

Electromagnetic Radiation from QCD Matter and Heavy-Ion Collisions

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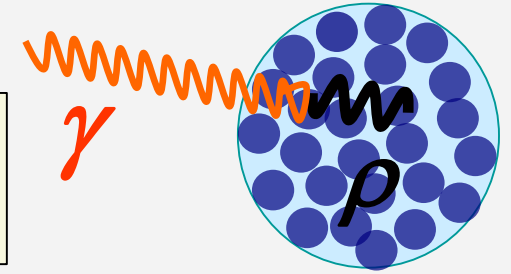
1.) Intro: Electromagnetic Probes of QCD Matter

→ **penetrating** probe

• Photon Scattering off Nuclei

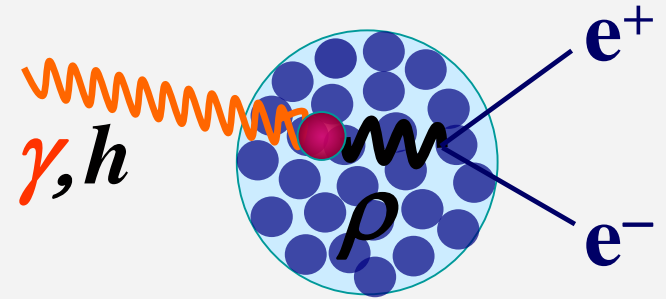
- Total Photo-Absorption

$$\frac{\sigma_{\gamma A}(q_0)}{A} = \frac{-4\pi\alpha}{q_0\rho_N} \rho_{\text{em}}(M=0, q; \mu_N)$$



- Dilepton Photo-/Hadro-Production

$$\frac{d\sigma_{\gamma A \rightarrow eeX}}{dM} \sim \int f^N |T_{\text{prod}}|^2 |D_V(M, q; \mu_N)|^2 \Gamma_{\gamma^* \rightarrow ee}$$



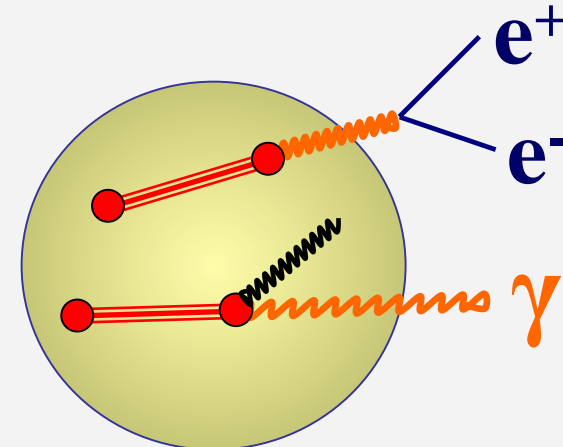
• Thermal Radiation in Heavy-Ion Collisions

- Dileptons

$$\frac{dR_{ee}}{d^4q} = \frac{-\alpha^2}{\pi^3 M^2} f^B(q_0; T) \rho_{\text{em}}(M, q; \mu_B, T)$$

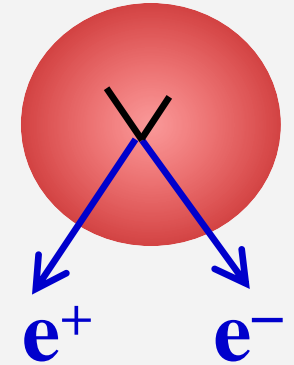
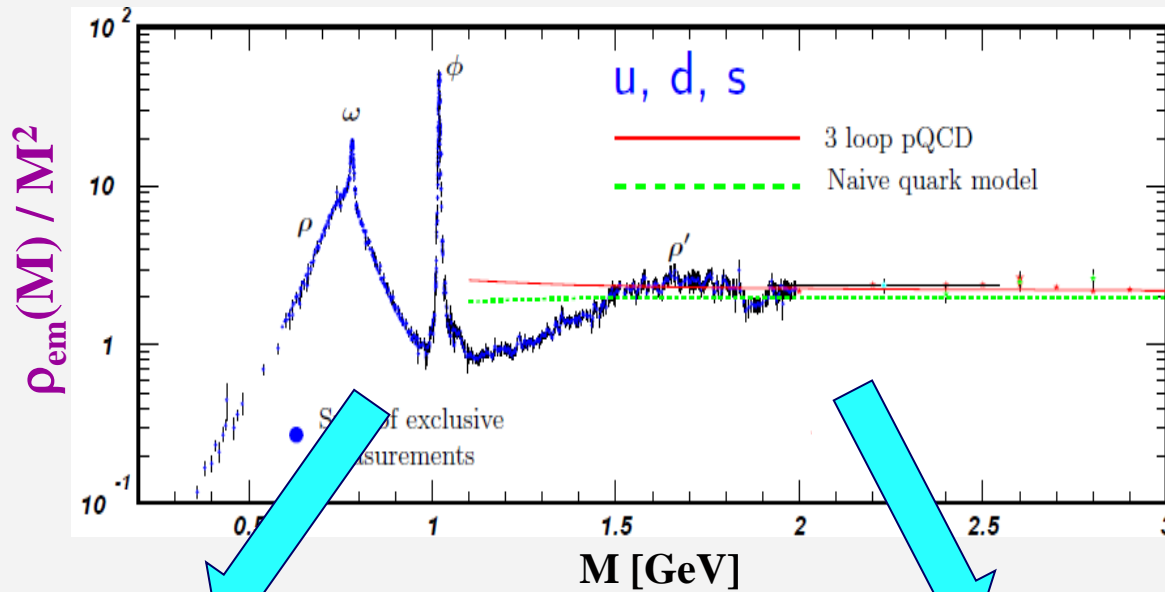
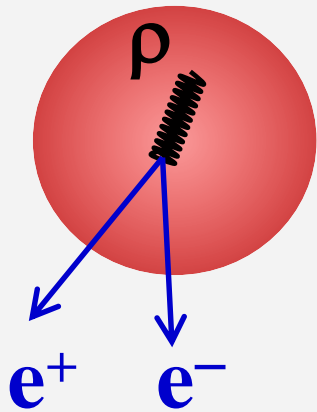
- Photons

$$q_0 \frac{dR_\gamma}{d^3q} = \frac{-\alpha}{\pi^2} f^B(q_0; T) \rho_{\text{em}}(M=0, q; \mu_B, T)$$



1.2 EM Spectral Function

Vacuum: $e^+e^- \rightarrow \text{hadrons}$



• **Hadronic Resonances:** $\rho_{em} \sim \text{Im } D_V$
massive, confined degrees of freedom

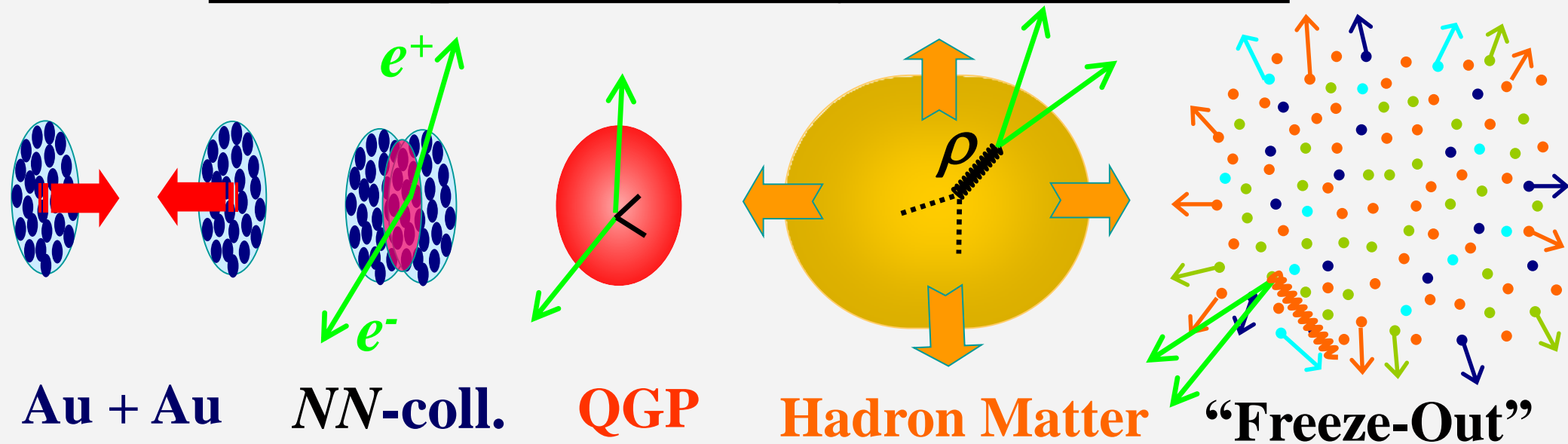
• **$q\bar{q}$ Continuum:**
perturbative

In Medium:

- change in **spectral shape, dofs?**
- restoration of **chiral symmetry?**
- **electric conductivity?**

- corrections $O(T^2/M^2)$
- measure **temperature**

1.3 Dileptons in Heavy-Ion Collisions



Sources of Dilepton Emission:

- “primordial” $q\bar{q}$ annihilation (Drell-Yan): $NN \rightarrow e^+e^-X$
- **thermal radiation**
 - **Quark-Gluon Plasma:** $q\bar{q} \rightarrow e^+e^-, \dots$
 - **Hot+Dense Hadron Gas:** $\pi^+\pi^- \rightarrow e^+e^-, \dots$
- final-state hadron decays: $\pi^0, \eta \rightarrow \gamma e^+e^-, D, \bar{D} \rightarrow e^+e^-X, \dots$

Outline

1.) Introduction

2.) EM Emission Rates

- **Quark-Gluon Plasma + Lattice QCD**
- **Hadronic Matter + in-Medium Vector Mesons**

3.) Thermal Emission in Heavy-Ion Collisions

- **Spectral Shape, Fireball Temperature + Lifetime**
- **Photon Puzzle?**

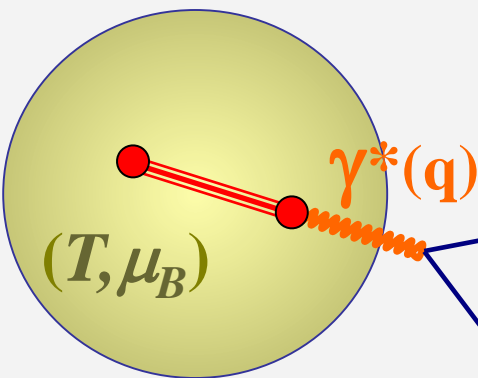
4.) Chiral Symmetry Restoration

- **QCD + Weinberg Sum Rules; Baryons**

5.) Electric Conductivity

6.) Conclusions

2.1 EM Correlator + Thermal Dilepton Rate



$$\frac{\Gamma_{ee}}{V} = \frac{dN_{ee}}{d^4x} = e^4 \int \frac{\Pi_i d^3 p_i}{(2\pi)^3 2E_i} \frac{\Pi_f d^3 p_f}{(2\pi)^3 2E_f} 2\pi \delta(P_i - P_f - Q) \\ \times \langle i | j_\mu^{\text{em}} | f \rangle \langle f | j_\nu^{\text{em}} | i \rangle f^i (1 \pm f^f) (j_e^\mu \frac{1}{Q^4} j_e^\nu)$$

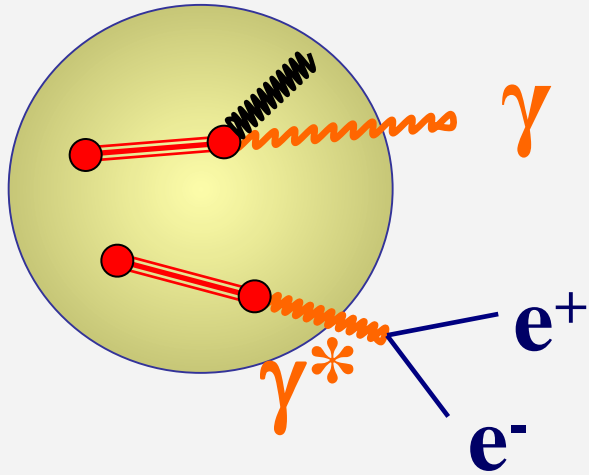
[McLerran+Toimela '85]

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

- EM Correlation Fct.: $\Pi_{\text{em}}^{\mu\nu}(Q) = -i \int d^4x e^{iQx} \langle\langle j_{\text{em}}^\mu(x) j_{\text{em}}^\nu(0) \rangle\rangle$
- Quark basis: $j_{\text{em}}^\mu = \frac{2}{3} \bar{u} \gamma^\mu u - \frac{1}{3} \bar{d} \gamma^\mu d - \frac{1}{3} \bar{s} \gamma^\mu s$ **Continuum**
- Hadron basis: $j_{\text{em}}^\mu = \frac{1}{2} (\bar{u} \gamma^\mu u - \bar{d} \gamma^\mu d) + \frac{1}{6} (\bar{u} \gamma^\mu u + \bar{d} \gamma^\mu d) - \frac{1}{3} \bar{s} \gamma^\mu s$
 $= \frac{1}{\sqrt{2}} j_\rho^\mu + \frac{1}{3\sqrt{2}} j_\omega^\mu - \frac{1}{3} j_\phi^\mu$ **Vector Meson**
Dominance: 9 : 1 : 2

2.2 Versatility of EM Correlation Function

• Photon Emission Rate



$$q_0 \frac{dR_\gamma}{d^3q} = \frac{-\alpha_{\text{em}}}{\pi^2} f^B(q_0, T) \text{Im} \Pi_{\text{em}}(q_0=q) \sim O(\alpha_s)$$

$$\frac{dR_{ee}}{d^4q} = \frac{-\alpha_{\text{em}}^2}{\pi^3 M^2} f^B(q_0, T) \text{Im} \Pi_{\text{em}}(M, q) \sim O(1)$$

same correlator!

• EM Susceptibility (→ charge fluctuations)

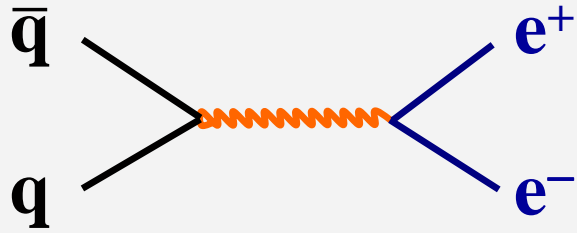
$$\langle Q^2 \rangle - \langle Q \rangle^2 = \chi_{\text{em}} = \Pi_{\text{em}}(q_0=0, q \rightarrow 0)$$

• EM Conductivity

$$\sigma_{\text{em}} = \lim(q_0 \rightarrow 0) [-\text{Im} \Pi_{\text{em}}(q_0, q=0) / 2q_0]$$

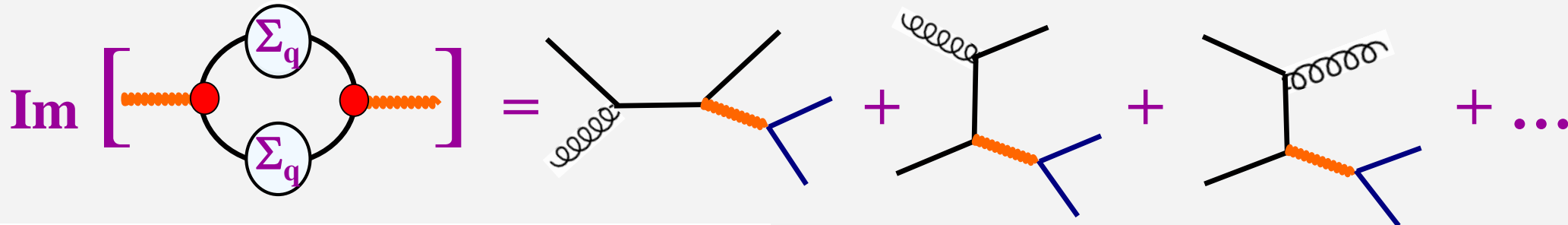
2.3 QGP Emission: Perturbative vs. Lattice QCD

Baseline:



small $M \rightarrow$ resummations,
finite- T perturbation theory (HTL)

[Braaten, Pisarski+Yuan '91]

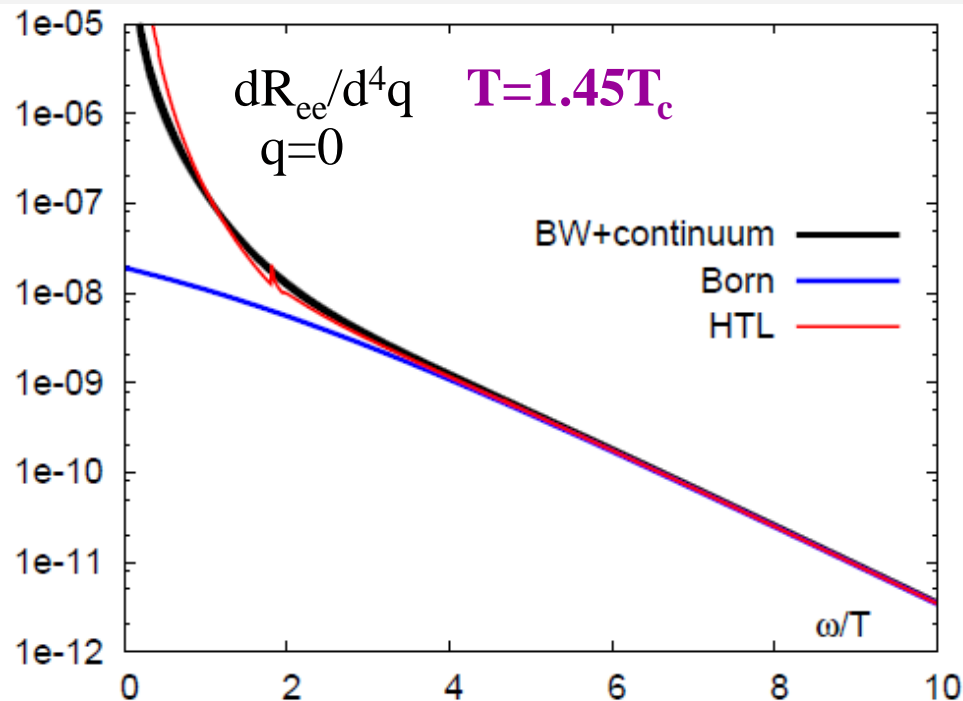


collinear enhancement:

$$D_{q,g} = (t - m_D^2)^{-1} \sim 1/\alpha_s$$

- marked low-mass enhancement
- comparable to lattice-QCD results

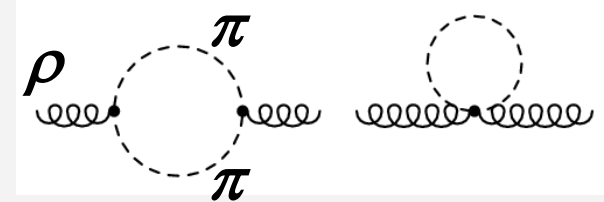
[Ding et al '10]



2.4.1 ρ -Meson in Vacuum

Introduce ρ as gauge boson into free $\pi + \rho$ Lagrangian \Rightarrow

$$\mathcal{L}_{\pi\rho}^{\text{int}} = g \vec{\rho}_\mu \cdot (\vec{\pi} \times \partial^\mu \vec{\pi}) - \frac{1}{2} g^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu \vec{\pi} \cdot \vec{\pi}$$



ρ -propagator:

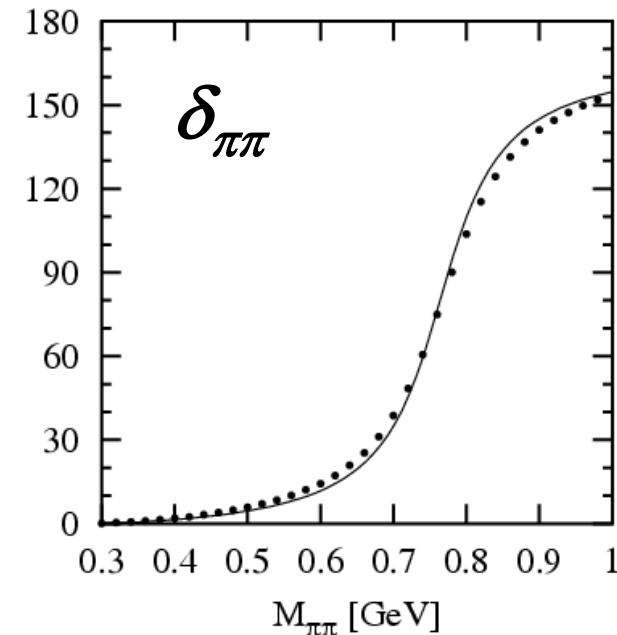
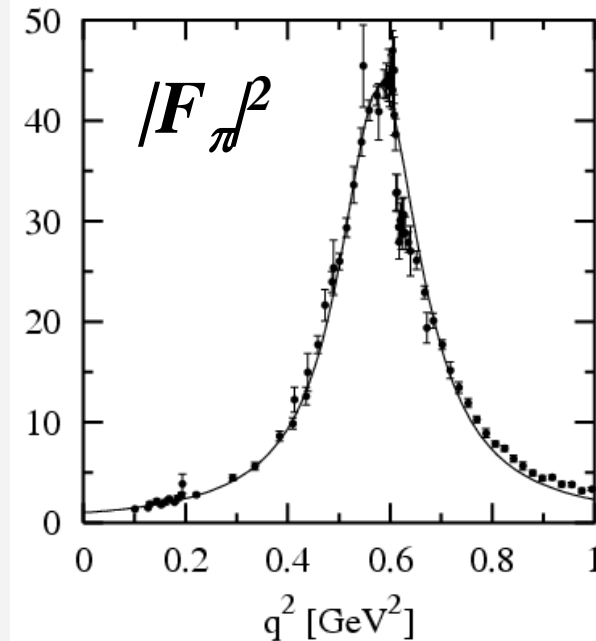
$$D_\rho(M) = [M^2 - (m_\rho^{(0)})^2 - \Sigma_{\rho\pi\pi}(M)]^{-1}$$

π EM formfactor

$$|F_\pi(M)|^2 = (m_\rho^{(0)})^4 |D_\rho(M)|^2$$

$\pi\pi$ scattering phase shift

$$\delta_{\pi\pi}(M) = \tan^{-1} \left(\frac{\text{Im } D_\rho(M)}{\text{Re } D_\rho(M)} \right)$$

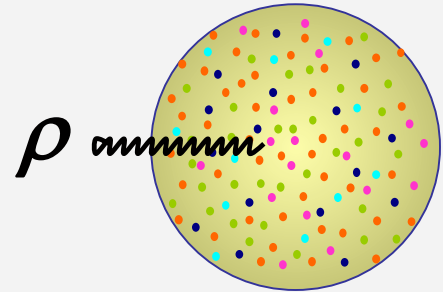


- 3 parameters: $m_\rho^{(0)}$, g , Λ_ρ

2.4.2 ρ -Meson in Matter: Many-Body Theory

interactions with hadrons from heat bath

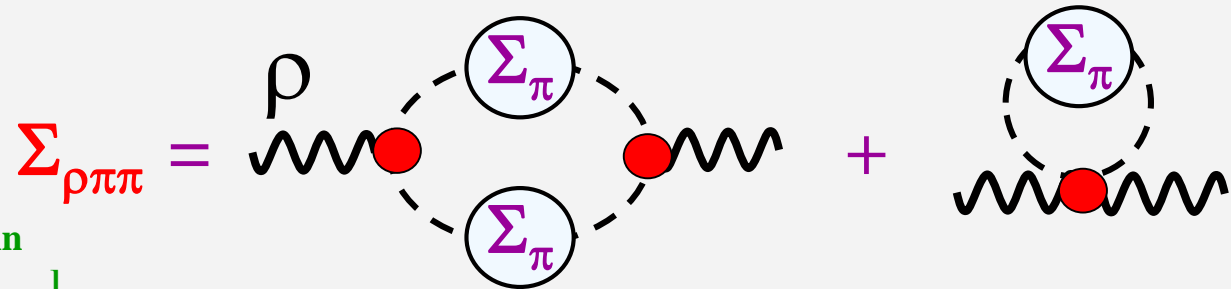
\Rightarrow In-Medium ρ -Propagator



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

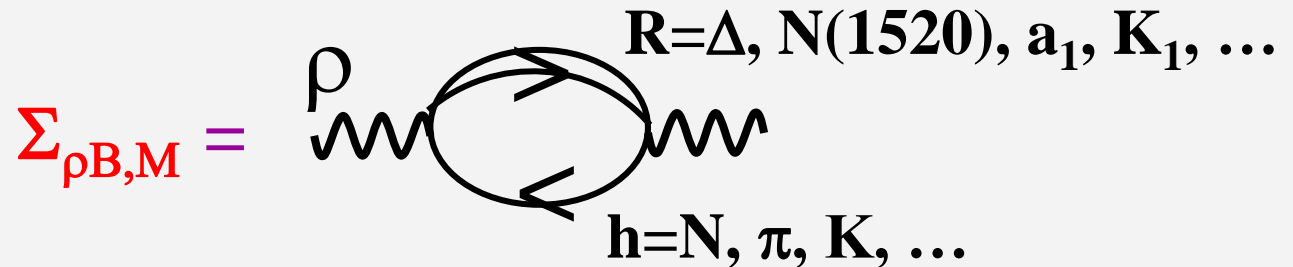
• In-Medium Pion Cloud

[Asakawa+Ko, Chanfray et al, Herrmann et al, Urban et al, Weise et al, Koch et al, ...]



• Direct ρ -Hadron Scattering

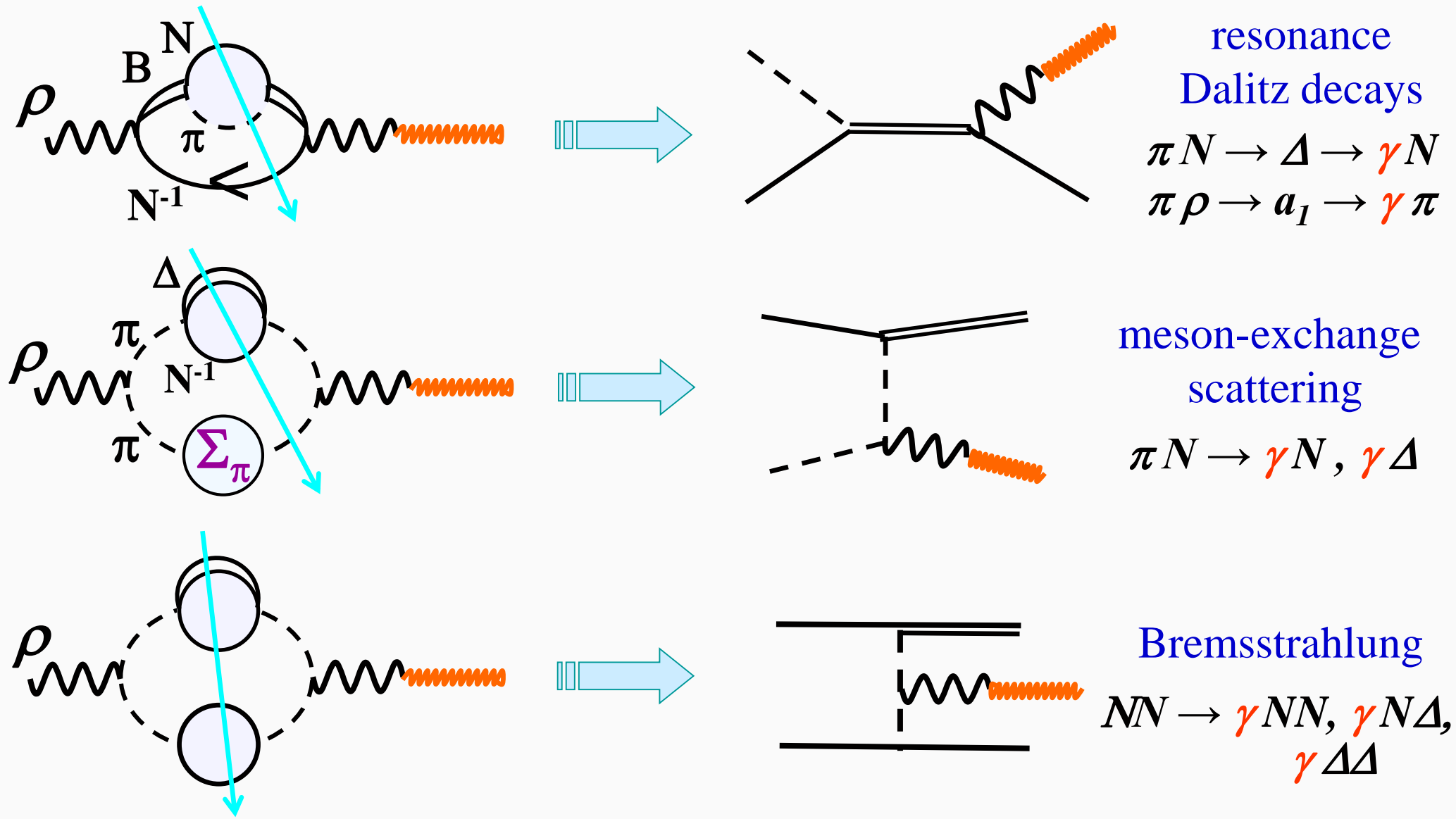
[Haglin, Friman et al, RR et al, Post et al, ...]



- estimate couplings from $R \rightarrow \rho h, \gamma h$
- comprehensively: scattering data ($\pi N \rightarrow \rho N, \gamma N/A, \dots$)

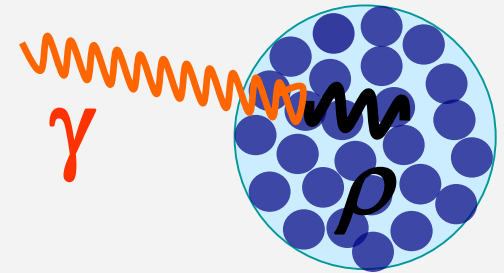
2.4.3 Production Processes from ρ Spectral Function

\leftrightarrow Cuts (imag. parts) of selfenergy diagrams:

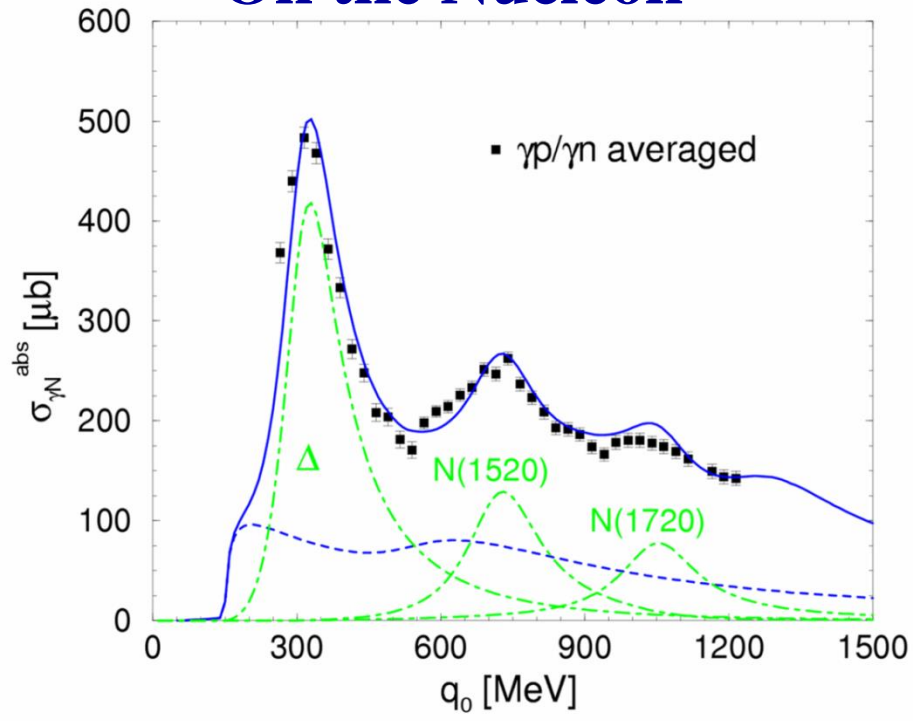


2.4.4 Constraints from Nuclear Photo-Absorption

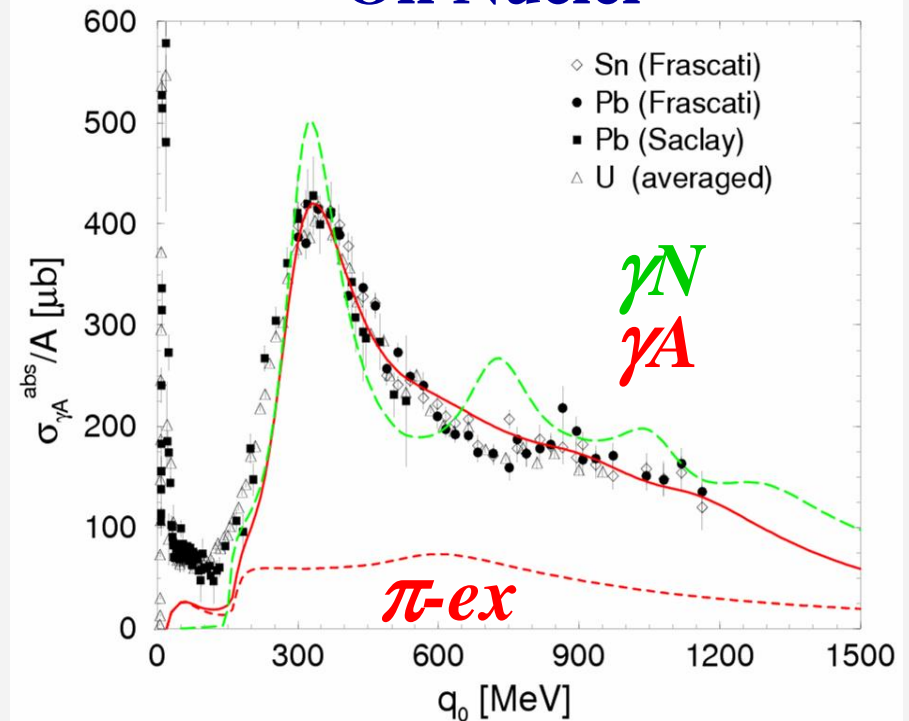
$$\frac{\sigma_{\nu A}(q_0)}{A} = \frac{-4\pi\alpha}{q_0\rho_N} \frac{m_\rho^4}{g_\rho^2} \text{Im } D_\rho(M=0, q; \rho_N)$$



On the Nucleon



On Nuclei



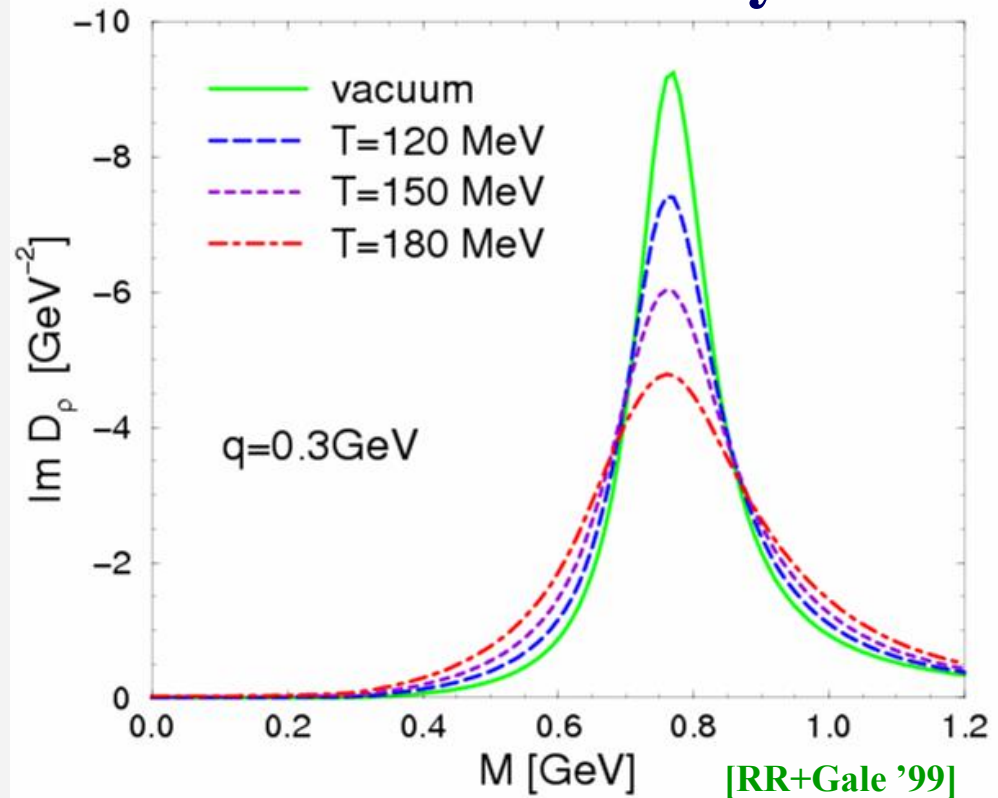
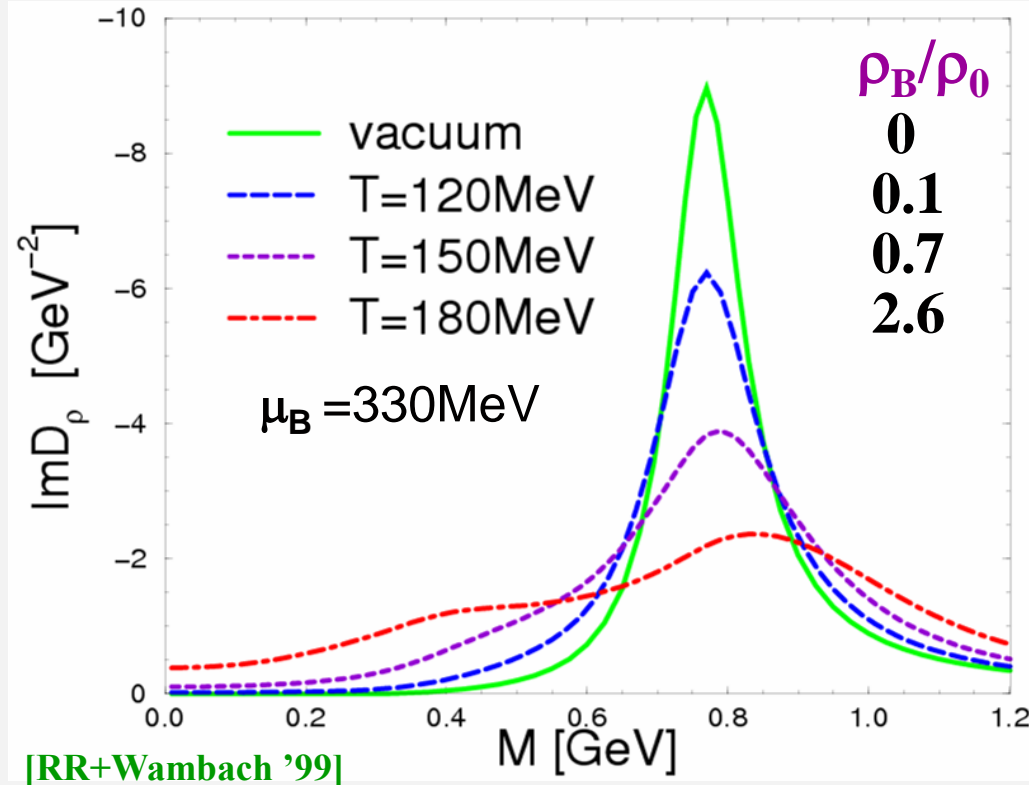
- constrain ρNB couplings + non-resonant pion cloud
- 2nd + 3rd resonances melt

2.5 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

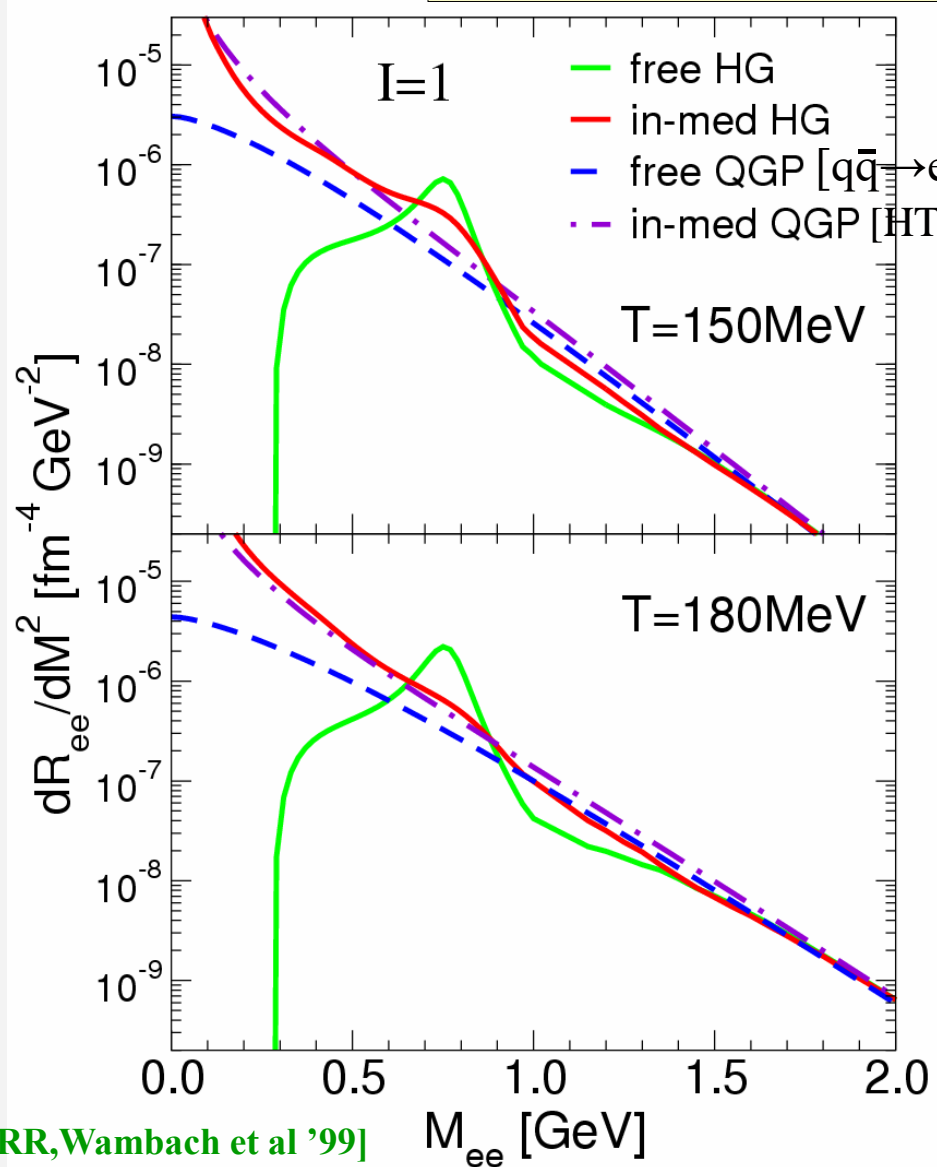
Meson Gas only



- ρ -meson strongly **broadens** in hadronic matter
- baryon density ρ_B dominant effect

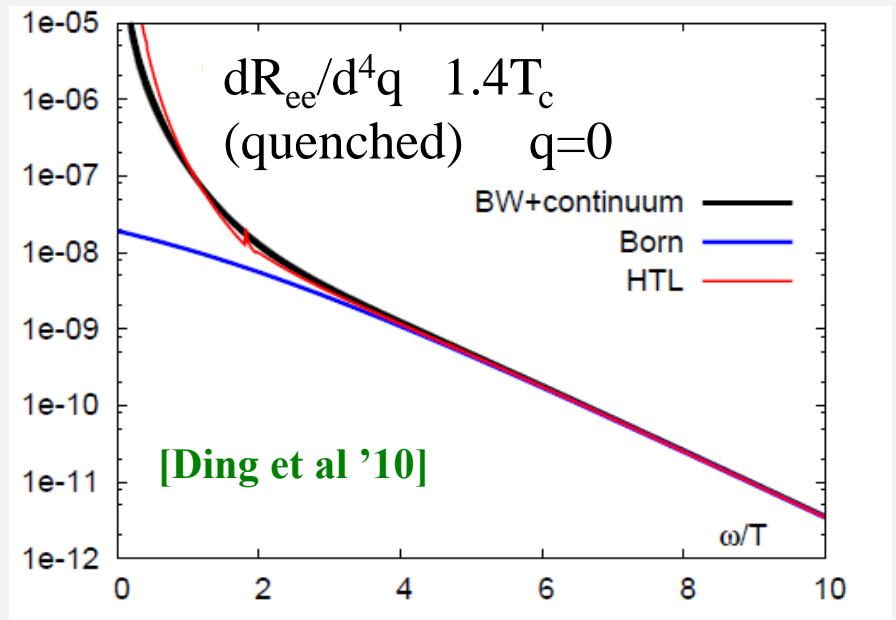
2.6 Dilepton Rates and Degrees of Freedom

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

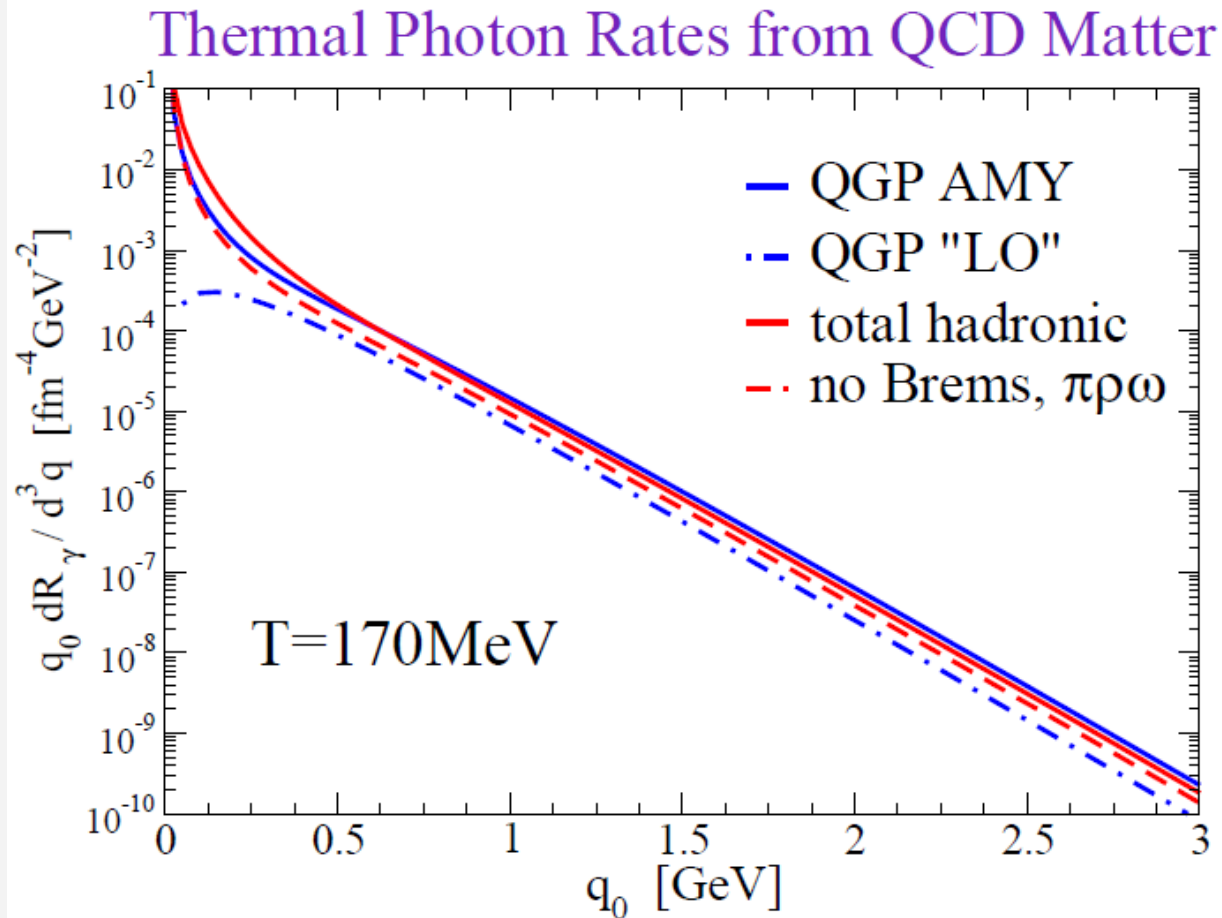


[RR, Wambach et al '99]

- ρ -meson resonance “melts”
 - spectral function merges into partonic description
- \Rightarrow Predicts transition
hadrons \rightarrow quarks + gluons



2.7 Photon Rates: Hadronic vs. QGP



- total hadronic \approx complete-LO QGP

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- **Spectral Shape, Fireball Temperature + Lifetime**
- **Photon Puzzle?**

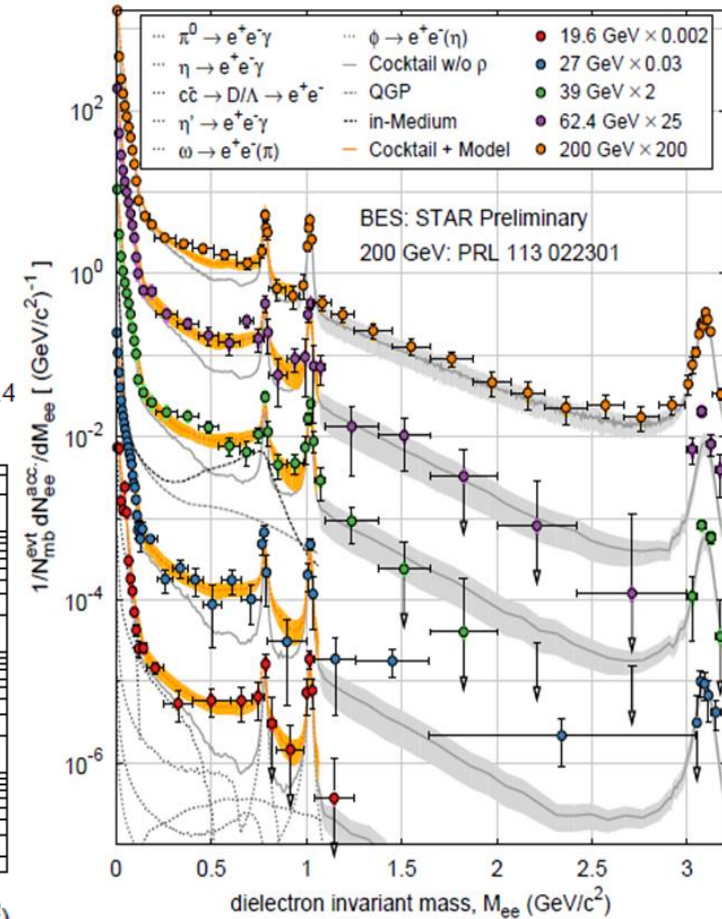
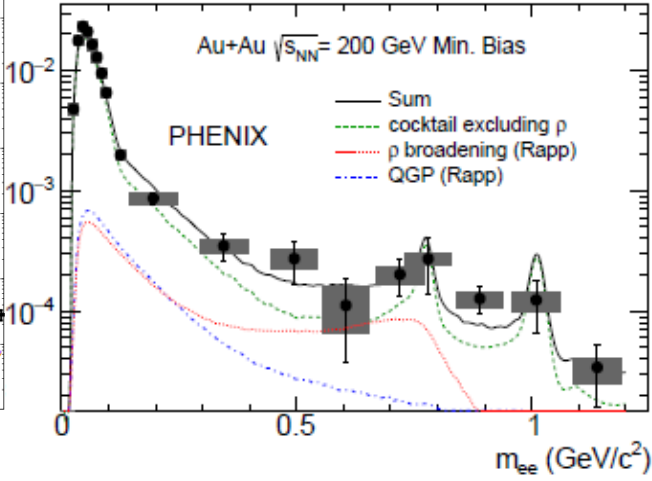
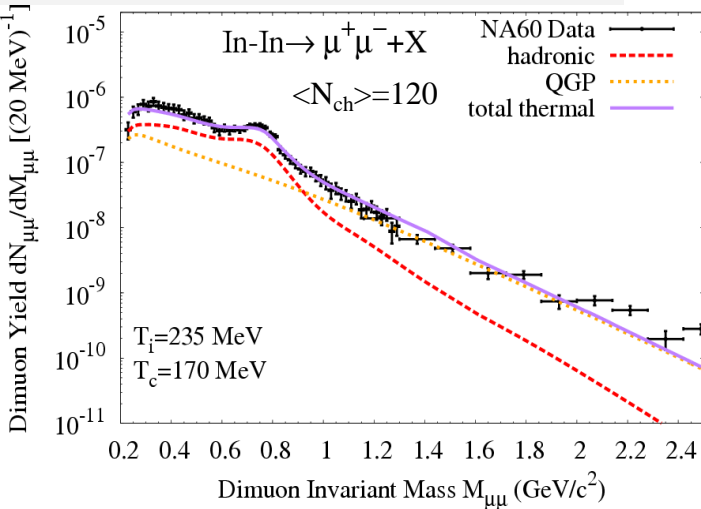
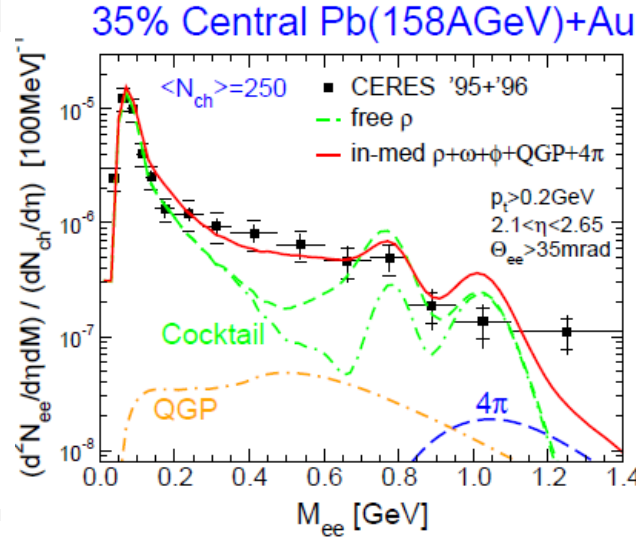
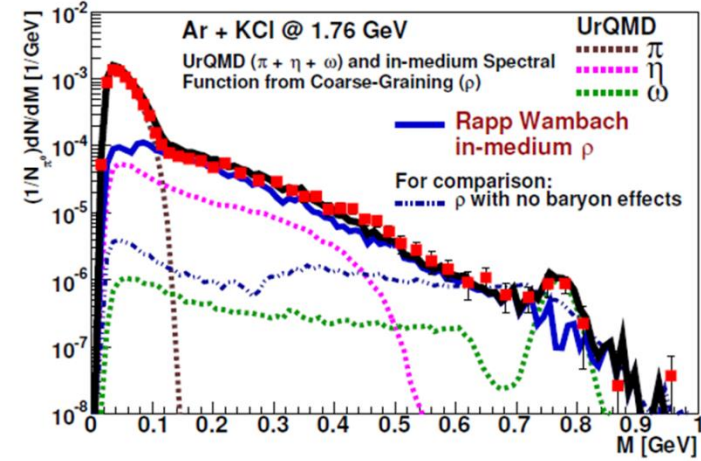
4.) Chiral Symmetry Restoration

- **QCD + Weinberg Sum Rules; Baryons**

5.) Electric Conductivity

6.) Conclusions

3.1 30 Years of Dileptons in Heavy-Ion Collisions



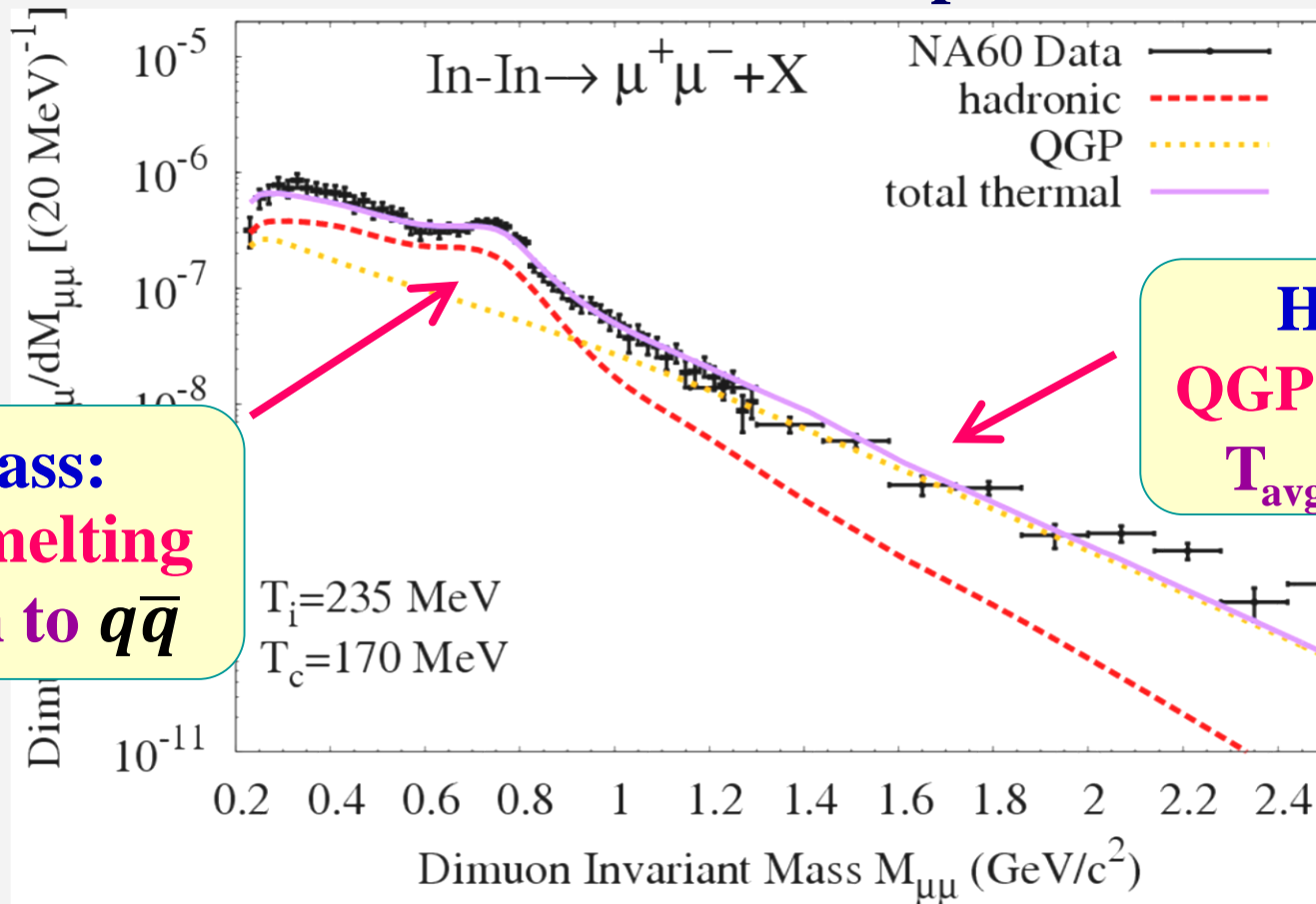
- Robust understanding across QCD phase diagram:
 QGP + hadronic radiation with **melting** ρ resonance

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

- Integrate rates over thermal fireball:

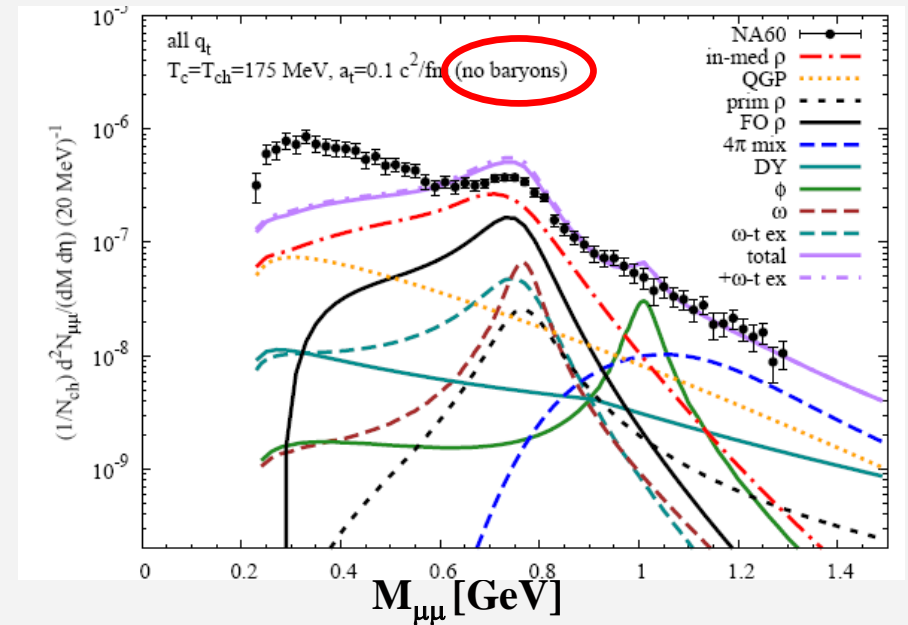
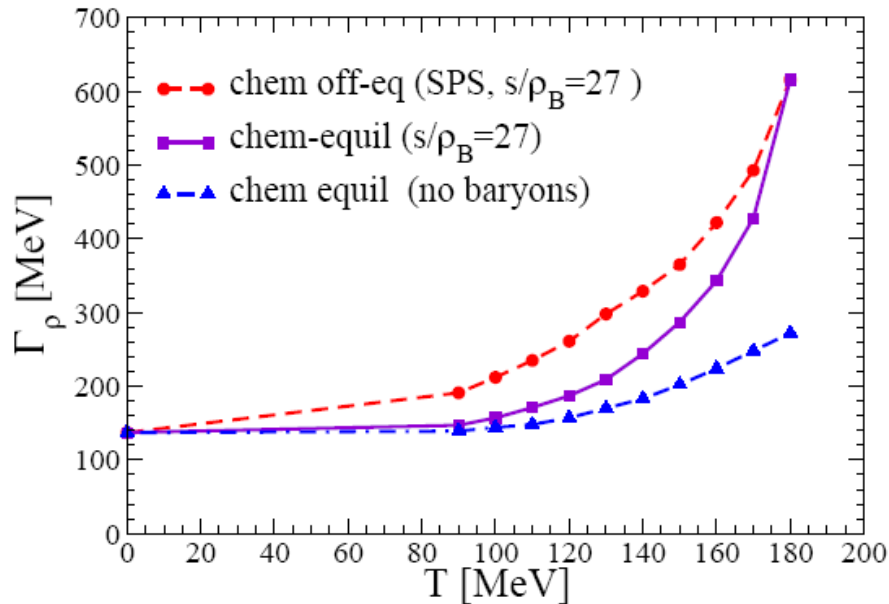
$$\frac{dN_{ll}}{dM} = \int d^4x \frac{M d^3q}{q_0} \frac{dN_{ll}}{d^4x d^4q}$$

Excess Radiation Spectrum



3.3 Sensitivity to Spectral Function

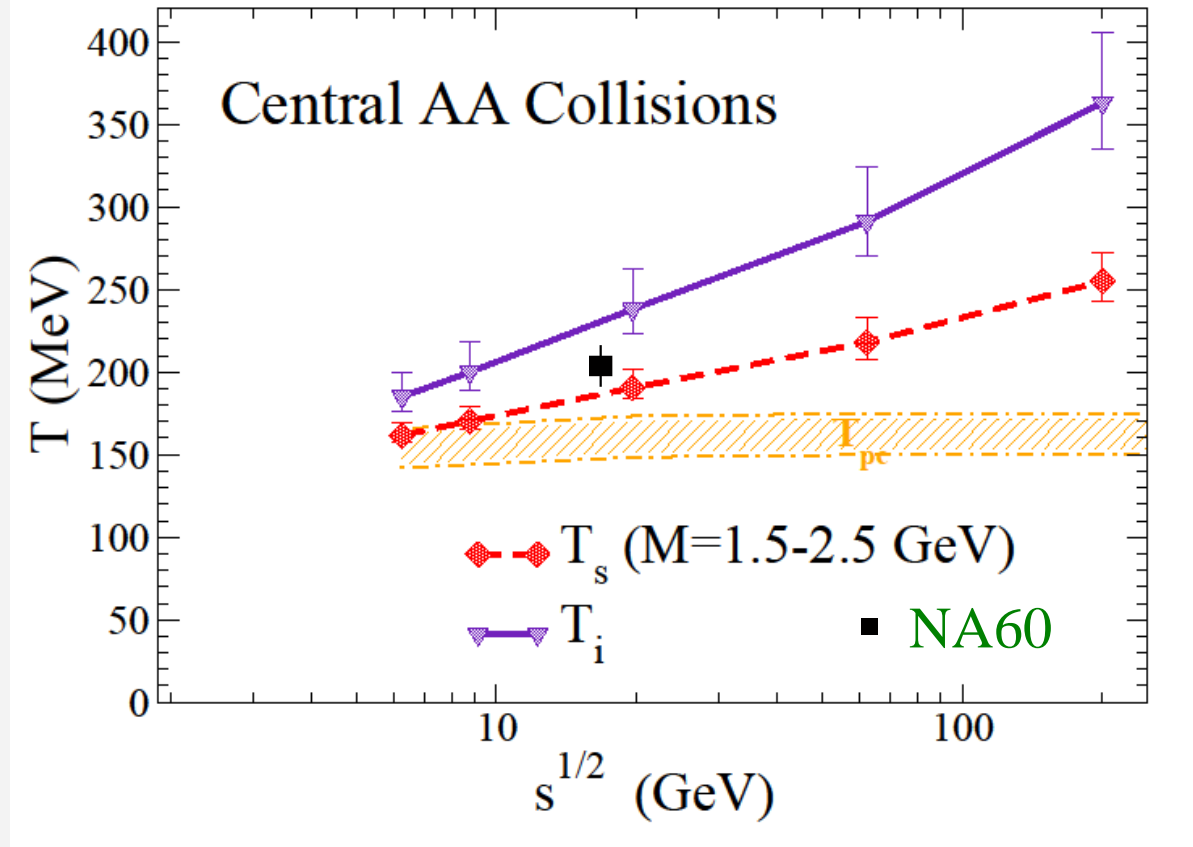
In-Medium ρ -Meson Width



- avg. $\Gamma_\rho(T \sim 150 \text{ MeV}) \sim 370 \text{ MeV} \Rightarrow \Gamma_\rho(T \sim T_c) \approx 600 \text{ MeV} \rightarrow m_\rho$
- driven by (anti-) baryons
- $\Gamma_\rho / KE_\rho \geq 1$ -- hadronic liquid!

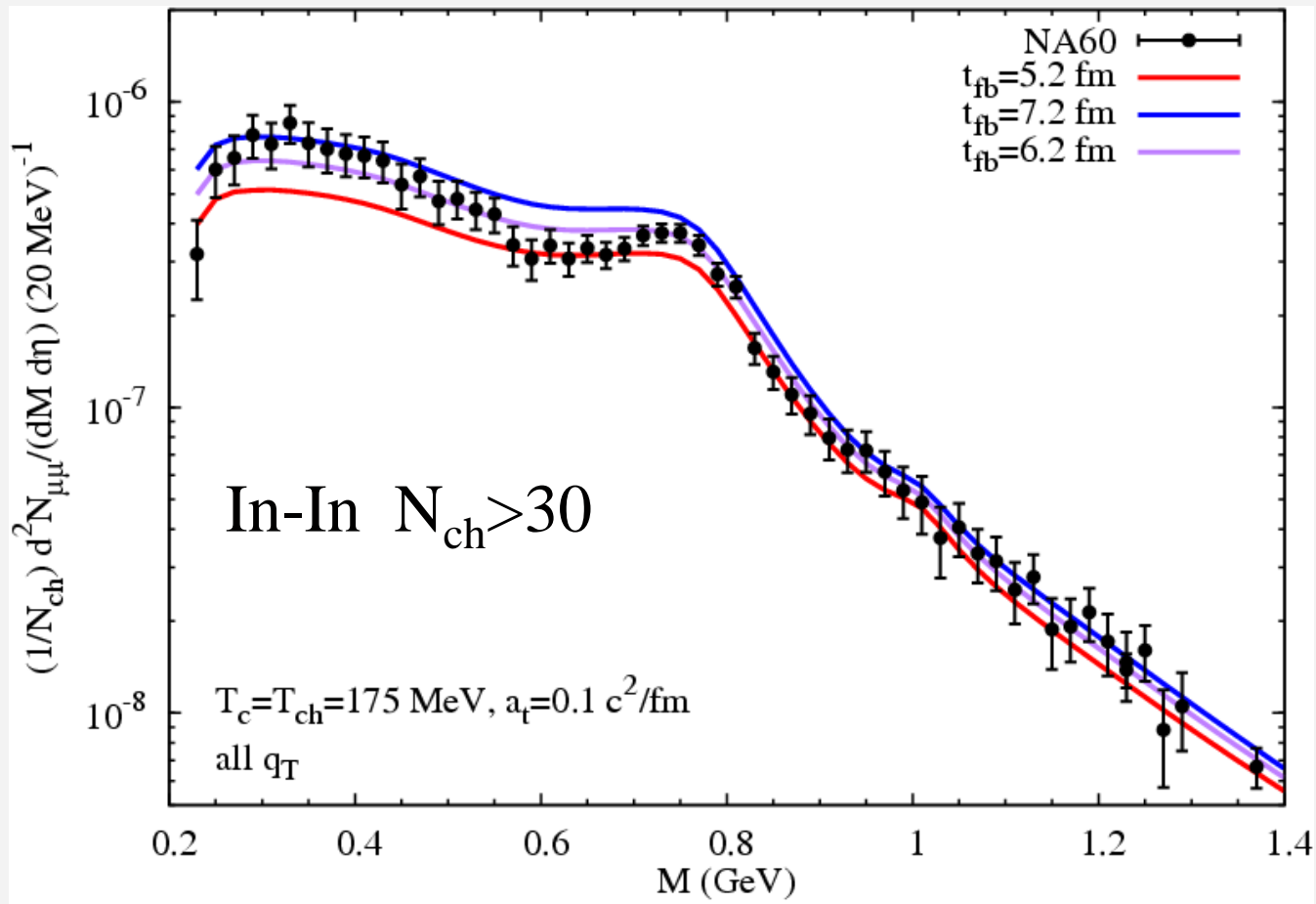
3.4 Fireball Temperature

Slope of Intermediate-Mass Dilepton Radiation



- unique “early” temperature measurement (no blue-shift!)
- T_s approaches T_i toward lower energies
- first-order “plateau” at **BES-II/CBM/NICA?**

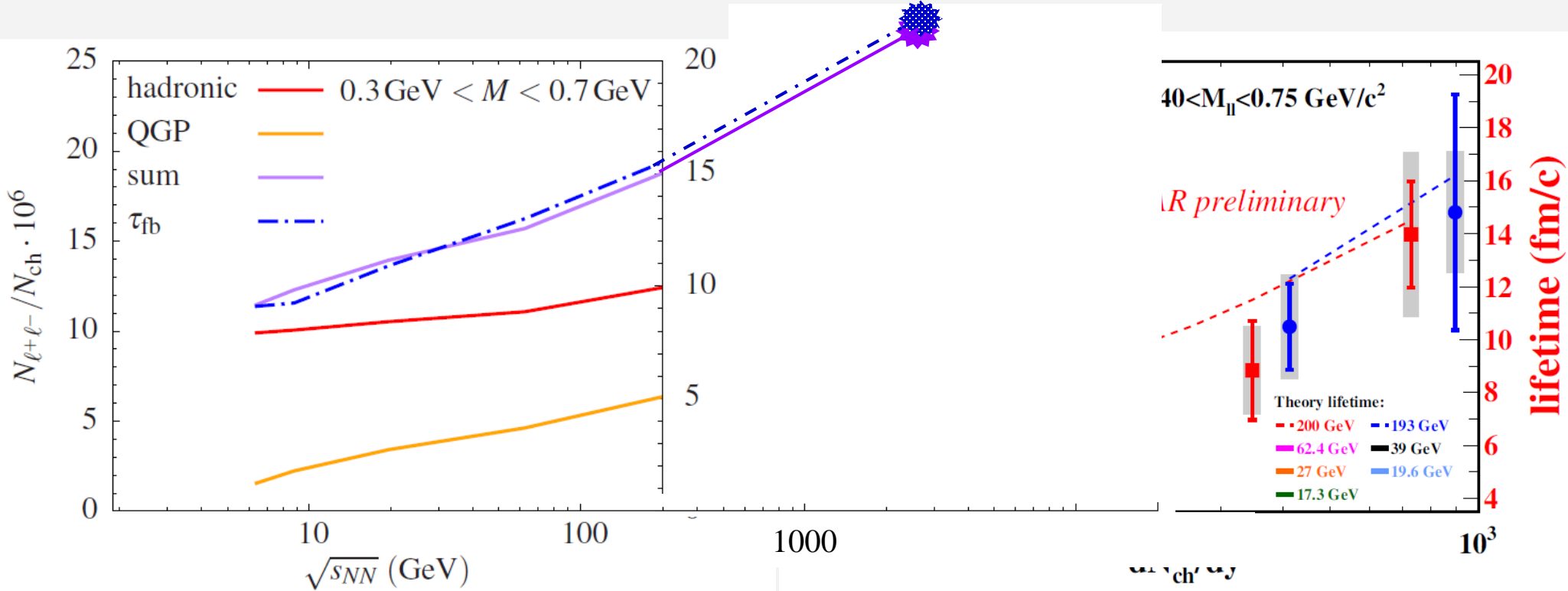
3.5 Low-Mass Dileptons: **Chronometer**



- first “explicit” measurement of interacting-fireball **lifetime**:
 $\tau_{FB} \approx (6.2 \pm 0.5) \text{ fm}/c$

3.5.2 Excitation Function of Fireball Lifetime

Excitation Function of Low-Mass Dilepton Excess Yield



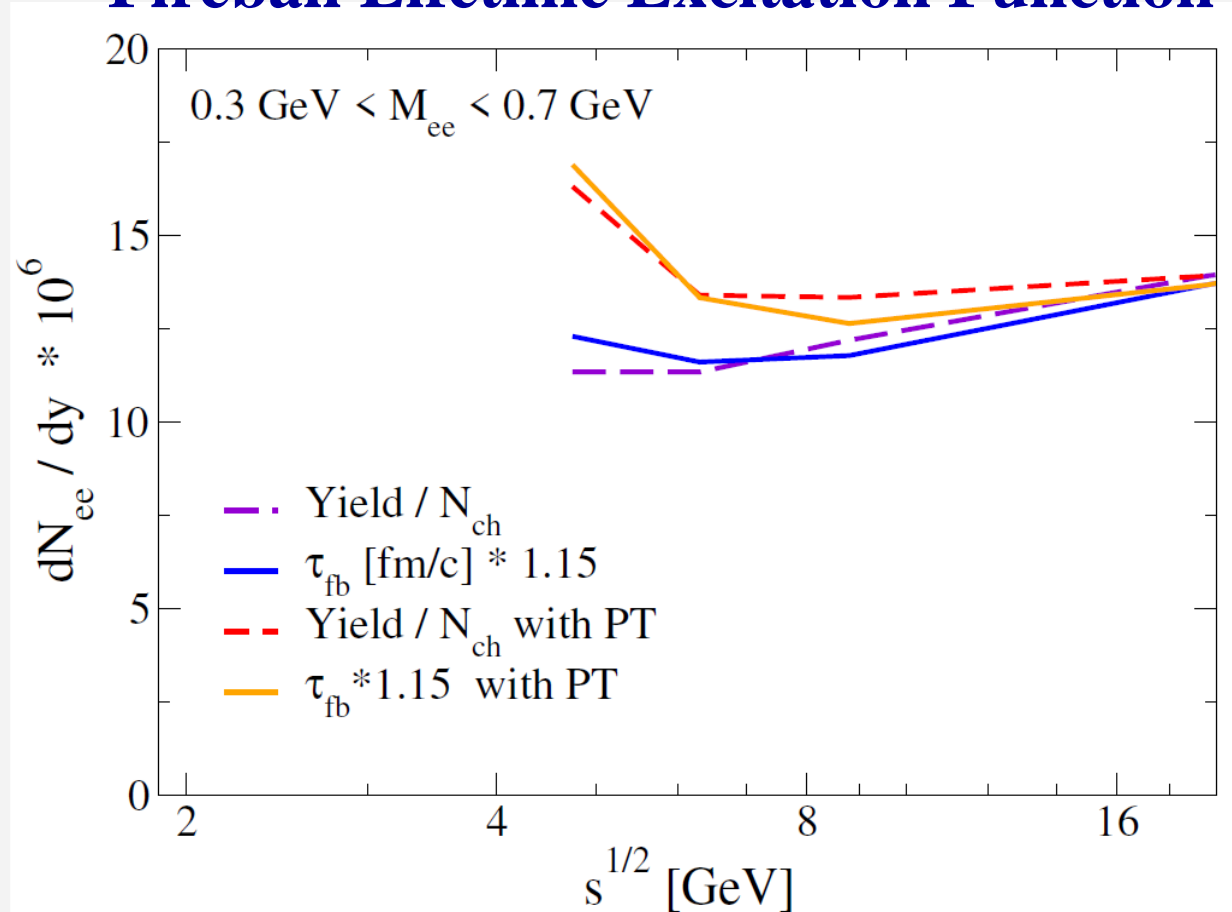
[RR+van Hees '14]

[STAR '15]

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

3.5.3 Dilepton Emission with 1st-Order Transition

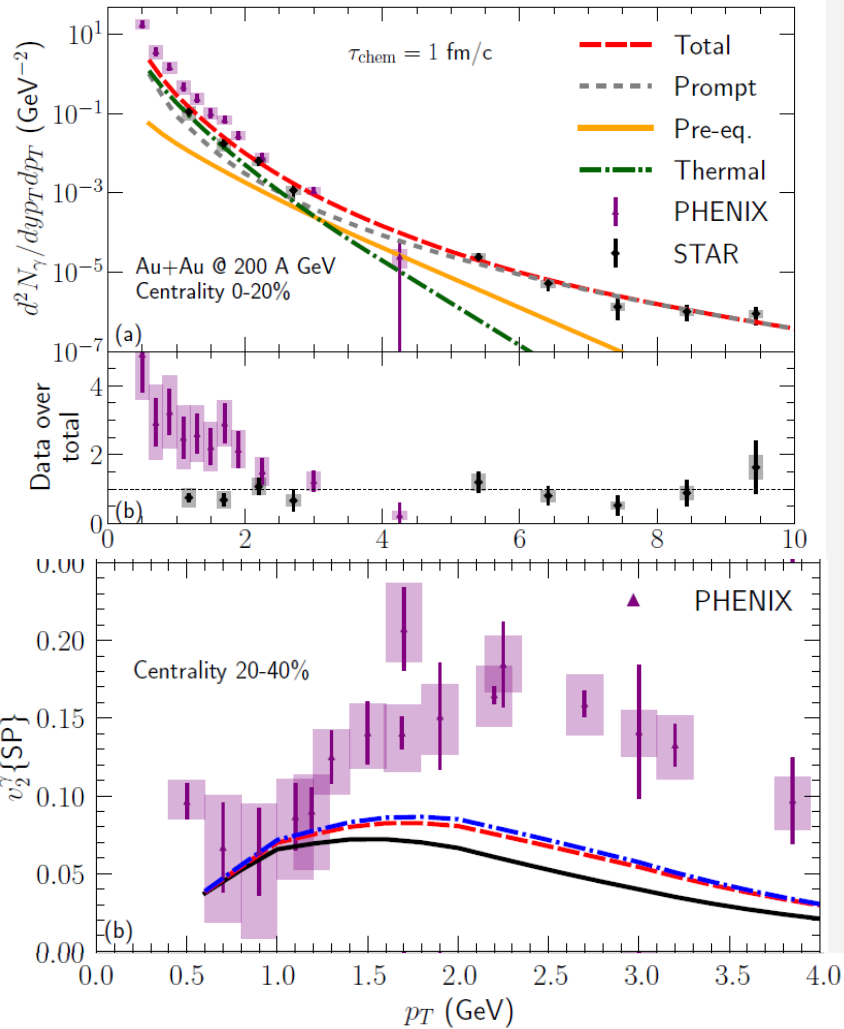
Fireball Lifetime Excitation Function



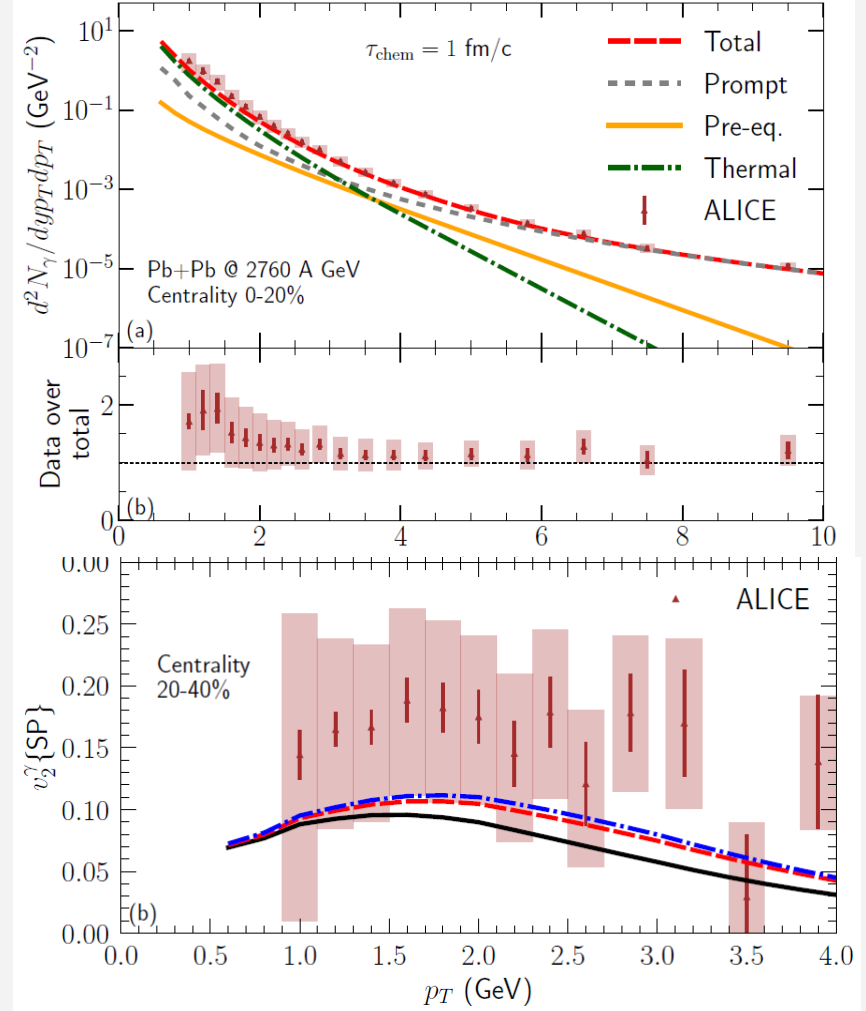
- Clear signature in low-mass yield due to lifetime increase

3.6 Photon Puzzle!?

RHIC



LHC



- **RHIC**: theory underpredicts **PHENIX** data but agrees with **STAR**
- **LHC**: reasonable agreement

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4.) Chiral Symmetry Restoration

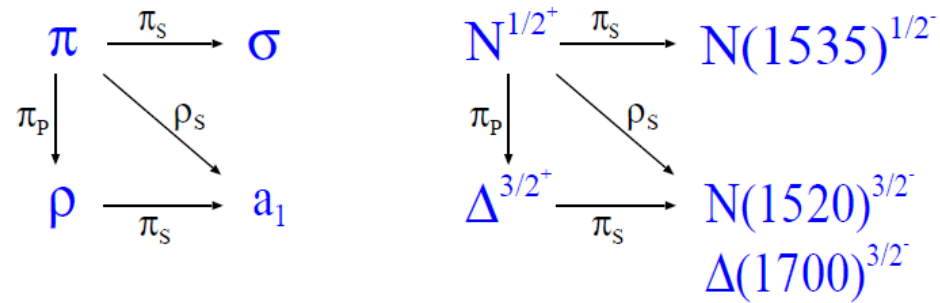
- **QCD + Weinberg Sum Rules; Baryons**

5.) Electric Conductivity

6.) Conclusions

4.1 Chiral Symmetry Breaking in Vacuum

- Mass **splitting**
within chiral multiplets



- Quantitative: Sum Rules

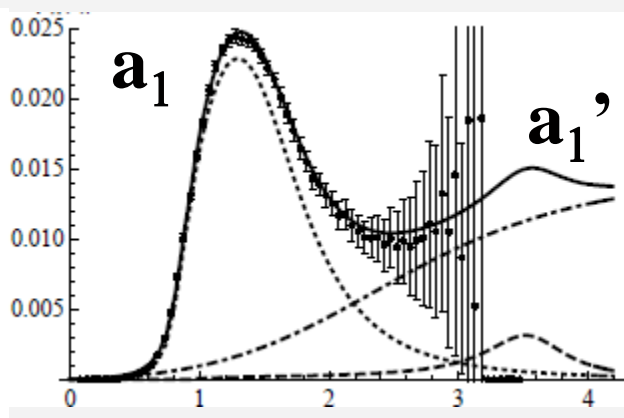
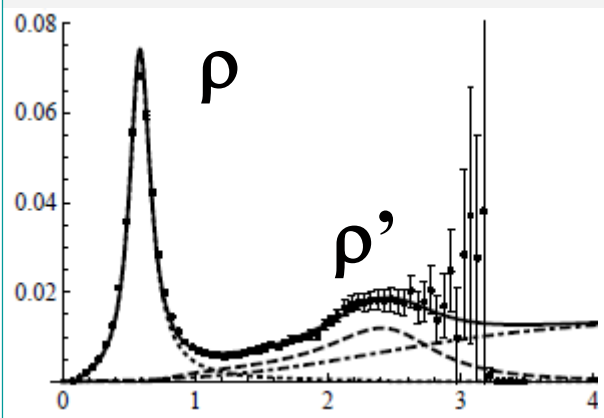
$$\int_0^\infty ds \frac{\Delta\rho(s)}{s^2} = \frac{1}{3} f_\pi^2 \langle r_\pi^2 \rangle - F_A$$

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

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

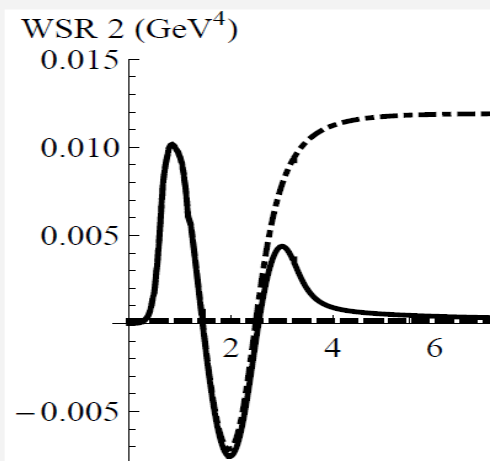
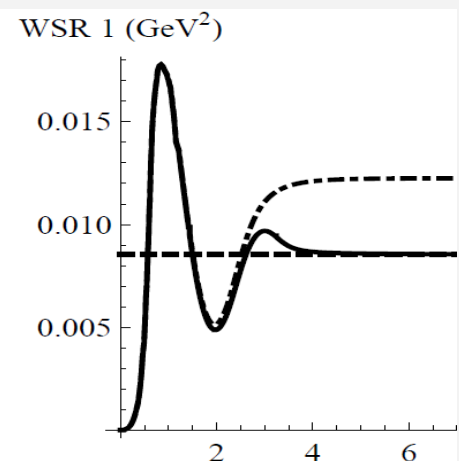
$$\int_0^\infty ds s \Delta\rho(s) = -2\pi\alpha_s \langle \mathcal{O}_4^{SB} \rangle$$

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



- QCD SRs [Hatsuda+Lee '91, Asakawa+Ko '93, Leupold et al '98, ...]

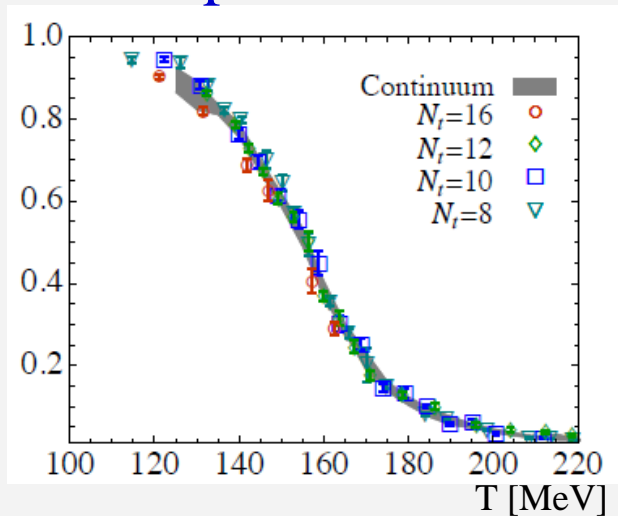
- Sensitive to excited states:
predict **a₁(1950)** state [Hohler+RR '12]



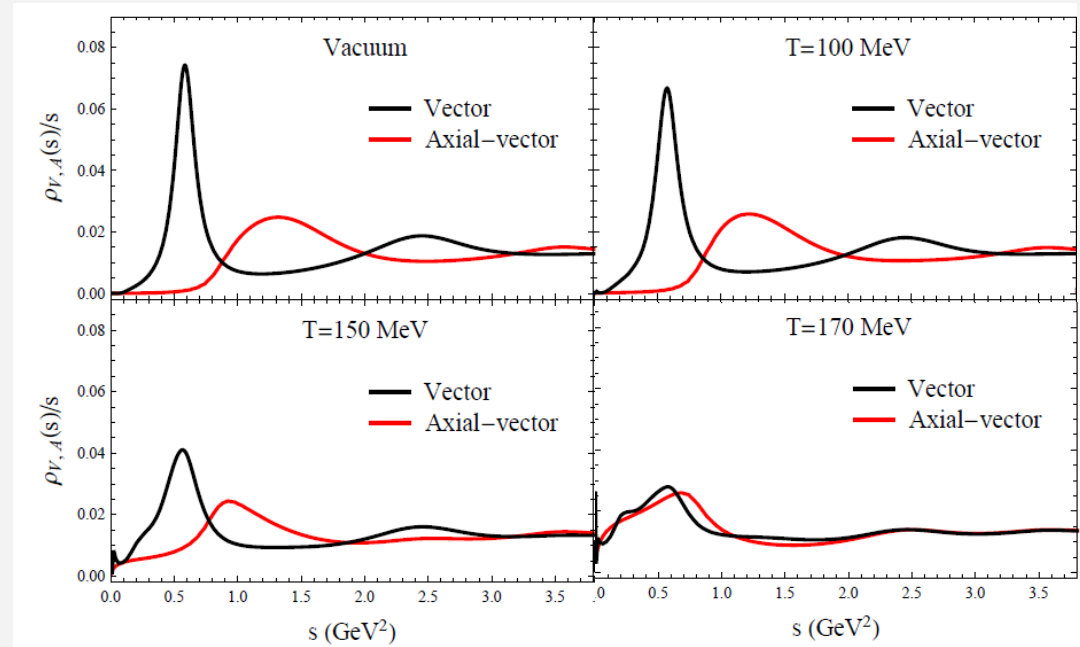
4.2 Mechanism of Chiral Restoration

Evaluate sum rules at finite T :

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



In-Medium Spectral Functions



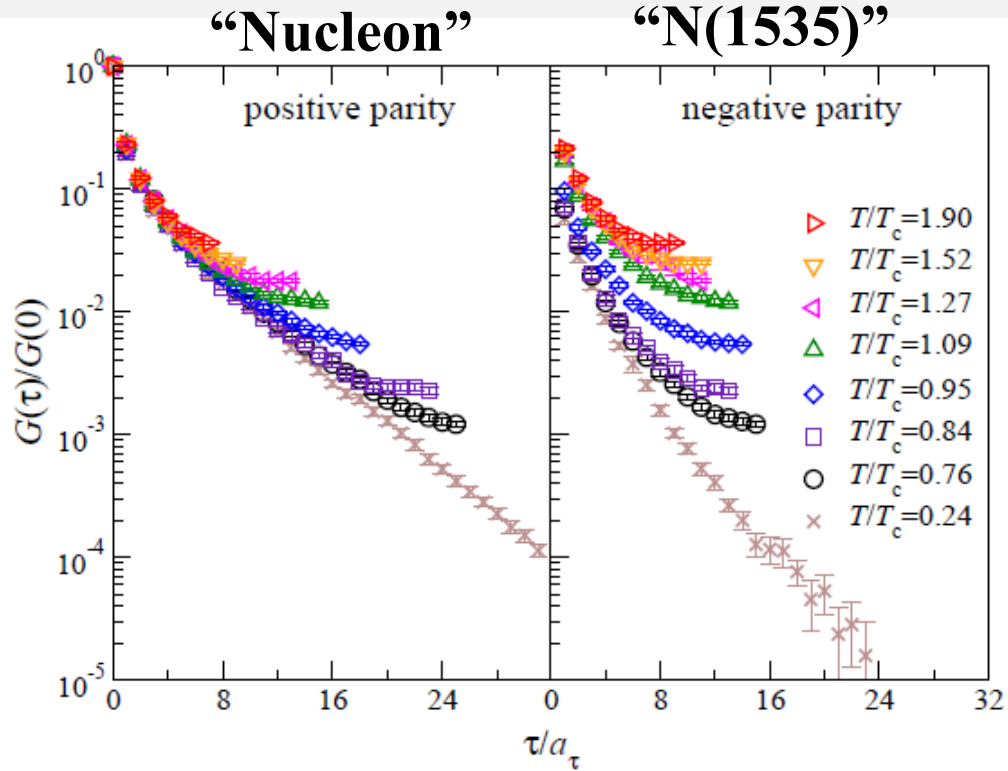
[Hohler+RR '13]

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...?

4.3 Lattice-QCD Results for N(940)-N(1535)

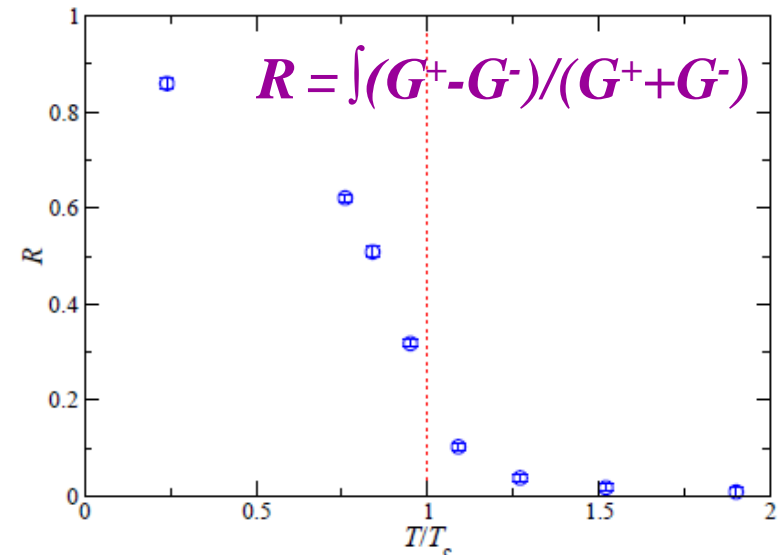
Euclidean Correlator Ratios



[Aarts et al '17]

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 $M_{N^*}(T) \rightarrow M_N(T) \approx M_N^{\text{vac}}$

Outline

1.) Introduction

2.) EM Emission Rates

- **Quark-Gluon Plasma + Lattice QCD**
- **Hadronic Matter + in-Medium Vector Mesons**

3.) Thermal Emission in Heavy-Ion Collisions

- **Spectral Shape, Fireball Temperature + Lifetime**
- **Photon Puzzle?**

4.) Chiral Symmetry Restoration

- **QCD + Weinberg Sum Rules; Baryons**

5.) Electric Conductivity

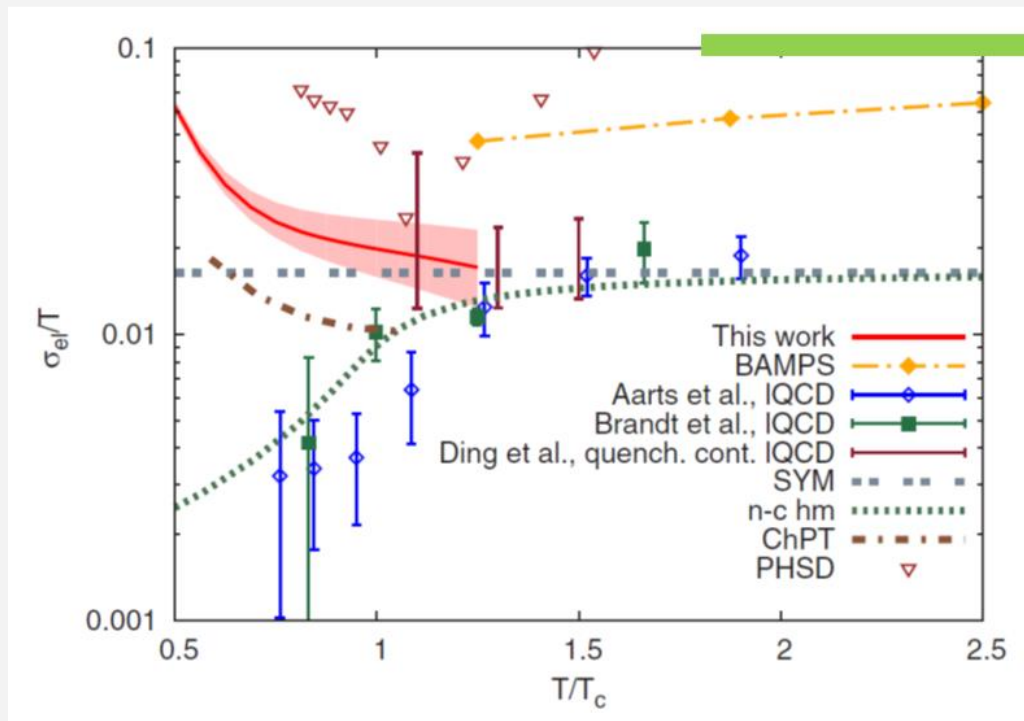
6.) Conclusions

5.) Electric Conductivity

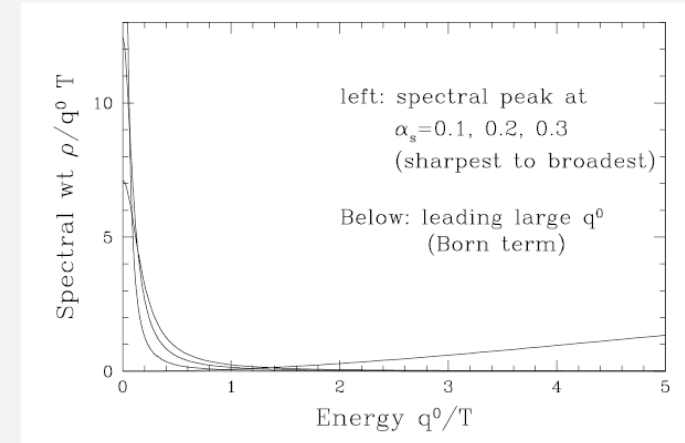
- Generic transport coefficient (charge): $\sigma_{\text{el}}/T \sim 4\pi \eta/s \sim 2\pi T \mathcal{D}_s^{\text{HF}}$
- Probes timelike long-wavelength limit of EM spectral function:

$$\sigma_{\text{el}}(T) = e^2 \lim_{q_0 \rightarrow 0} [\rho_{\text{em}}(q_0, q=0; T) / q_0]$$

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



pQCD
[Moore+Robert '06]

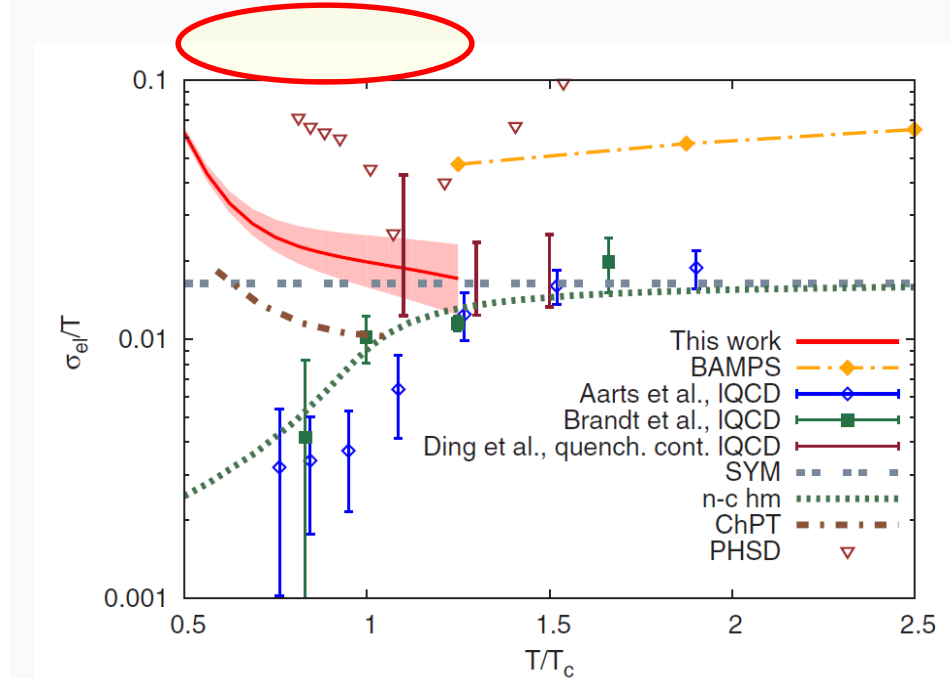
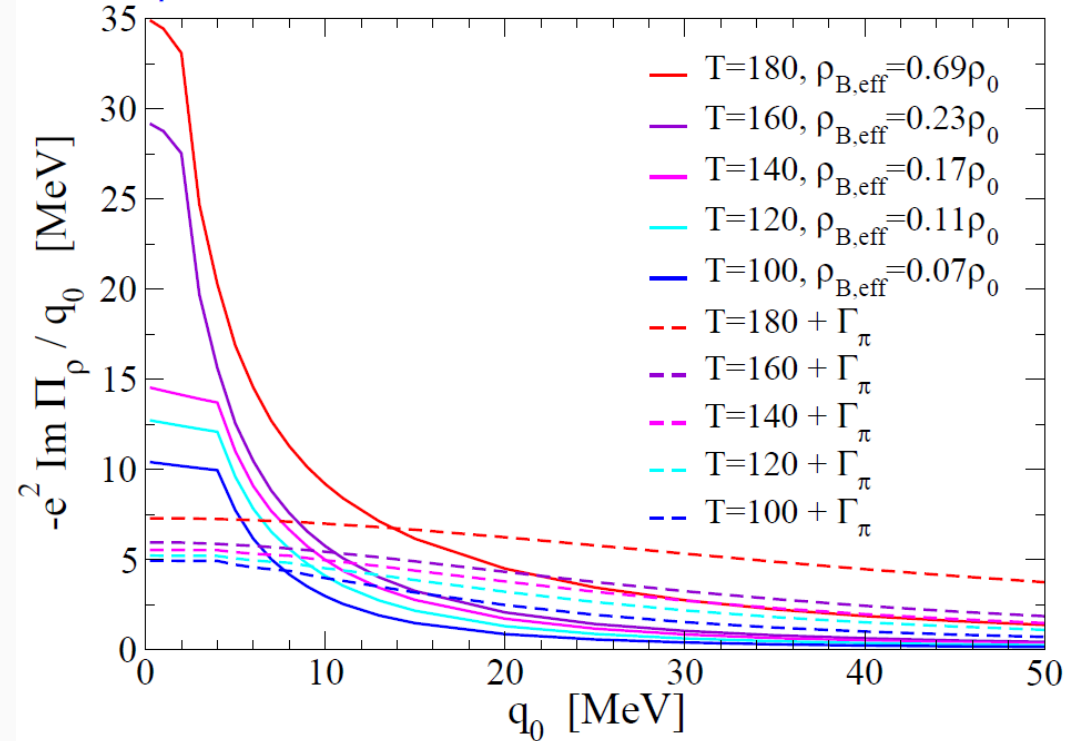


6.) Conclusions

- **Thermal EM radiation is versatile + unique probe of QCD matter in heavy-ion collision**
- **Low-mass dileptons: ρ -meson melting**
 - **transition** from hadrons to partons
 - strongly coupled hadronic **liquid**
 - mechanism of **chiral symmetry restoration**:
evaporation of chiral ρ - a_1 **mass splitting** (π - σ , N - $N^*(1535)$, ...)
 - “true” **lifetime** measurement via total yields
- **Intermediate-mass dileptons**
 - (early) **temperature** measurement, (well) **above T_c**
- **Very-low mass dileptons**
 - zero-energy conductivity peak
- **Photon puzzle?**

5.1 Sensitivity to Conductivity Peak

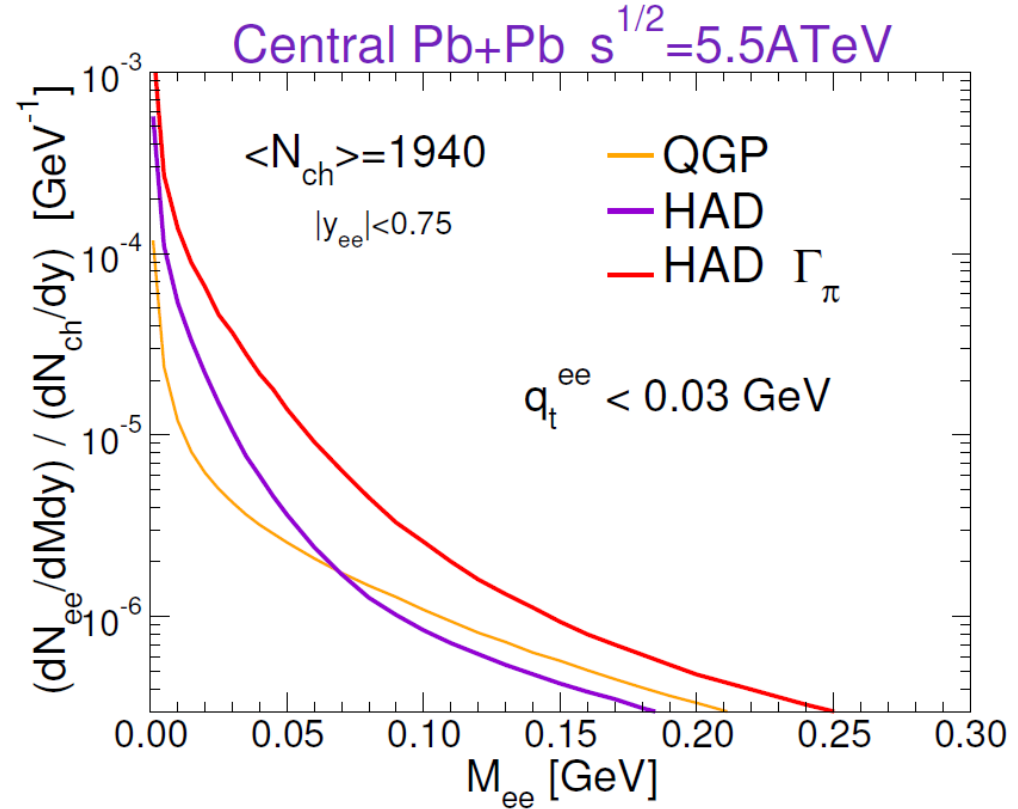
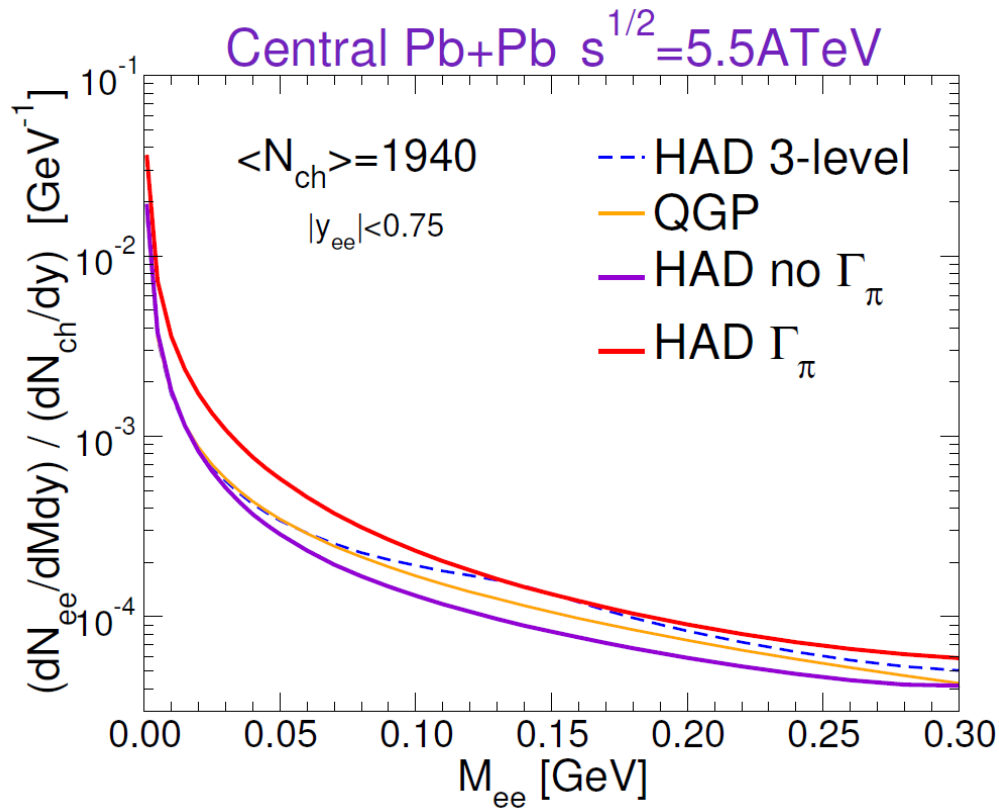
ρ -Meson Pion Cloud in Hot Anti-/Nuclear Matter



[Greif et al '16]

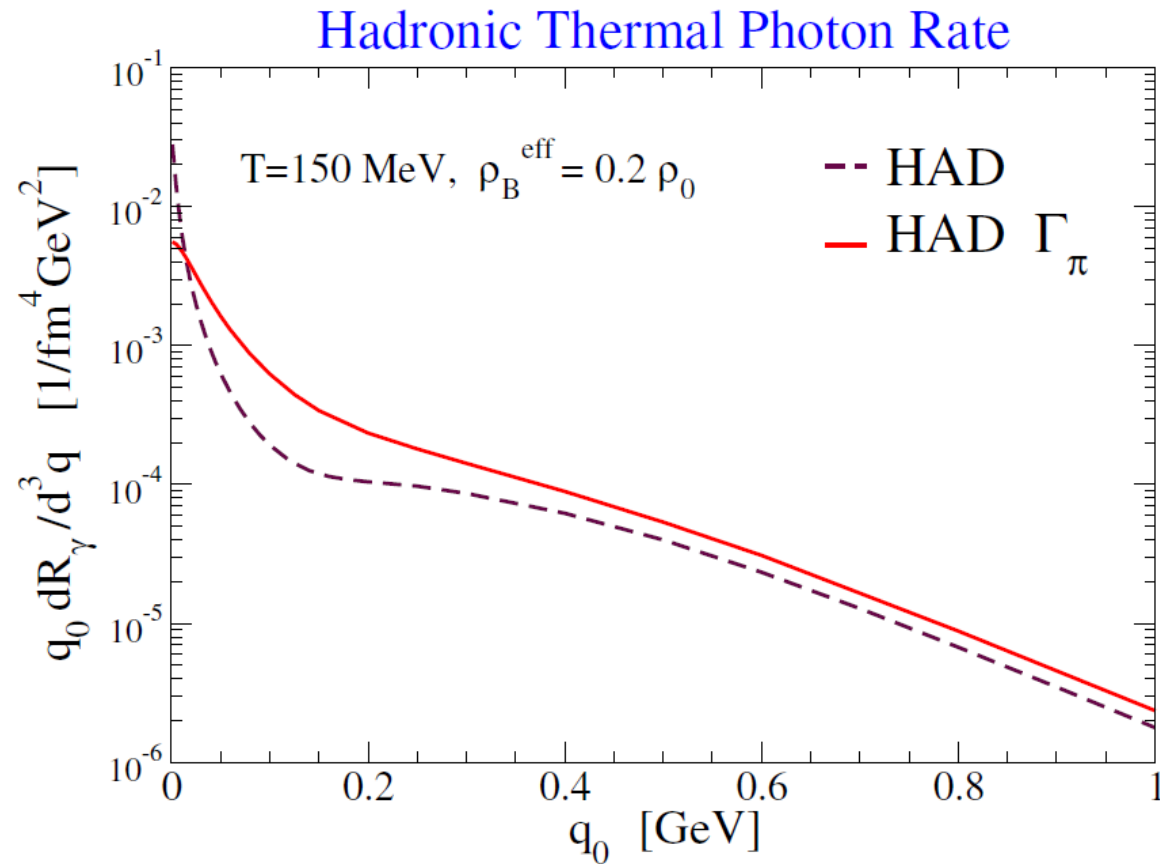
- With π -baryon interactions: $\sigma_{el} \sim 10\text{-}40$ MeV or $\sigma_{el}/T \sim 0.1\text{-}0.2$
 \Rightarrow inefficient in reducing σ_{el}
- much reduced upon inclusion of thermal- $\pi\pi$ interactions: $\sigma_{el}/T \sim 0.05\text{-}0.04$

5.2 Thermal Dileptons: **No** Single- e^\pm Cuts



- Only “shoulder enhancement” detectable
- Factor ~ 2 increase due to reduced σ_{el}
- Factor ~ 4 for $q_t^{ee} < 30 \text{ MeV}$

5.4 Effect of Conductivity on Thermal Photon Rate

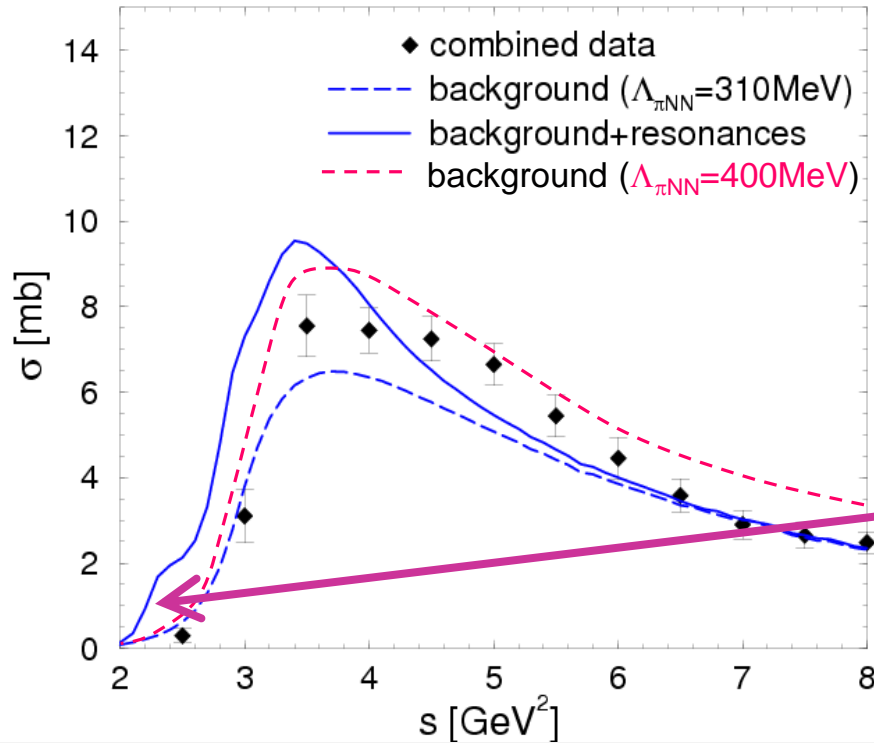


- Decrease in conductivity leads to increase in rate for $q_0 > 10 \text{ MeV}$

2.4.2 Constraints II: $\pi N \rightarrow \rho N$ Scattering

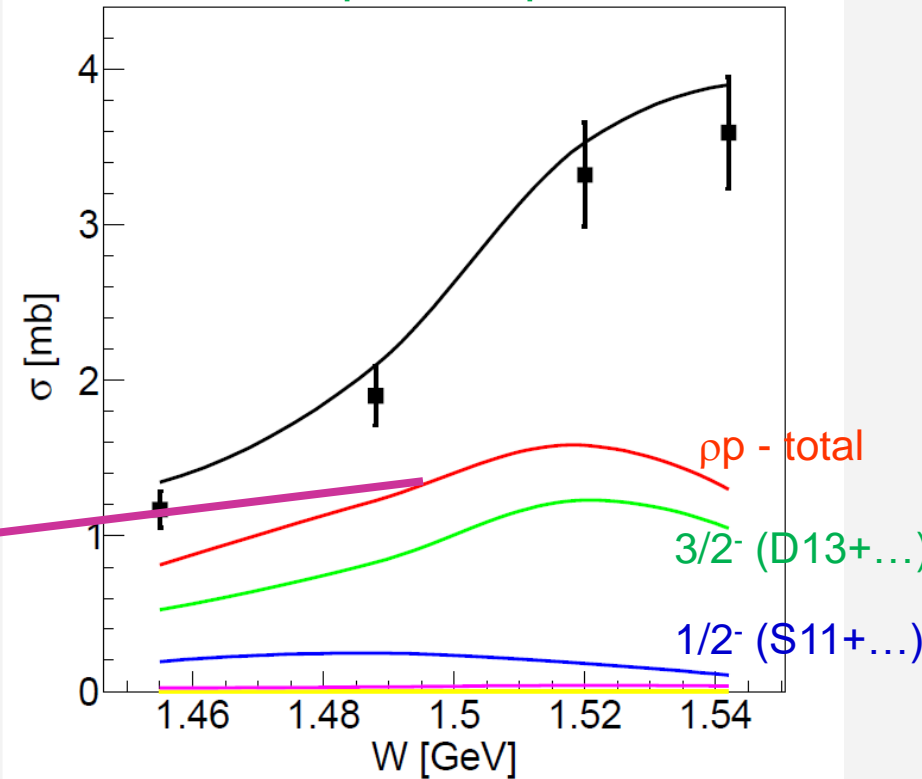
Cross Section Sum

$$(\pi^- p \rightarrow \rho^0 n) + (\pi^+ p \rightarrow \rho^+ p) + (\pi^- p \rightarrow \rho^- p)$$



HADES

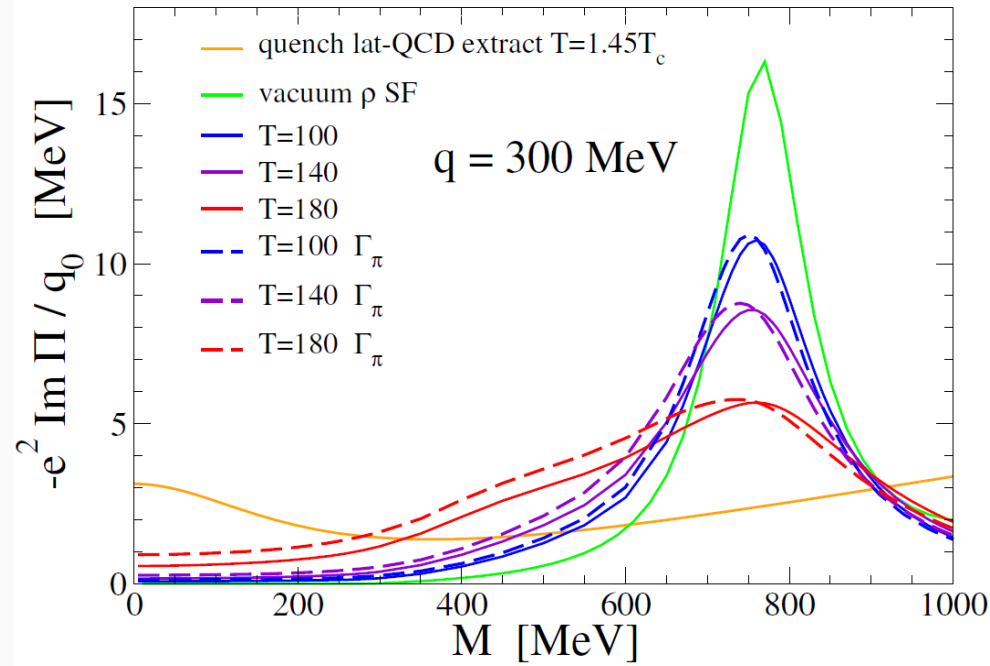
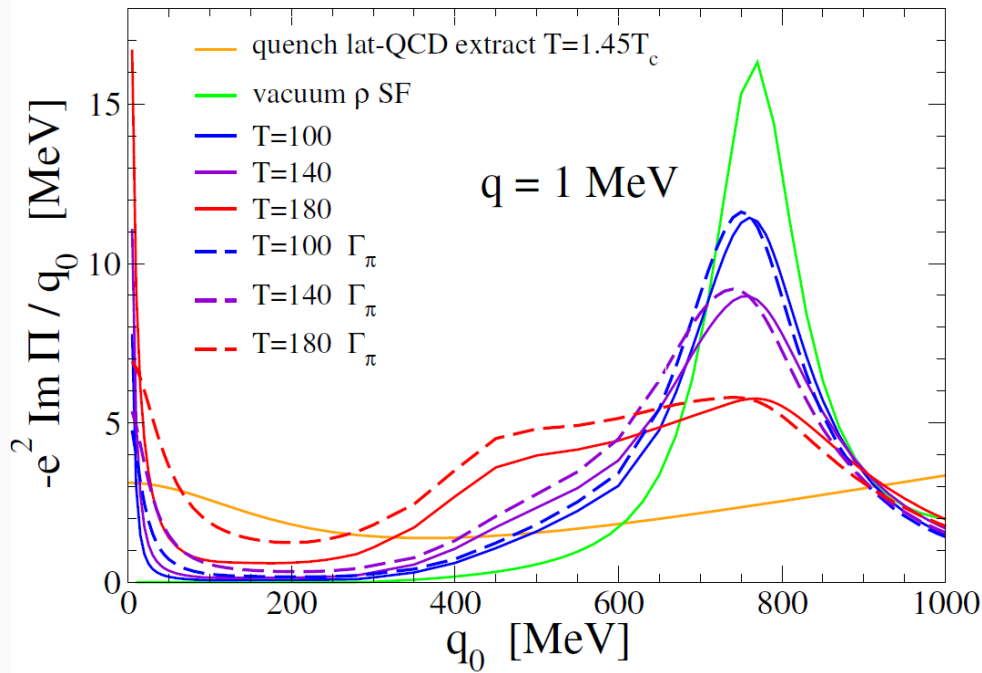
$$\pi^- p \rightarrow \pi^- \pi^0 p$$



[Urban, Buballa,
 RR+Wambach '98]

- strong constraint on pion cloud coupling to nucleons
- similarly small cutoff in $\pi N \rightarrow \Delta \rightarrow \pi N$ scattering!

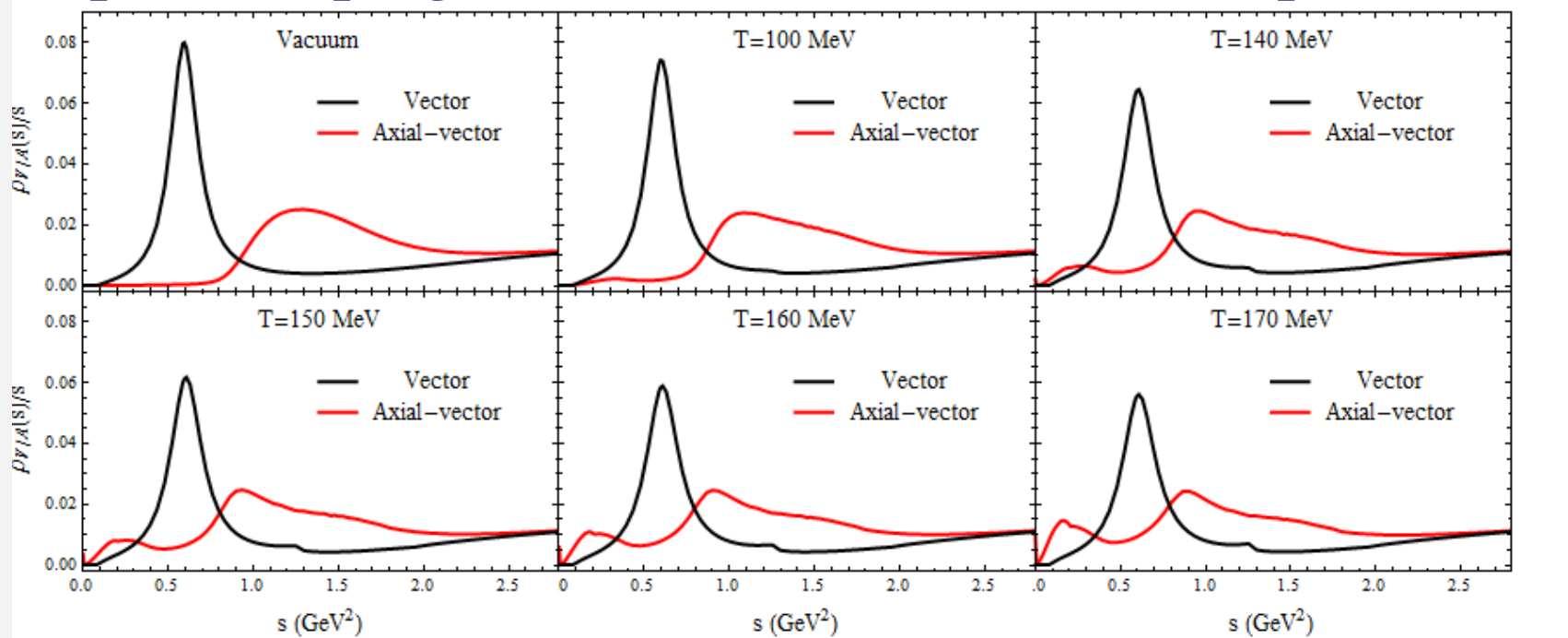
5.1 Conductivity Peak in Hadronic Matter



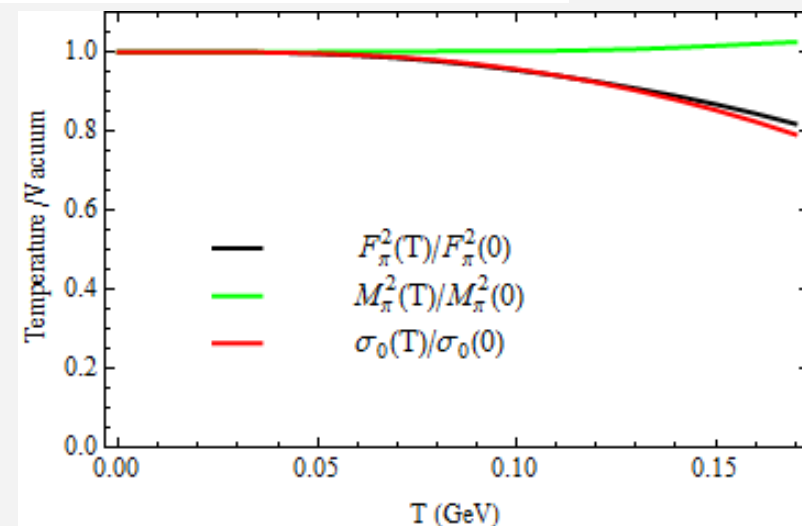
- Conductivity peak at zero energy
stronger interaction \rightarrow broadening reduces peak + enhances shoulder
- Peak quickly disappears at finite 3-momentum (non-zero energies)

3.2 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]



5.3 Functional Renormalization Group Approach

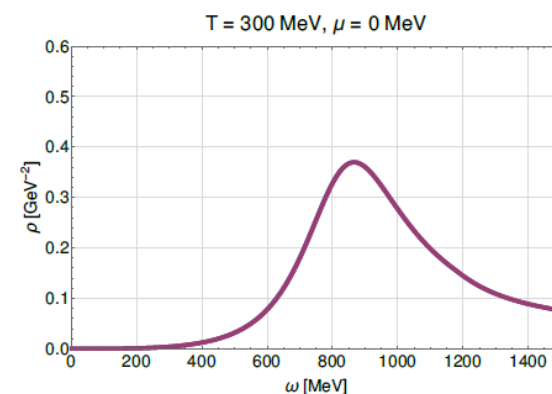
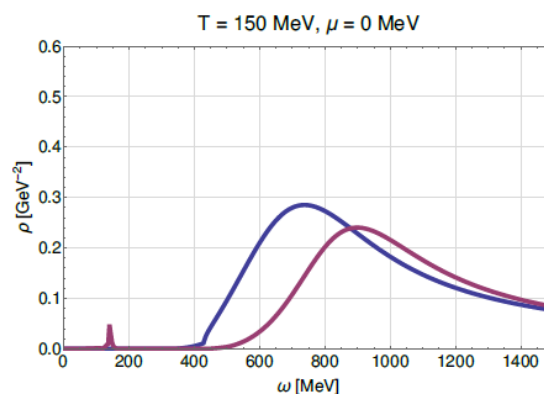
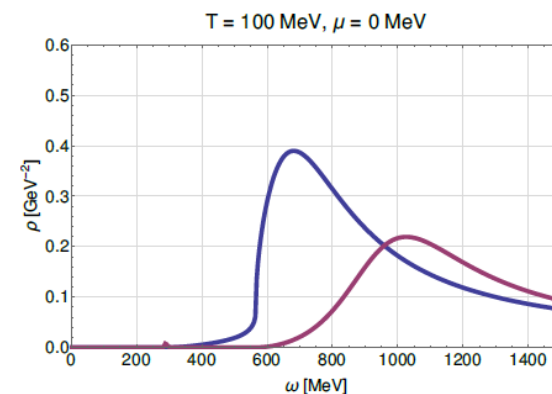
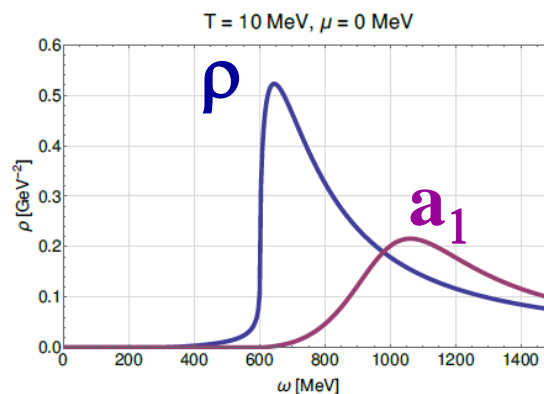
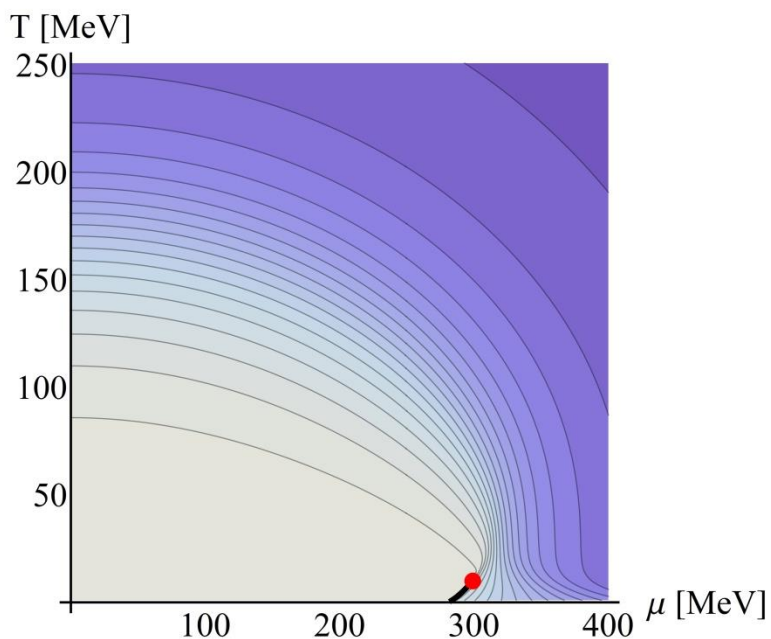
- Quark-Meson model:

$$\partial_k \Gamma_{\rho,k}^{(2)} = \text{diagram 1} - \frac{1}{2} \text{diagram 2} - 2 \text{diagram 3}$$

$$\partial_k \Gamma_{a_1,k}^{(2)} = \text{diagram 4} + \text{diagram 5} - \frac{1}{2} \text{diagram 6} - \frac{1}{2} \text{diagram 7} - 2 \text{diagram 8}$$

The diagrams represent various loop corrections to the two-point functions of the ρ and a_1 mesons in the quark-meson model. Diagram 1 shows a loop of pions (π) with a ρ meson insertion. Diagram 2 shows a loop of pions (π) with a ρ meson insertion and a ghost loop. Diagram 3 shows a loop of quarks (ψ) with a ρ meson insertion. Diagram 4 shows a loop of pions (π) with an a_1 meson insertion. Diagram 5 shows a loop of pions (π) with an a_1 meson insertion and a ghost loop. Diagram 6 shows a loop of pions (π) with an a_1 meson insertion and a ghost loop. Diagram 7 shows a loop of pions (π) with an a_1 meson insertion and a ghost loop. Diagram 8 shows a loop of quarks (ψ) with an a_1 meson insertion.

Phase Diagram

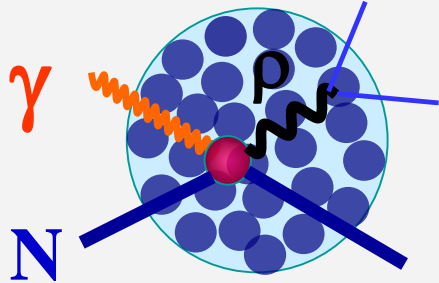


- qualitatively similar to hadronic many-body calculations!

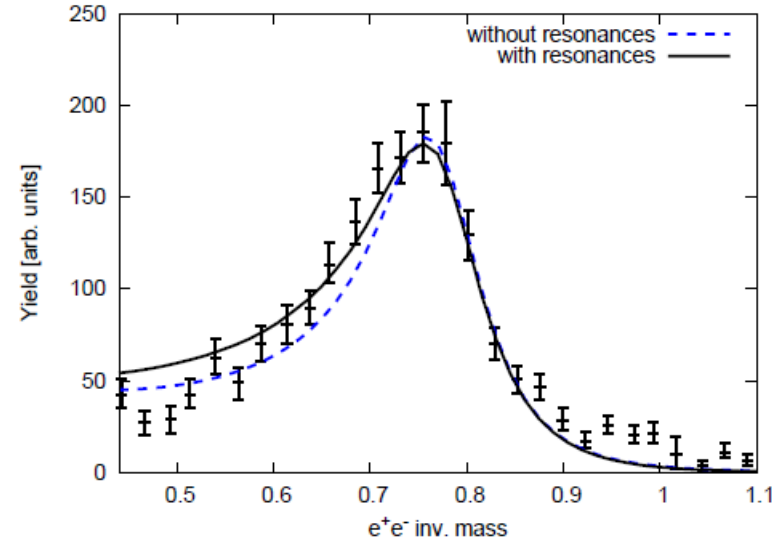
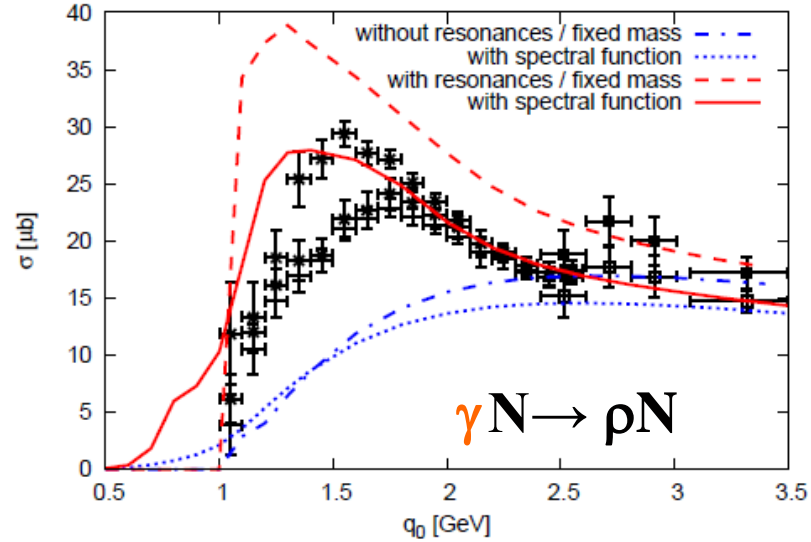
[Tripolt et al '17]

3.1 Nuclear ρ and e^+e^- Photoproduction

(a) Production Amplitude: t -channel + resonances (ρ spectr. fct.!)



[Oh+Lee '04,
Riek et al '08, '10]

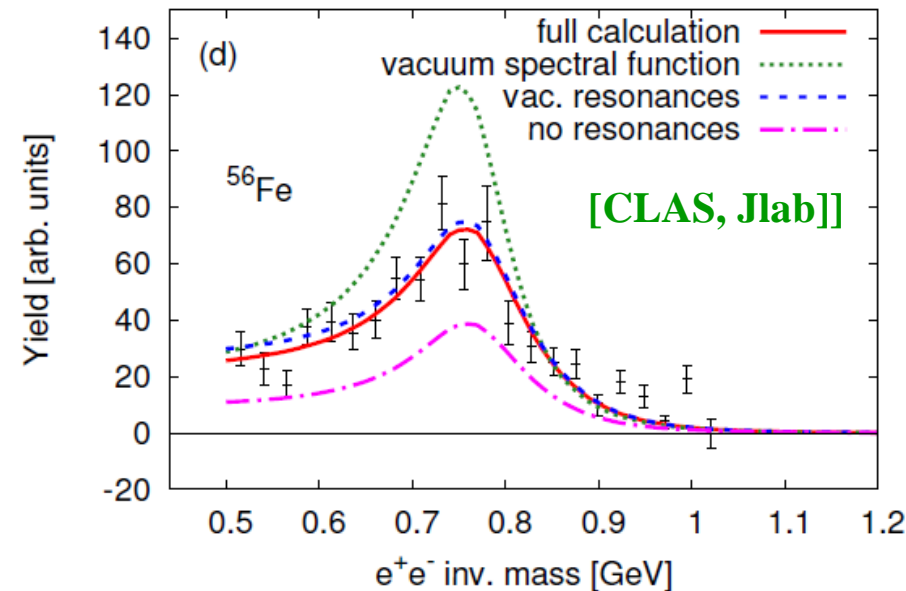


(b) Medium Effects:

- ρ propagator in cold nuclear matter

$$\frac{d\sigma_{\gamma A \rightarrow eeX}}{dM} \sim \int f^N |T_{\text{prod}}|^2 |D_\rho(M, q; \mu_N)|^2 \Gamma_{\gamma^* \rightarrow ee}$$

- Avg. in-medium ρ -width $\Gamma_\rho \approx 220$ MeV

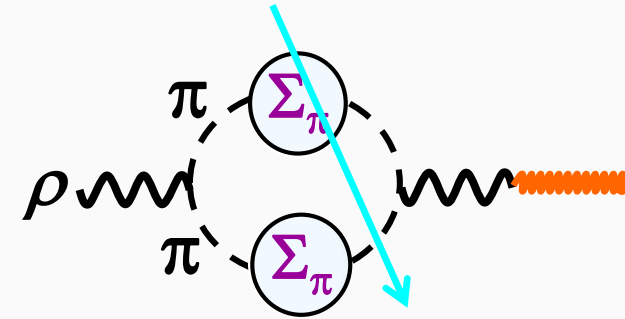


3.5 Unitarity vs. Landau Cut

$$G_{\pi\pi}^T(\Omega_\lambda, \vec{k}_1, \vec{k}_2) = T \sum_{z_\nu} D_\pi(z_\nu, \vec{k}_1) D_\pi(\Omega_\lambda - z_\nu, \vec{k}_2)$$

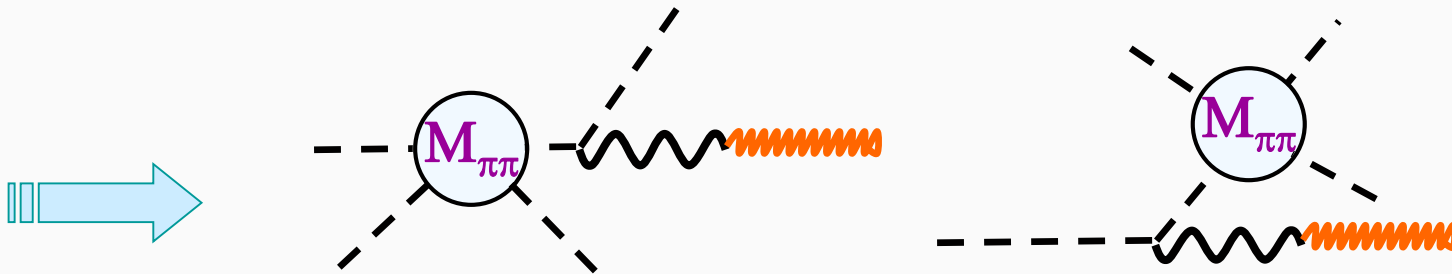
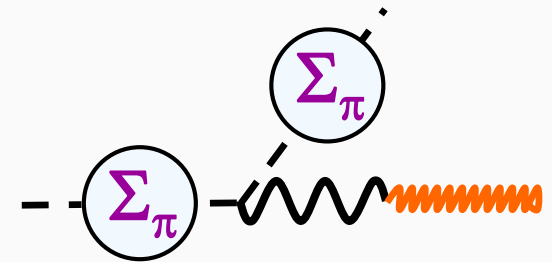
Unitarity Cut:

$$\text{Im}G_{\pi\pi}^{T,A}(E_+, k) = - \int_0^E \frac{d\omega}{\pi} [1 + f^\pi(\omega) + f^\pi(E - \omega)] \text{Im}D_\pi(\omega_+, k) \text{Im}D_\pi(E - \omega_-, k)$$



Landau Cut (“zero mode”):

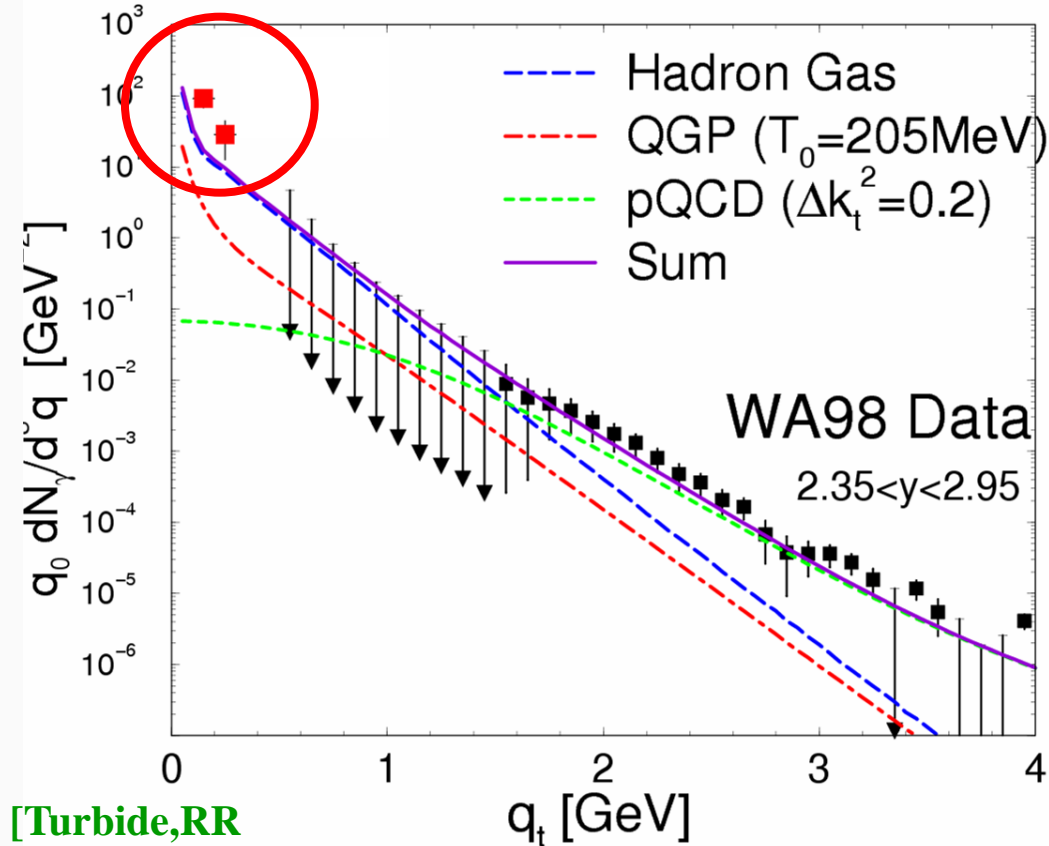
$$\text{Im}G_{\pi\pi}^{T,B}(E_+, k) = - \int_E^\infty \frac{2d\omega}{\pi} [f^\pi(\omega - E) - f^\pi(\omega)] \text{Im}D_\pi(\omega_+, k) \text{Im}D_\pi(\omega_+ - E, k)$$



ππ Bremsstrahlung!

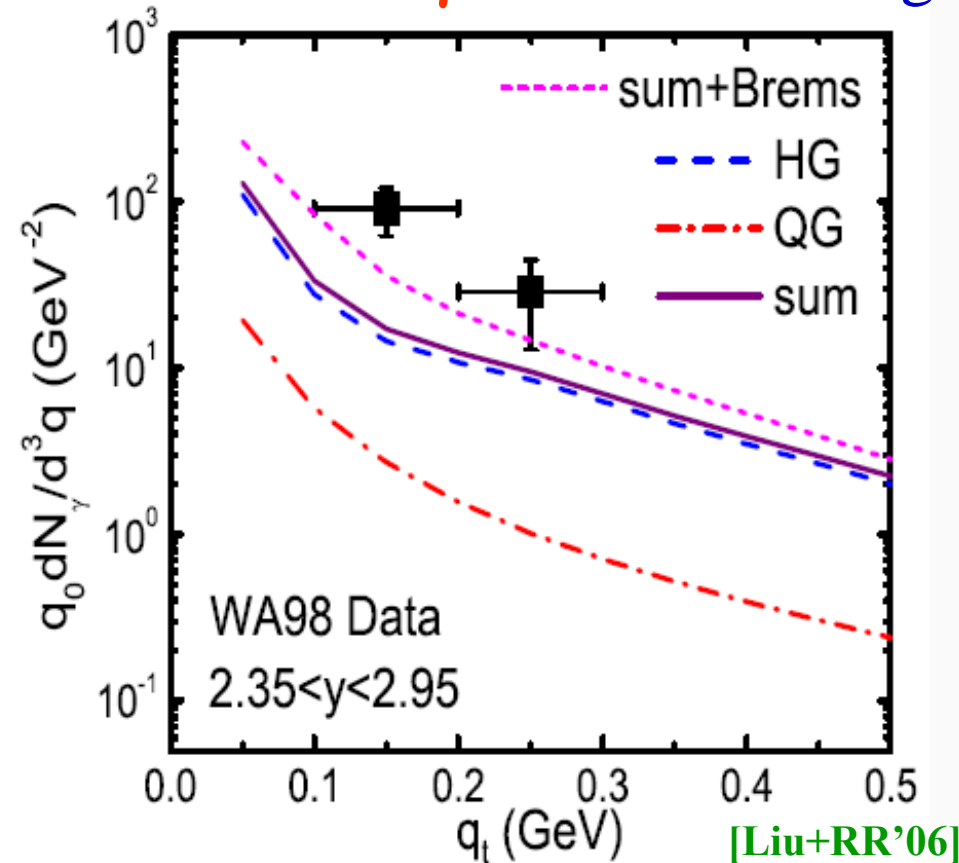
4.) Direct Photons at SPS: **WA98**

Thermal Radiation + pQCD



- pQCD+Cronin at $q_t > 2 \text{ GeV}$

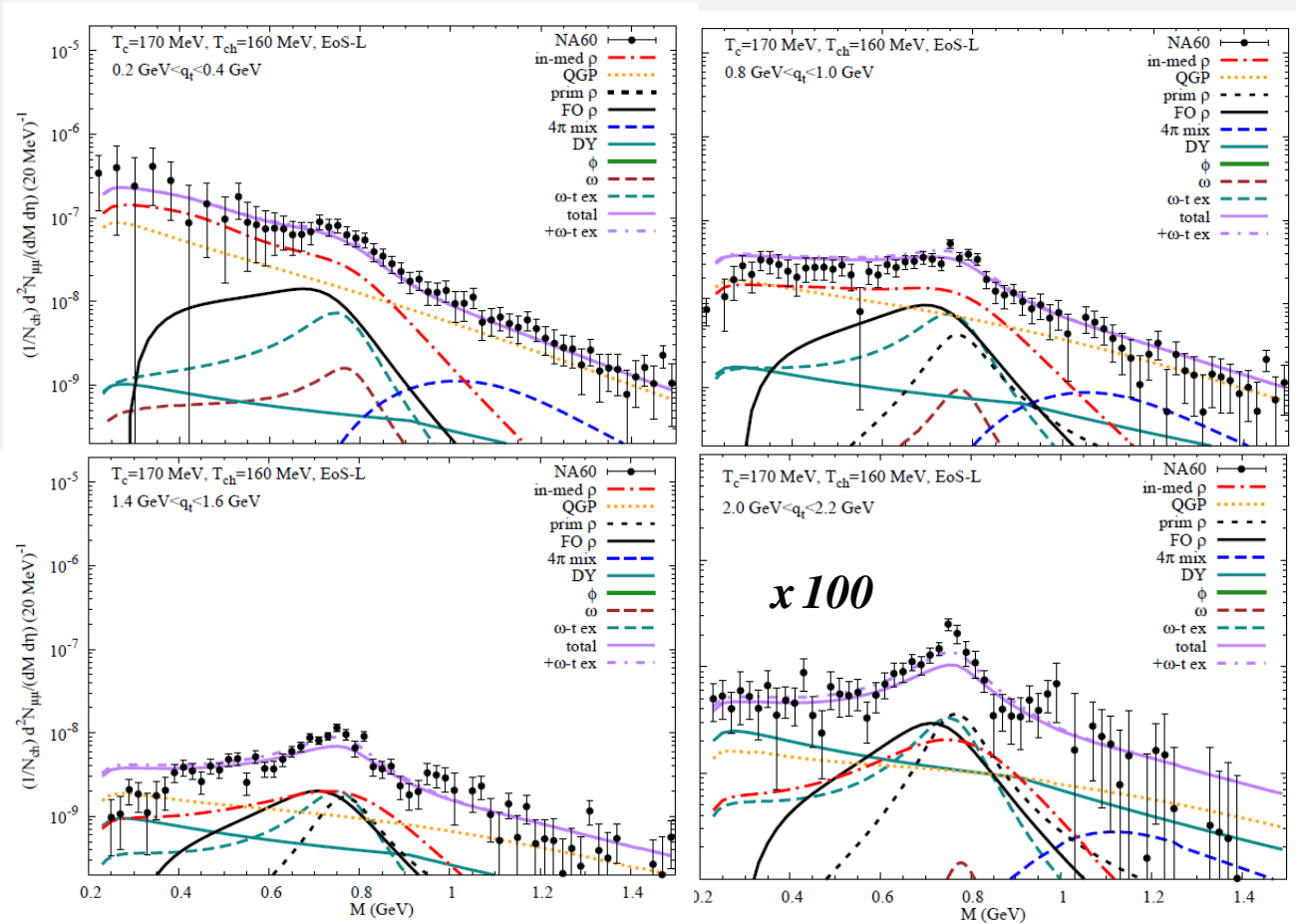
Add $\pi\pi \rightarrow \pi\pi\gamma$ Bremsstrahlung



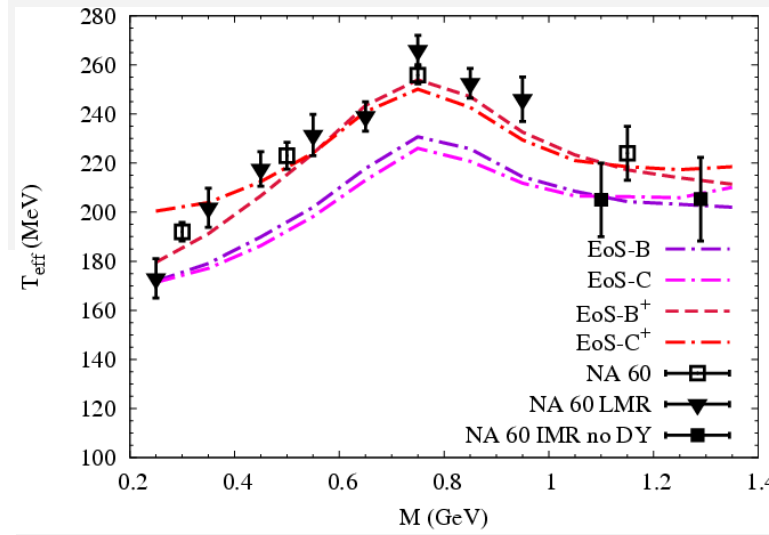
$$q_0 \frac{dN_\gamma}{d^4x d^3q} (q_0 \rightarrow 0) = \frac{T}{4\pi^3} \sigma_{\text{EM}} \quad ?$$

2.2 Transverse-Momentum Dependence

p_T -Sliced Mass Spectra



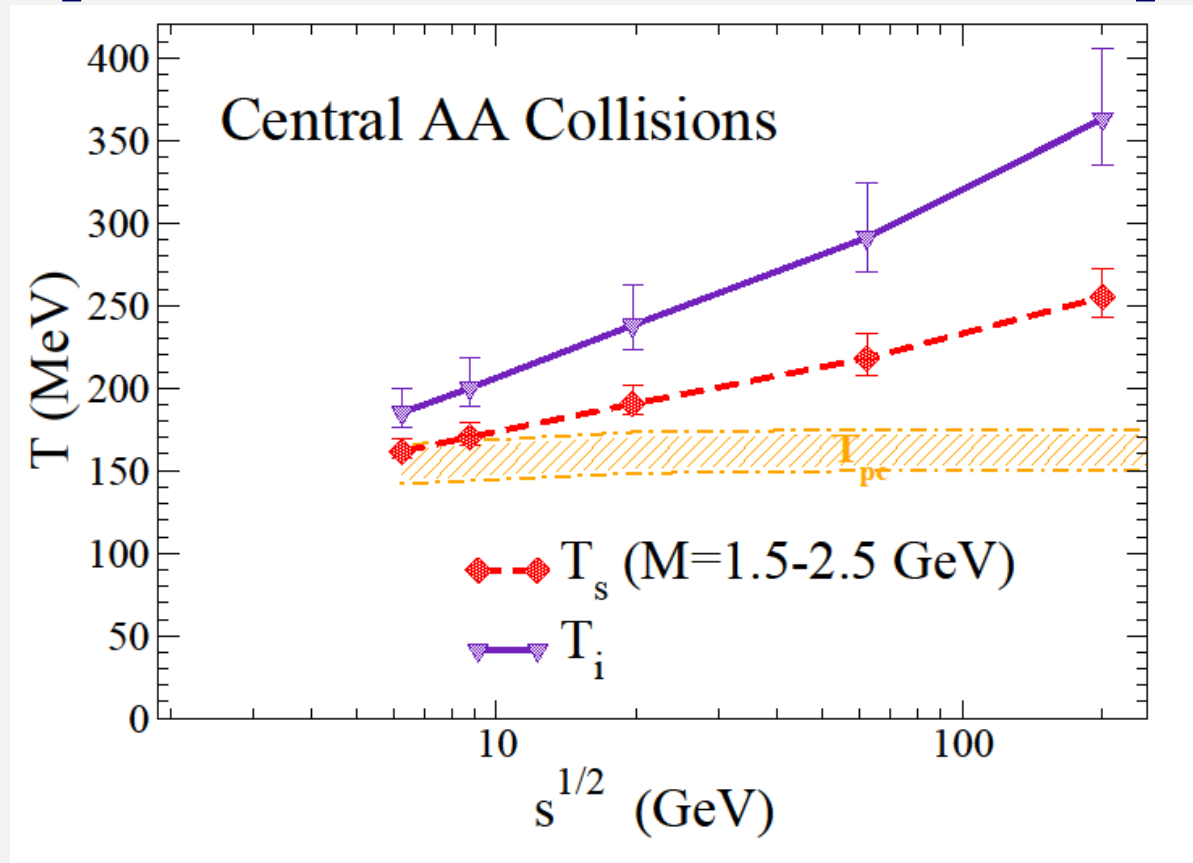
m_T -Slopes



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

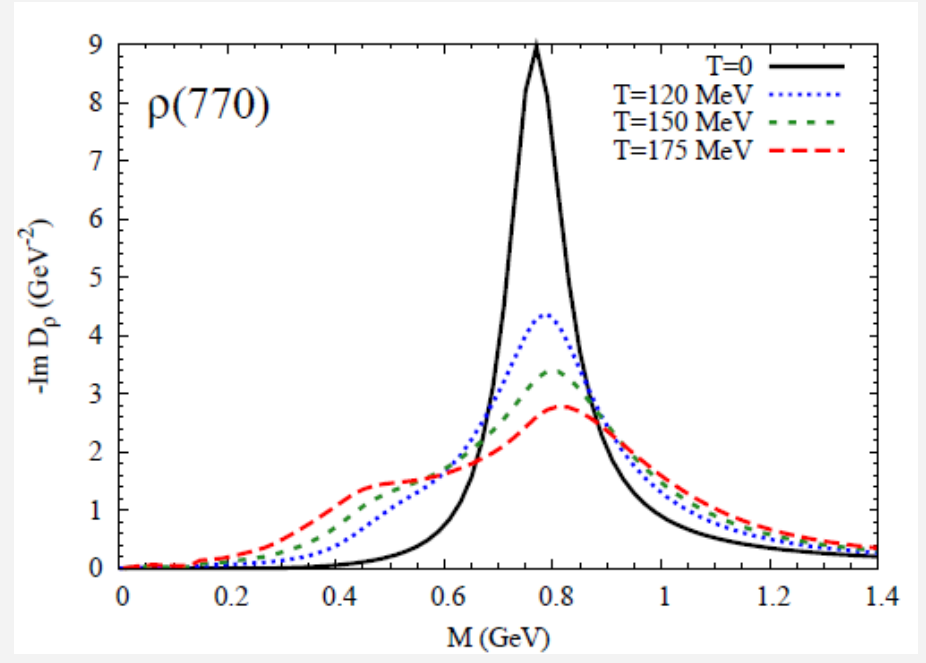
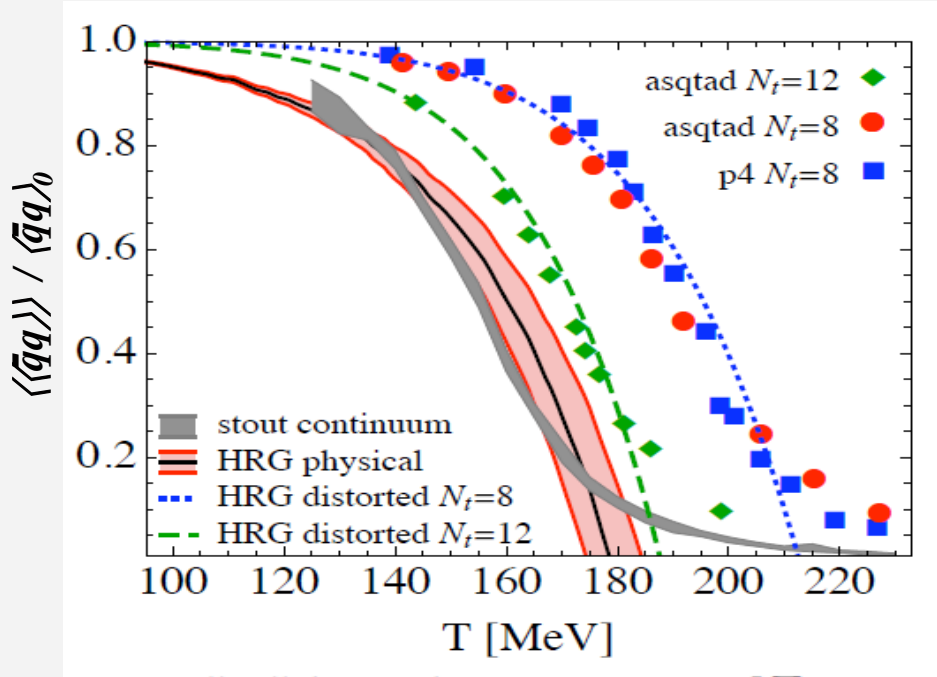
4.2 Fireball Temperature

Slope of Intermediate-Mass Excess Dileptons

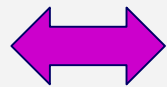


- unique “early” temperature measurement (no blue-shift!)
- T_s approaches T_i toward lower energies
- first-order “plateau” at **BES-II/CBM/NICA?**

2.2 Chiral Condensate + ρ -Meson Broadening

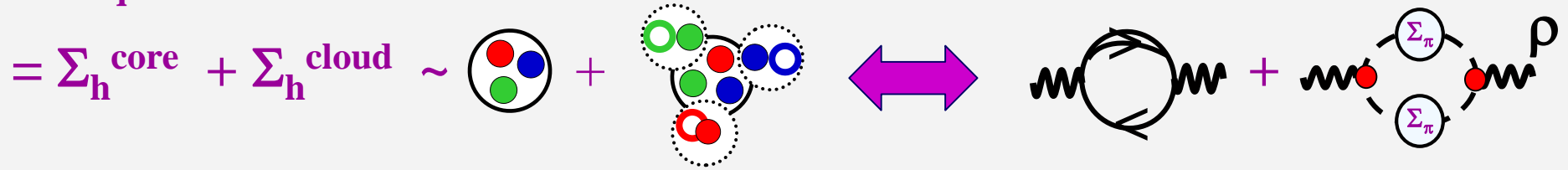


$$\frac{\langle\langle \bar{q}q \rangle\rangle(T, \mu_B)}{\langle \bar{q}q \rangle} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$$



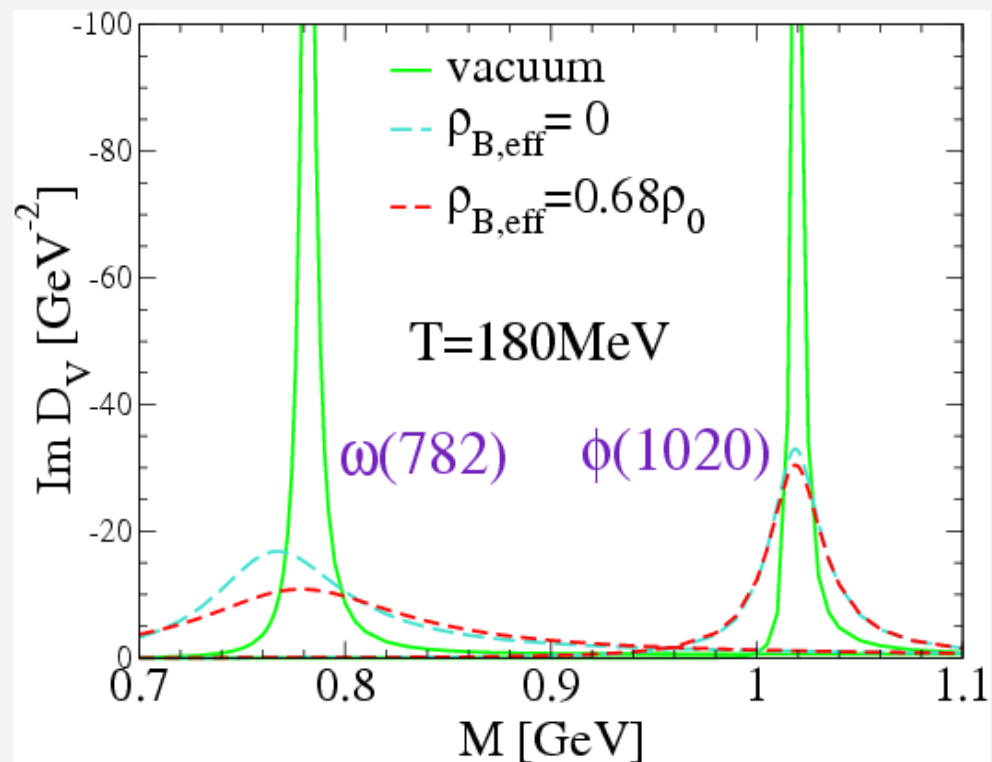
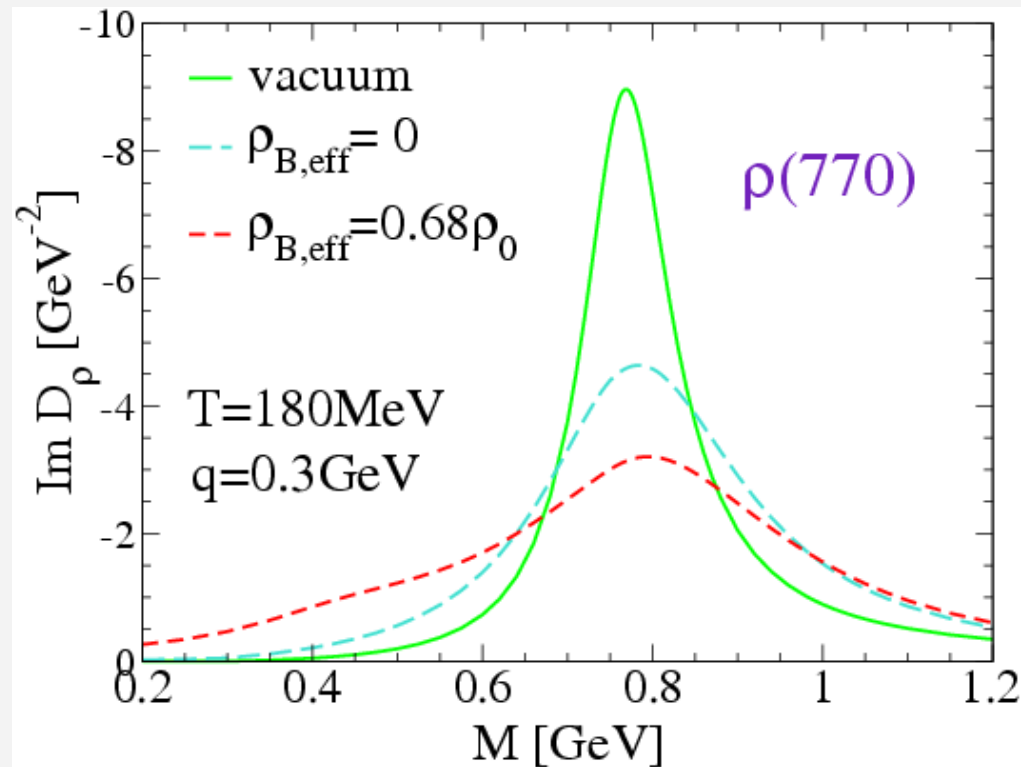
effective hadronic theory

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



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

2.1 In-Medium Vector Mesons at RHIC + LHC

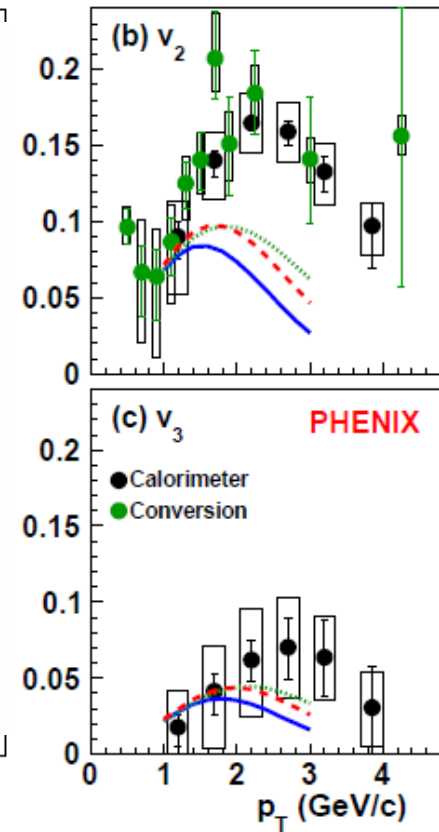
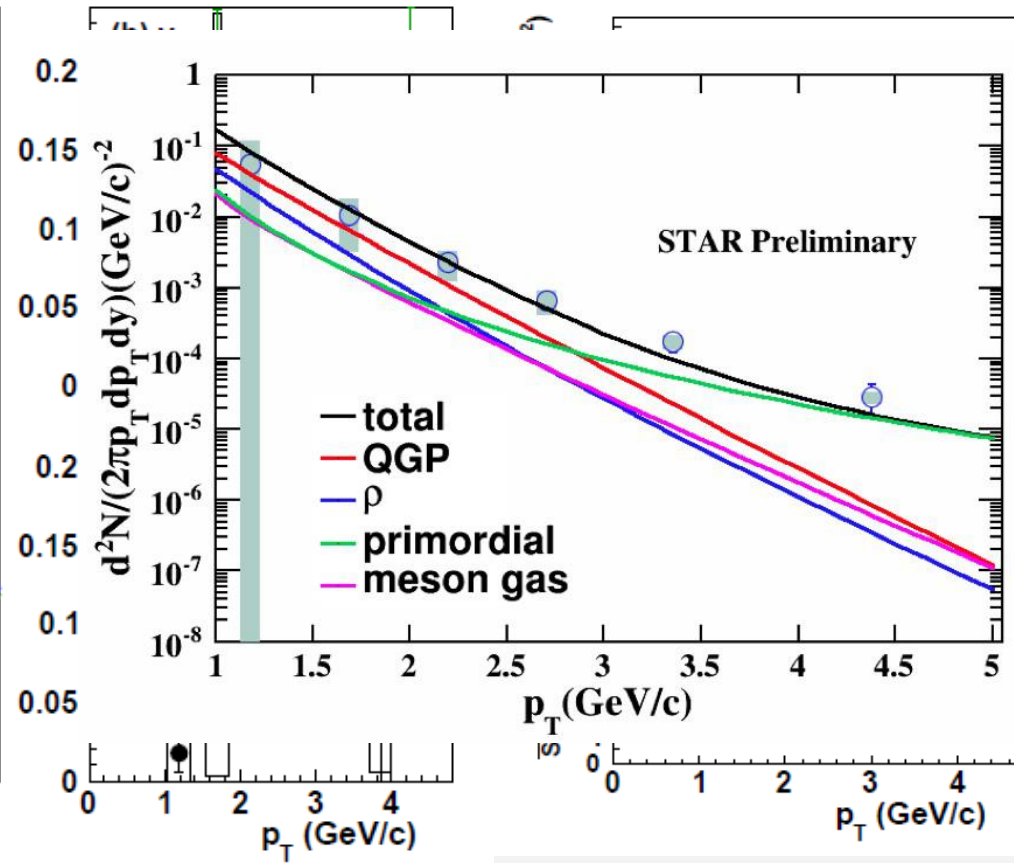
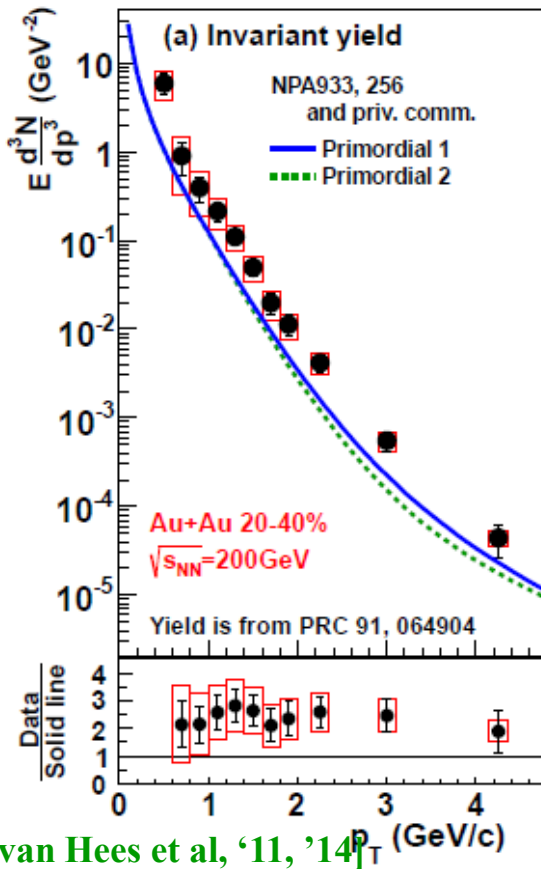


- Anti-/baryon effects melt the ρ meson
- ω also melts, ϕ more robust \leftrightarrow OZI

4.3 Comparison to Data: **RHIC**

Ideal Hydro

Viscous Hydro

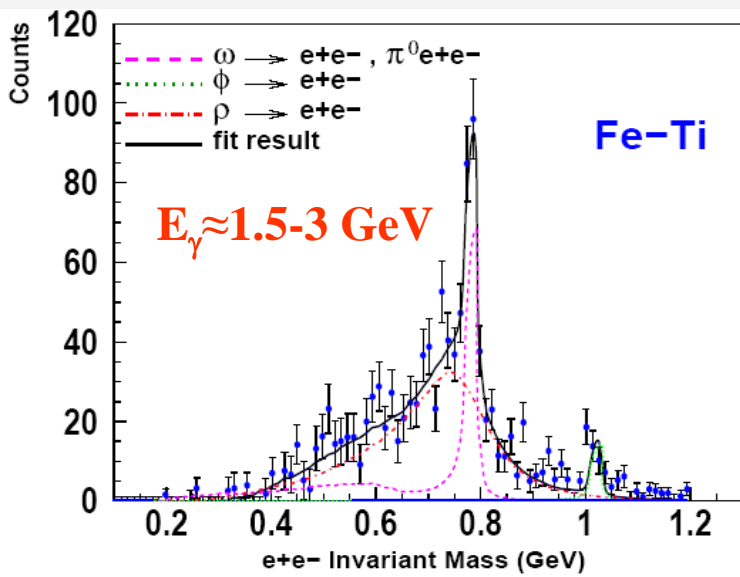
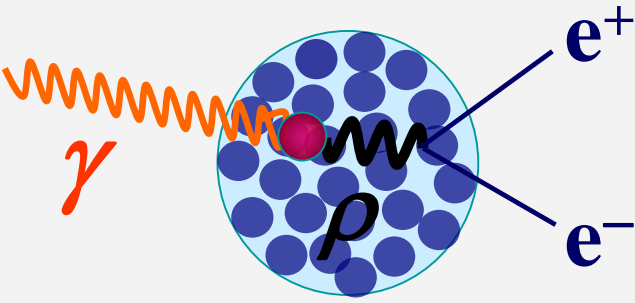


[Paquet et al '16]

- same rates + initial flow \Rightarrow similar results from various evolution models

3.2 Nuclear Photoproduction: ρ Meson in Cold Matter

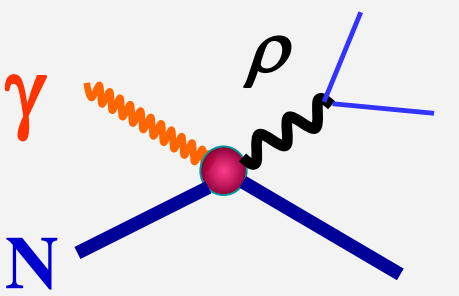
$$\gamma + A \rightarrow e^+e^- X$$



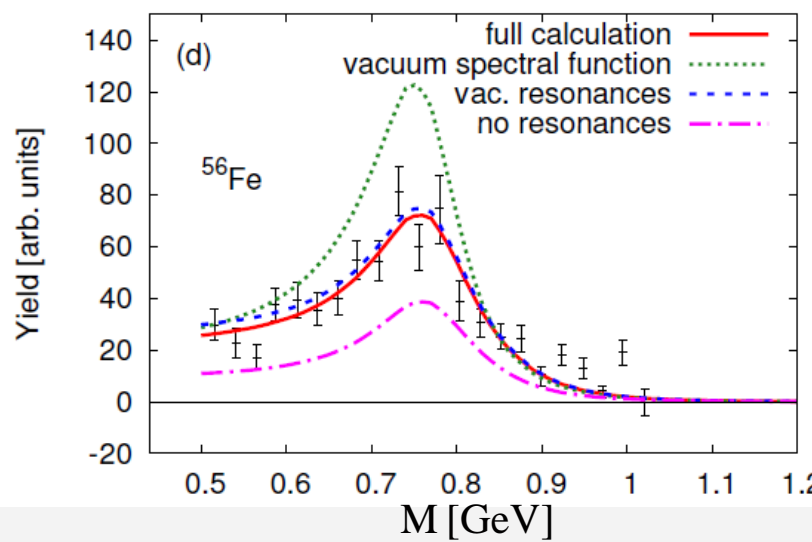
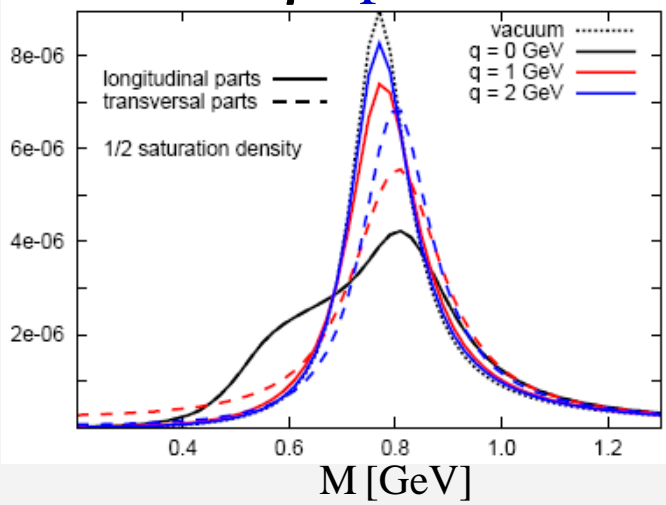
- extracted “in-med” ρ -width $\Gamma_\rho \approx 220$ MeV
- [CLAS+GiBUU '08]

• Microscopic Approach:

production amplitude + in-med. ρ spectral fct.



[Riek et al '08, '10]



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

3.2 Massive Yang-Mills Approach in Vacuum

- Gauge $\rho + \mathbf{a}_1$ into chiral pion lagrangian:
- problems with vacuum phenomenology

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

- Recent progress:

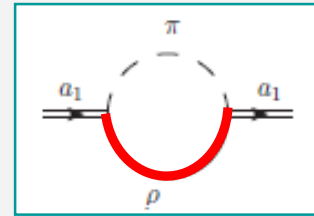
- full ρ propagator in \mathbf{a}_1 selfenergy
- vertex corrections to preserve

PCAC:

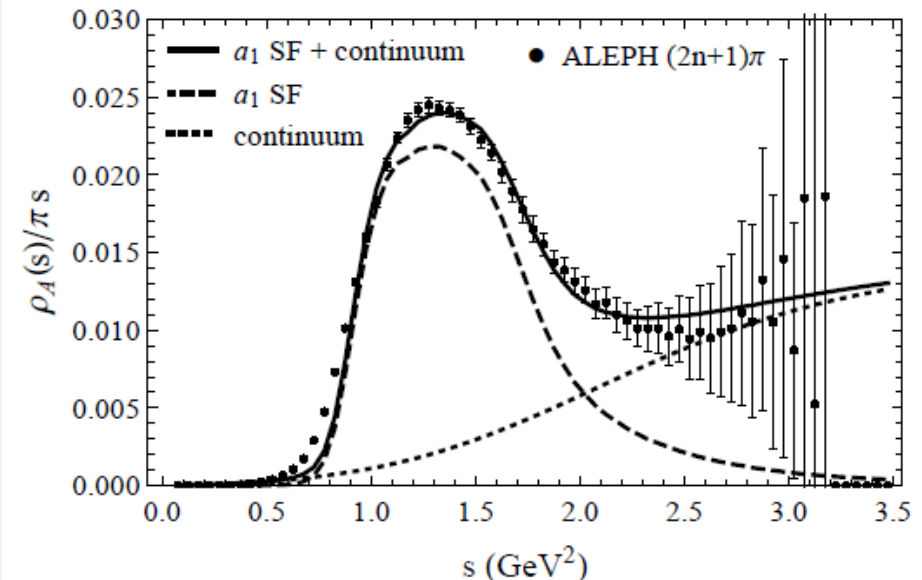
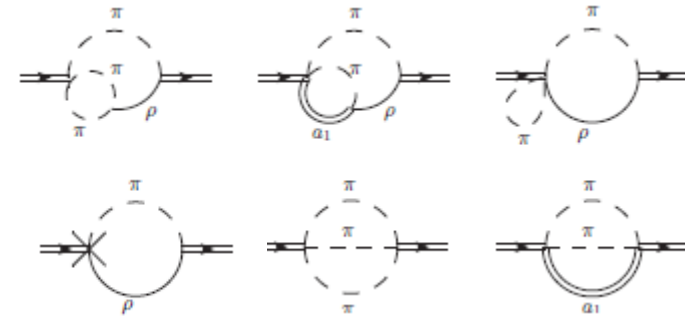
$$\int \frac{(-\text{Im}\Pi_A^L)}{\pi s} ds = \frac{F_\pi^2}{2}$$

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

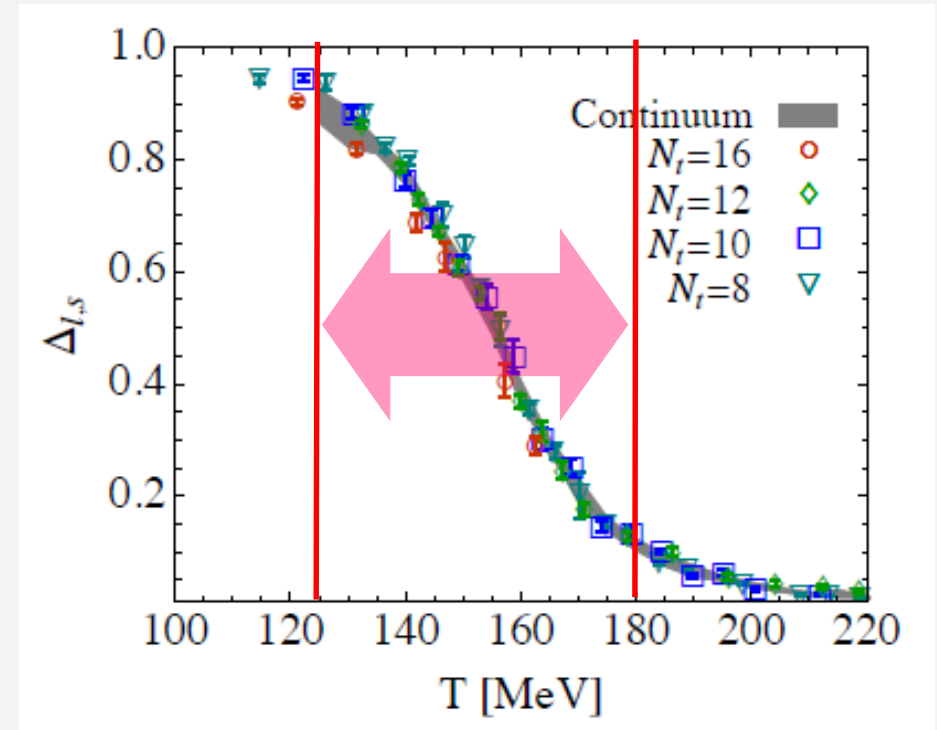
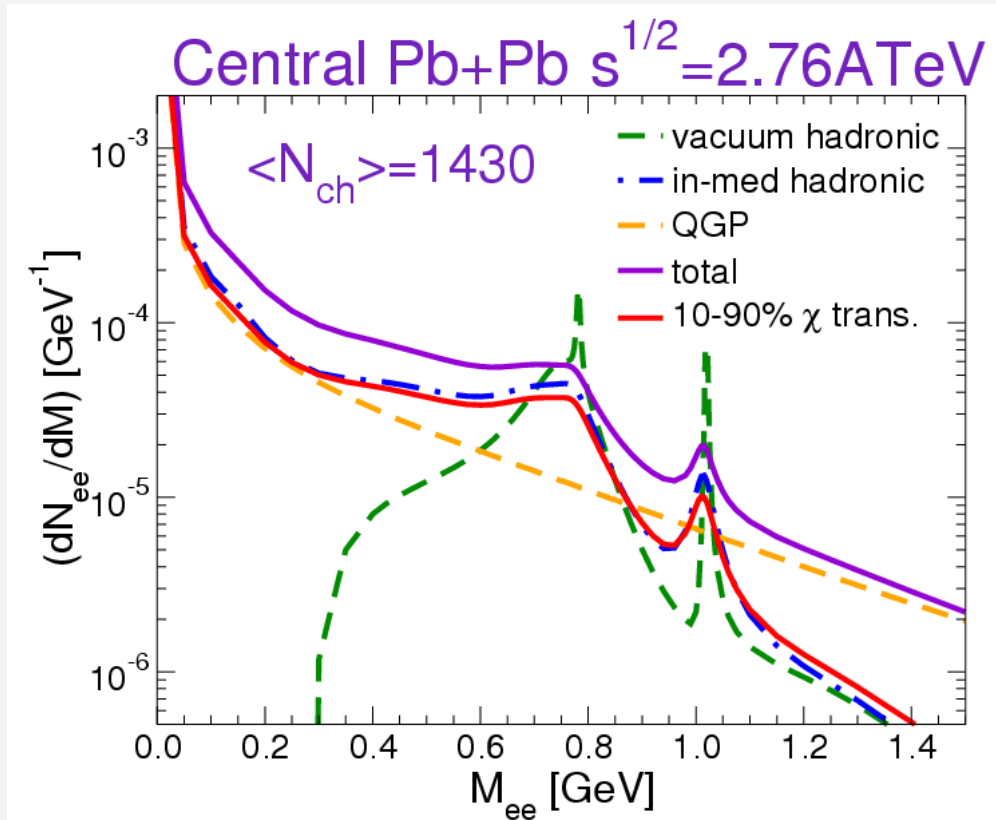
$$\begin{aligned} \mathcal{L}_{\text{MYM}} = & \frac{\tilde{f}_\pi^2}{8} (\text{Tr}[D_\mu U^\dagger D^\mu U] + \tilde{m}_\pi^2 \text{Tr}[U + U^\dagger - 2]) \\ & - \frac{1}{2} \text{Tr}[F_L^2 + F_R^2] + m_0^2 \text{Tr}[A_L^2 + A_R^2] \\ & - i\xi \text{Tr}[D_\mu U D_\nu U^\dagger F_L + D_\mu U^\dagger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



[Hohler +RR '14]

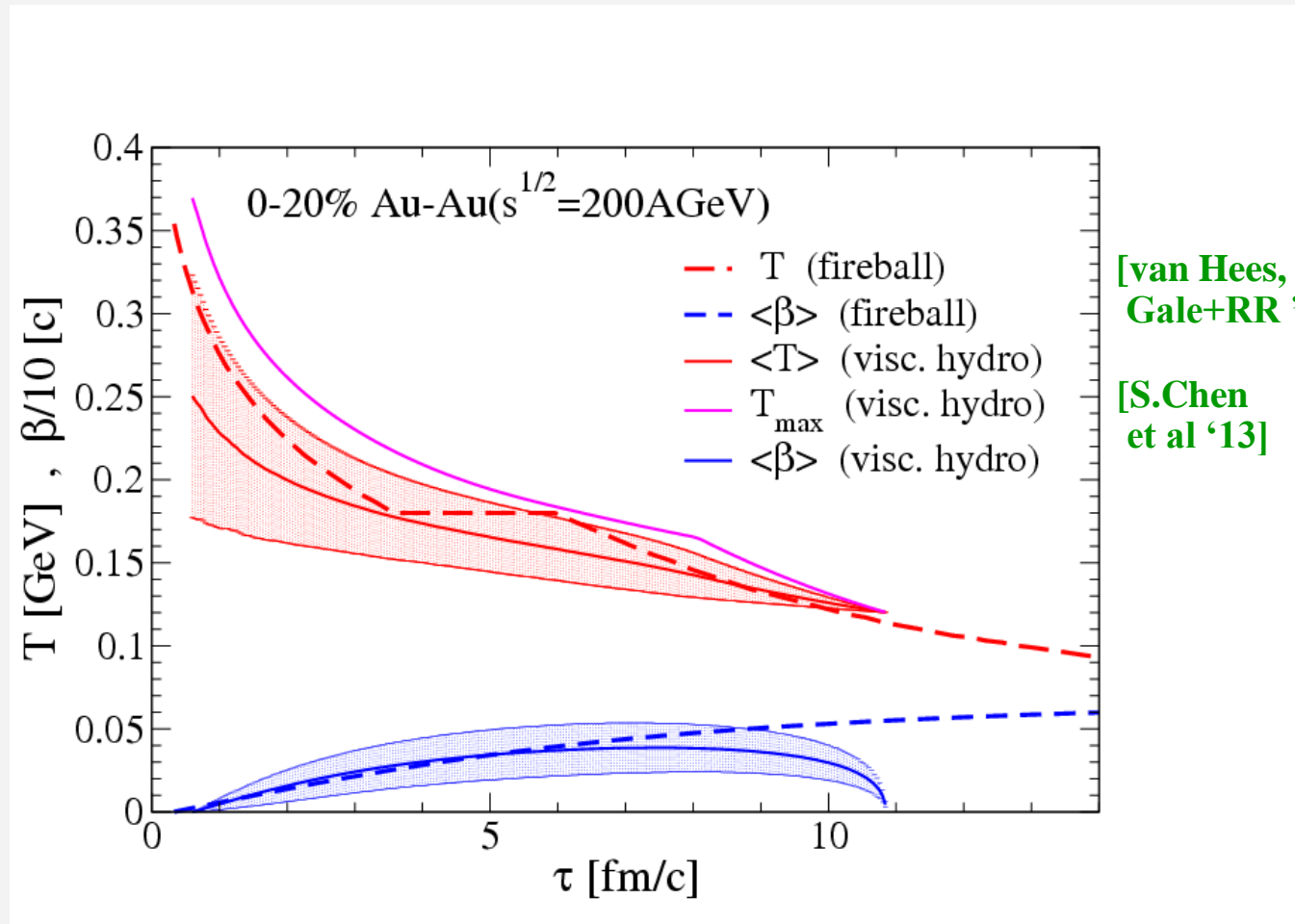


5.2 Chiral Restoration Window at LHC



- low-mass spectral shape in chiral restoration window:
 ~60% of thermal low-mass yield in “chiral transition region”
 (T=125-180MeV)
- enrich with (low-) p_t cuts

3.3.2 Fireball vs. Viscous Hydro Evolution



- very similar!