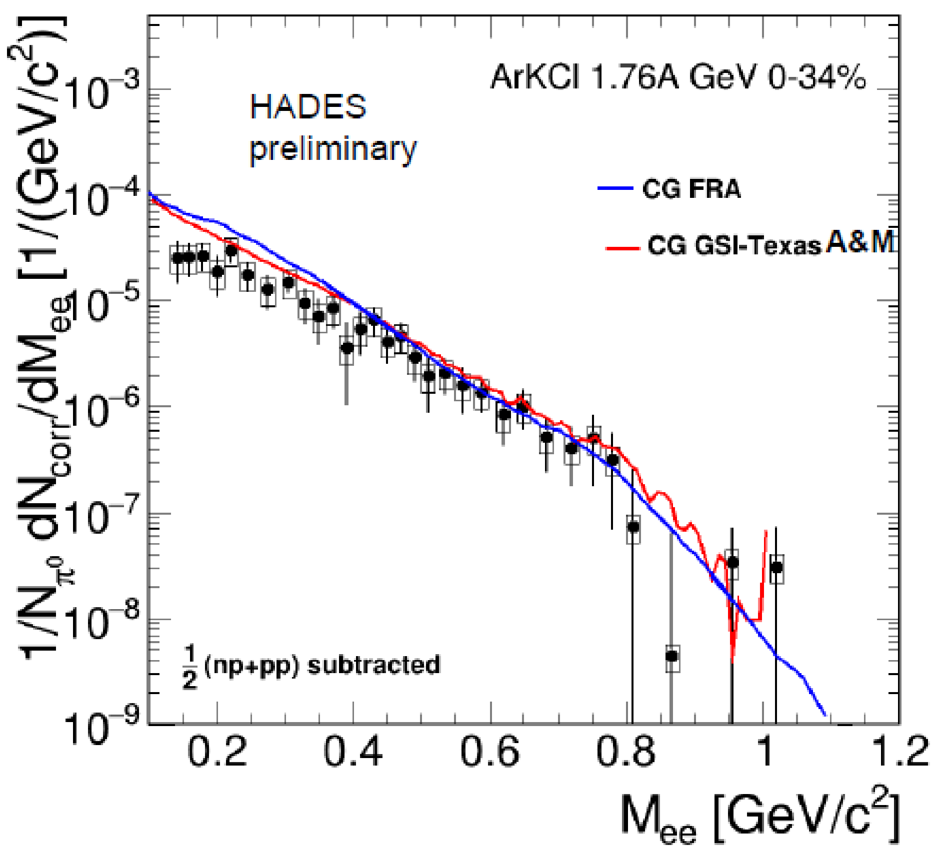
5.3 Low-Mass Dileptons in p-Pb (5.02GeV)

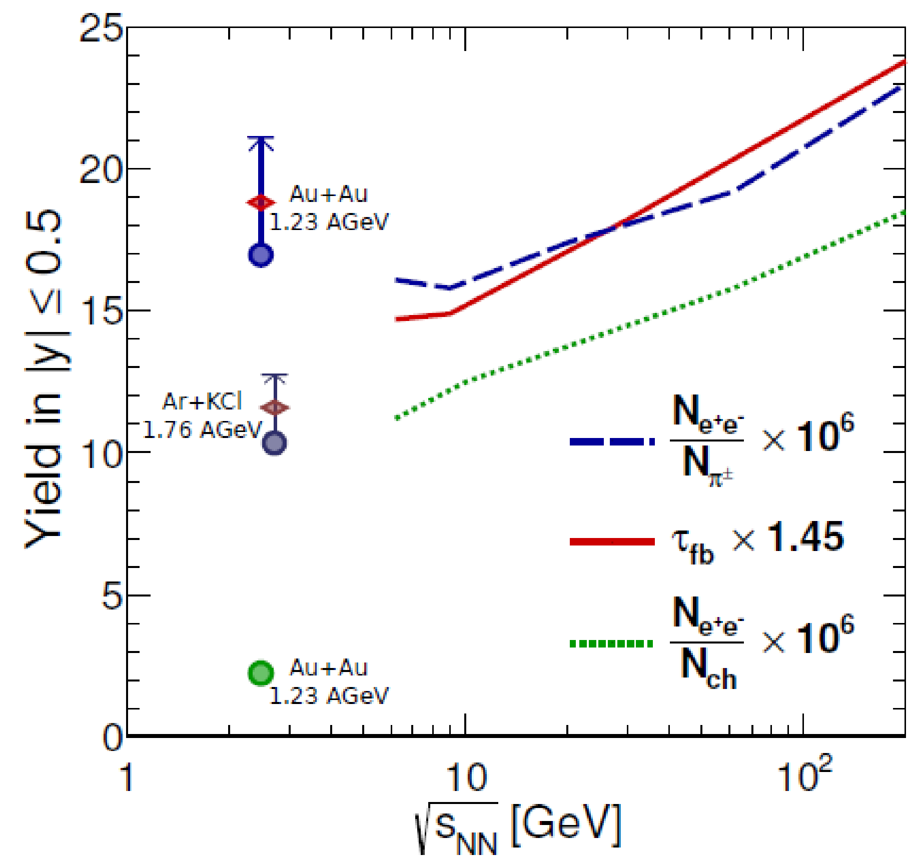


- Thermal radiation at **~10%** of cocktail
- follows excess-lifetime systematics

4.4.2 Dileptons at HADES: Spectra + Lifetimes

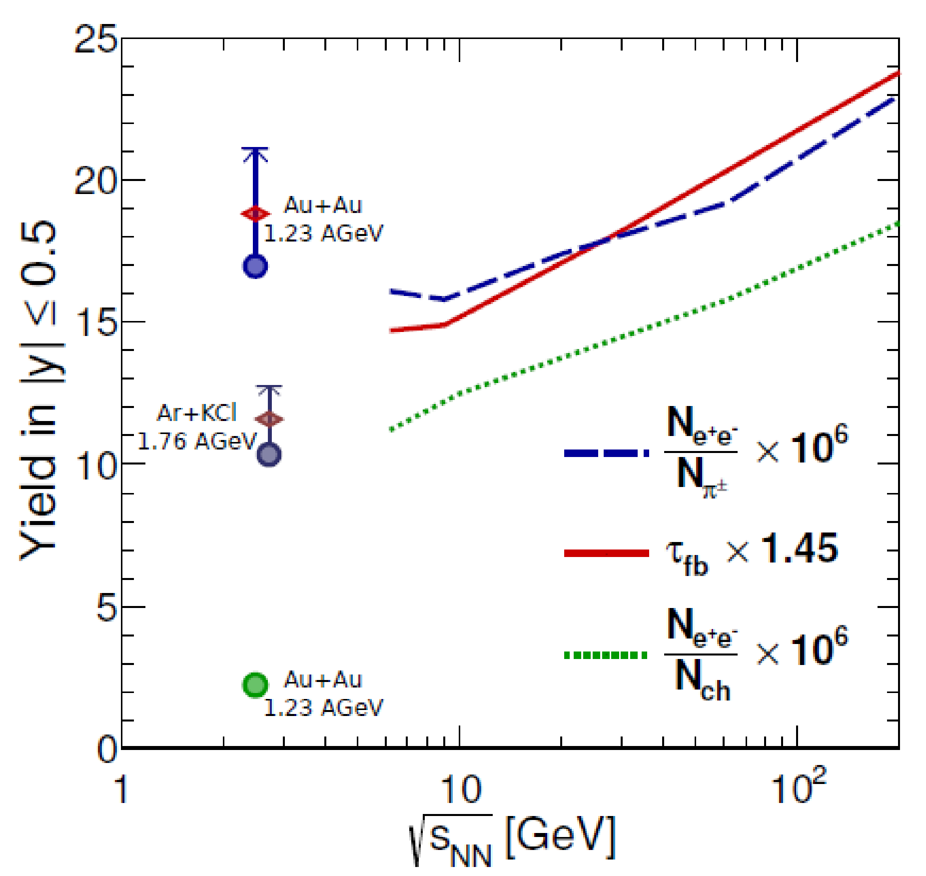
Coarse-Graining Results with in-Medium Spectral Functions

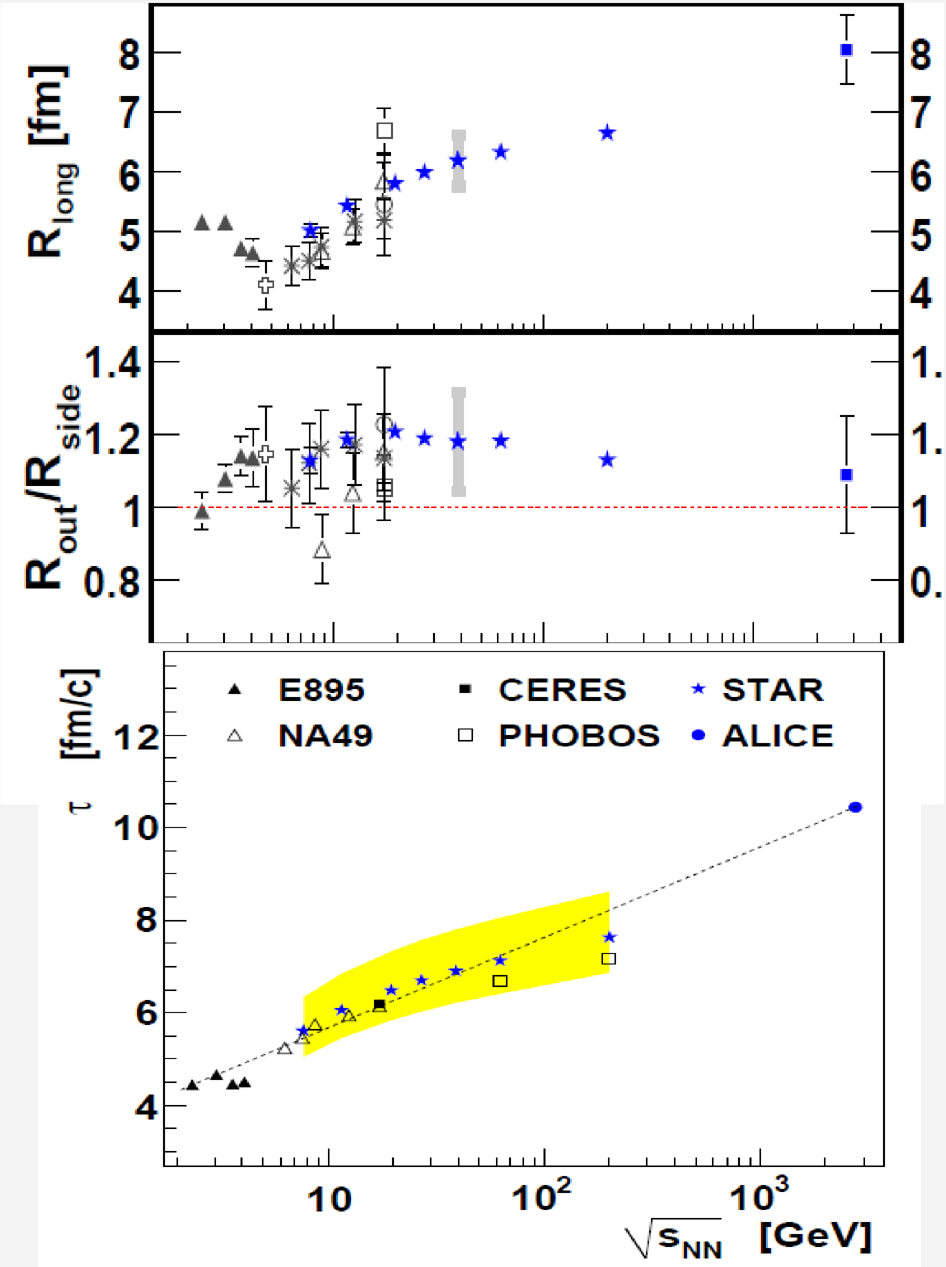




- Fair consistency with mass spectra and lifetime systematics

4.5 Lifetime from Dileptons vs. HBT Radii





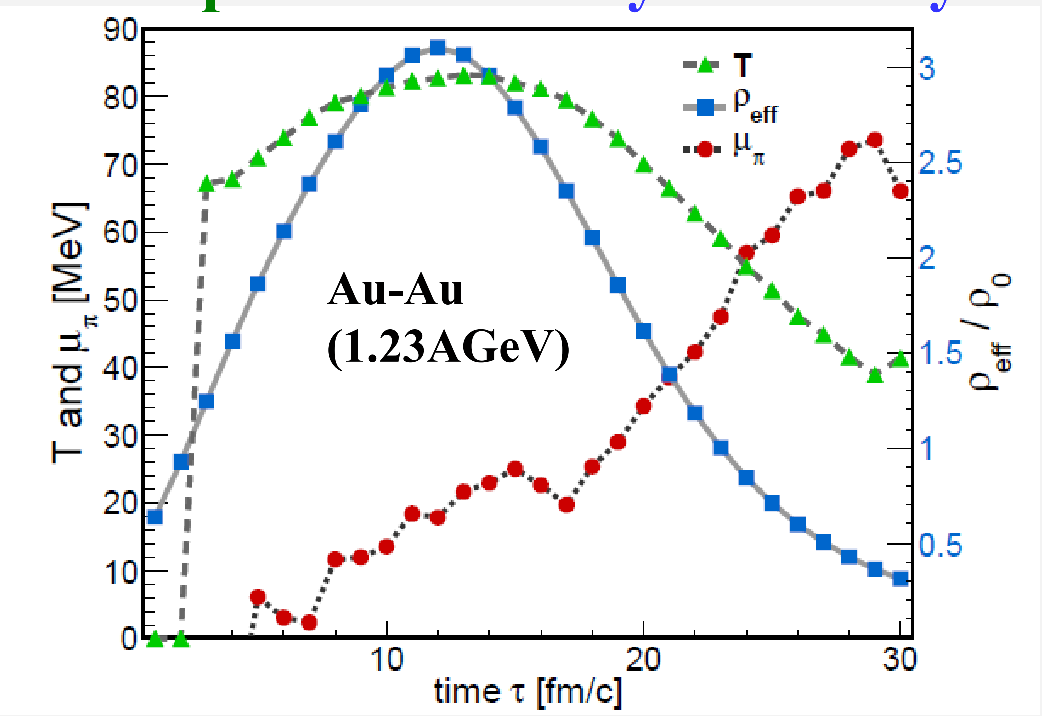
- $\mathbf{R_{long}}$ qualitatively consistent, quantitatively much smaller

4.4 Dileptons at HADES: Coarse Graining

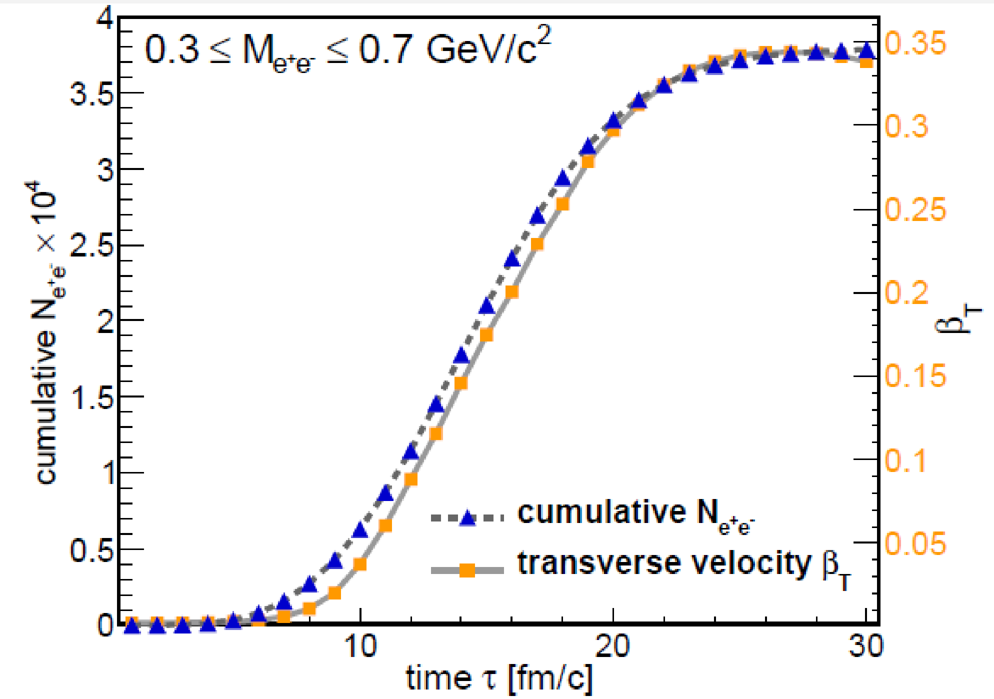
- Coarse-graining of hadronic transport to
  → extract thermodynamic variables
  → convolute with **thermal** dilepton rate

[Huovinen et al. '02, Endres et al '15, Galatyuk et al '16]

Temperature + Baryon Density



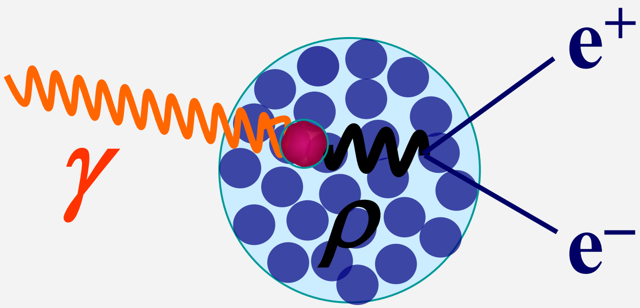
Dilepton Yield vs. Nucleon Flow

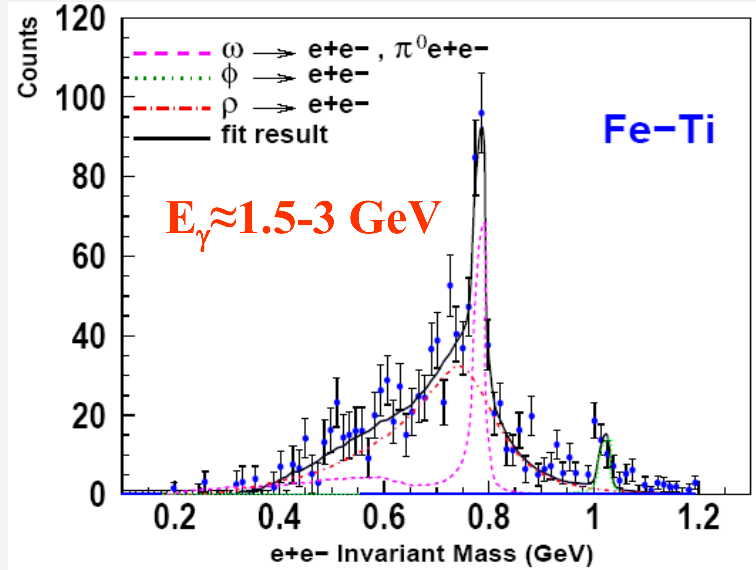


- build-up of collectivity ↔ EM radiation ↔ "thermal" fireball
- fireball lifetime "only" τ_{fb} ~ 13 fm/c

4.1 Nuclear Photoproduction: ρ Meson in Cold Matter

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



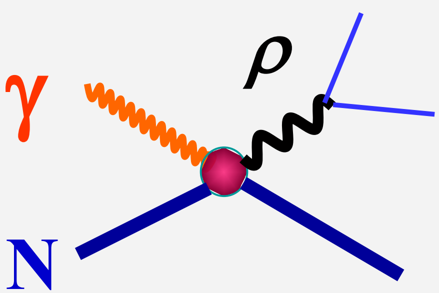


- extracted "in-med" ρ-width $\Gamma_\rho \approx 220$ MeV

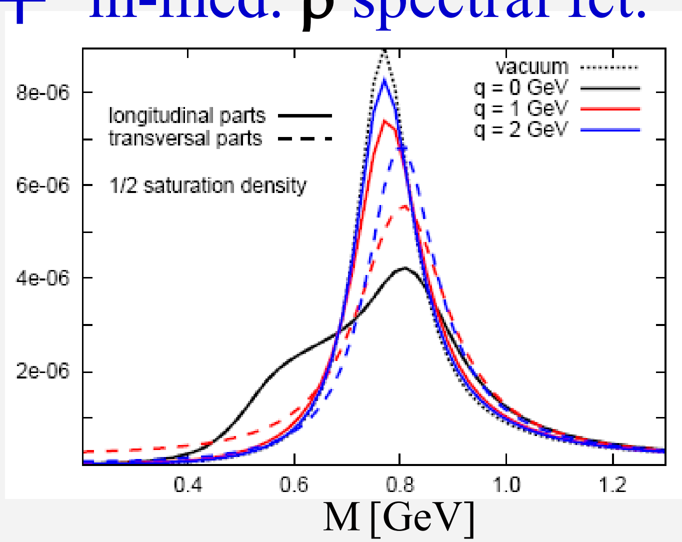
[CLAS+GiBUU '08]

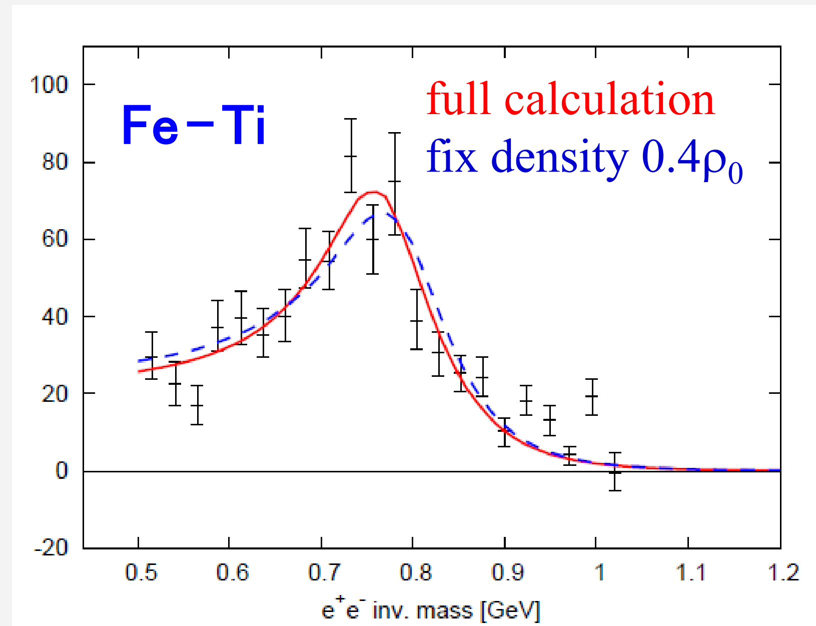
- **Microscopic Approach:**

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



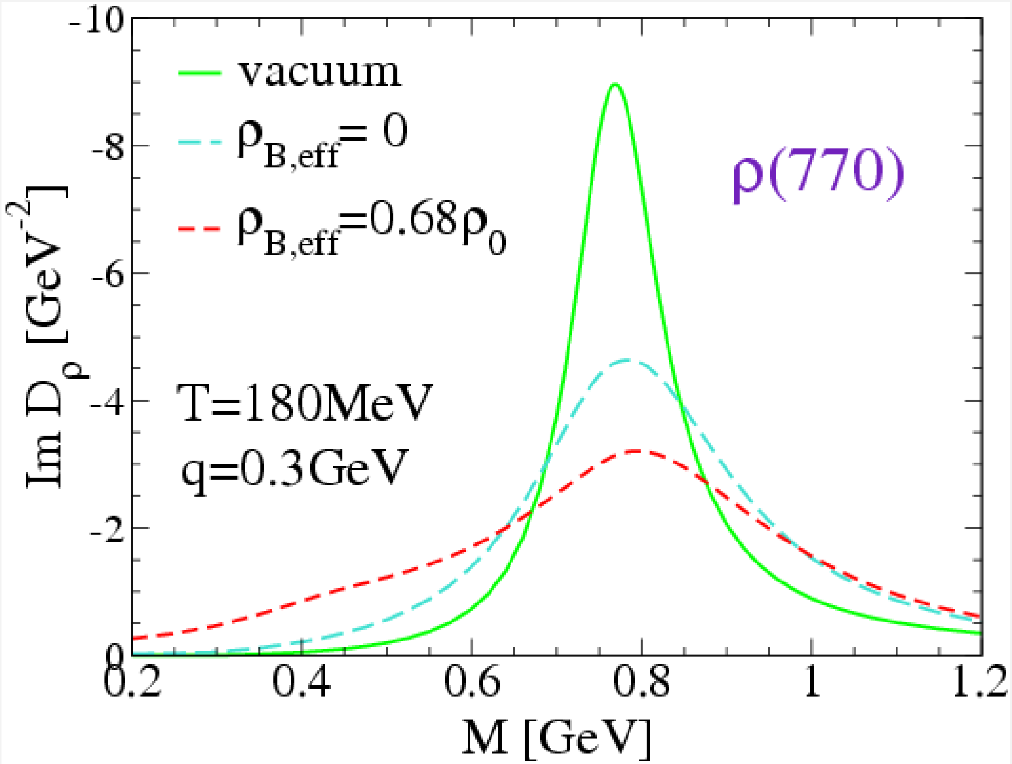
[Riek et al '08, '10]

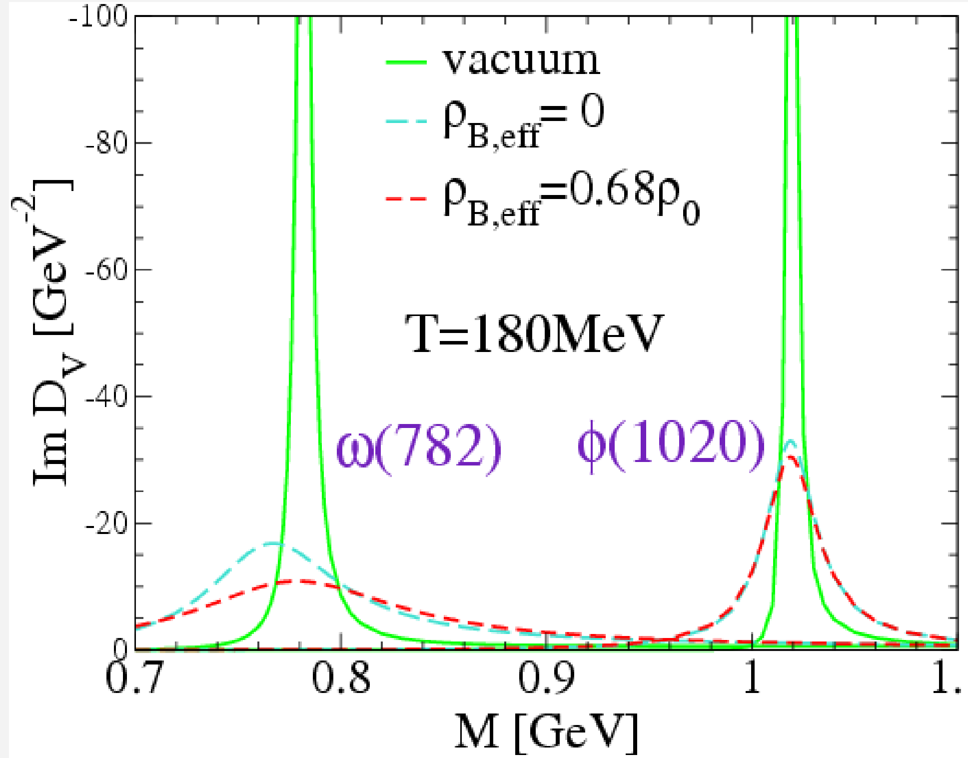




- ρ-broadening reduced at high 3-momentum; **need low momentum cut!**

2.1 In-Medium Vector Mesons at RHIC + LHC



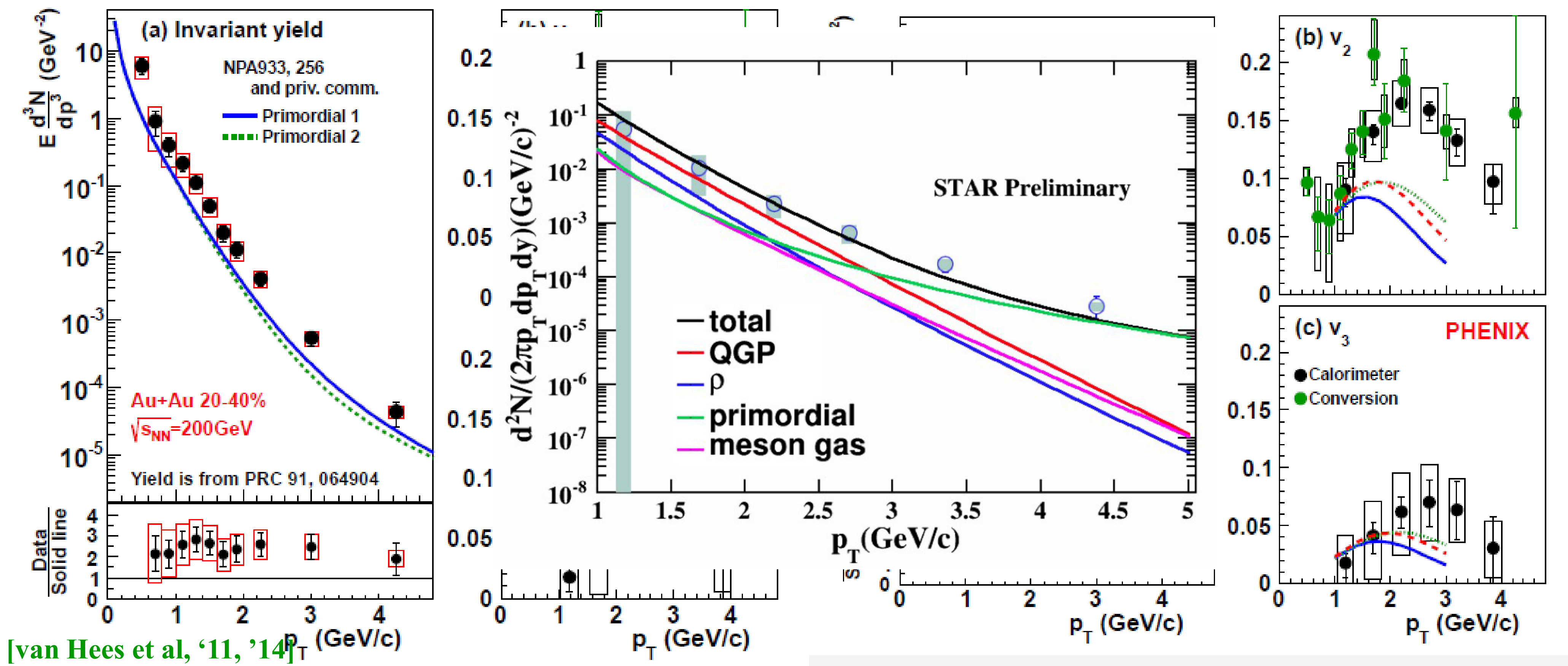


- Anti-/baryon effects melt the ρ meson
- ω also melts, ϕ more robust ↔ OZI

4.3 Comparison to Data: RHIC

Ideal Hydro

Viscous Hydro



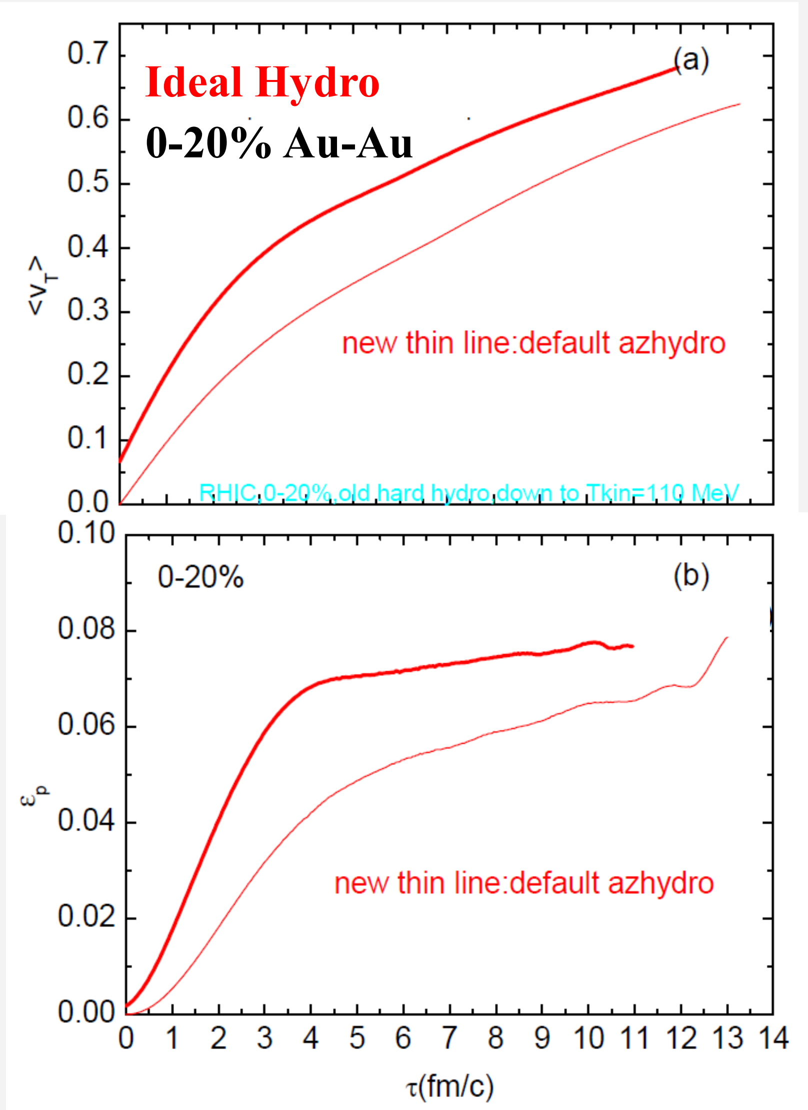
[van Hees et al, ‘11, ’14]

[Paquet et al ’16]

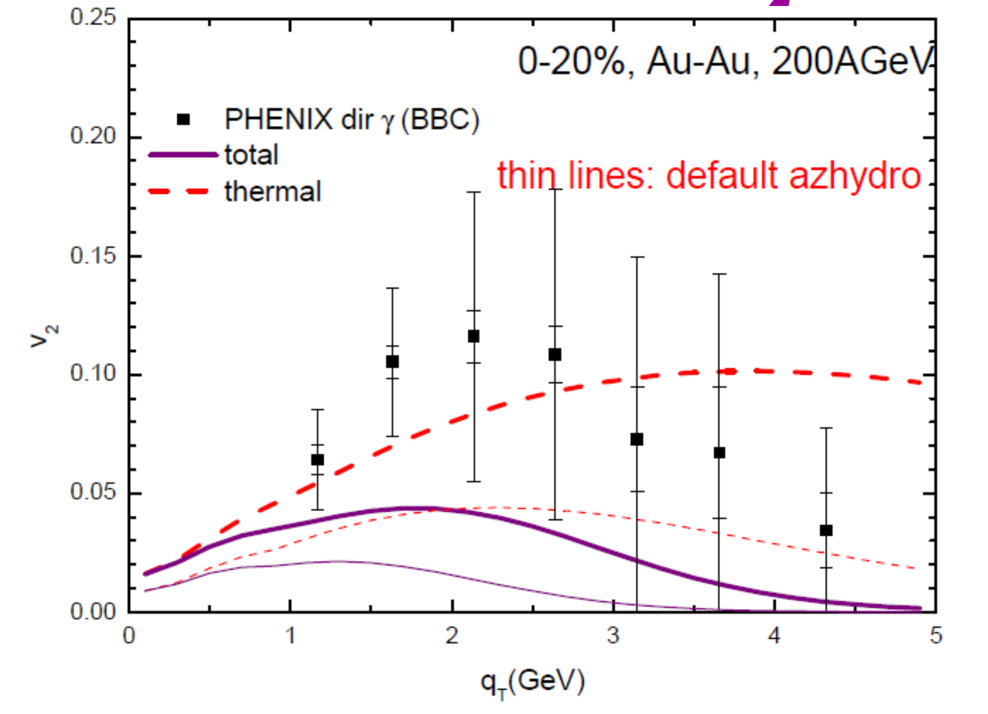
- same rates + intial flow ⇒ similar results from various evolution models

4.1 Initial Flow + Thermal Photon-v_2

Bulk-Flow Evolution



Direct-Photon v_2

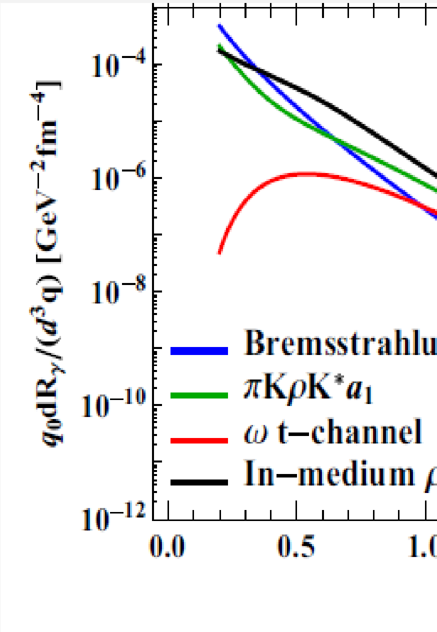


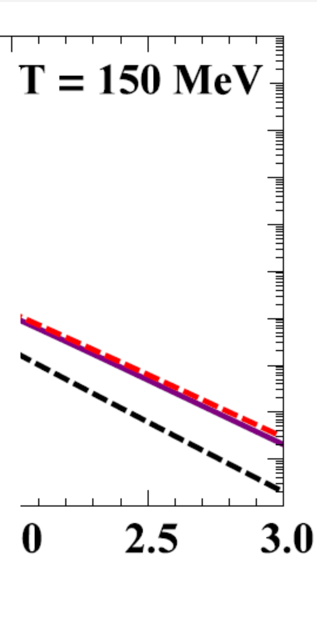
[He et al '14]

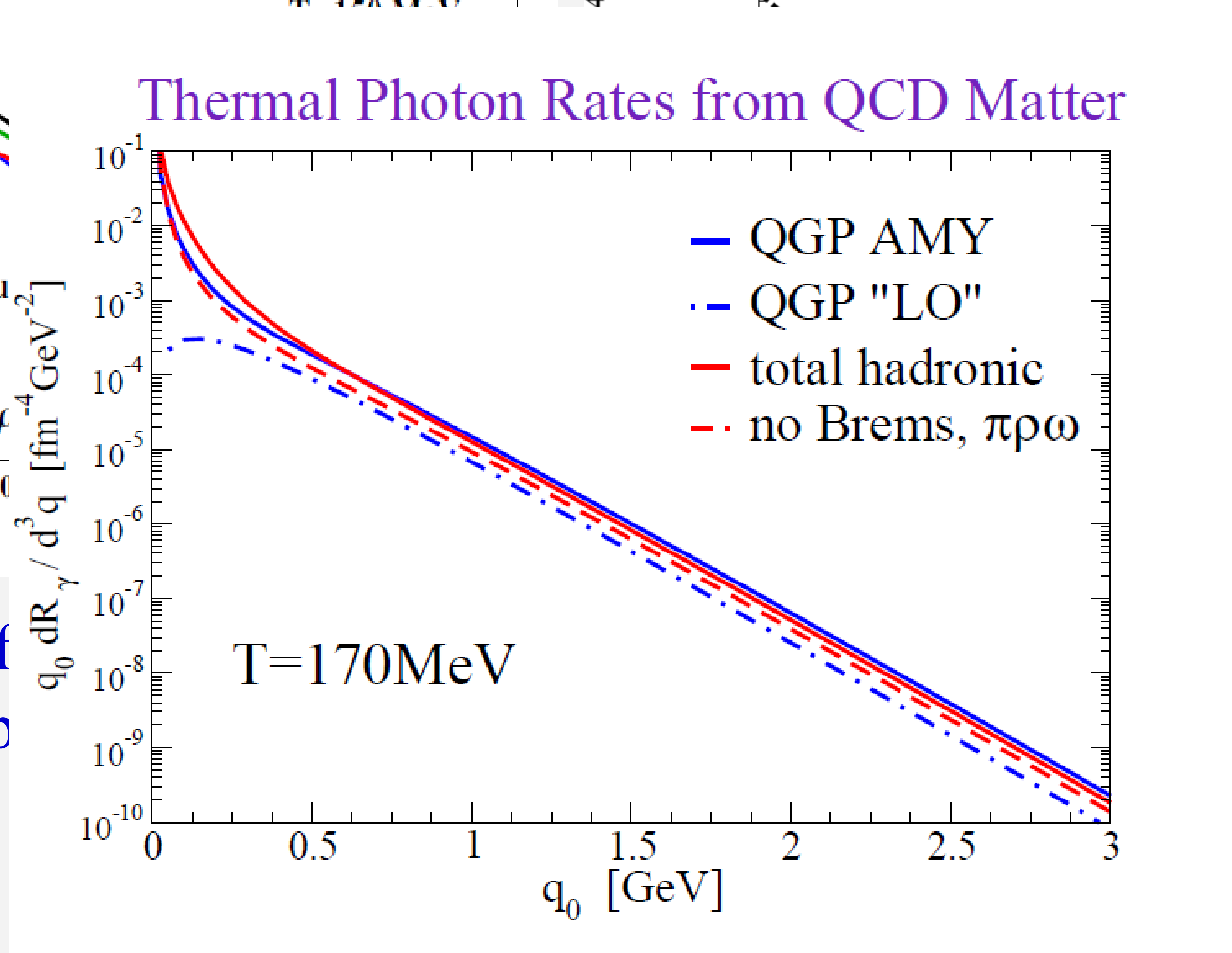
- initial radial flow: - accelerates bulk v_2
  - harder radiation spectra

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

4.2 Thermal Photon Rates







• ``Cocktail" of … ources:
(available in p … ρω → γπ

[Heffernan … Iohler+RR in prep]

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

3.2 Massive Yang-Mills Approach in Vaccum

- Gauge ρ + $\mathbf{a_1}$ into chiral pion lagrangian:

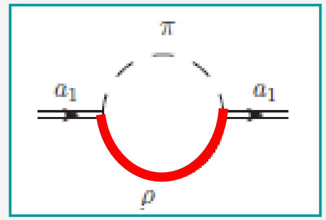
$$\mathcal{L}_{\rm MYM} = \frac{\tilde{f}_\pi^2}{8}\left(\mathrm{Tr}[D_\mu U^\dagger D^\mu U] + \tilde{m}_\pi^2 \mathrm{Tr}[U + U^\dagger - 2]\right) - \frac{1}{2}\mathrm{Tr}[F_L^2 + F_R^2] + m_0^2 \mathrm{Tr}[A_L^2 + A_R^2] - i\xi\ \mathrm{Tr}[D_\mu U D_\nu U^\dagger F_L + D_\mu U^\dagger D_\nu U F_R]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

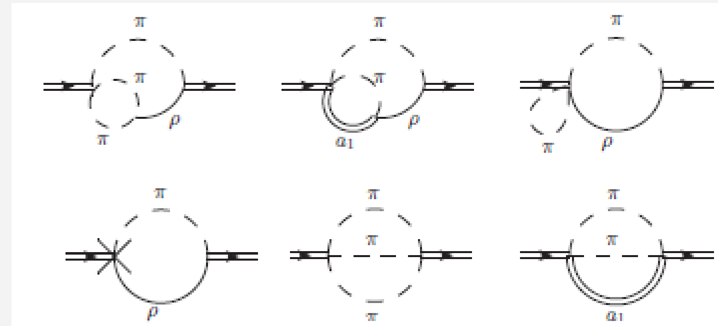
- problems with vacuum phenomenology

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

- Recent progress:
  - **full** ρ propagator in $\mathbf{a_1}$ selfenergy
  - **vertex corrections** to preserve **PCAC:**

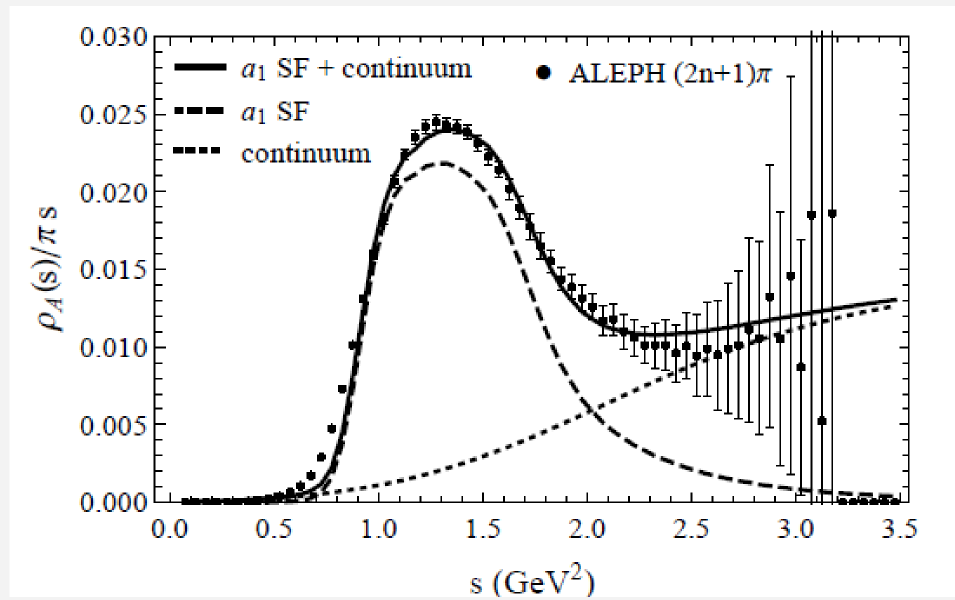
$$\int \frac{(-\mathrm{Im}\Pi_A^L)}{\pi s} ds = \frac{F_\pi^2}{2}$$



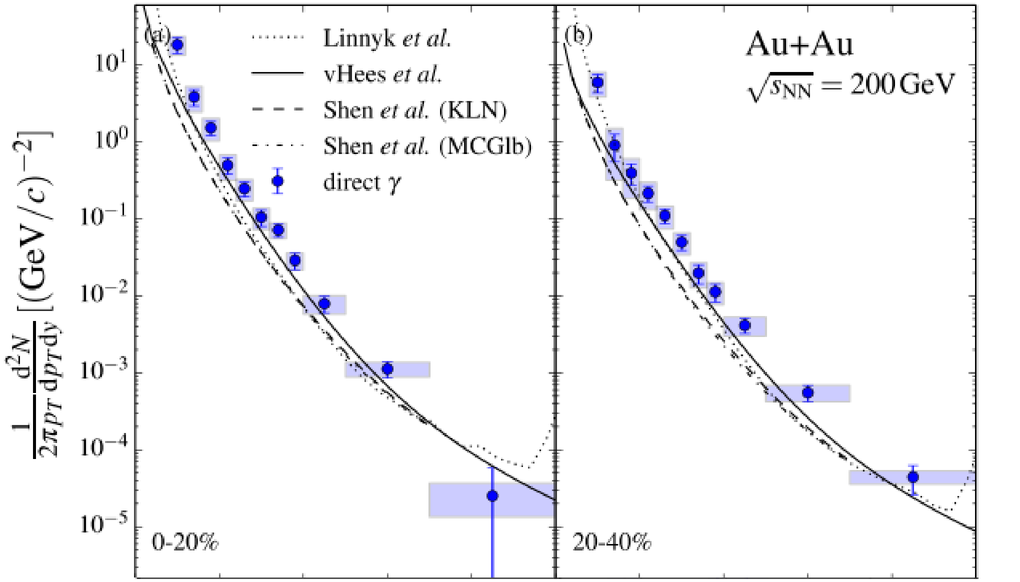


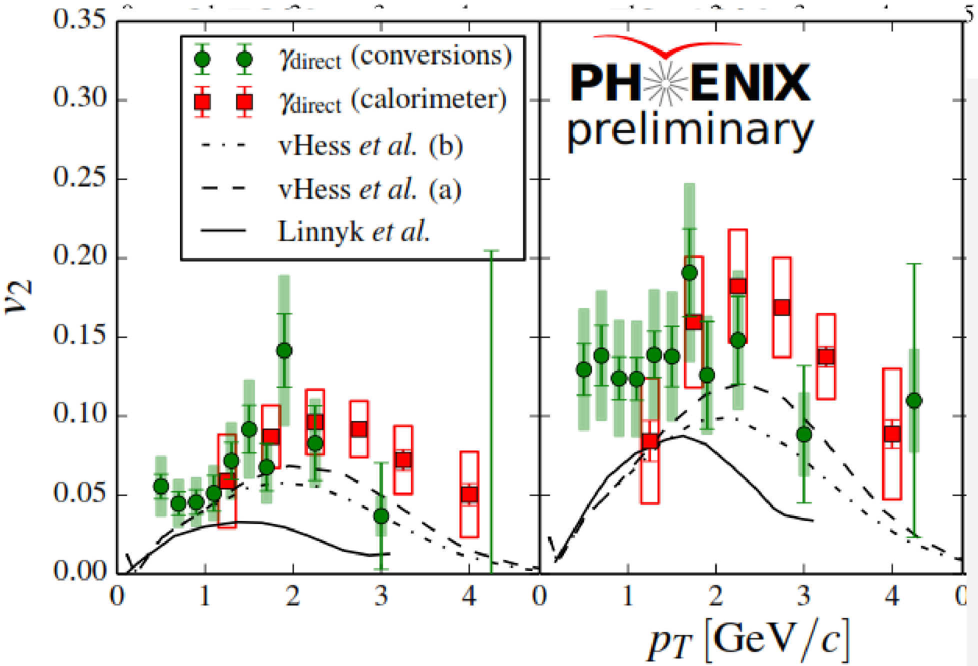
[Hohler +RR ‘14]

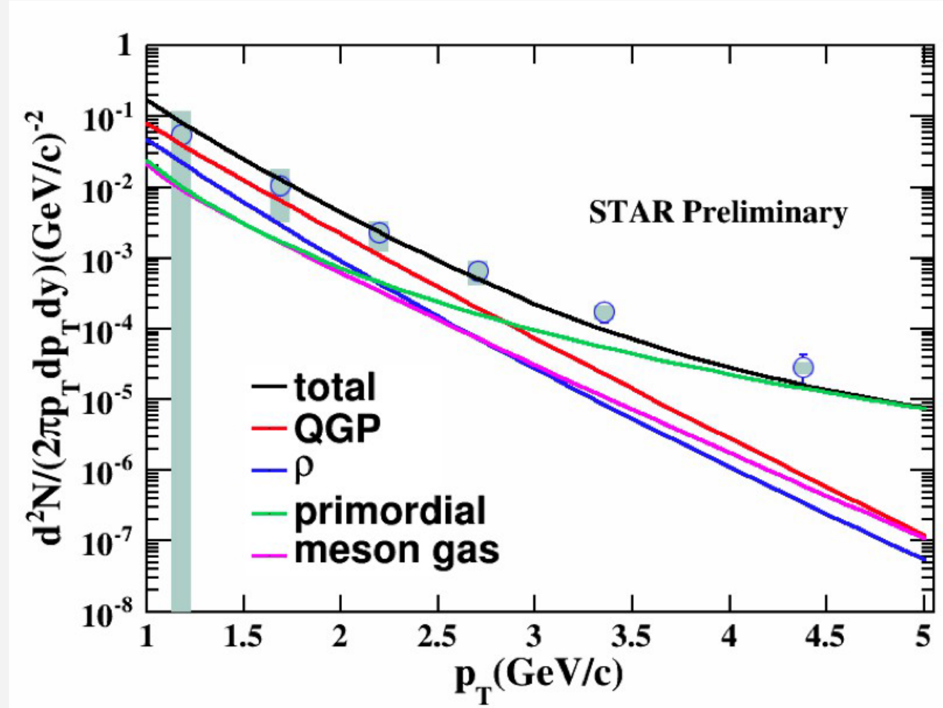
- enables fit to τ-decay data!
- local-gauge approach viable
- starting point for addressing **chiral restoration in medium**



4.3.2 Photon Puzzle!?





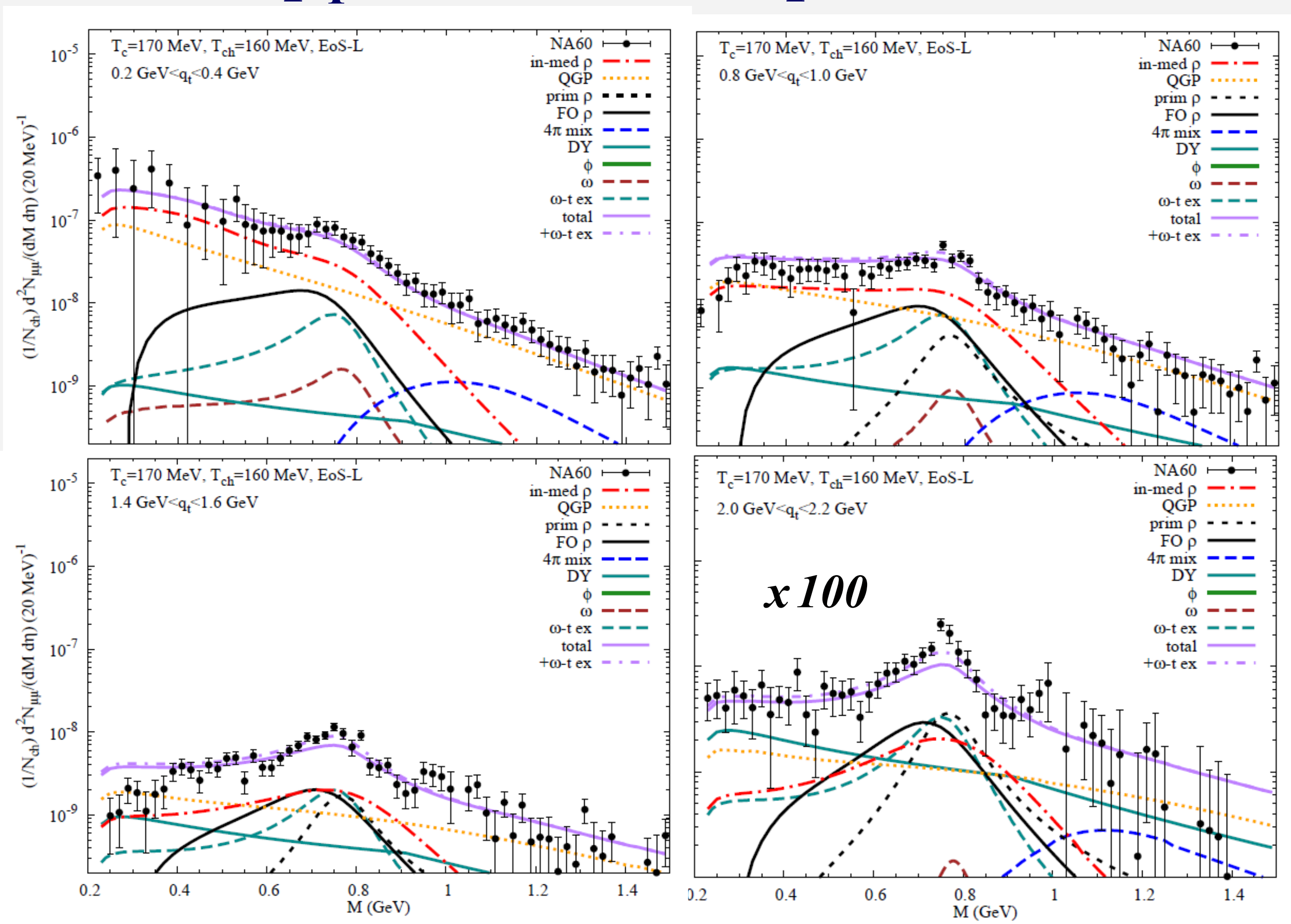


- T_{slope}^{excess} ~240 MeV
- blue-shift: $T_{slope} \sim T\,\sqrt{(1+\beta)/(1-\beta)}$

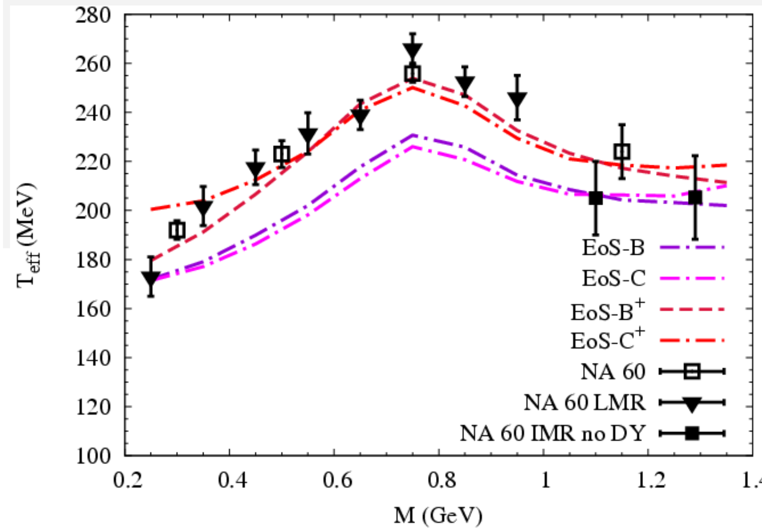
  $\Rightarrow T \sim 240/1.4 \sim 170$ MeV

2.2 Transverse-Momentum Dependence

p_T -Sliced Mass Spectra

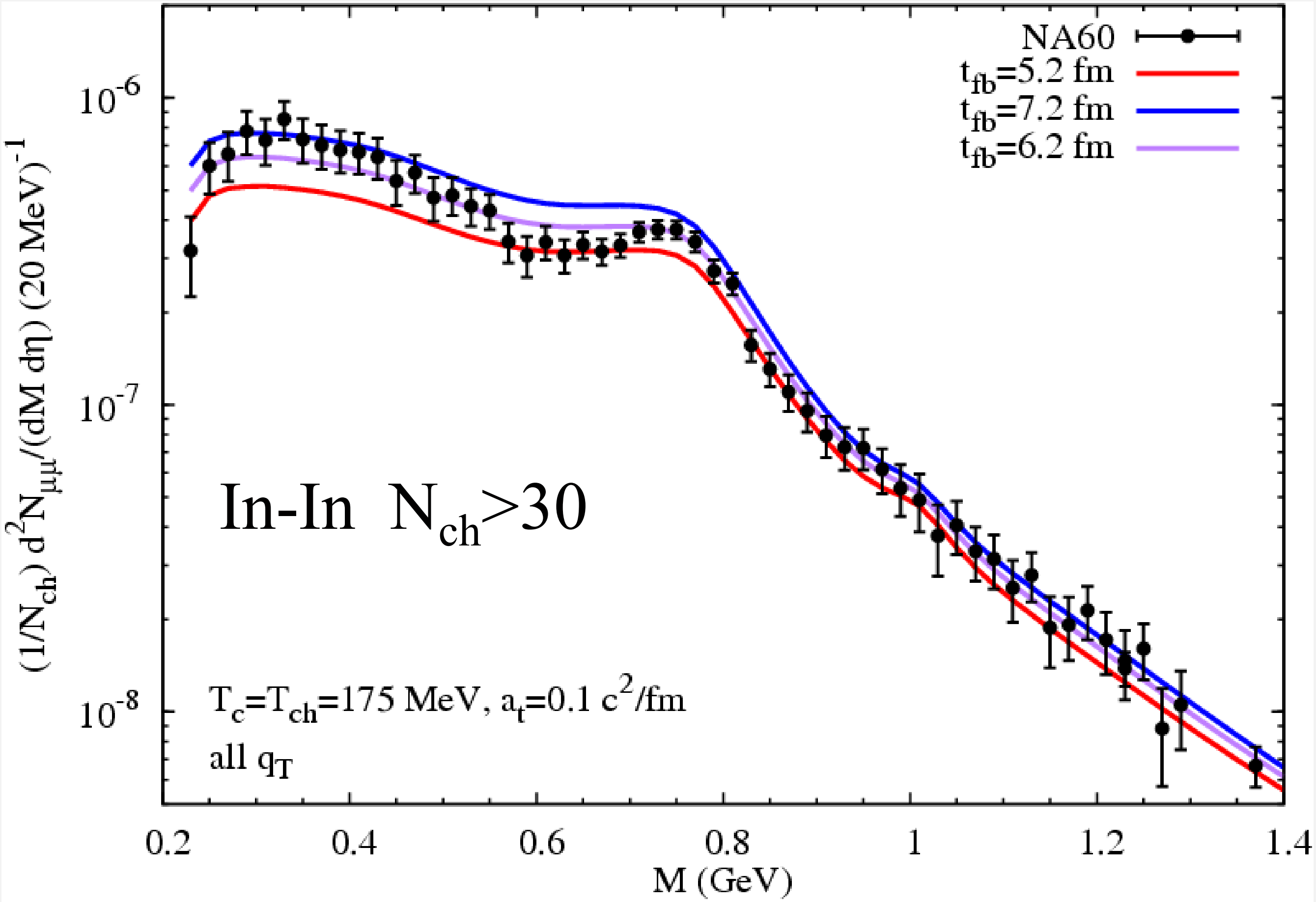


m_T -Slopes



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

4.2 Low-Mass Dileptons: Chronometer

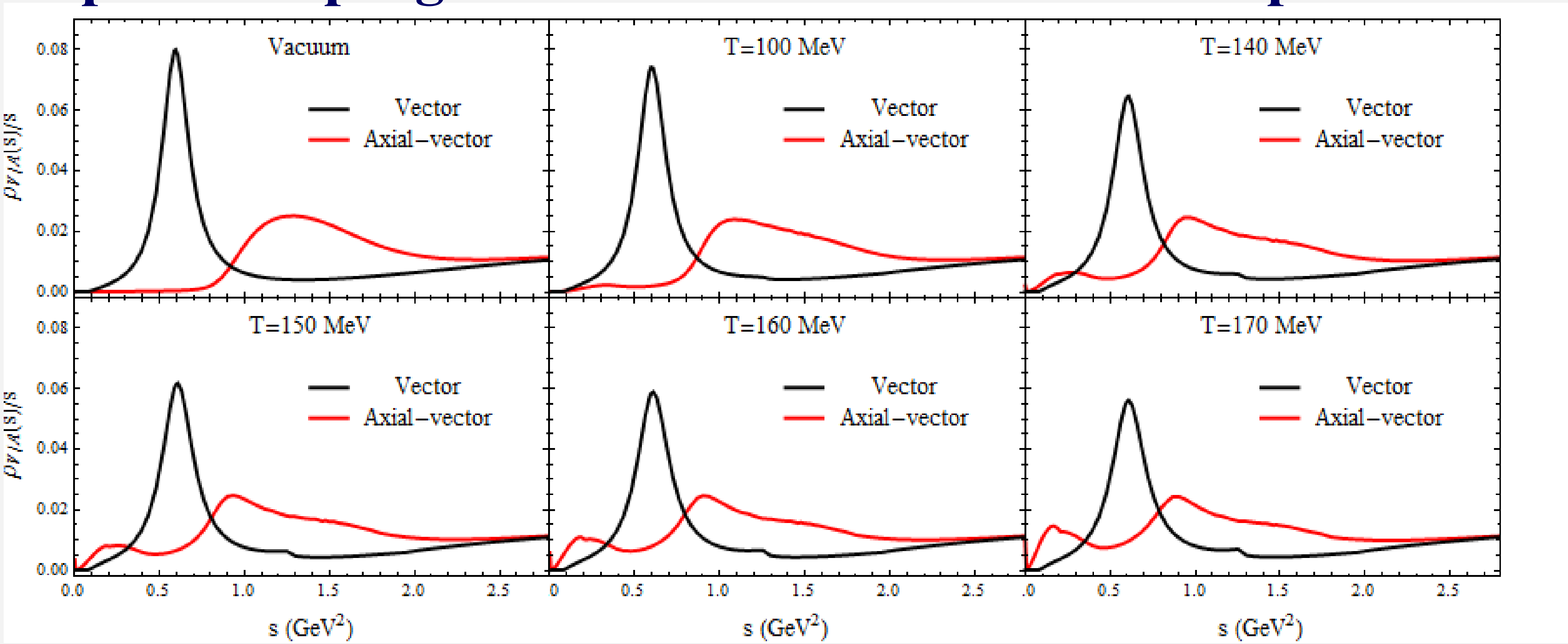


- first "explicit" measurement of interacting-fireball **lifetime**:

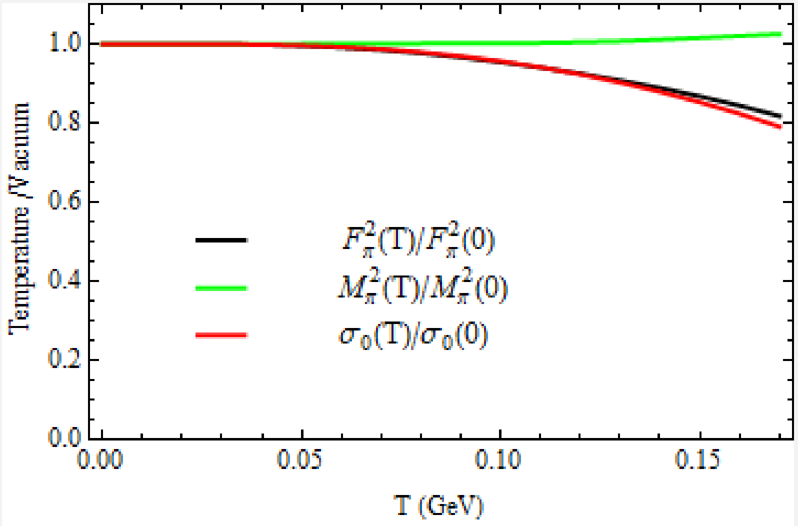
  $\tau_{FB} \approx (7\pm1)$ fm/c

3.2 Massive Yang-Mills in Hot Pion Gas

Temperature progression of vector + axialvector spectral functions

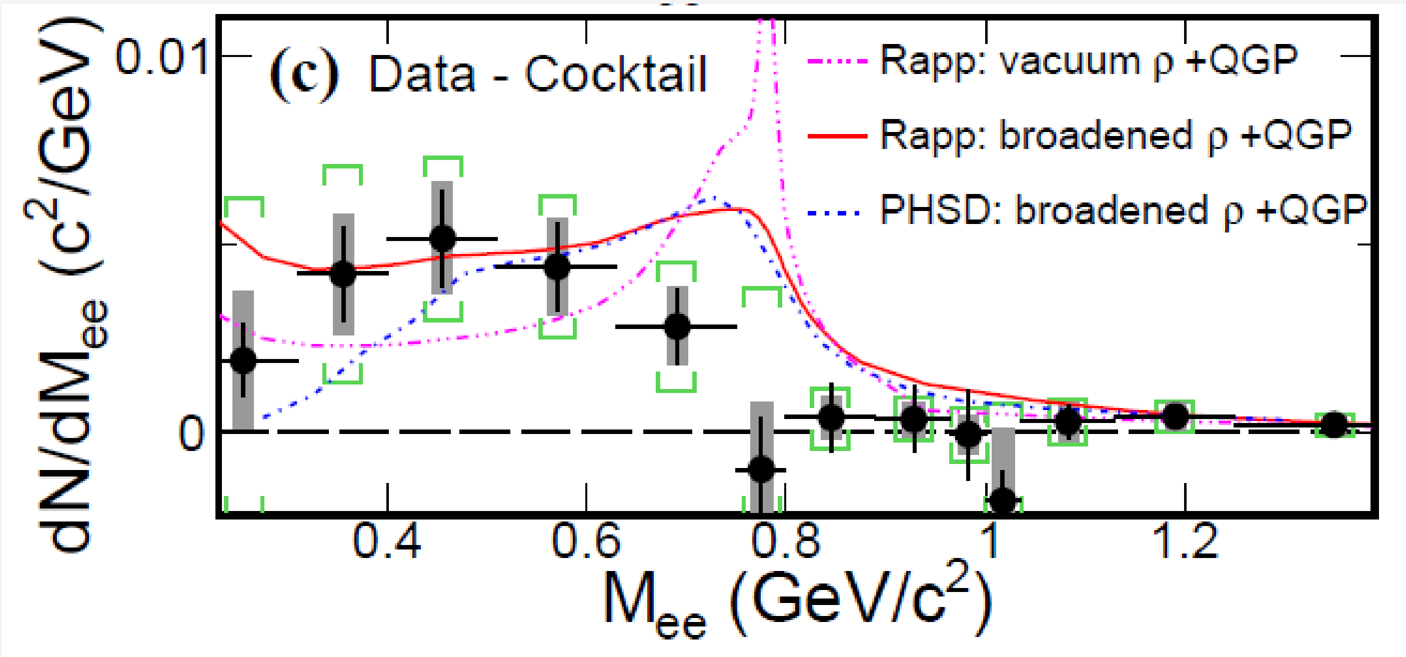


- supports "burning" of chiral-mass splitting as mechanism for chiral restoration [as found in sum rule analysis]



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

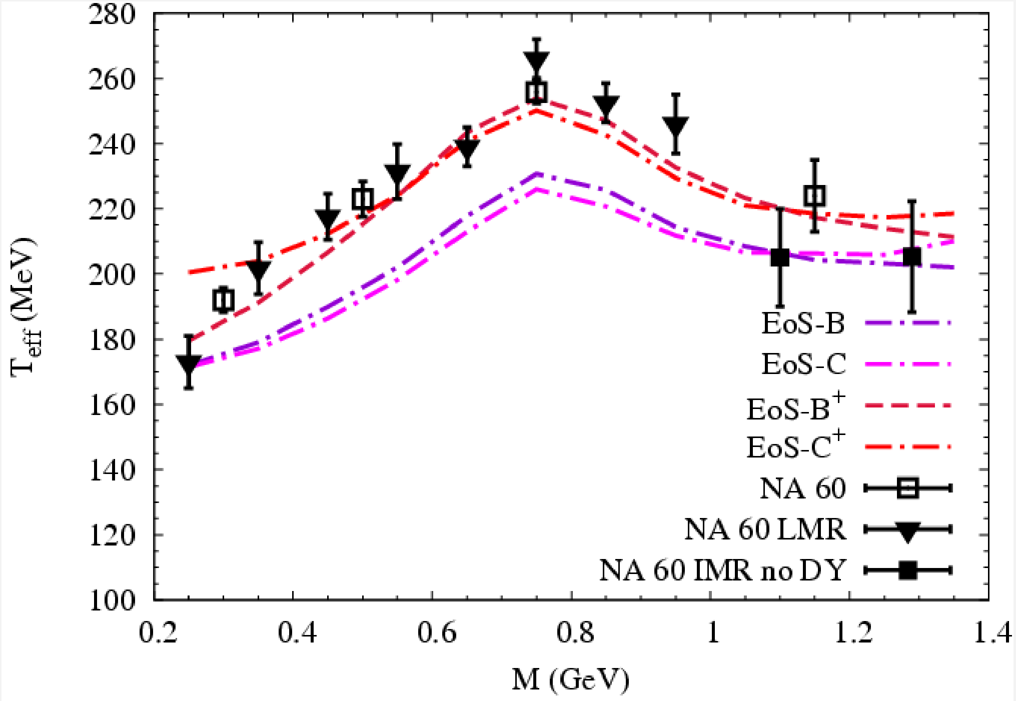
STAR Excess Dileptons [STAR '14]



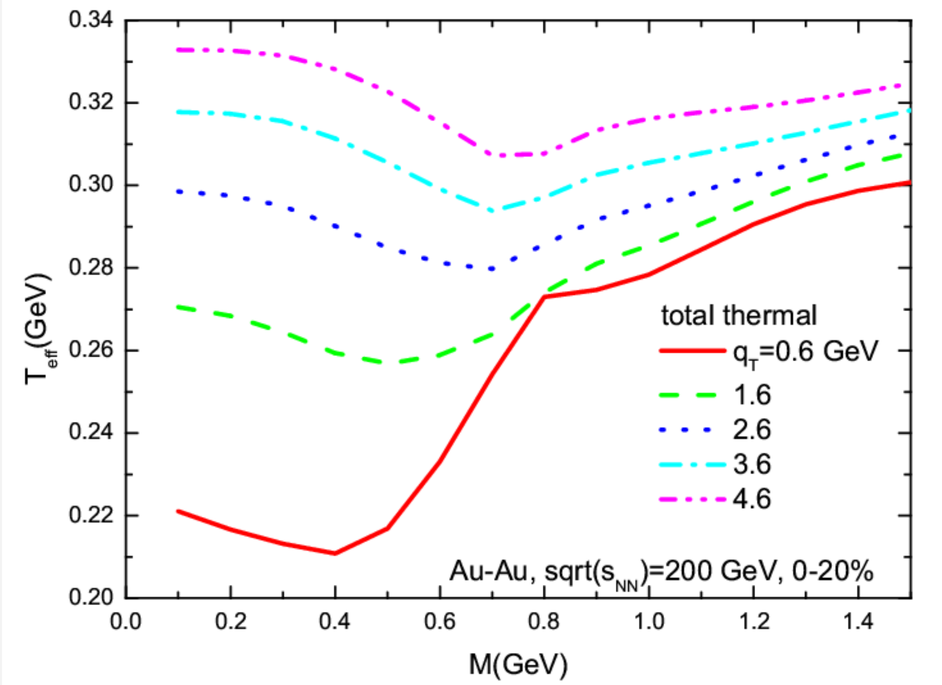
- rather different spectral shapes compatible with data
- QGP contribution?

4.5 QGP Barometer: Blue Shift vs. Temperature

SPS

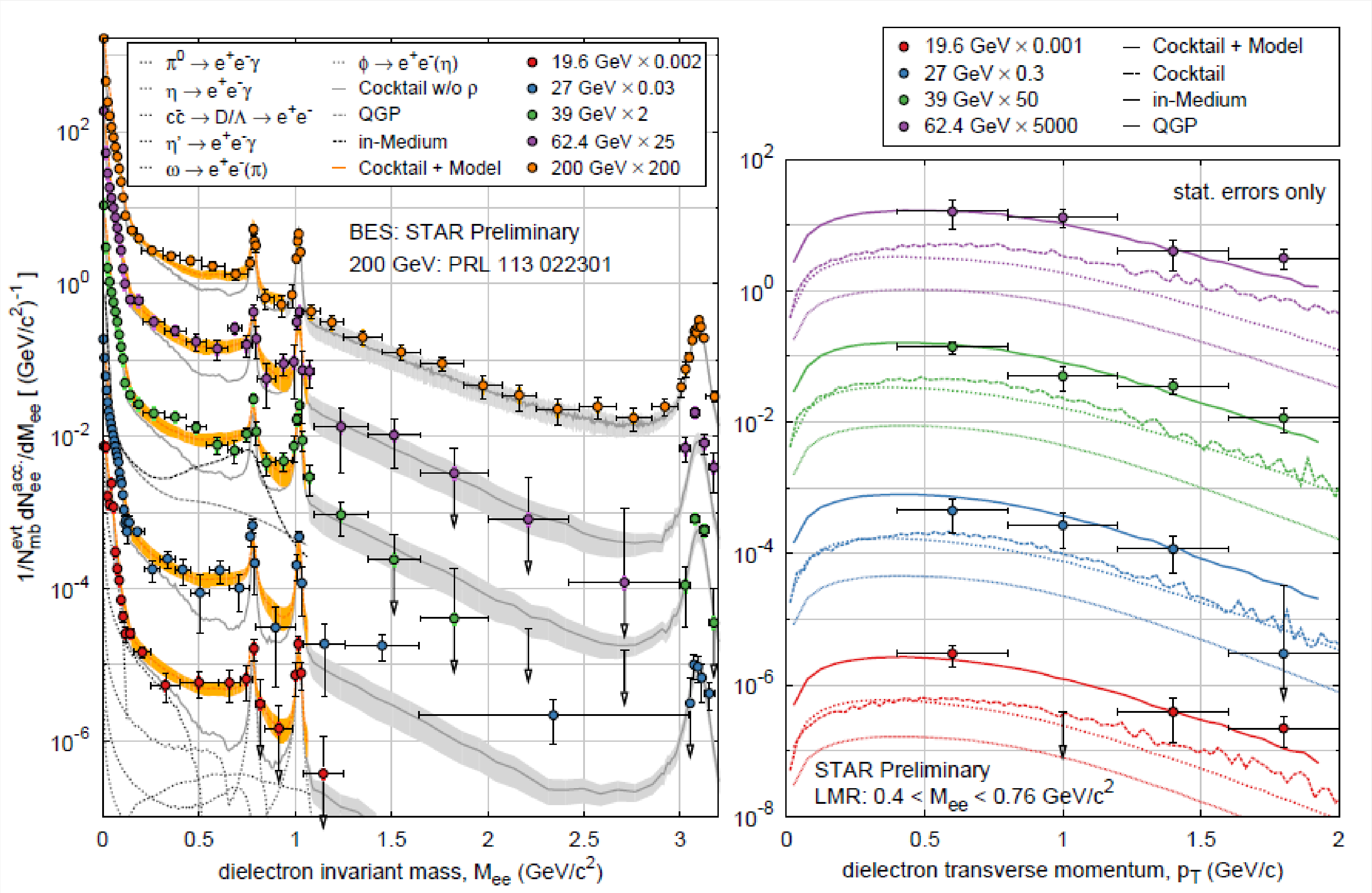


RHIC



- 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)

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

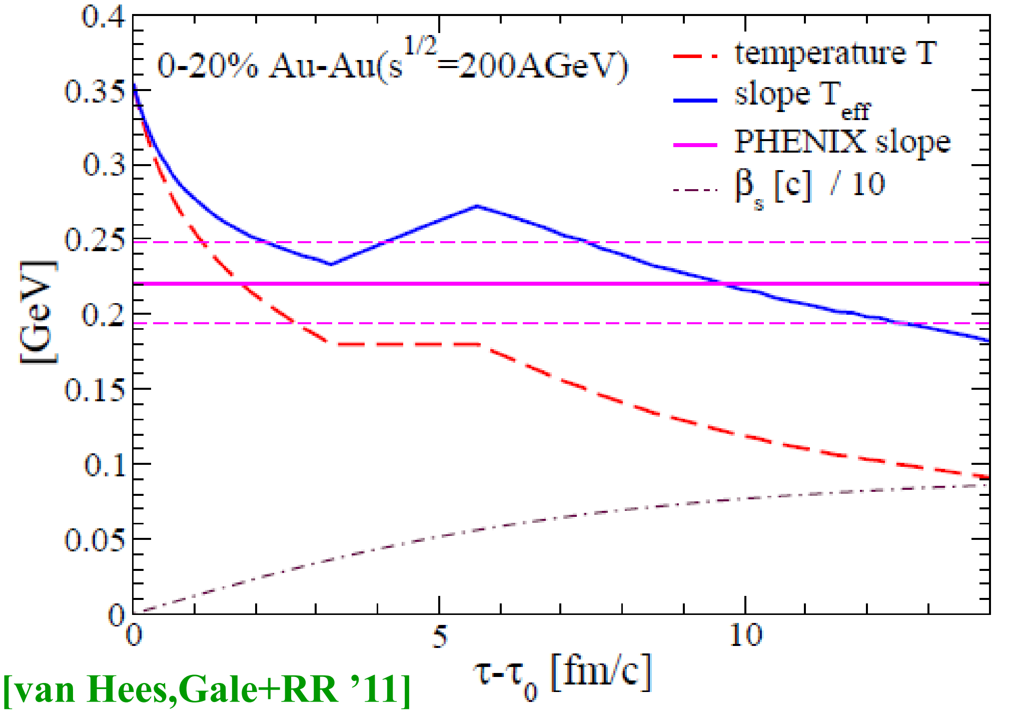


P. Huck et al. [STAR], QM14

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

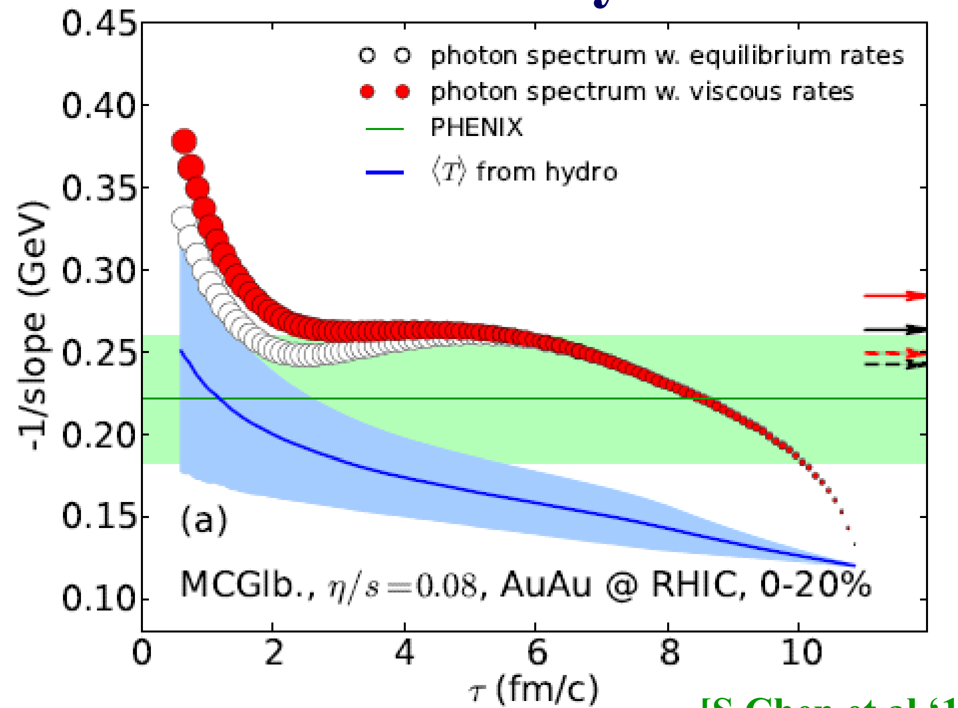
3.3.2 Effective Slopes of Thermal Photons

Thermal Fireball



[van Hees,Gale+RR '11]

Viscous Hydro



[S.Chen et al '13]

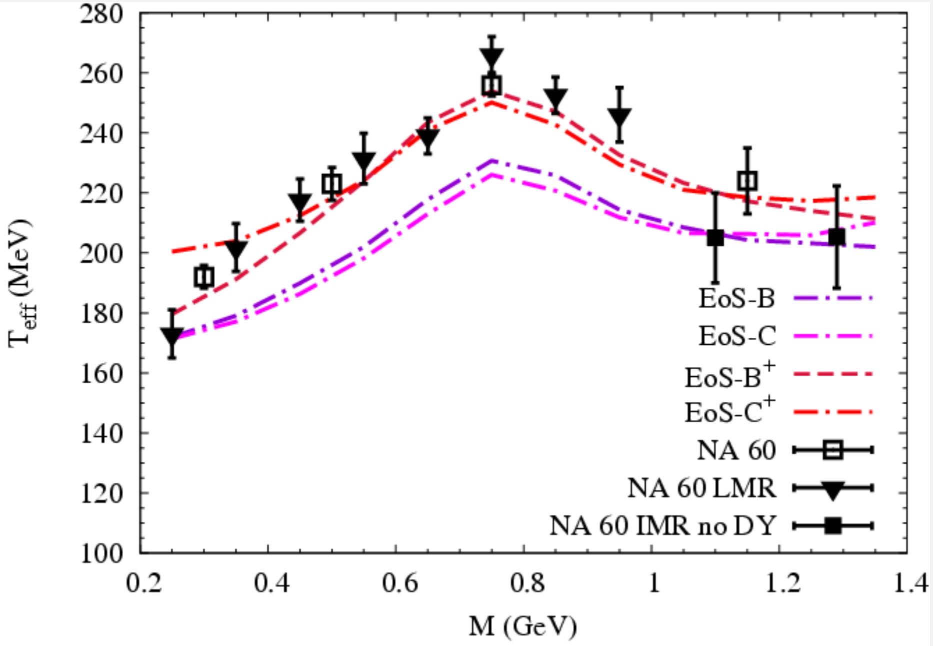
- thermal slope can only arise from $\mathbf{T \leq T_c}$ (constrained by hadron data)
- closely confirmed by hydro
- exotic mechanisms: glasma BE? Magnetic fields+ $\mathbf{U_A(1)}$?

[Liao at al '12, Skokov et al '12, F. Liu '13,…]

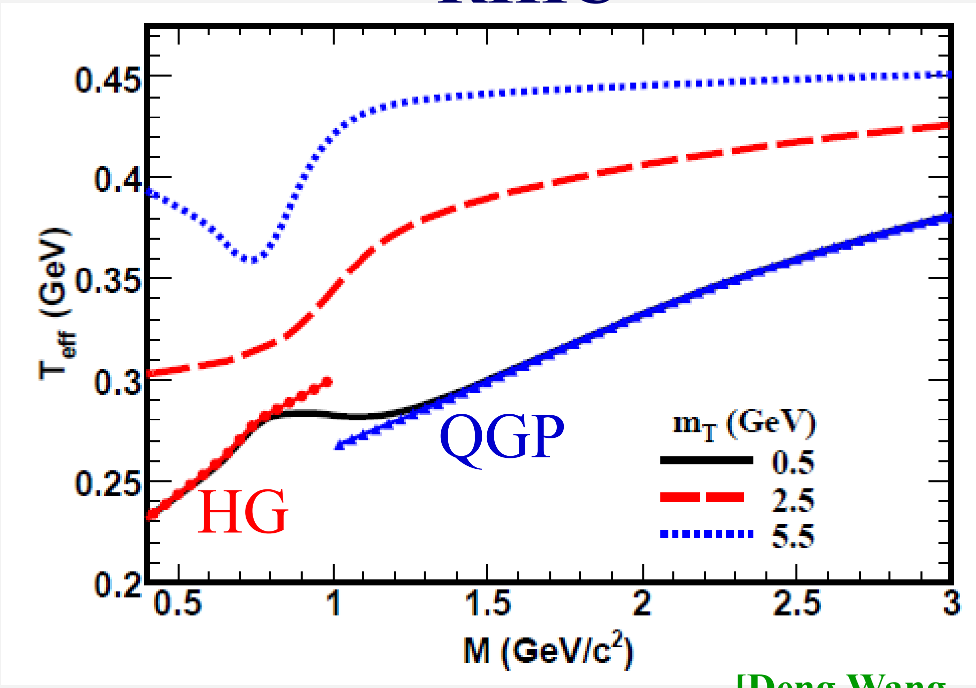
3.1.2 Transverse-Momentum Spectra: Baro-meter

Effective Slope Parameters

SPS



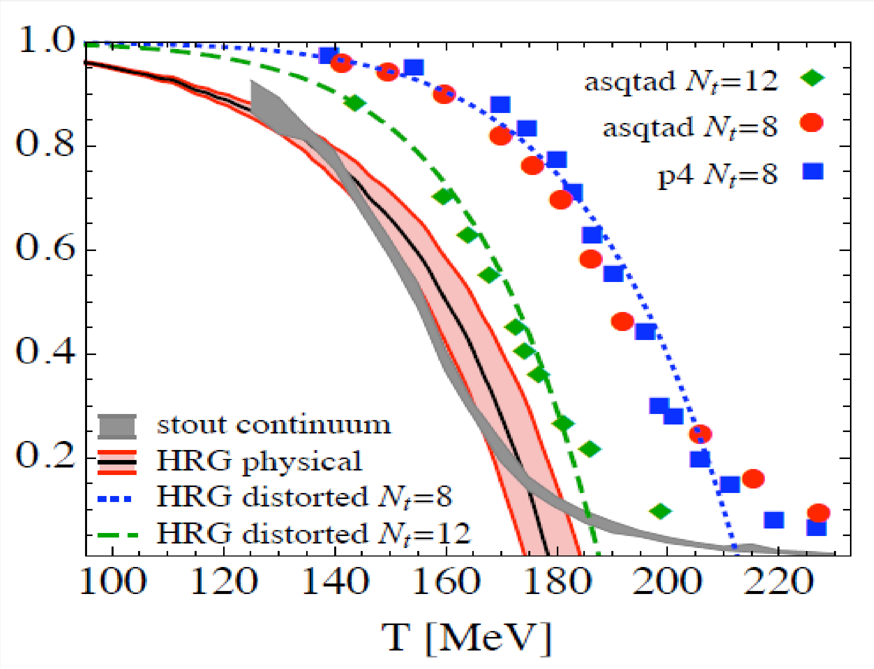
RHIC

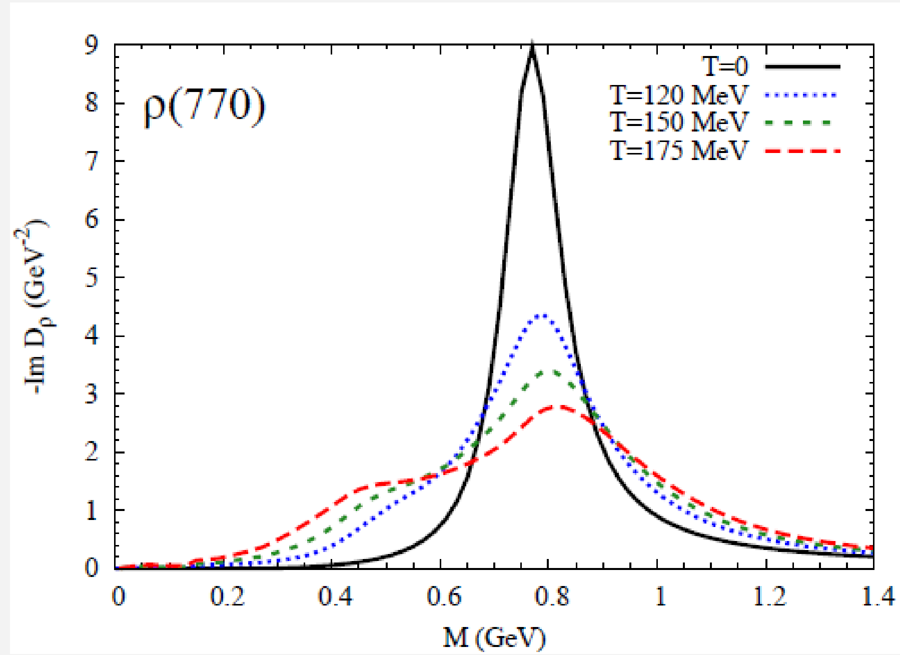


[Deng,Wang, Xu+Zhuang '11]

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

2.2 Chiral Condensate + ρ-Meson Broadening



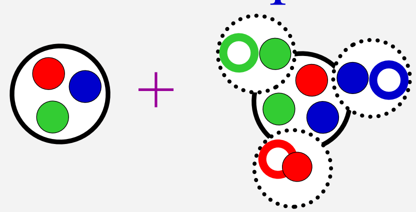


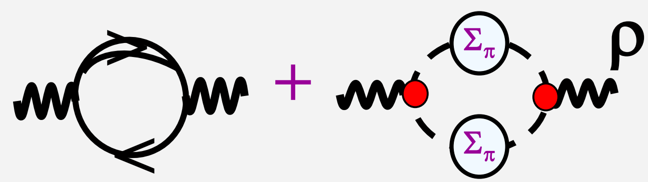
$$\frac{\langle\langle\bar{q}q\rangle\rangle(T,\mu_B)}{\langle\bar{q}q\rangle} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$$

⟷ effective hadronic theory

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

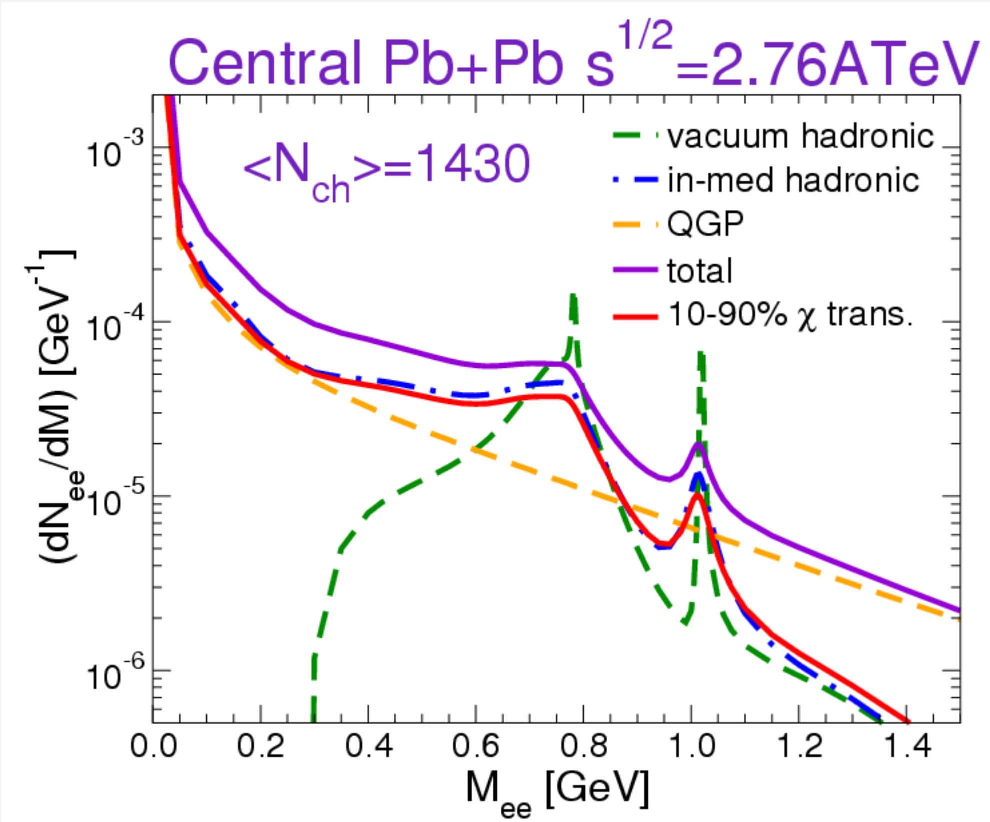
$= \Sigma_h^{core} + \Sigma_h^{cloud}$ ~

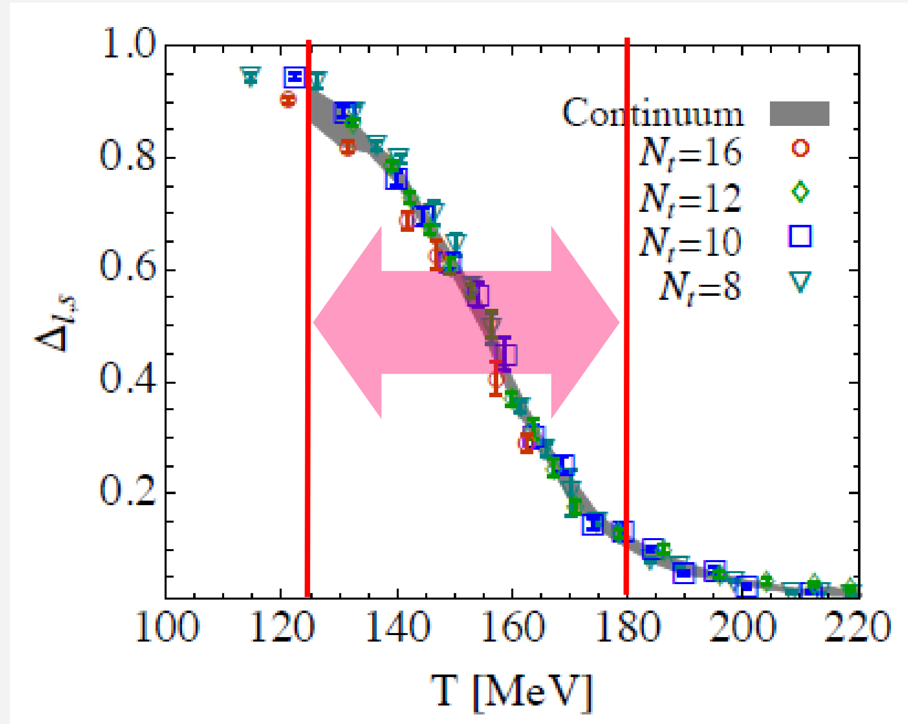




- **matches spectral medium effects: resonances + pion cloud**
- **resonances + chiral mixing drive ρ-SF toward chiral restoration**

5.2 Chiral Restoration Window at LHC



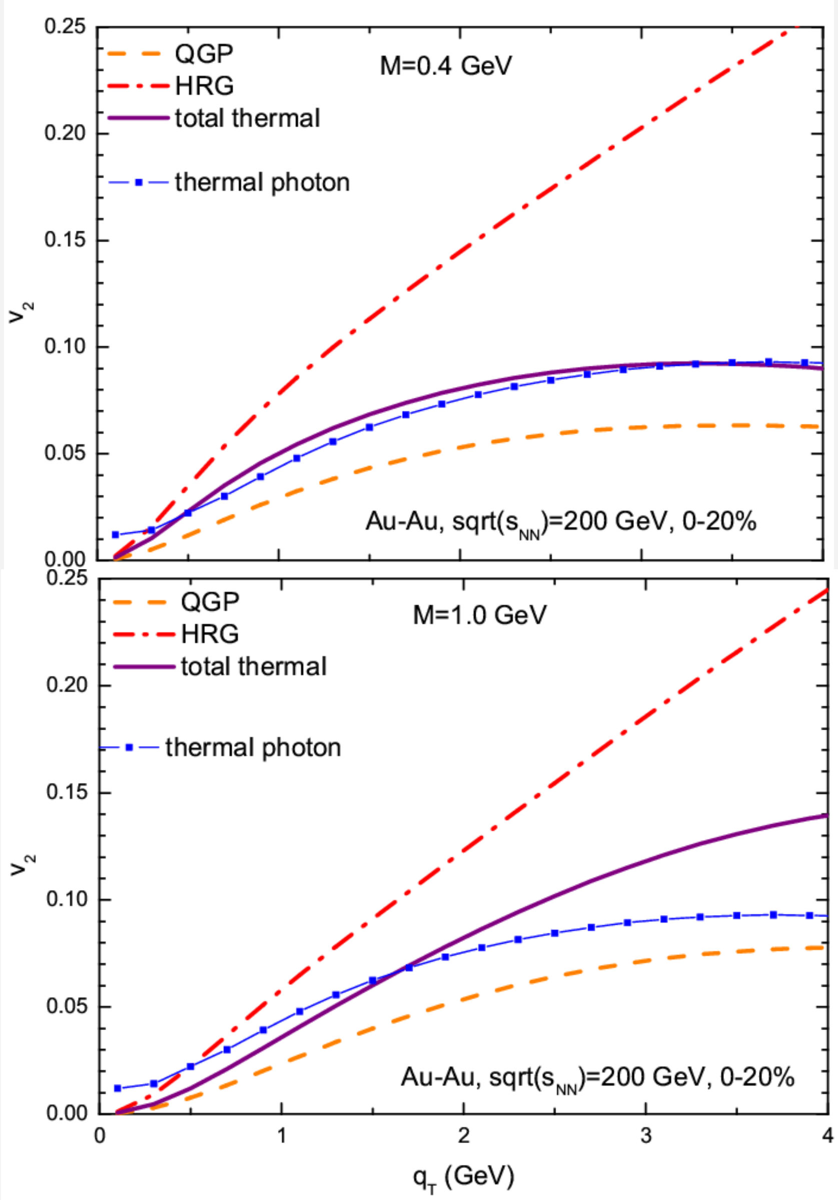


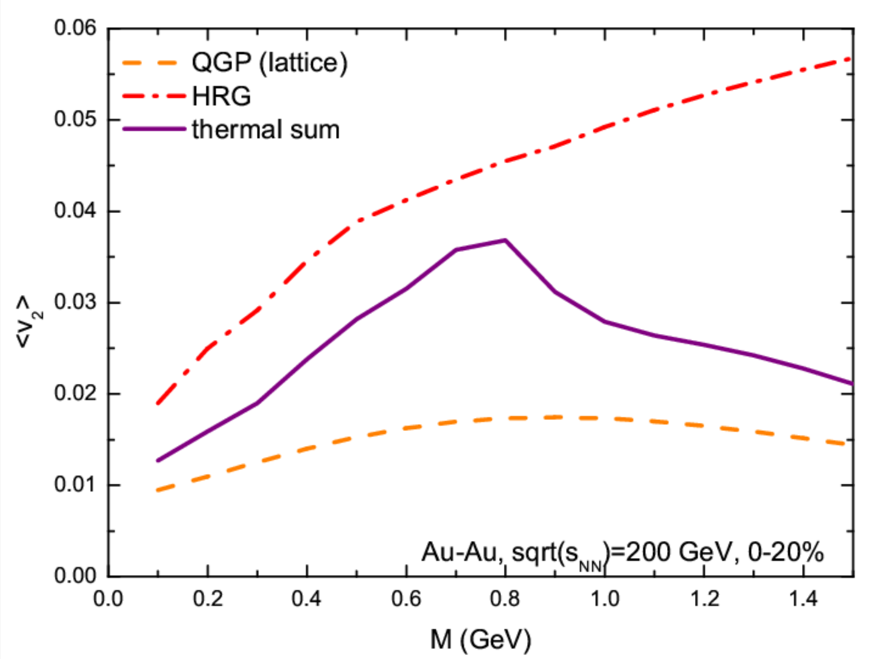
- low-mass spectral shape in chiral restoration window:

  ~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



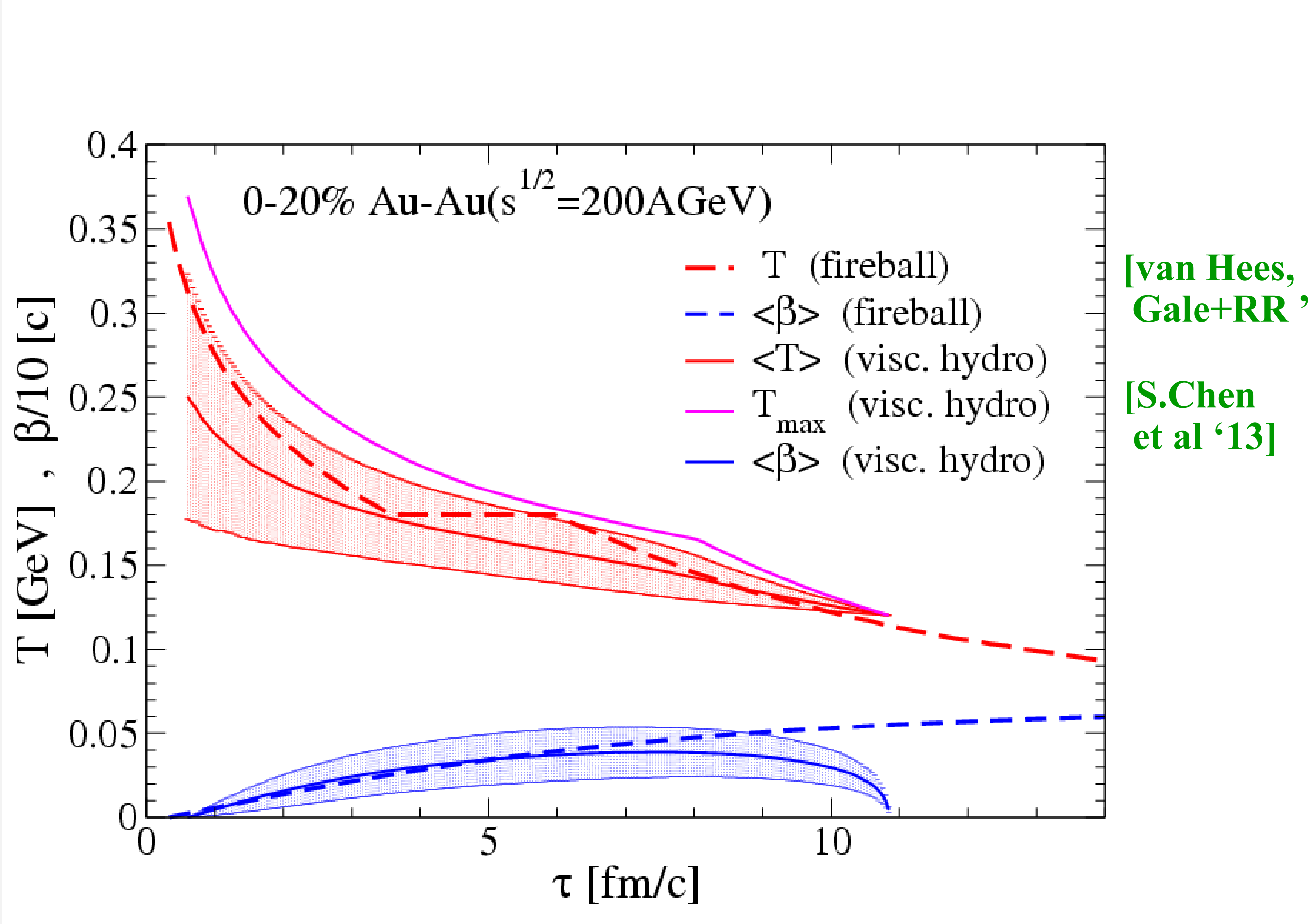


- maximum structure due to late ρ decays

[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!