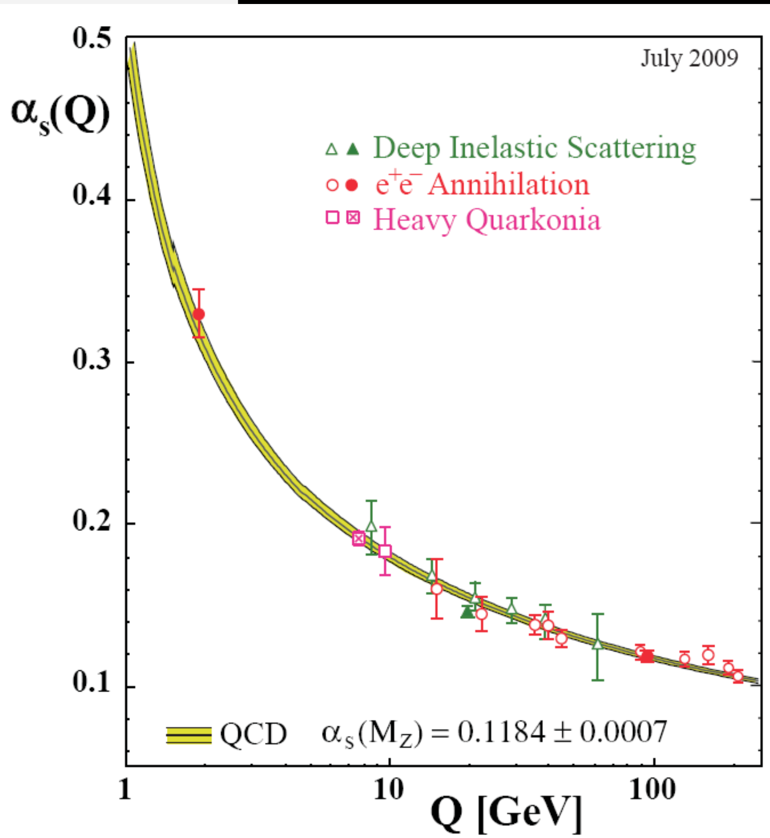
Electromagnetic Radiation
Probing QCD Matter

Ralf Rapp

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

Theoretical Physics Colloquium
Arizona State University (online), 14.12.22

1.1 Quantum Chromodynamics (QCD)



$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - \mathcal{M}_q)q - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

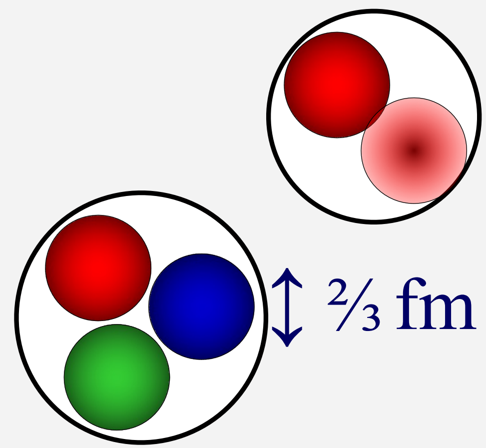
[Gross,Politzer+Wilczek '73]

Well tested at high energies, $Q^2 > 1\,GeV^2$

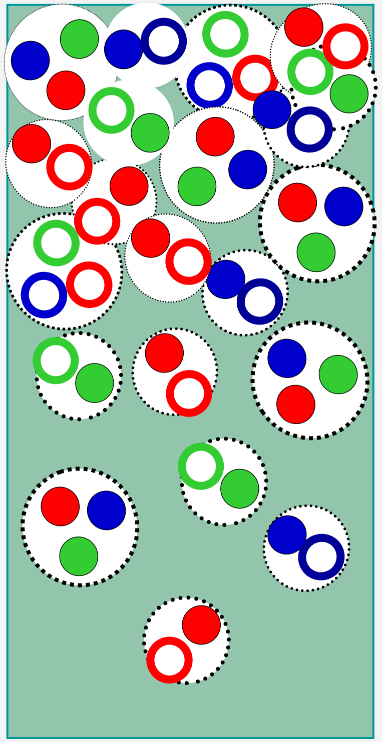
- perturbation theory ($\alpha_s = g^2/4\pi << 1$)
- degrees of freedom = quarks + gluons ($m_u \approx m_d \approx 5\,MeV$)

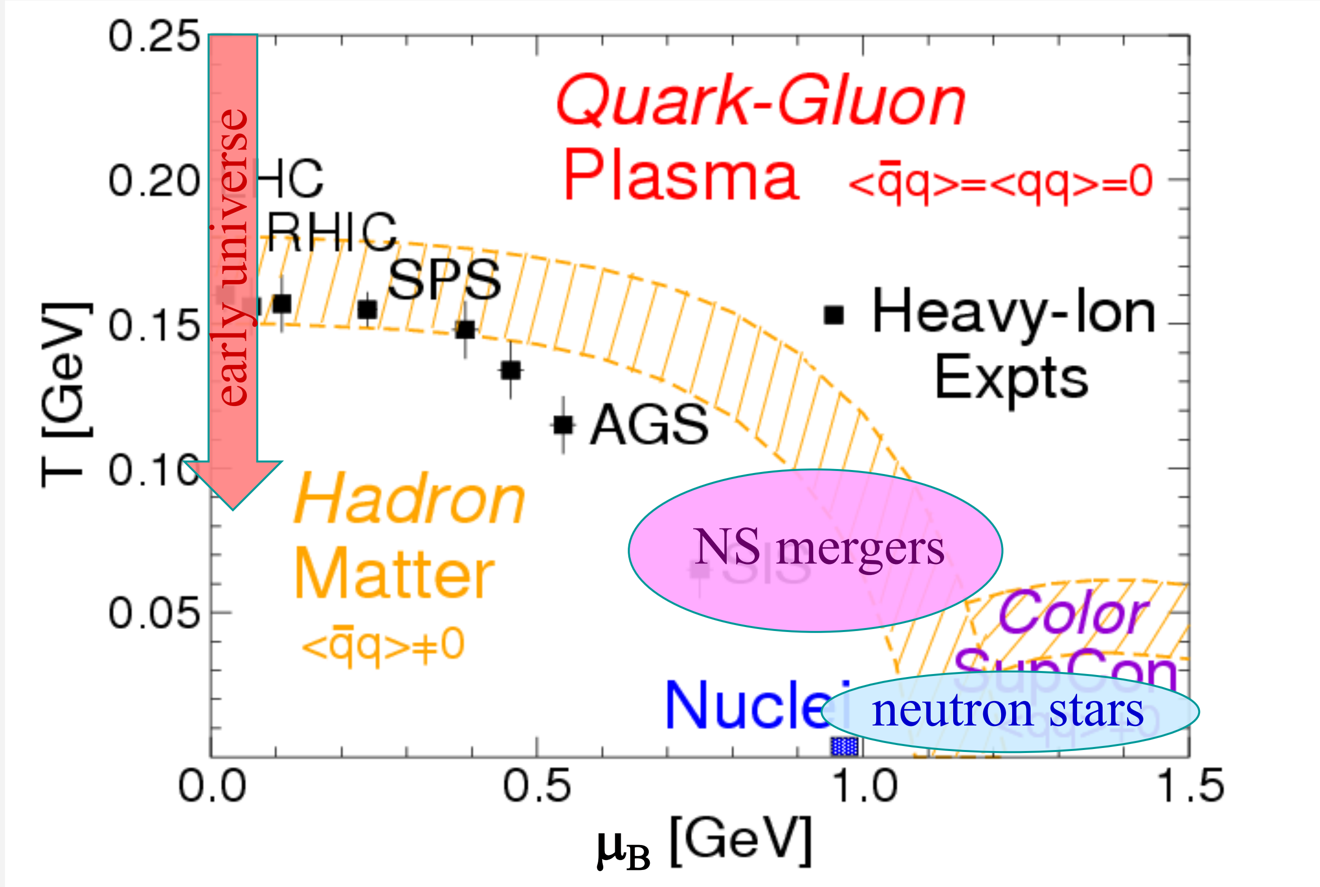
$Q^2 \leq 1\,GeV^2 \rightarrow$ **Transition to "strong QCD"**

- effective d.o.f. = hadrons: **Confinement**
- **mass generation**: $M_{proton} = 940\,MeV \approx 3M_q$



1.2 Strong-Interaction Matter





- De-confinement and mass de-generation at high **T** (**μ_B**?)
- Create in laboratory using heavy-ion collisions
- **Microscopic structure + interactions**?

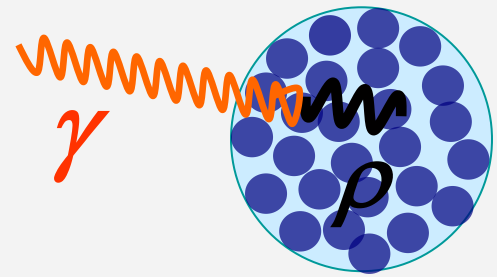
1.3 Electromagnetic Probes of QCD Matter

→ penetrating probe

- **Photon Scattering off Nuclei**

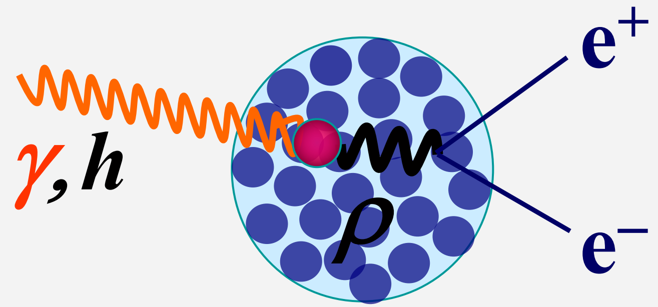
  - Total Photo-Absorption

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



  - Dilepton Photo-/Hadro-Production

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



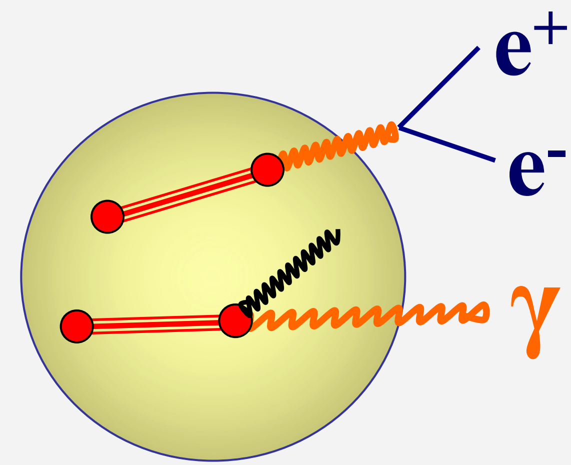
- **Thermal Radiation in Heavy-Ion Collisions**

  - Dileptons

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

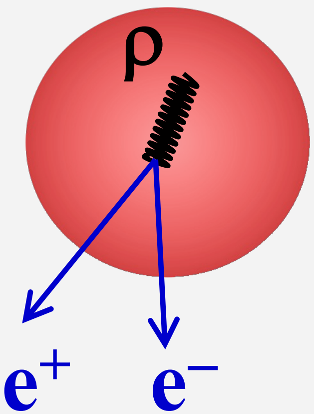
  - Photons

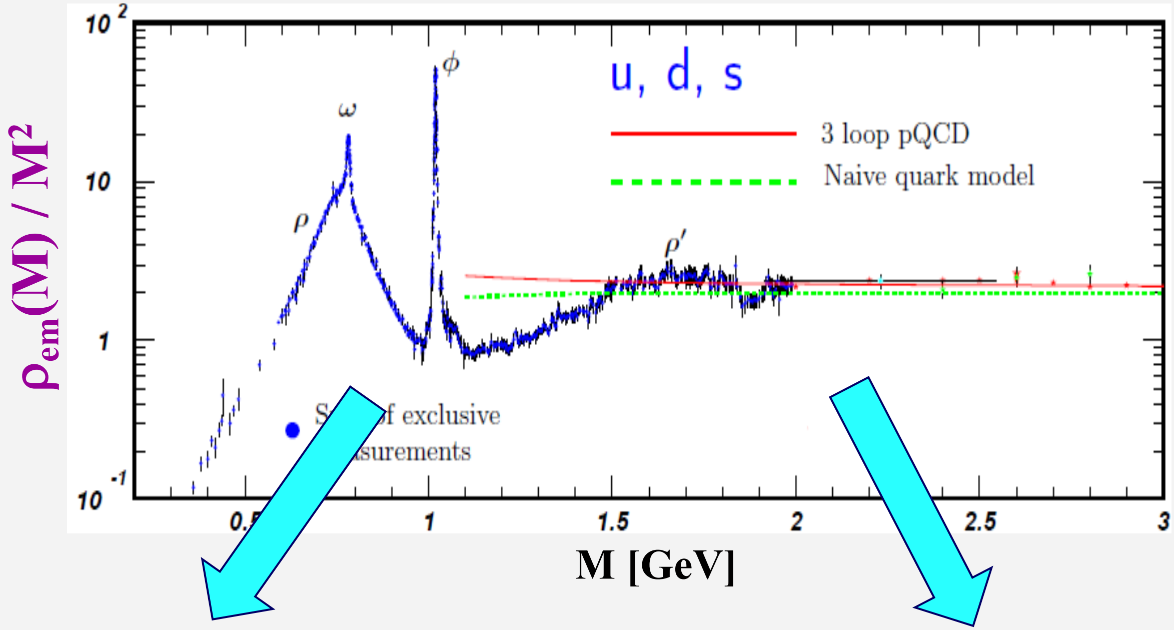
$$q_0 \frac{dR_\gamma}{d^3q} = \frac{\alpha}{\pi^2} f^B(q_0;T)\, \rho_{em}(M{=}0,q;\mu_B,T)$$

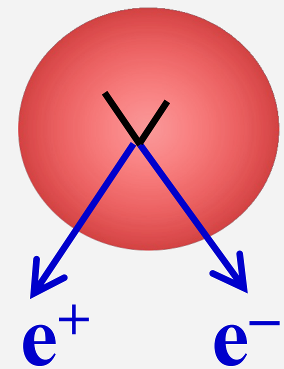


1.4 Electromagnetic Spectral Function

Vacuum: $e^+e^- \rightarrow$ hadrons







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

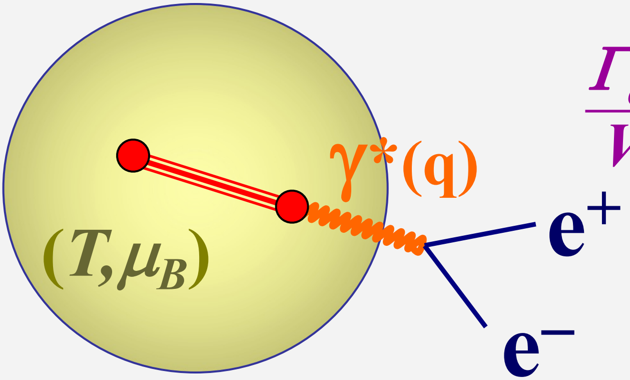
- **$q\bar{q}$ Continuum:**
  perturbative

In Medium:

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

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

1.5 EM Correlator + Thermal Dilepton Rate



$$\frac{\Gamma_{ee}}{V} = \frac{dN_{ee}}{d^4x} = e^4 \int \frac{\Pi_i\, d^3p_i}{(2\pi)^3 2E_i} \frac{\Pi_f\, d^3p_f}{(2\pi)^3 2E_f} 2\pi\delta(P_i - P_f - Q)$$

$$\times \langle i | j_\mu^{em} | f\rangle \langle f | j_\nu^{em} | i\rangle\, f^i (1 \pm f^f)\, (j_e^\mu \frac{1}{Q^4} j_e^\nu)$$

[McLerran+Toimela '85]

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

- **EM Correlation Fct.:** $\Pi_{em}^{\mu\nu}(Q) = -i \int d^4x\, e^{iQx} \langle\langle j_{em}^\mu(x) j_{em}^\nu(0) \rangle\rangle$

- **Quark basis:** $j_{em}^\mu = \frac{2}{3}\bar{u}\gamma^\mu u - \frac{1}{3}\bar{d}\gamma^\mu d - \frac{1}{3}\bar{s}\gamma^\mu s$ **Continuum**

- **Hadron basis:** $j_{em}^\mu = \frac{1}{2}(\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d) + \frac{1}{6}(\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d) - \frac{1}{3}\bar{s}\gamma^\mu s$

$$= \frac{1}{\sqrt{2}} j_\rho^\mu + \frac{1}{3\sqrt{2}} j_\omega^\mu - \frac{1}{3} j_\phi^\mu$$

Vector Meson Dominance: 9 : 1 : 2

Outline

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2.) **In-Medium Spectral Functions**

- Hadronic Many-Body Theory + Constraints

3.) **Thermal Dileptons in Heavy-Ion Collisions**

- Spectral Shape, Fireball Temperature + Lifetime

4.) **Chiral Symmetry Restoration**

- QCD + Weinberg Sum Rules; Baryons

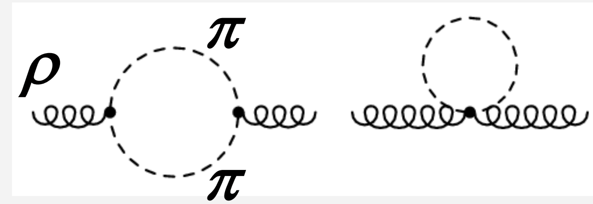
5.) **Electric Conductivity**

6.) **Conclusions**

2.1 Hadronic EM Current: ρ-Meson in Vacuum

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

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



ρ -propagator:

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

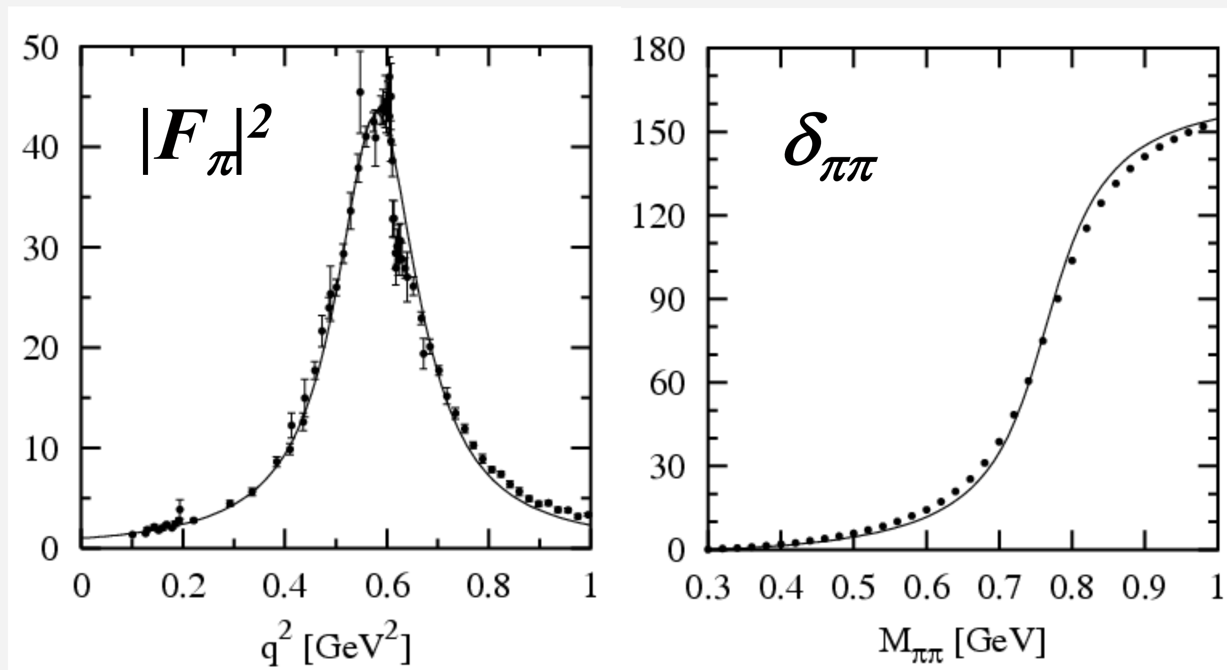
π EM formfactor

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

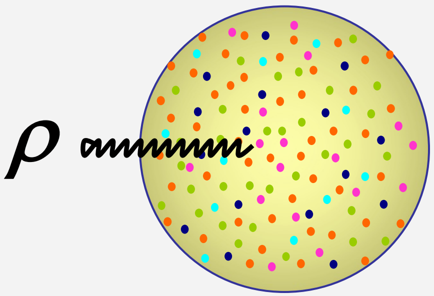
ππ scattering phase shift

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

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



2.2 ρ-Meson in Matter: Many-Body Theory



interactions with hadrons from heat bath

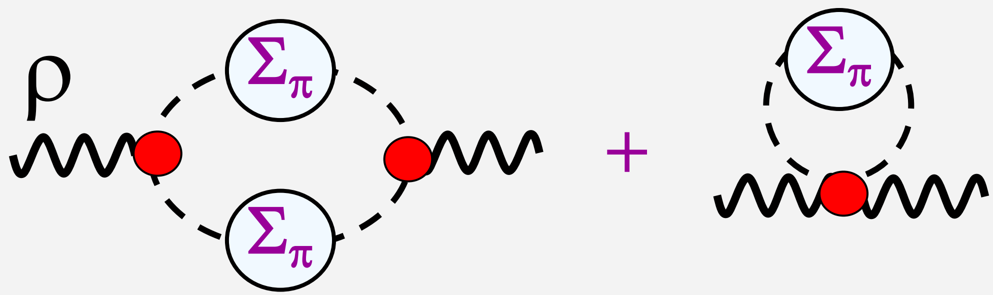
⇒ **In-Medium ρ-Propagator**

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

- **In-Medium Pion Cloud**

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

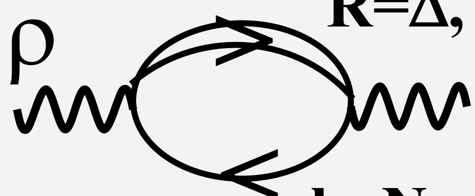
$\Sigma_{\rho\pi\pi} =$



- **Direct ρ-Hadron Scattering**

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

$\Sigma_{\rho B,M} =$



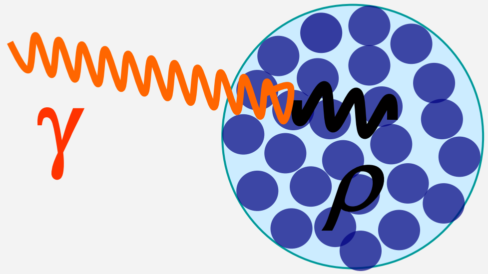
R=Δ, N(1520), a_1, K_1, …

h=N, π, K, …

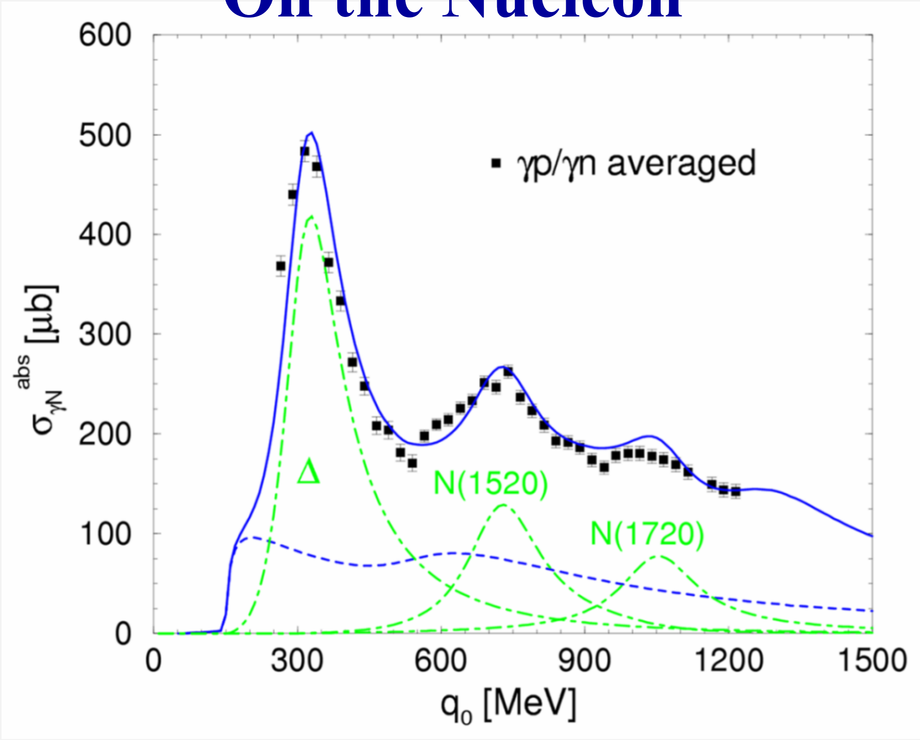
- estimate couplings from **R→ ρh, γh**
- comprehensively: scattering data (**πN→ρN, γN/A**,…)

2.3 Constraints from Nuclear Photo-Absorption

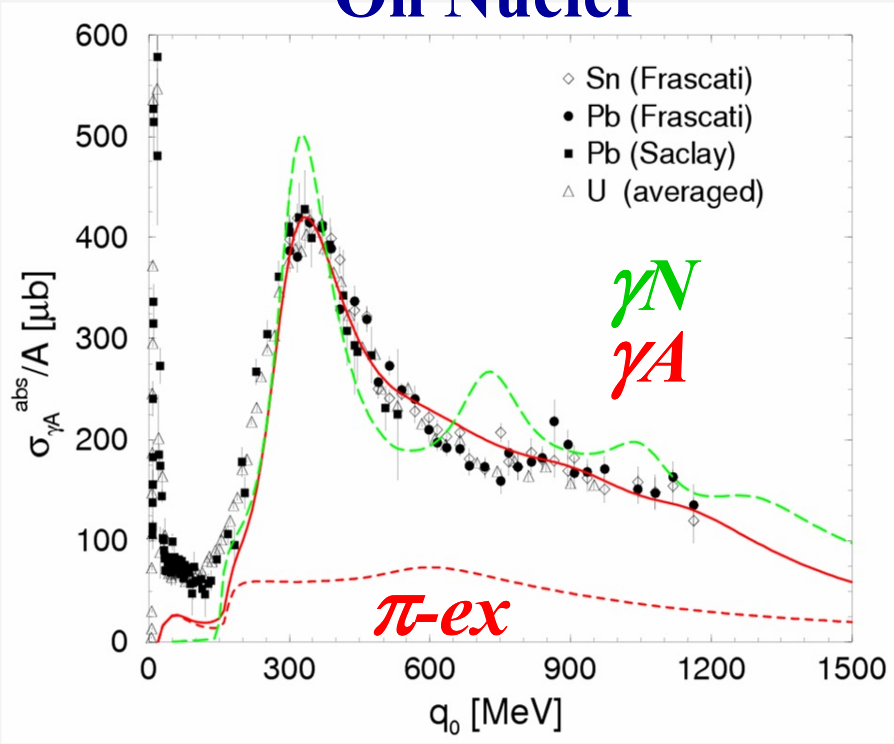
$$\frac{\sigma_{\gamma A}(q_0)}{A} = \frac{-4\pi\alpha}{q_0\rho_N}\frac{m_\rho^4}{g_\rho^2}\,\mathrm{Im}\,D_\rho(M{=}0,q;\rho_N)$$



On the Nucleon



On Nuclei

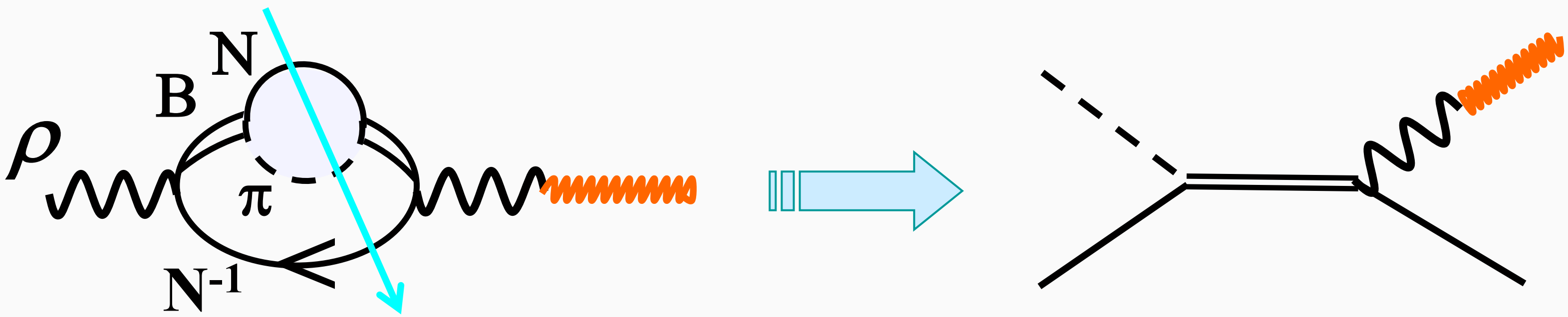


- constrain *ρNB* couplings + non-resonant pion cloud
- 2nd + 3rd resonances melt

[Urban et al '98]

2.4 Production Processes from ρ Spectral Function

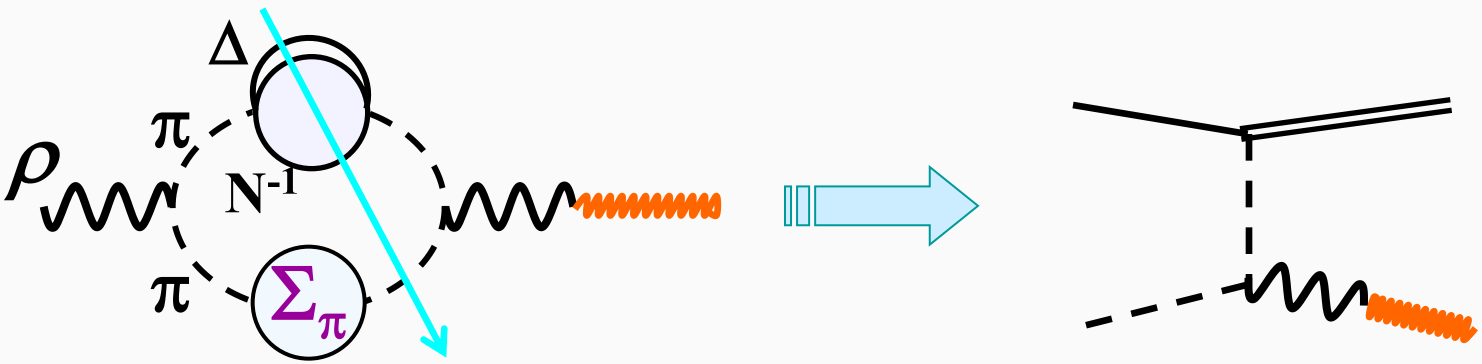
↔ Cuts (imag. parts) of selfenergy diagrams:



resonance Dalitz decays

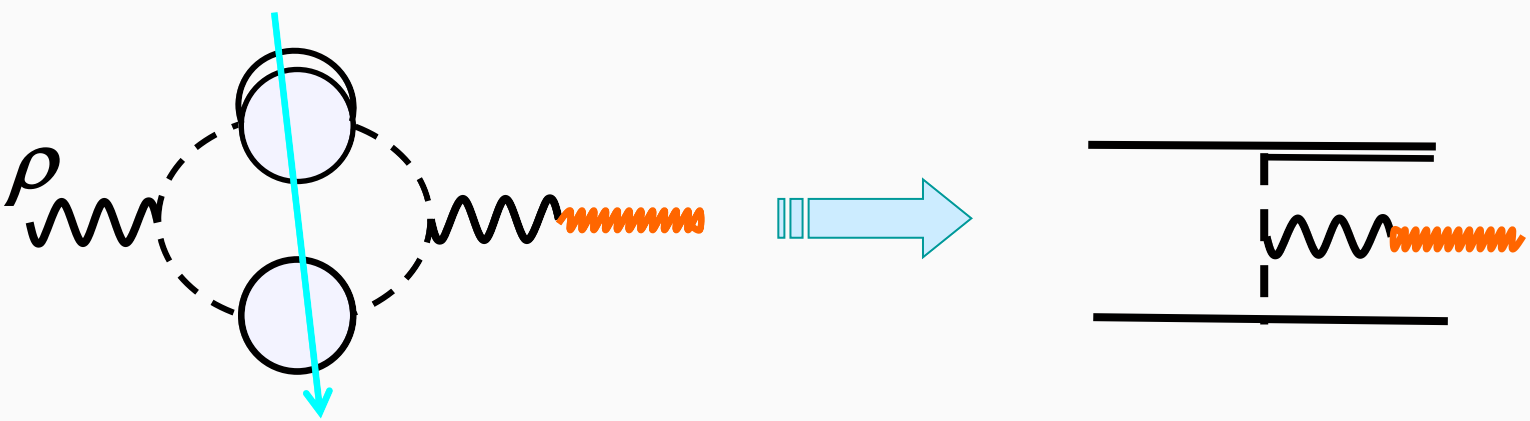
$\pi N \rightarrow \Delta \rightarrow \gamma N$

$\pi \rho \rightarrow a_1 \rightarrow \gamma \pi$



meson-exchange scattering

$\pi N \rightarrow \gamma N\,,\ \gamma \Delta$



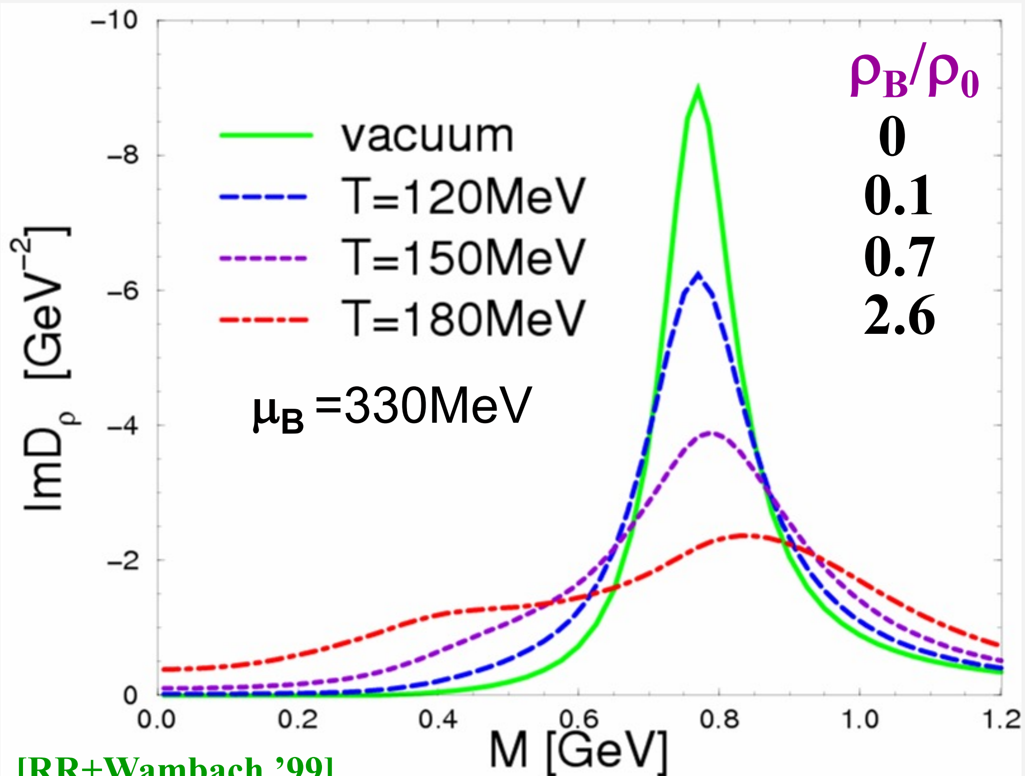
Bremsstrahlung

$NN \rightarrow \gamma NN,\ \gamma N\Delta,\ \gamma \Delta\Delta$

2.5 In-Medium ρ-Meson Spectral Functions

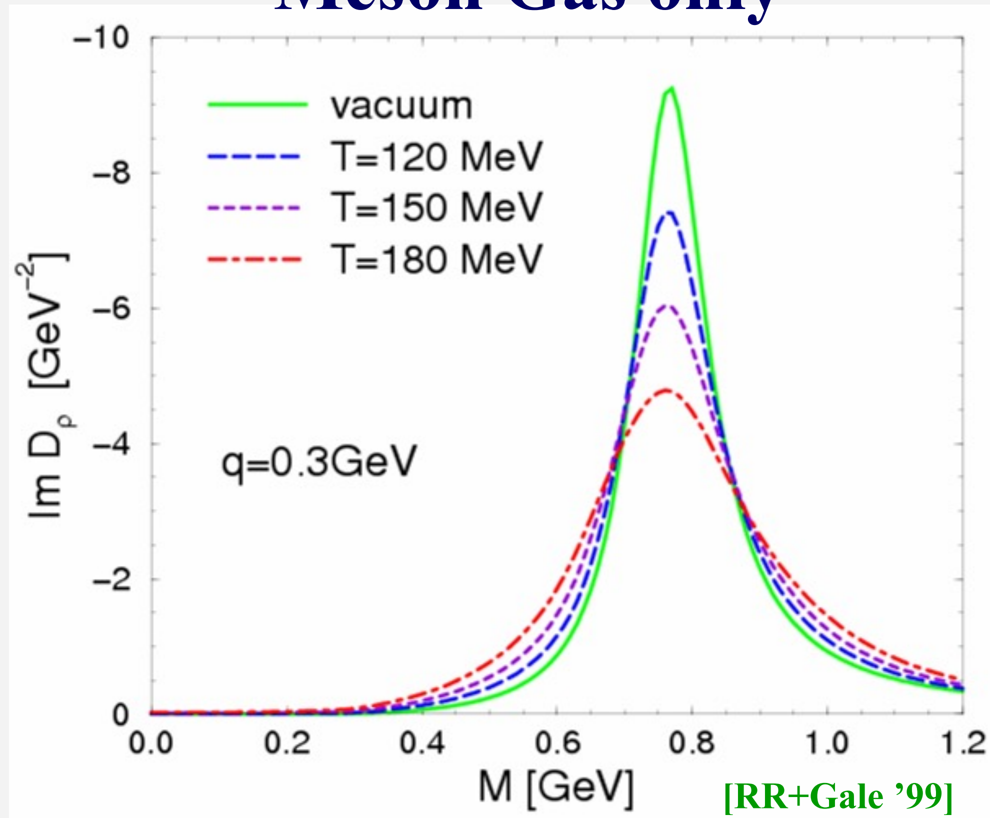
$$D_\rho (M,q;\mu_B,T) = 1 / [M^2 - (m_\rho^{(0)})^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]$$

Hot + Dense Matter



[RR+Wambach '99]

Meson Gas only

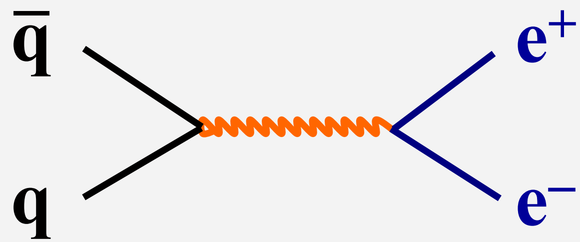


[RR+Gale '99]

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

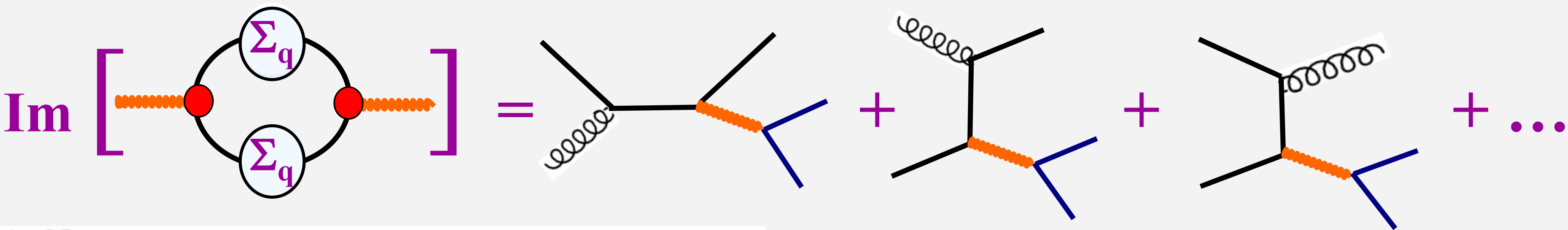
2.6 QGP Emission: Perturbative vs. Lattice QCD

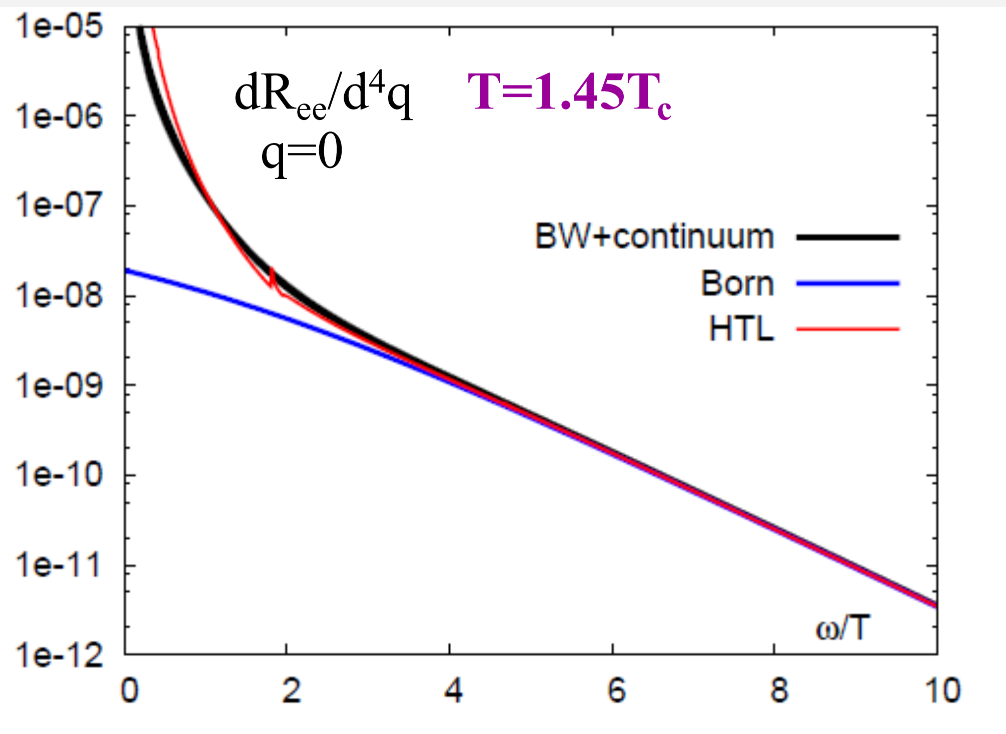
Baseline:



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

[Braaten,Pisarski+Yuan '91]





collinear enhancement:

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

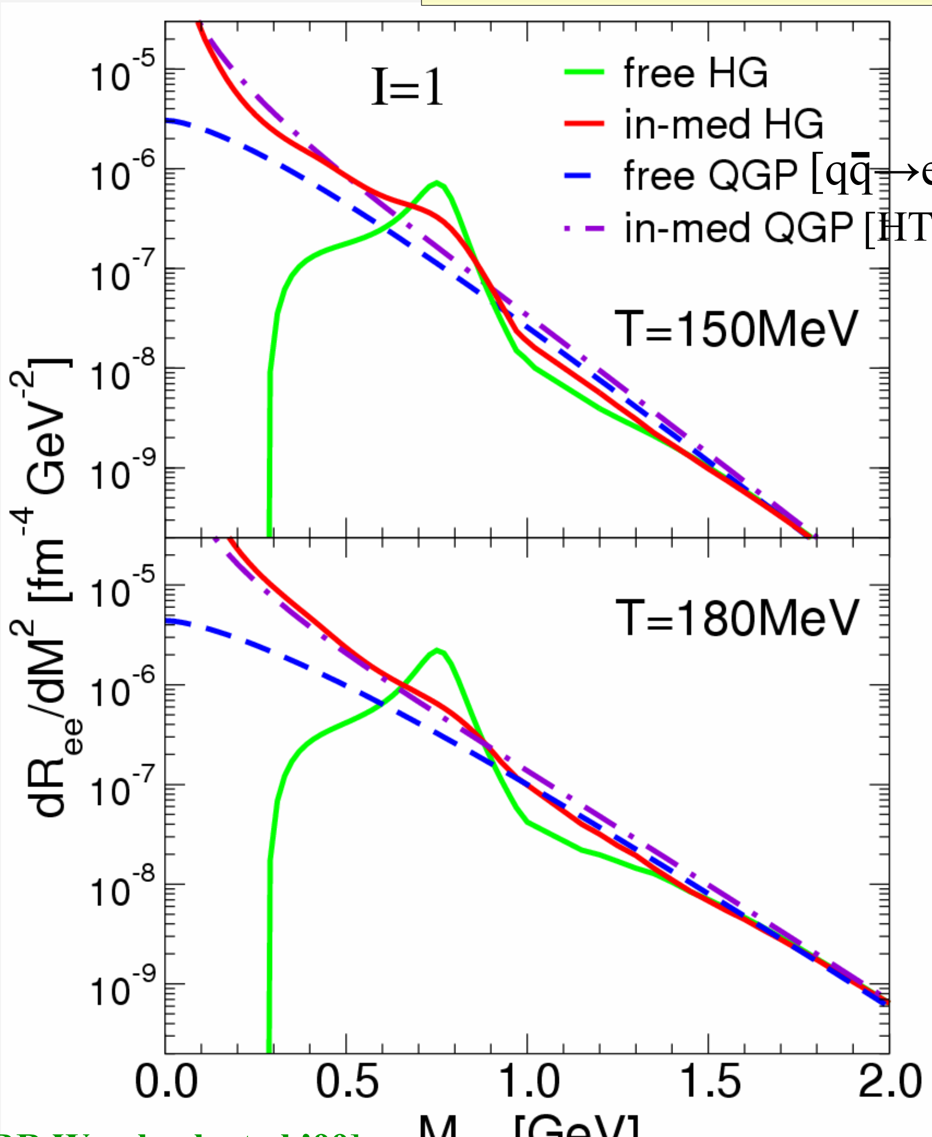
- marked low-mass enhancement
- comparable to lattice-QCD results

[Ding et al '10]

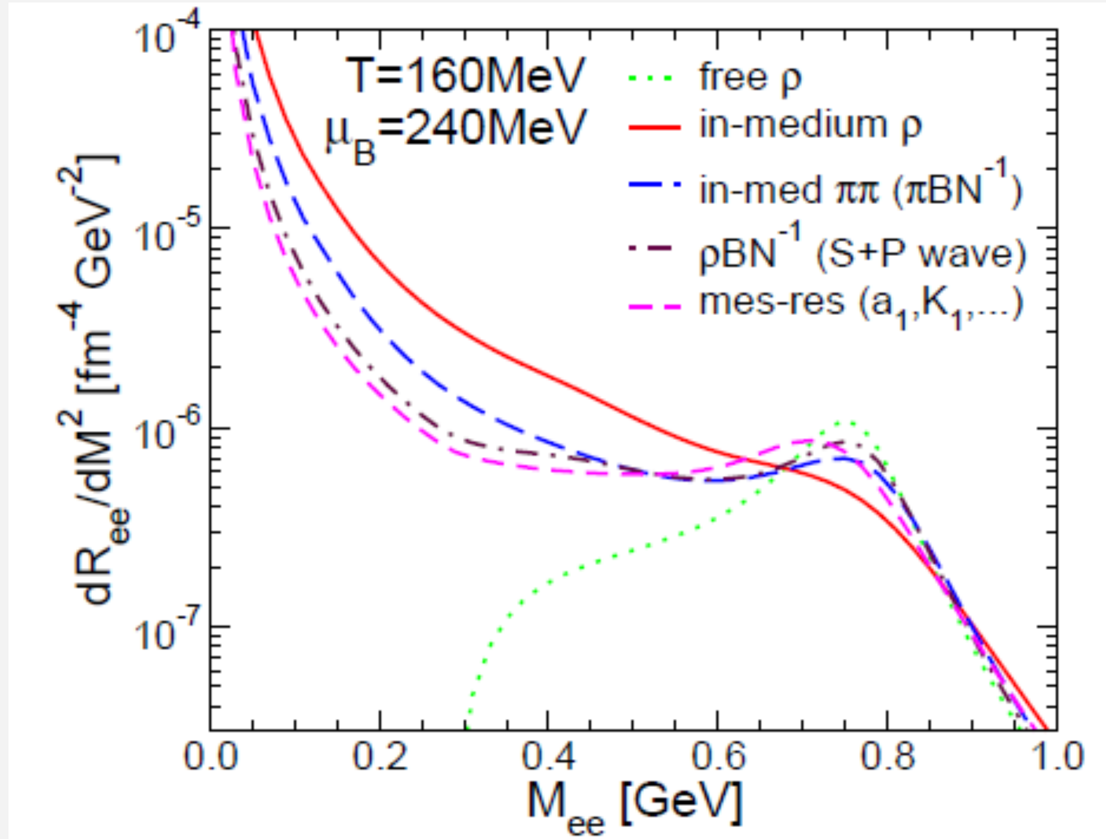
2.7 Dilepton Rates and Degrees of Freedom

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

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



[RR,Wambach et al '99]



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   - Hadronic Many-Body Theory + Constraints

3.) **Thermal Dileptons in Heavy-Ion Collisions**
   - Spectral Shape, Fireball Temperature + Lifetime

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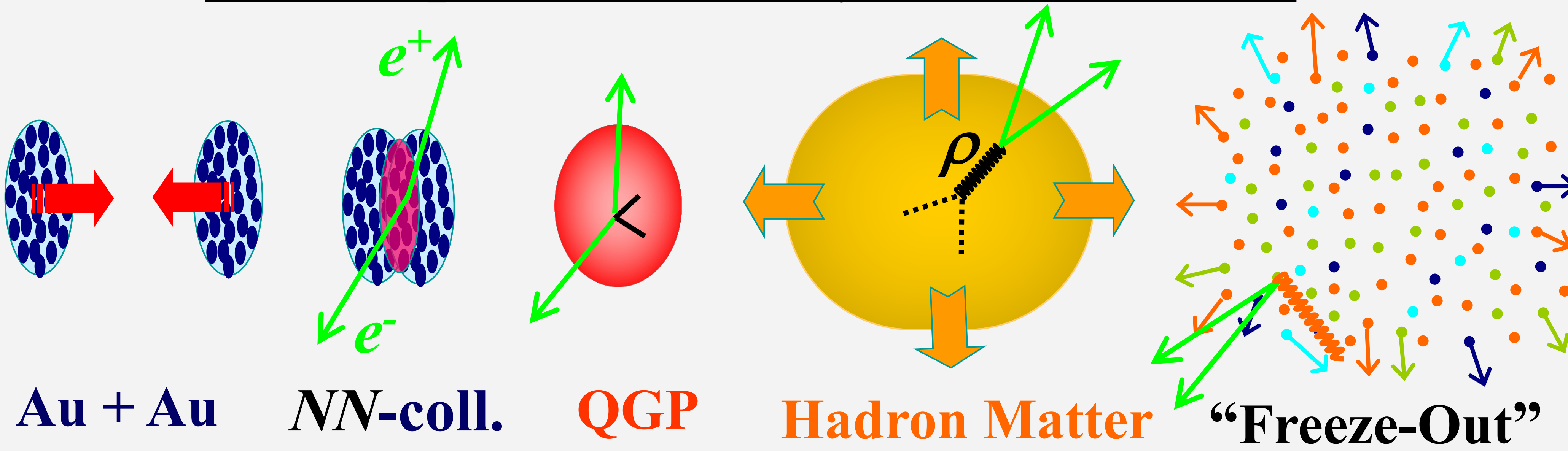
   - QCD + Weinberg Sum Rules; Baryons

5.) **Electric Conductivity**

6.) **Conclusions**

3.1 Dileptons in Heavy-Ion Collisions



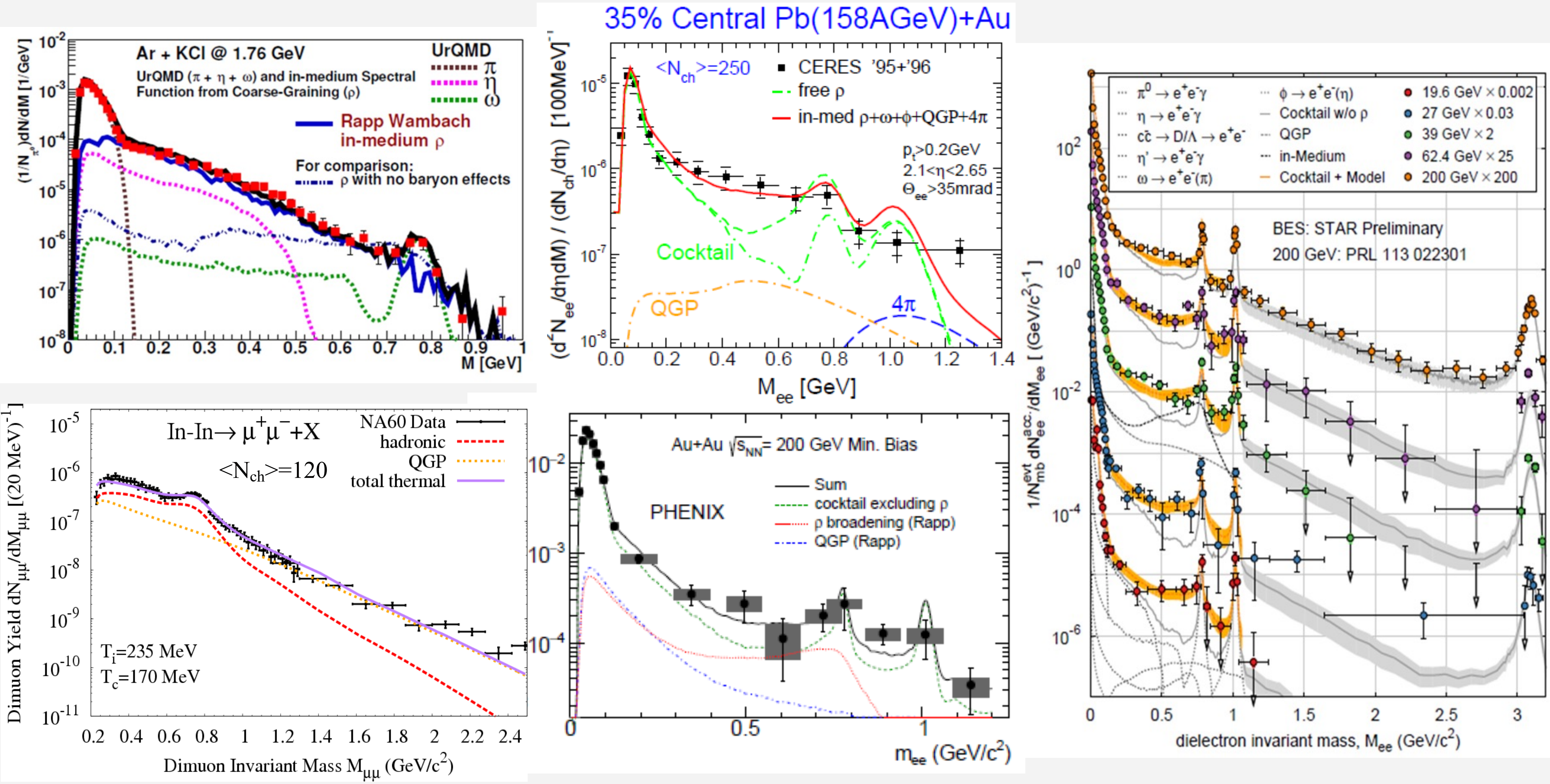
Sources of Dilepton Emission:

- "primordial" $q\bar{q}$ annihilation (Drell-Yan): $NN \to e^+e^-X$

- **thermal radiation**
  - **Quark-Gluon Plasma:** $q\bar{q} \to e^+e^-, \ldots$
  - **Hot+Dense Hadron Matter:** $\pi^+\pi^- \to e^+e^-, \ldots$

- final-state hadron decays: $\pi^0, \eta \to \gamma e^+e^-$, $D, \bar{D} \to e^+e^- X, \ldots$

3.2 30 Years of Dileptons in Heavy-Ion Collisions



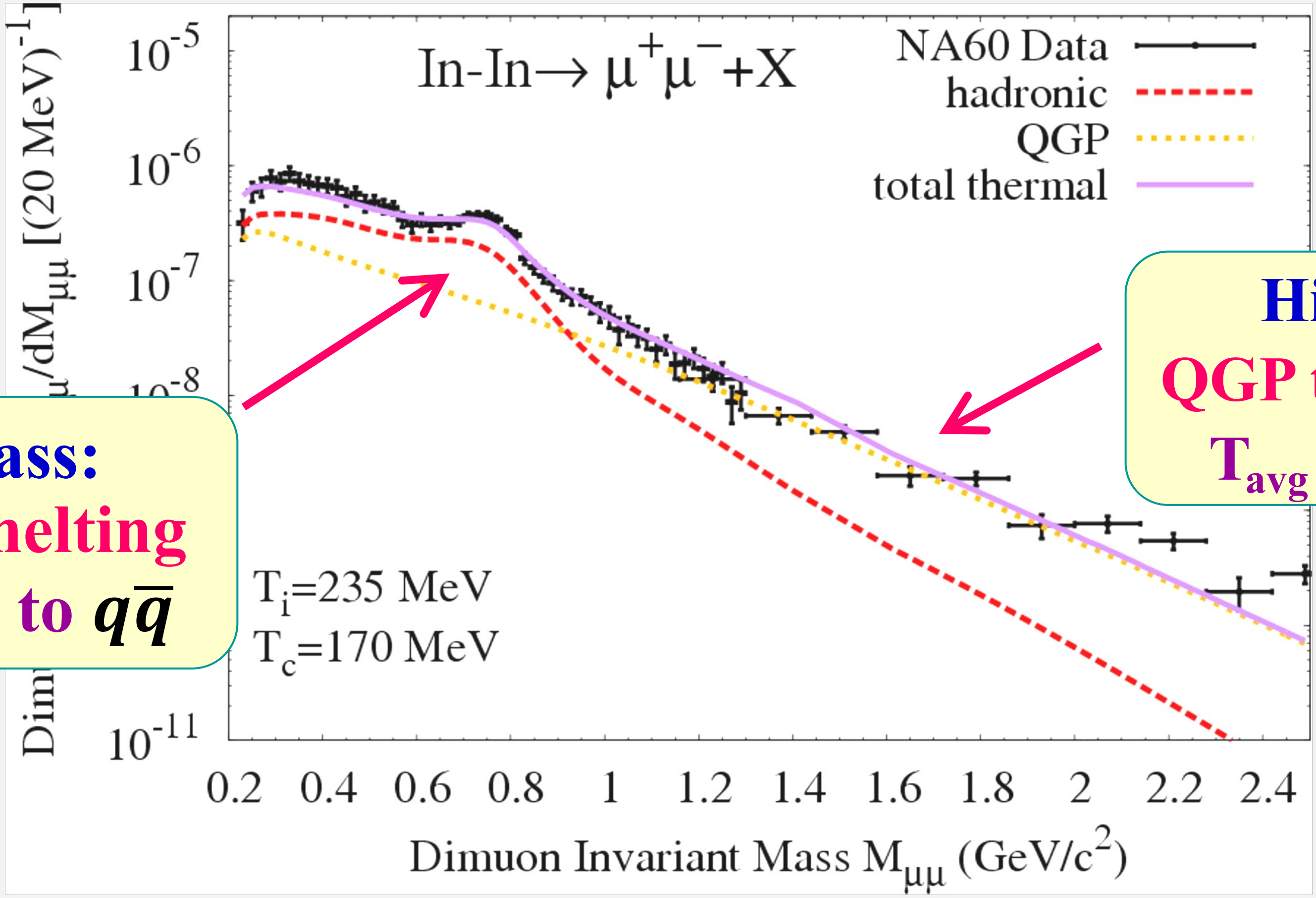
- **Robust understanding across QCD phase diagram: QGP + hadronic radiation with melting ρ resonance**

3.3 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

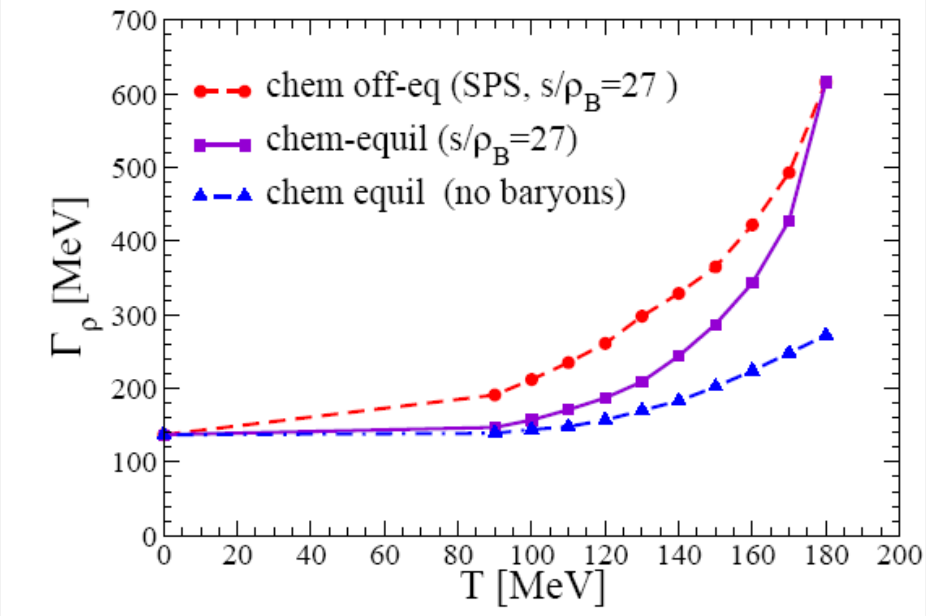


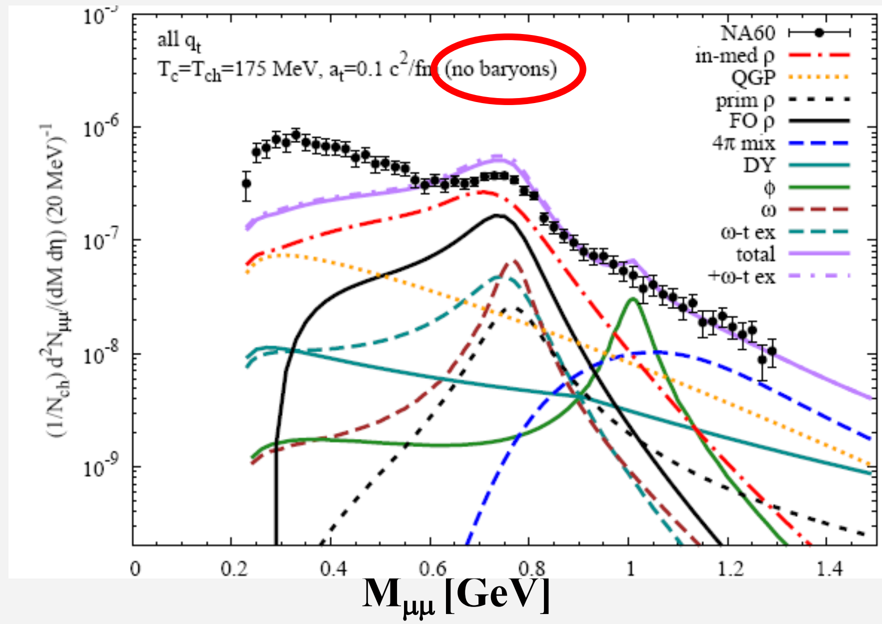
Low mass:
ρ-meson melting
transition to $q\bar{q}$

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

3.4 Sensitivity to Spectral Function

In-Medium ρ-Meson Width





- avg. Γ_ρ(T~150MeV)~370 MeV ⇒ Γ_ρ (T~T_c) ≈ 600 MeV → m_ρ
- driven by (anti-) baryons
- Γ_ρ / KE_ρ ≥ 1 -- **liquid!**

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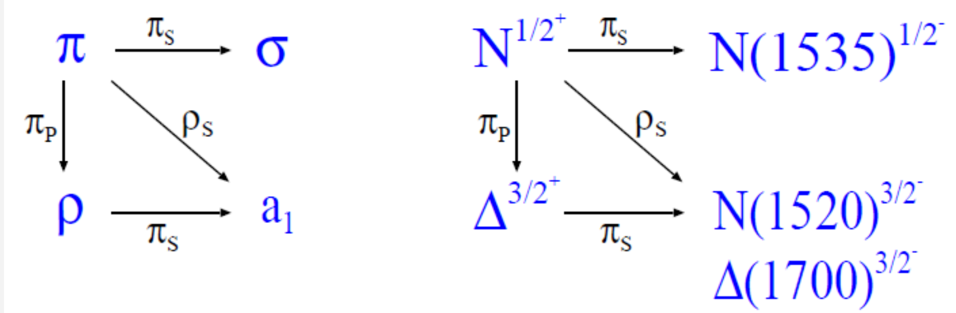
4.1 Chiral Symmetry Breaking in Vacuum

- Mass **splitting** within chiral multiplets



- Quantitative: Sum Rules

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

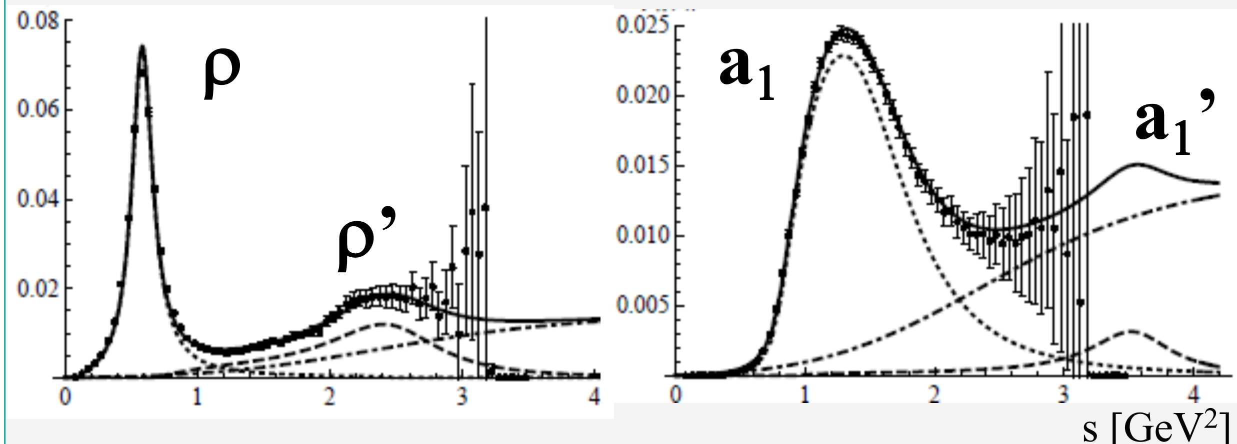
$$\int_0^\infty ds\, \frac{\Delta\rho(s)}{s} = f_\pi^2 \ ,$$

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

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

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

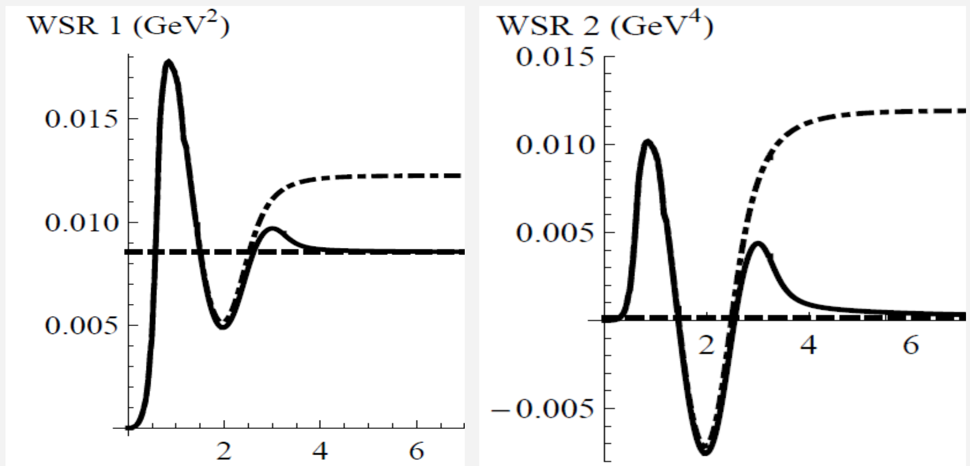
[Weinberg '67, Das et al '67; Kapusta+Shuryak '94]



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

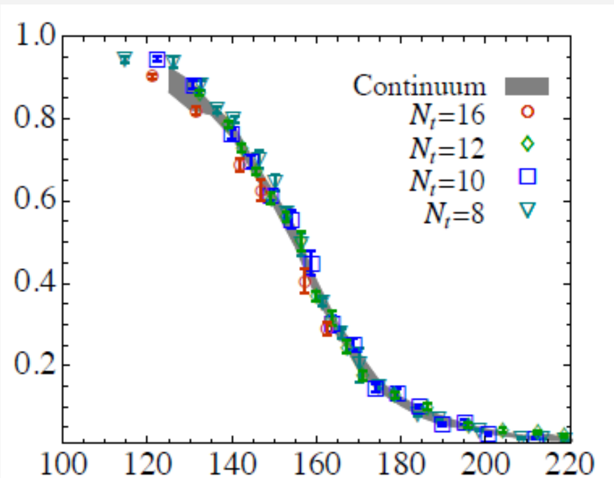
- Sensitive to excited states: predict **a_1(1950)** state

[Hohler+RR '12]



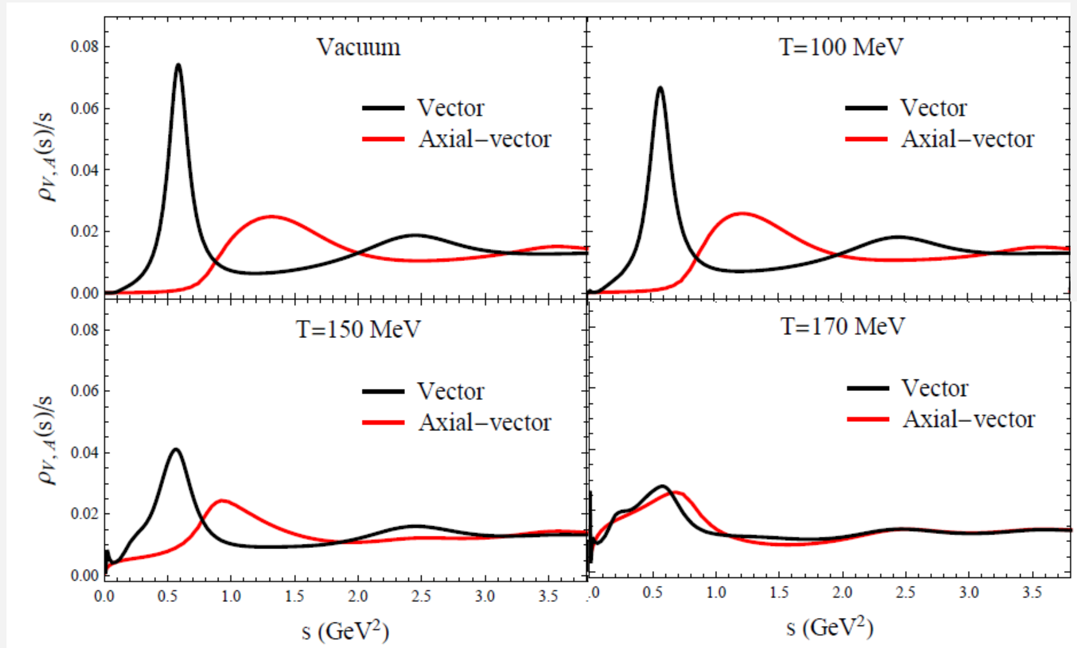
4.2 Mechanism of Chiral Restoration

Evaluate sum rules at finite T:
- In-medium ρ spectral fct.
- Lattice-QCD for chiral order parameters



⇒

In-Medium Spectral Functions



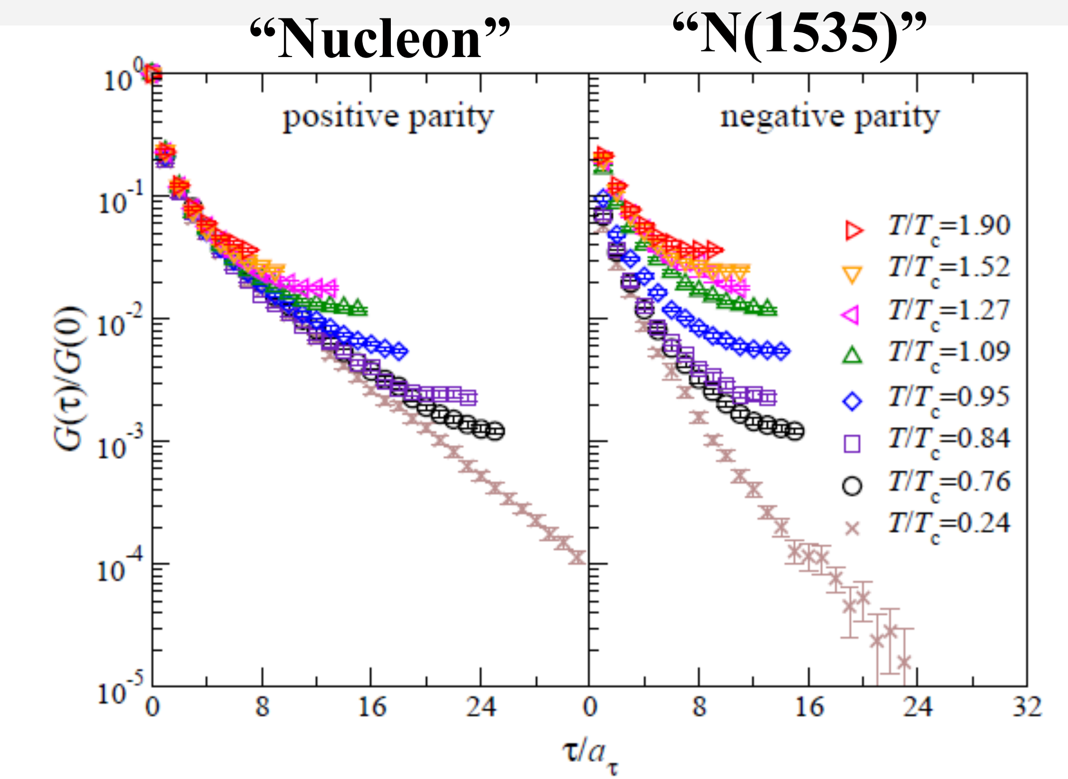
[Hohler+RR '13]

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)

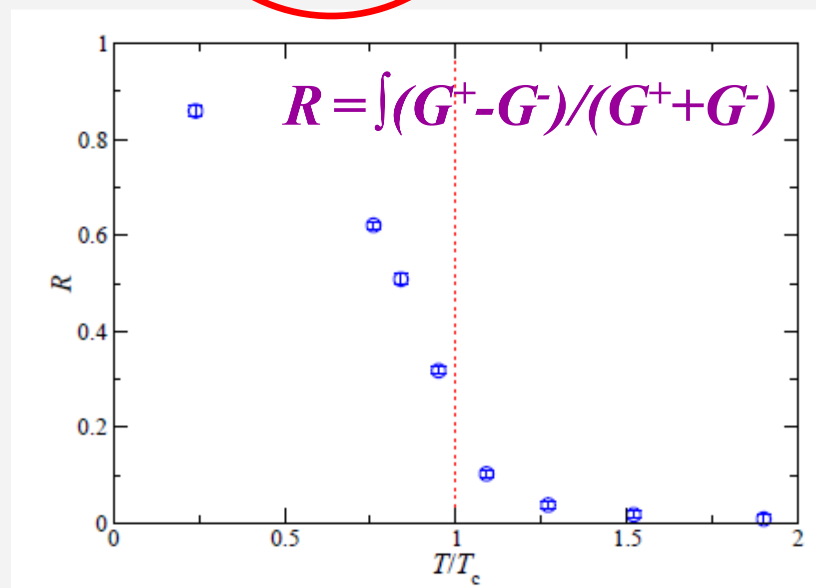
Euclidean Correlator Ratios



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

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2.) **In-Medium Spectral Functions**

- Hadronic Many-Body Theory + Constraints

3.) **Thermal Dileptons in Heavy-Ion Collisions**

- Spectral Shape, Fireball Temperature + Lifetime

4.) **Chiral Symmetry Restoration**

- QCD + Weinberg Sum Rules; Baryons

5.) **Electric Conductivity**

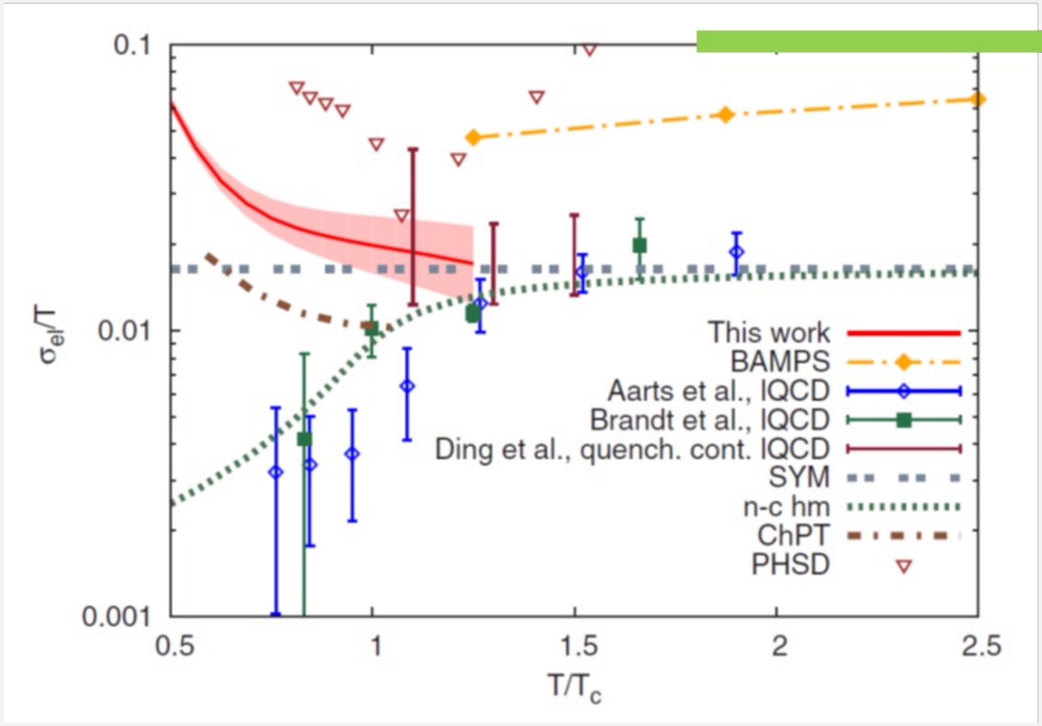
6.) **Conclusions**

5.) Electric Conductivity

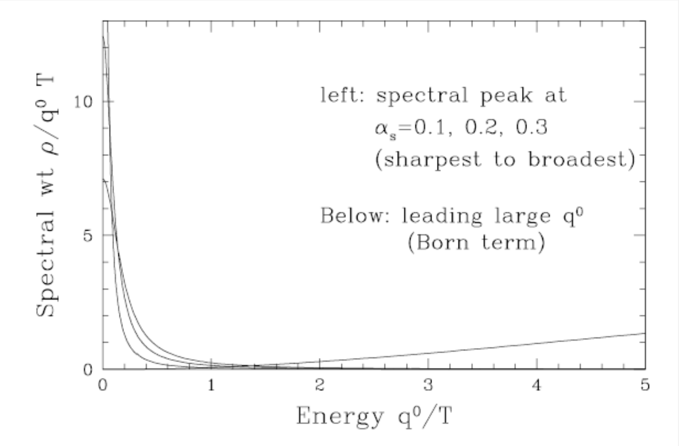
- Generic transport coefficient (charge): $\sigma_{el}/T \sim 4\pi\ \eta/s \sim 2\pi T\ \mathcal{D}_s^{HF}$
- Probes timelike long-wavelength limit of EM spectral function:

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

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



pQCD
[Moore+Robert '06]

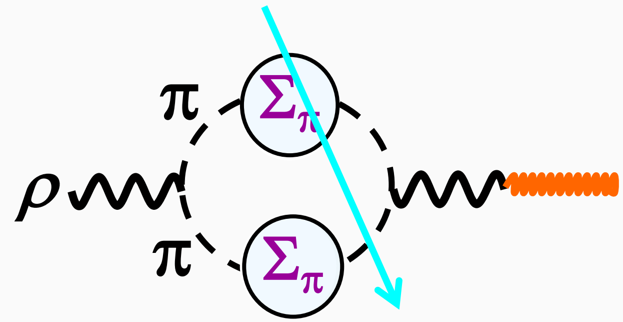


5.1 Unitarity vs. Landau Cut

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

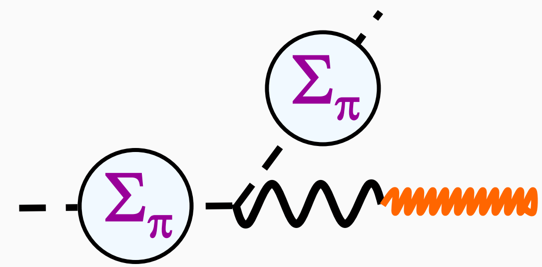
Unitarity Cut:

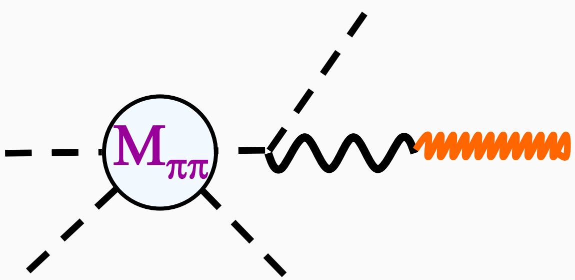
$$ImG^{T,A}_{\pi\pi}(E_+, k) = -\int_0^E \frac{d\omega}{\pi}[1 + f^\pi(\omega) + f^\pi(E-\omega)]ImD_\pi(\omega_+, k)ImD_\pi(E-\omega_-, k)$$

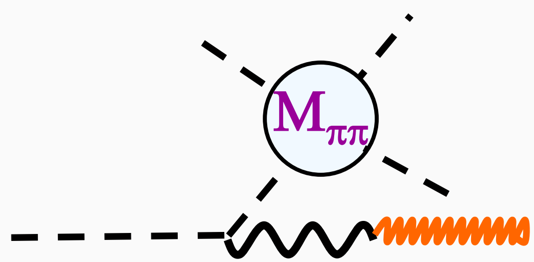


Landau Cut ("zero mode"):

$$ImG^{T,B}_{\pi\pi}(E_+, k) = -\int_E^\infty \frac{2d\omega}{\pi}[f^\pi(\omega-E) - f^\pi(\omega)]ImD_\pi(\omega_+, k)ImD_\pi(\omega_+ - E, k)$$

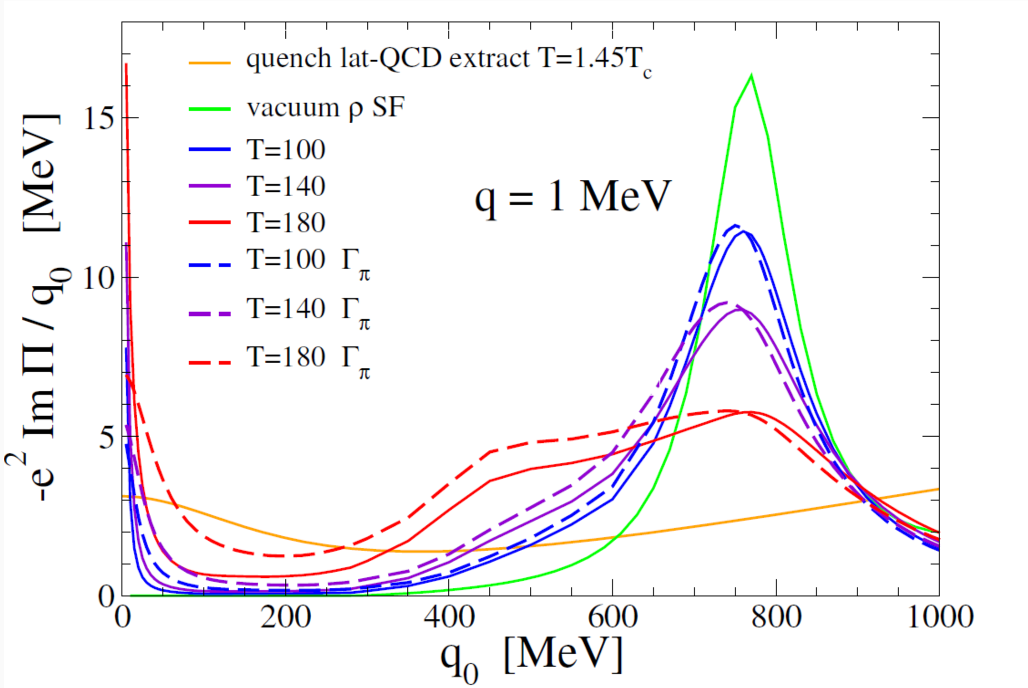


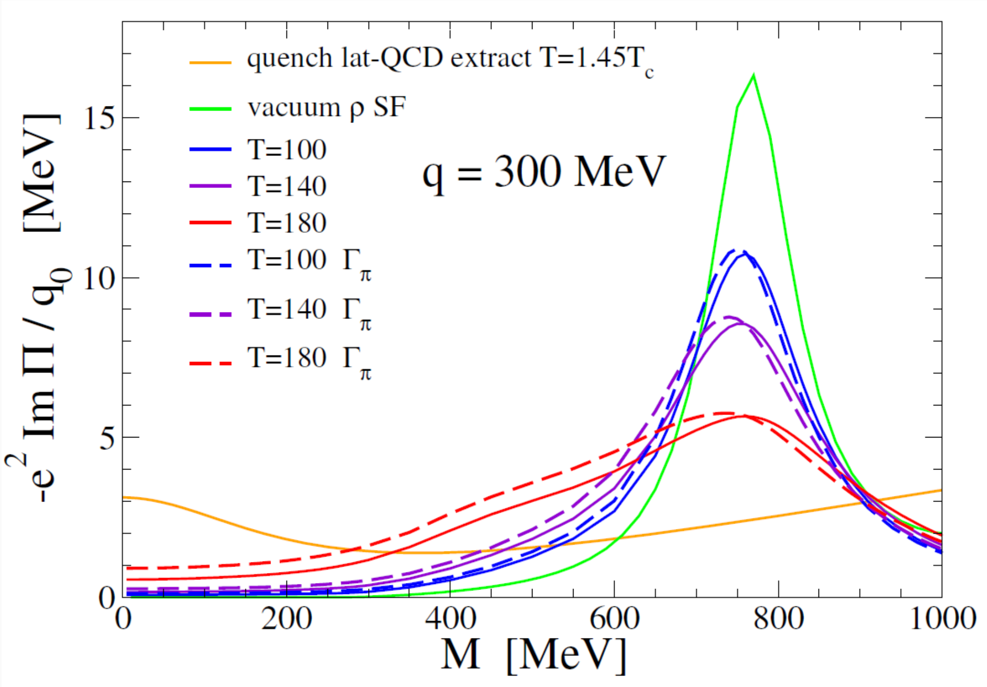




ππ **Bremsstrahlung!**

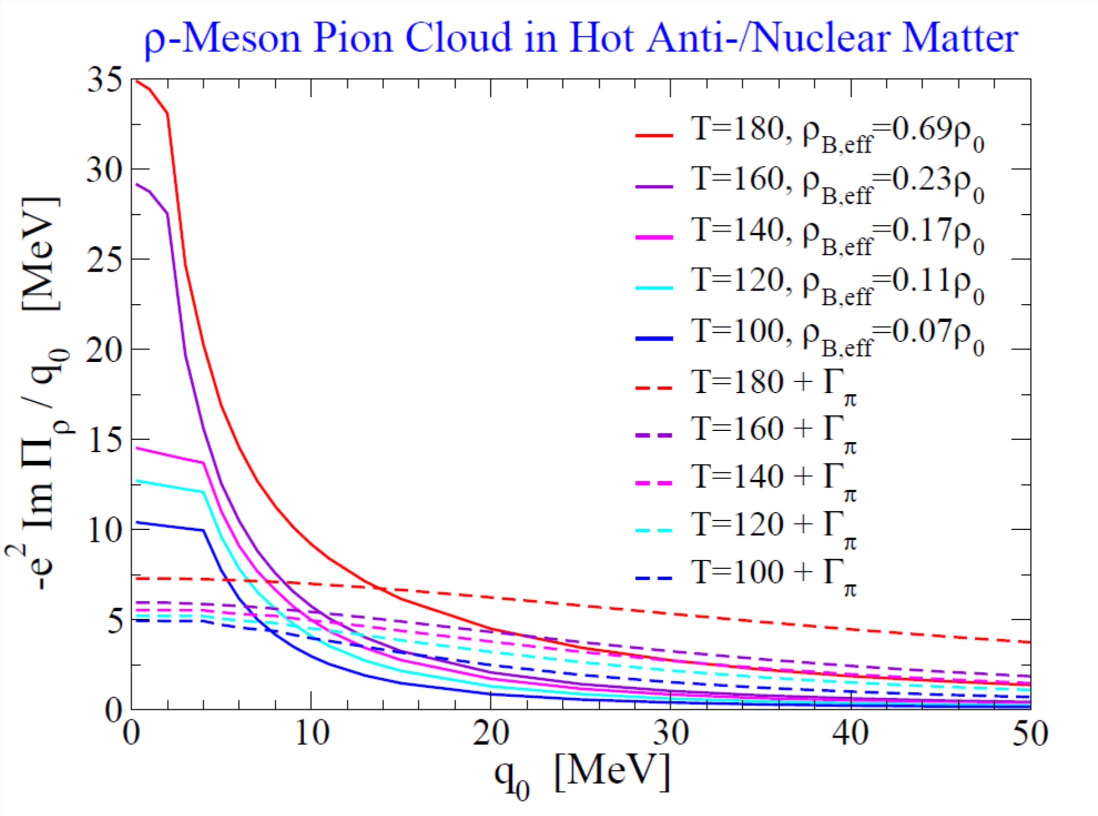
5.2 Conductivity Peak in Hadronic Matter



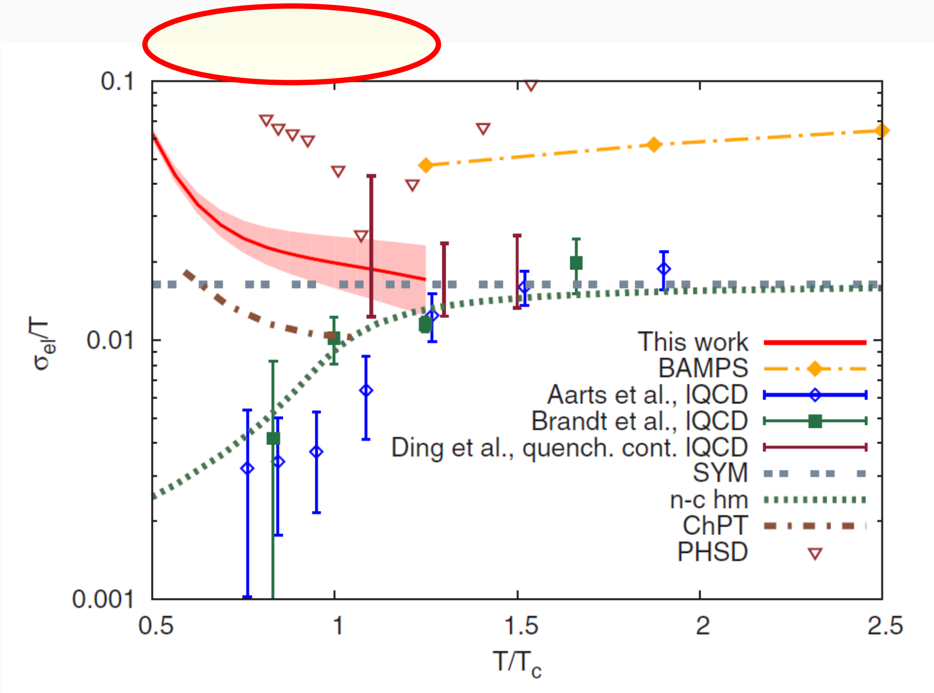


- Conductivity peak at zero energy
  stronger interaction → broadening reduces peak + enhances shoulder
- Peak quickly disappears at finite 3-momentum (non-zero energies)

5.3 Sensitivity to Conductivity Peak



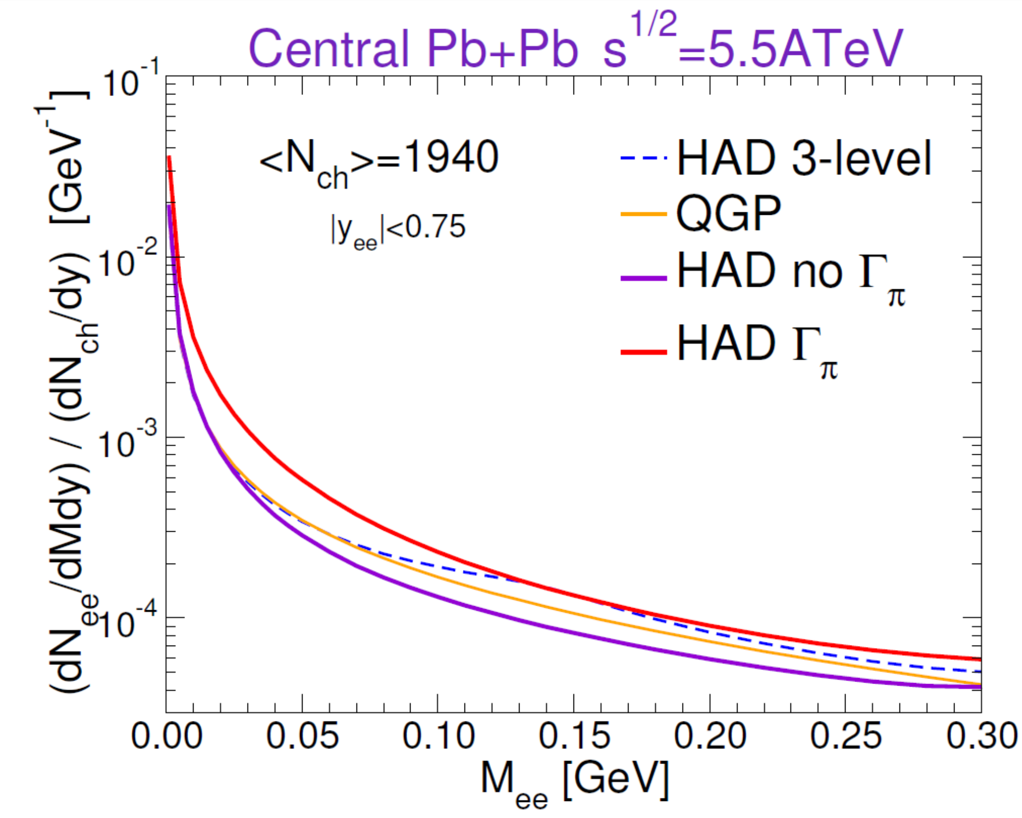
[Atchison+RR '22]

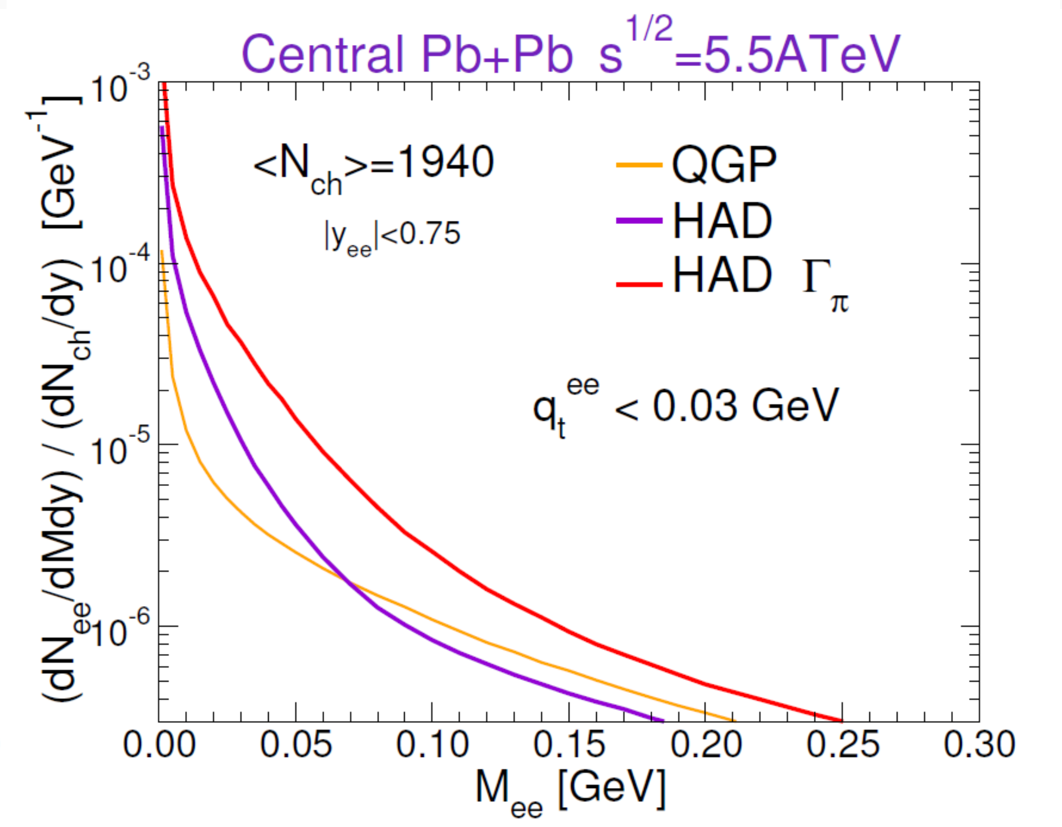


[Greif et al '16]

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

5.4 Conductivity Peak in Thermal-Dilepton Spectra





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

6.) Conclusions: A Tale of 3 Peaks

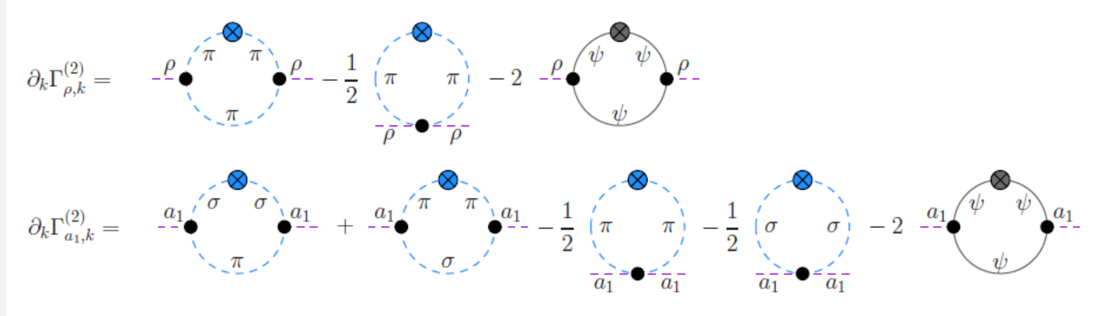
- **In-medium ρ spectral function** (low-mass dileptons)
  - strongly broadened in hadronic matter (**liquid**)
  - resonance **melting** toward the hadron-to-parton transition

- **In-medium a_1 Spectral Function** (sum rules, intermediate mass)
  - chiral restoration via **evaporation** of chiral ρ-a_1 **mass splitting**
  - also for other chiral partners

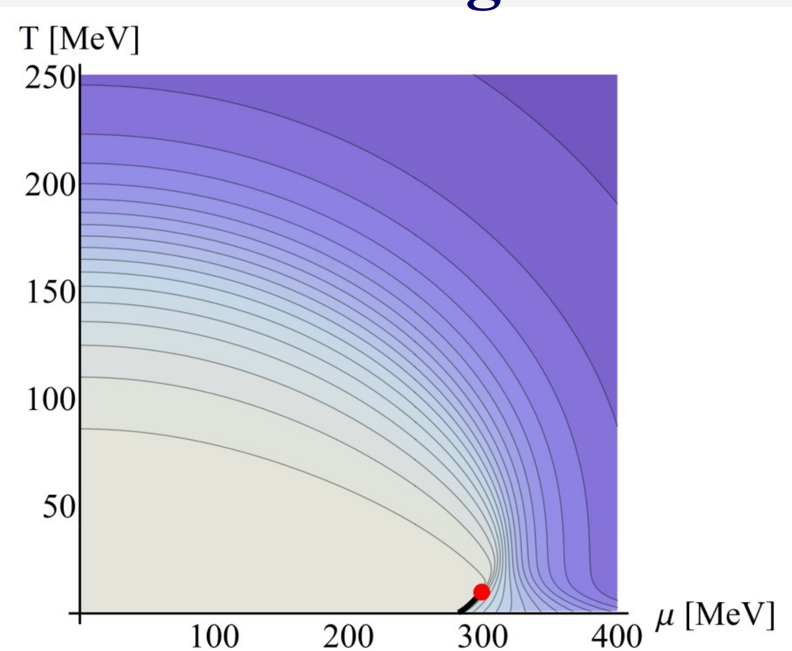
- **Zero-energy conductivity peak** (very low-mass)
  - extract σ_{el} from **width** rather than intercept

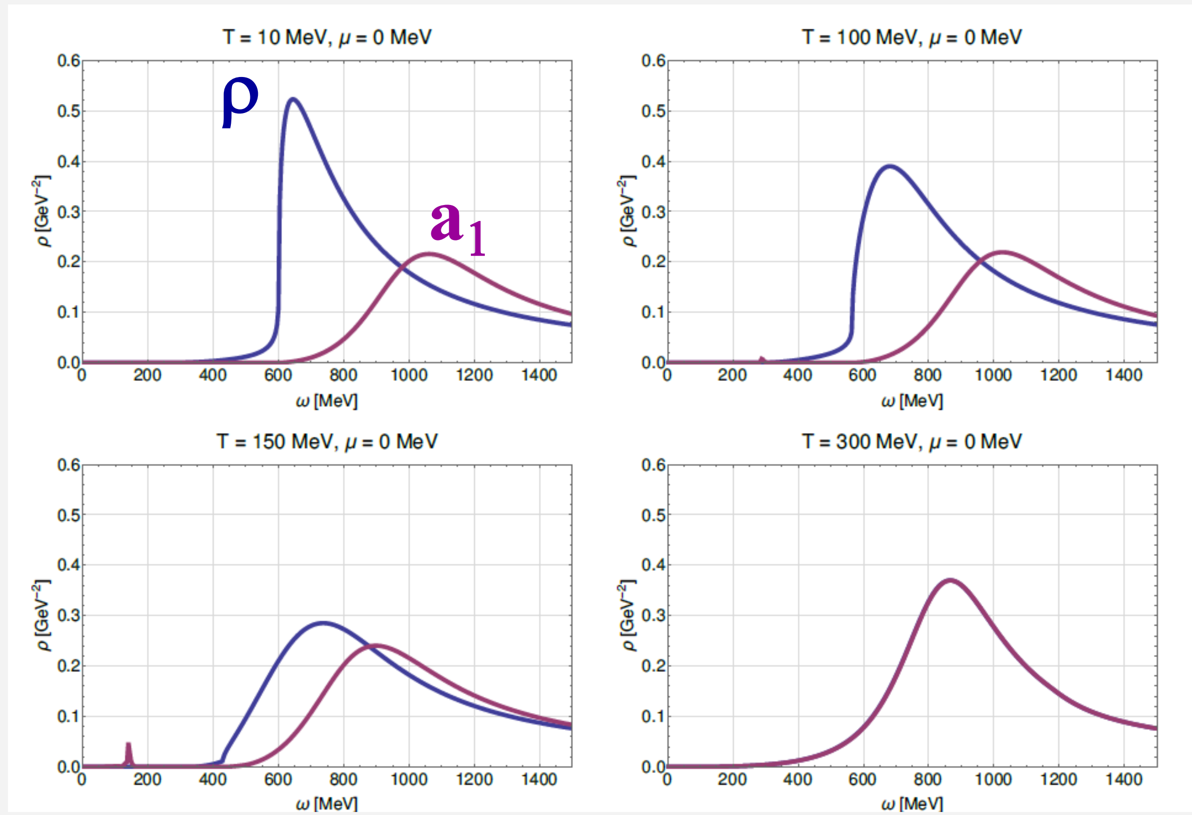
5.3 Functional Renormalization Group Approach

- Quark-Meson model:



Phase Diagram

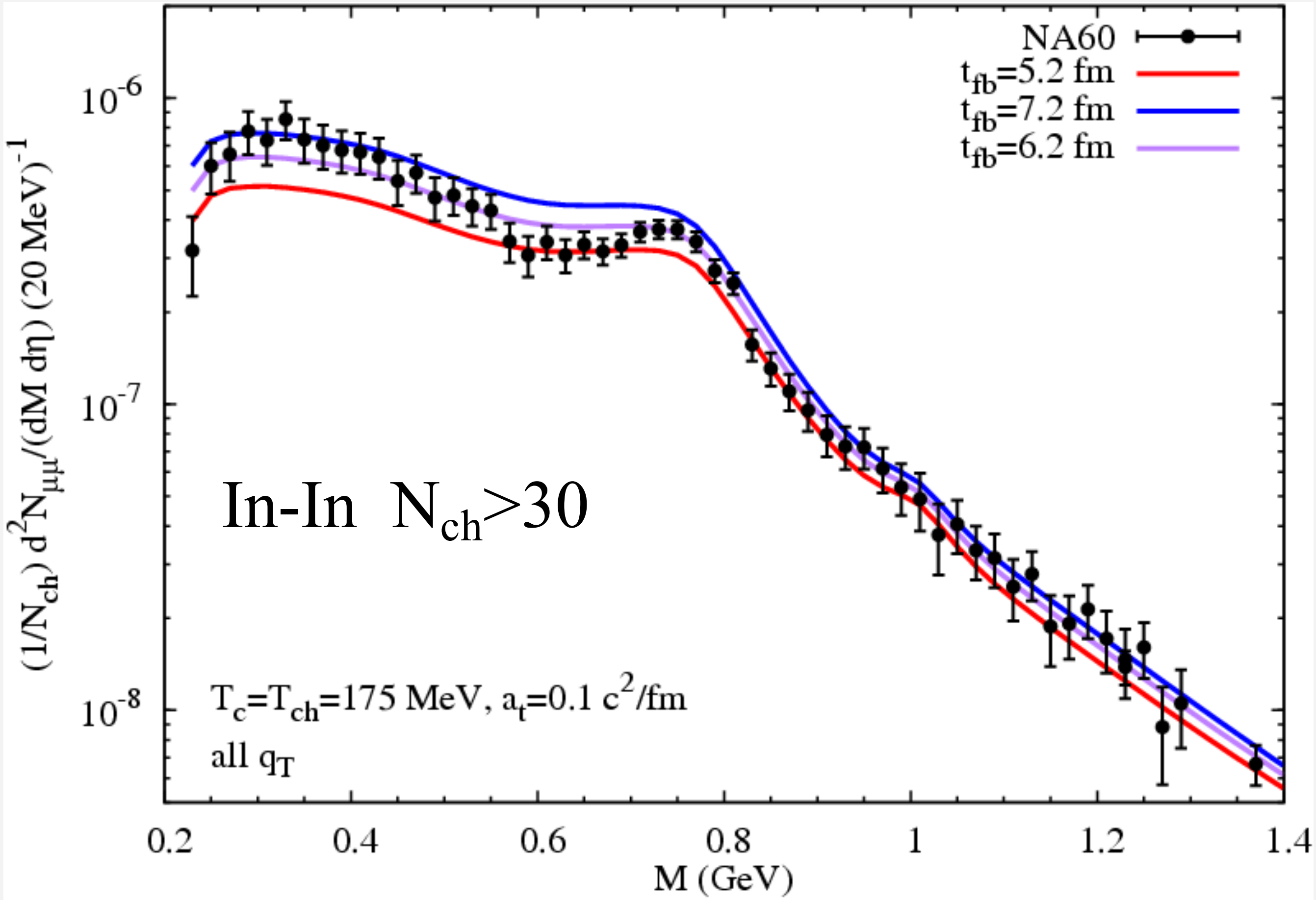




- qualitatively similar to hadronic many-body calculations!

[Tripolt et al '17]

3.4 Low-Mass Dileptons: Chronometer

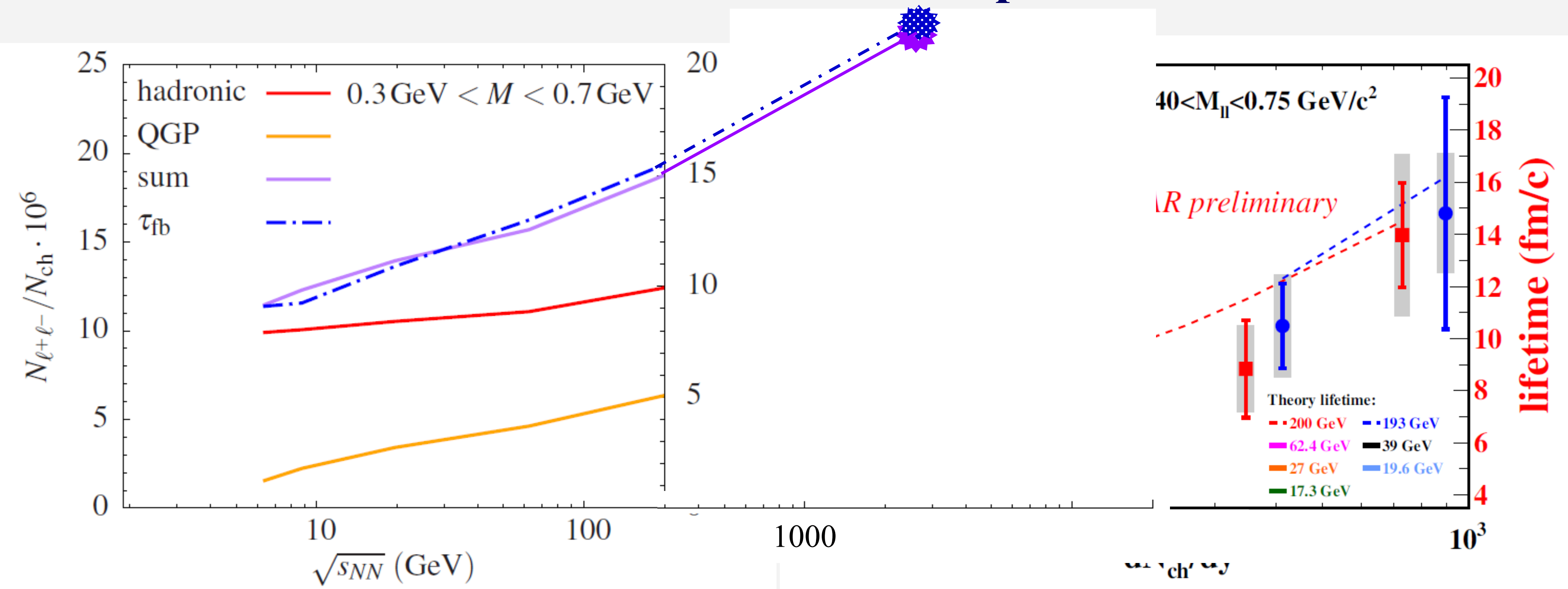


- first "explicit" measurement of interacting-fireball **lifetime**:

  $\tau_{FB} \approx (6.2 \pm 0.5)$ fm/c

3.5 Fireball Lifetime

Excitation Function of Low-Mass Dilepton Excess Yield

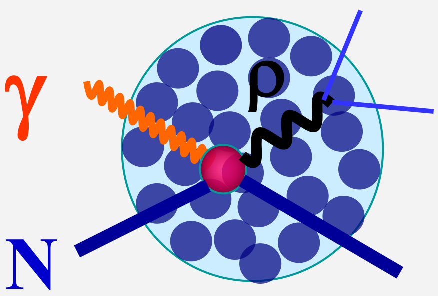


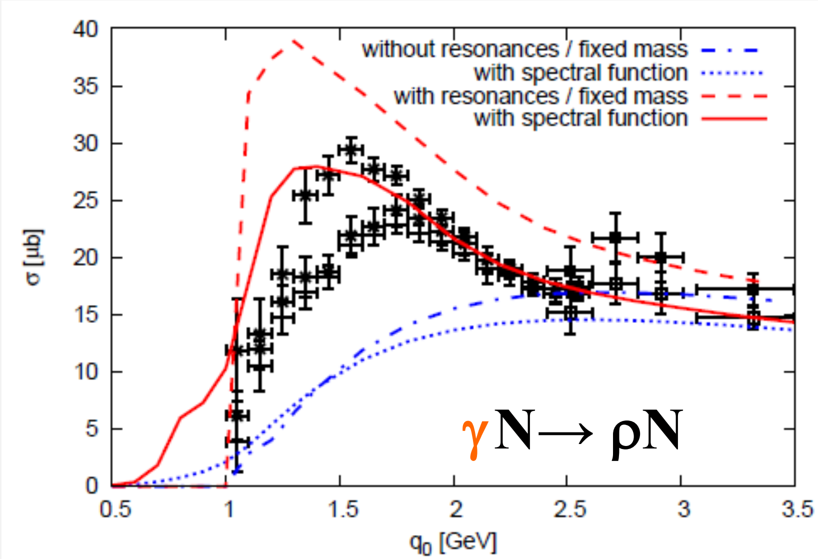
[RR+van Hees '14] [STAR '15]

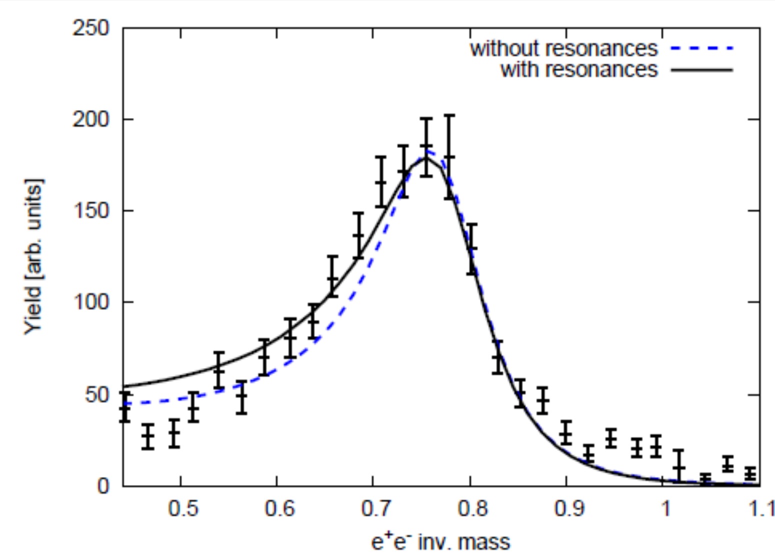
- Low-mass excess tracks lifetime well (medium effects!)
- Tool for critical point search?

2.5 Nuclear ρ and e^+e^- Photoproduction

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







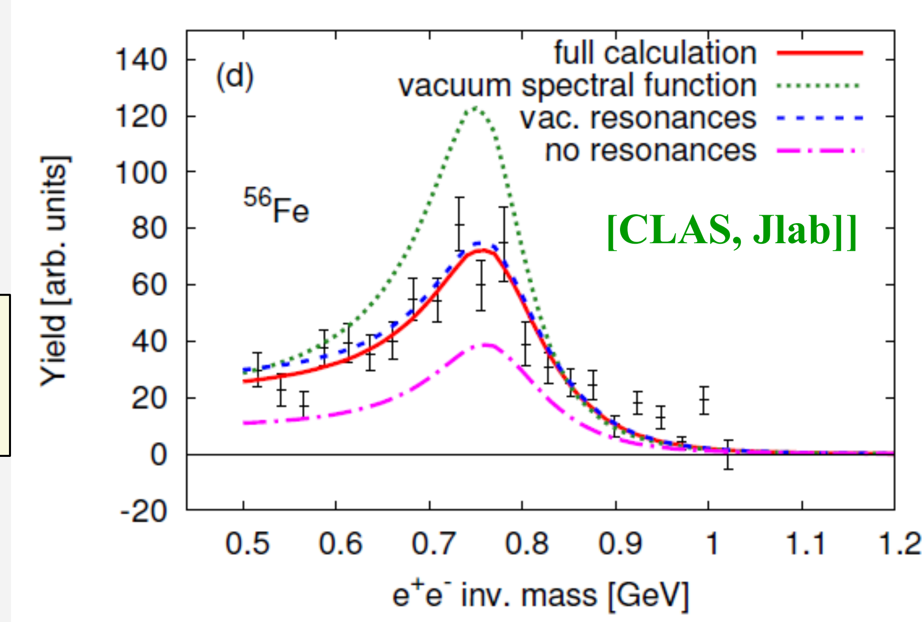
[Oh+Lee '04,
Riek et al '08, '10]

(b) Medium Effects:

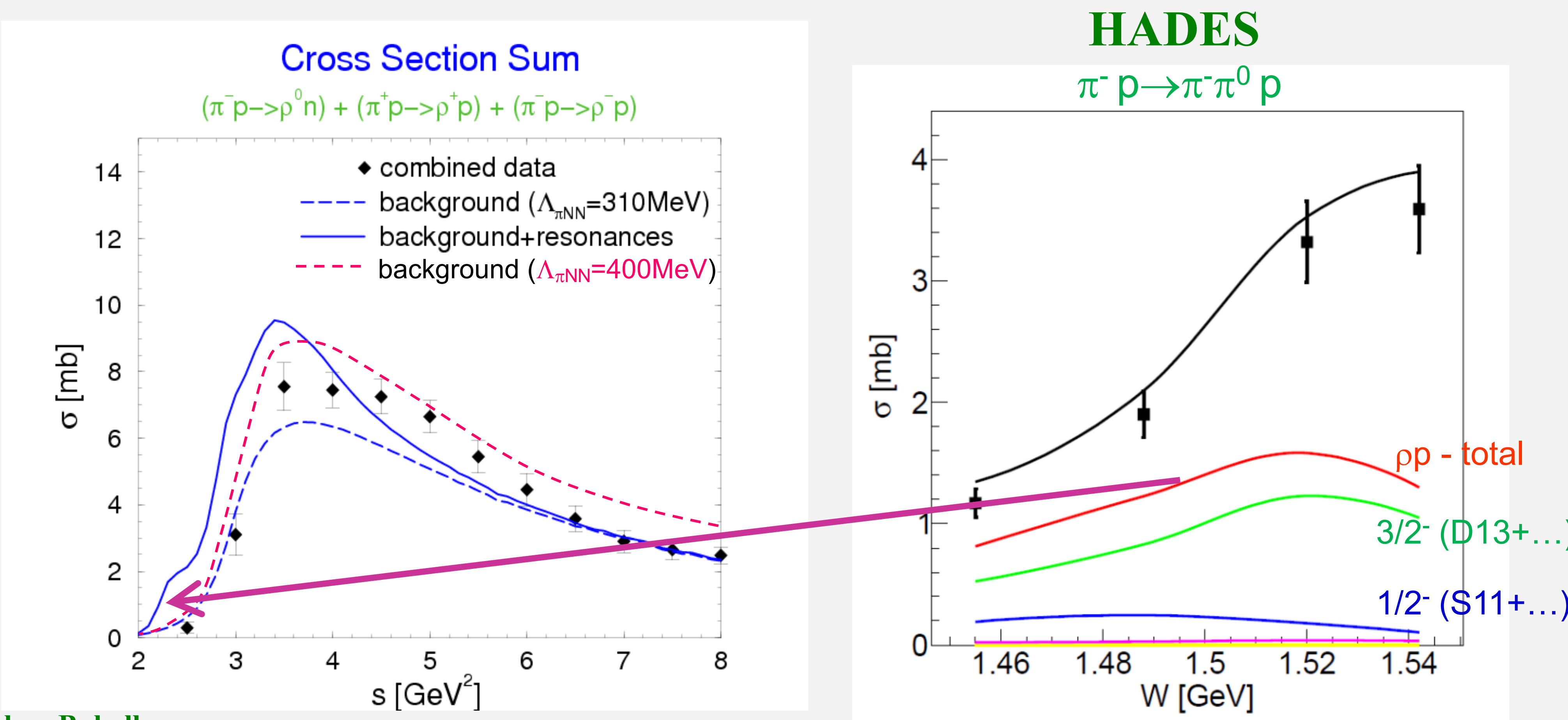
- ρ propagator in cold nuclear matter

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

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



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

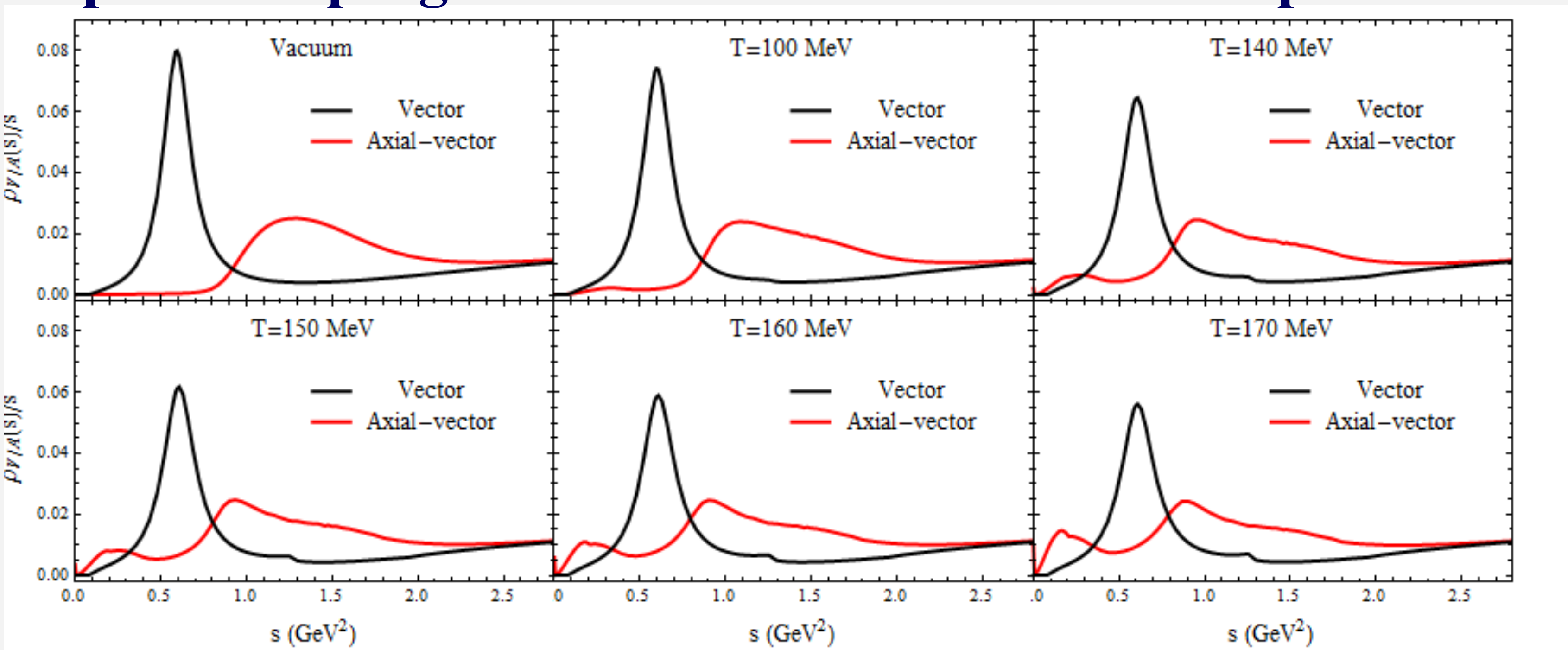


[Urban,Buballa, RR+Wambach '98]

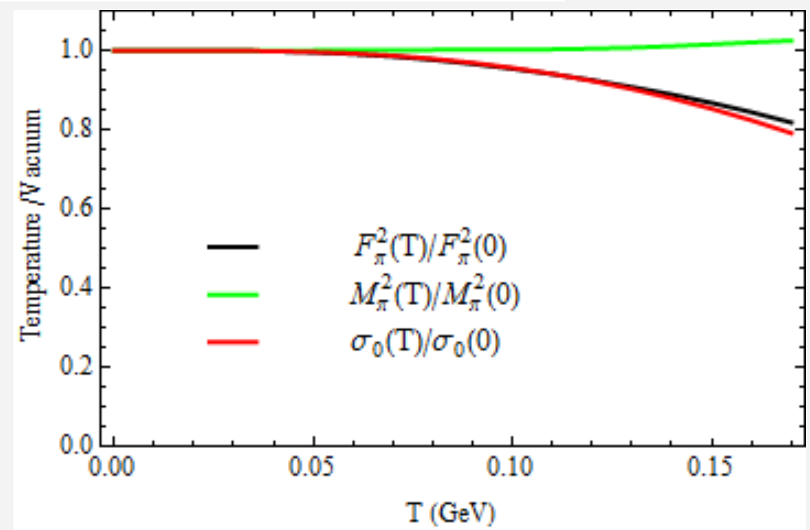
- strong constraint on pion cloud coupling to nucleons
- similarly small cutoff in $\pi N \rightarrow \Delta \rightarrow \pi N$ scattering!

3.2 Massive Yang-Mills in Hot Pion Gas

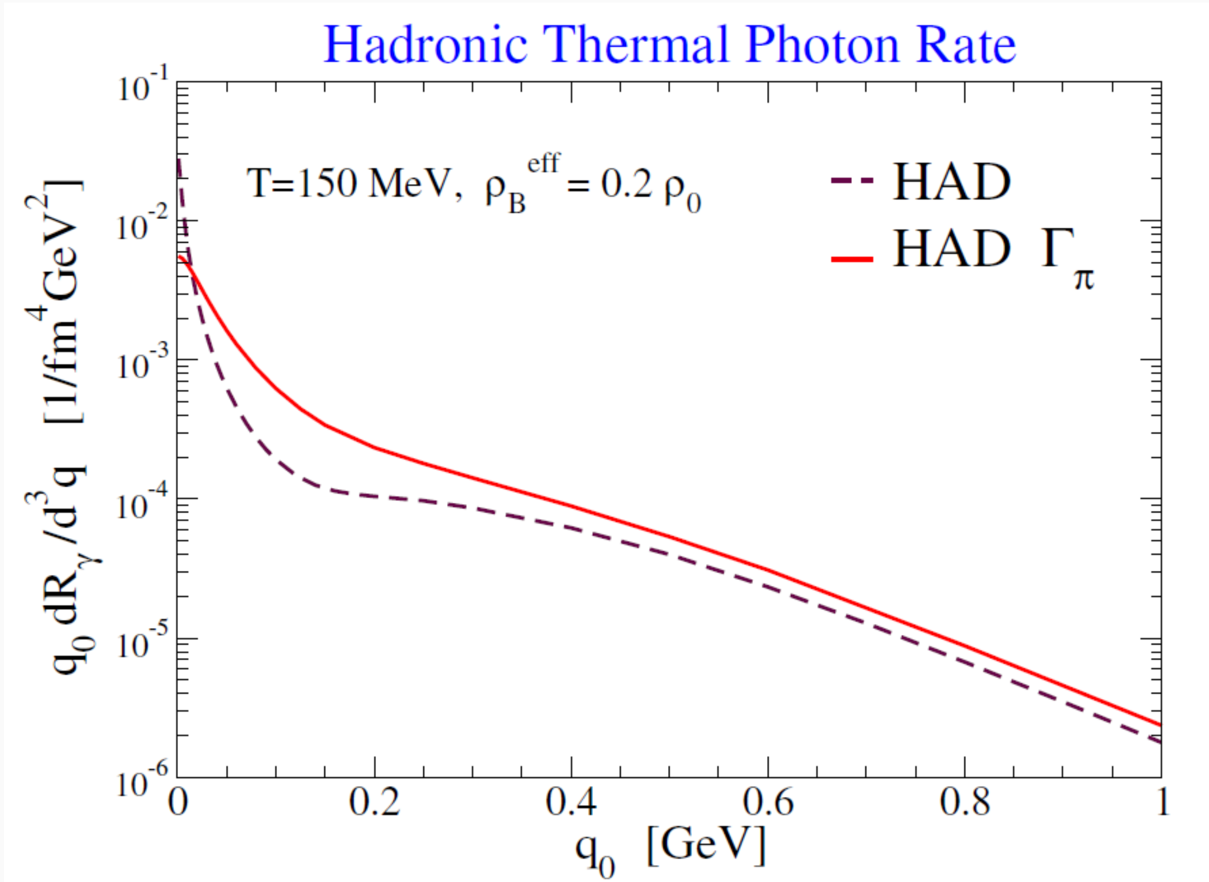
Temperature progression of vector + axialvector spectral functions



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



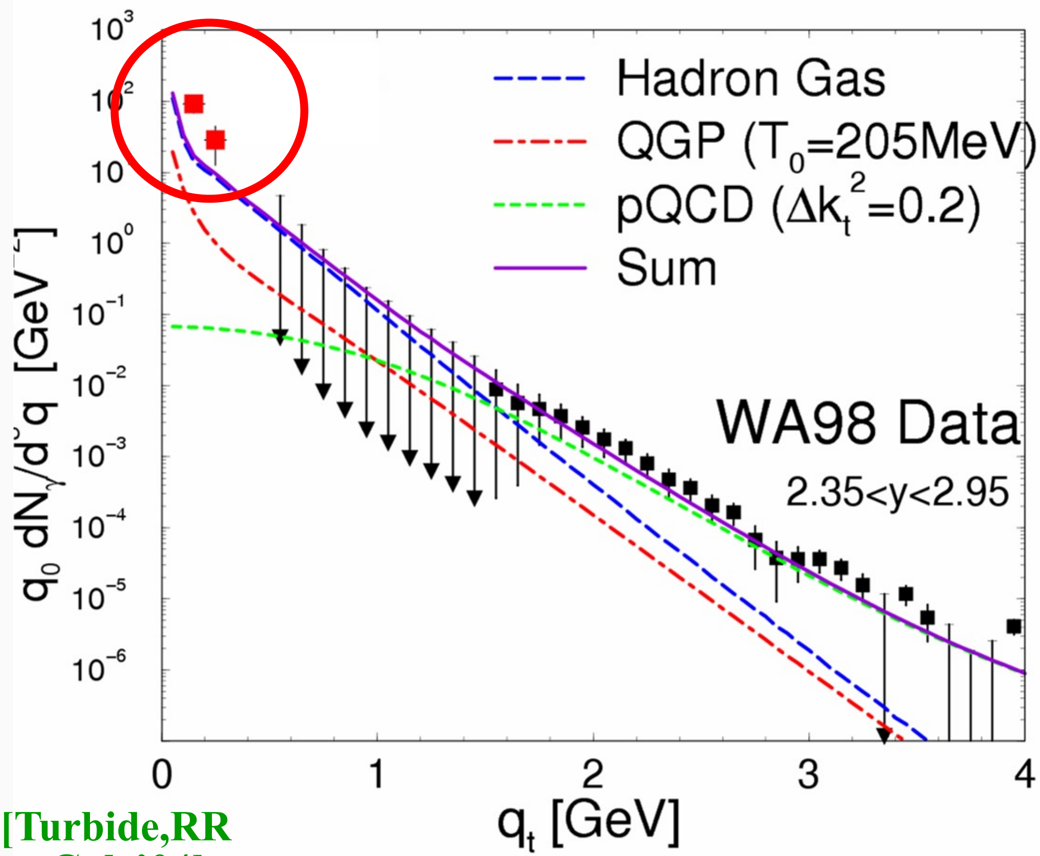
5.4 Effect of Conductivity on Thermal Photon Rate



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

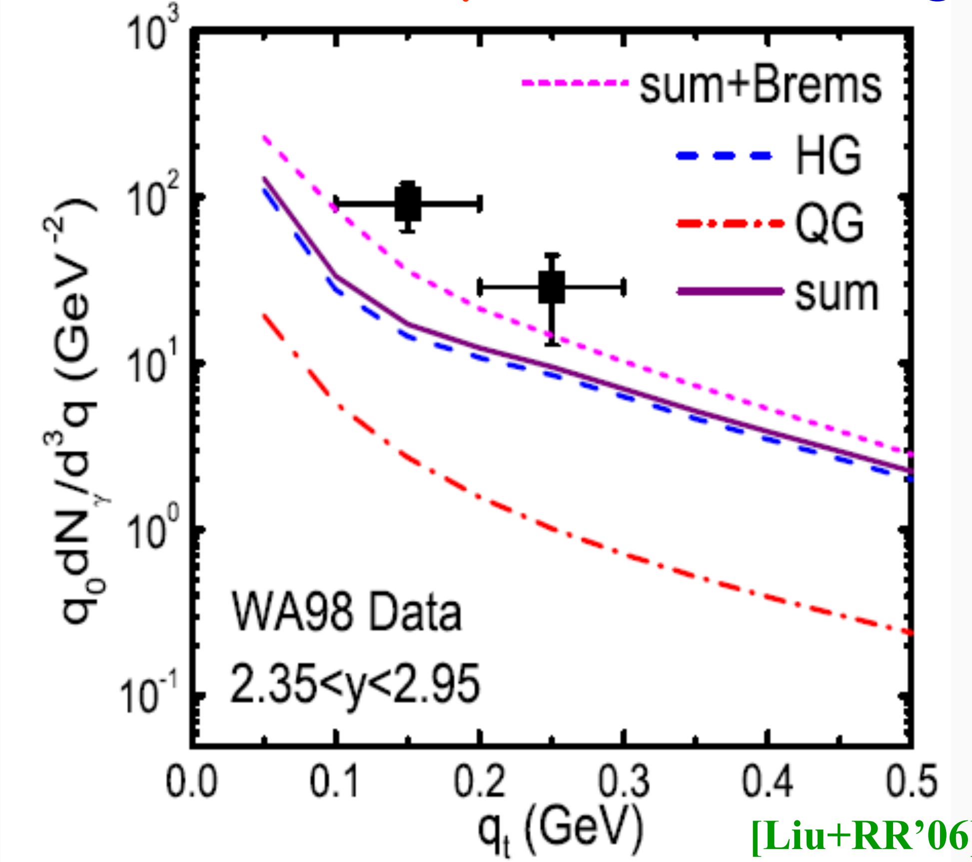
4.) Direct Photons at SPS: WA98

Thermal Radiation + pQCD



[Turbide,RR +Gale'04]

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



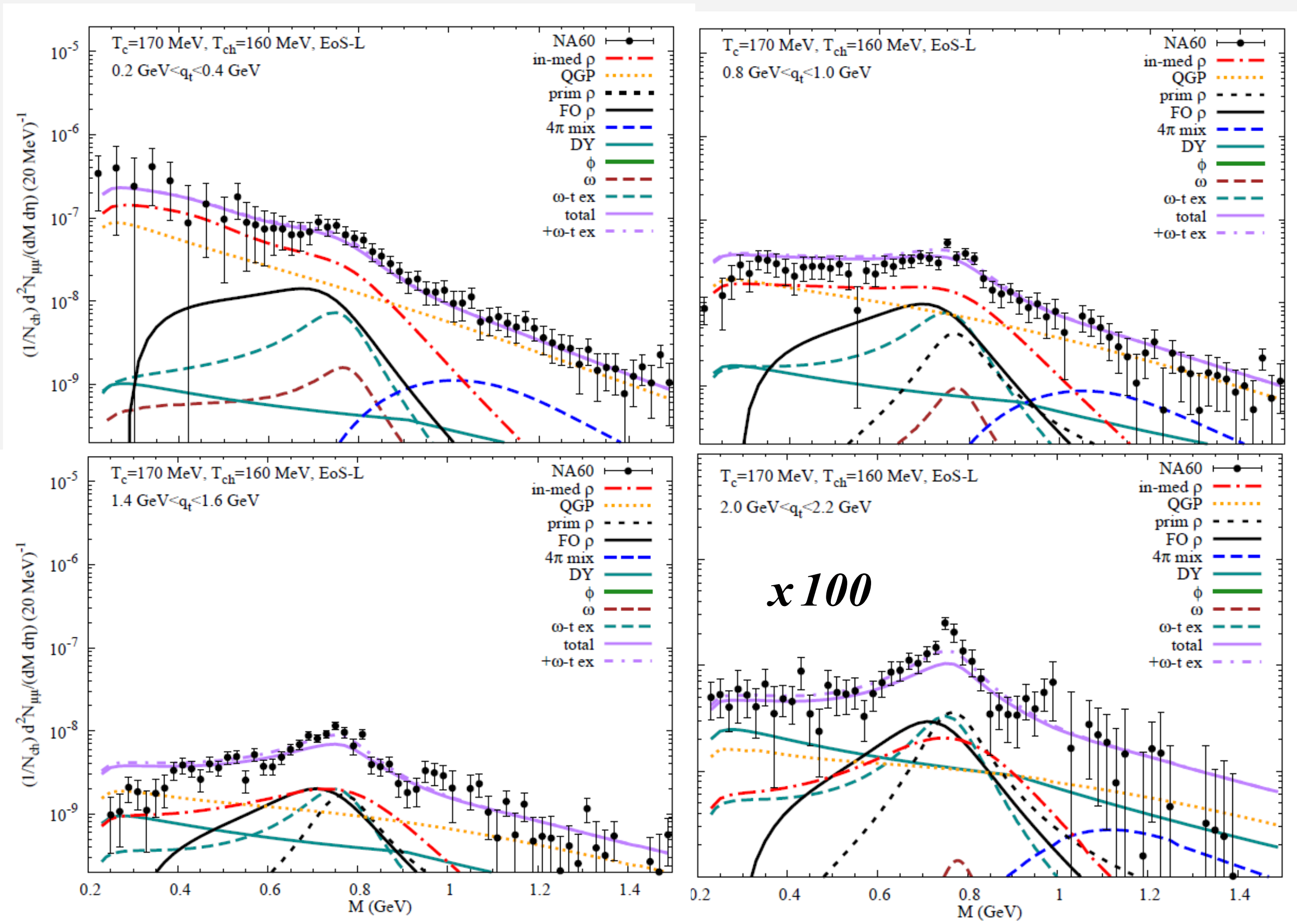
[Liu+RR'06]

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

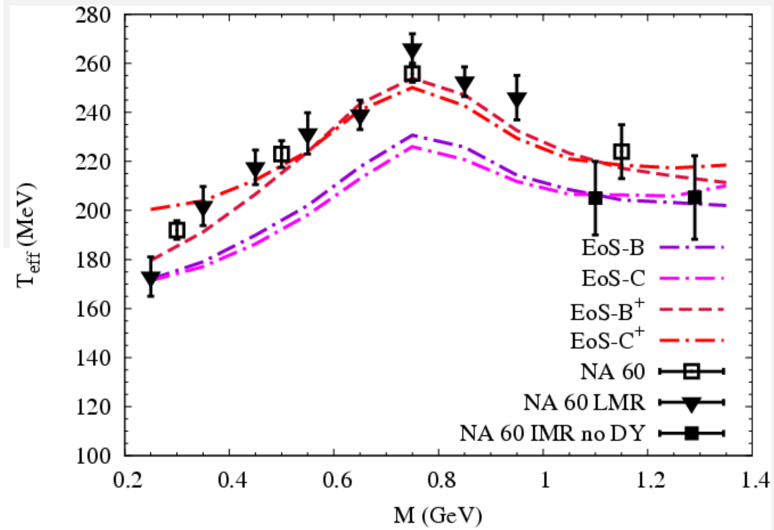
$$q_0 \frac{dN_\gamma}{d^4x\,d^3q}(q_0 \rightarrow 0) = \frac{T}{4\pi^3}\,\sigma_{EM} \quad ?$$

2.2 Transverse-Momentum Dependence

p_T -Sliced Mass Spectra



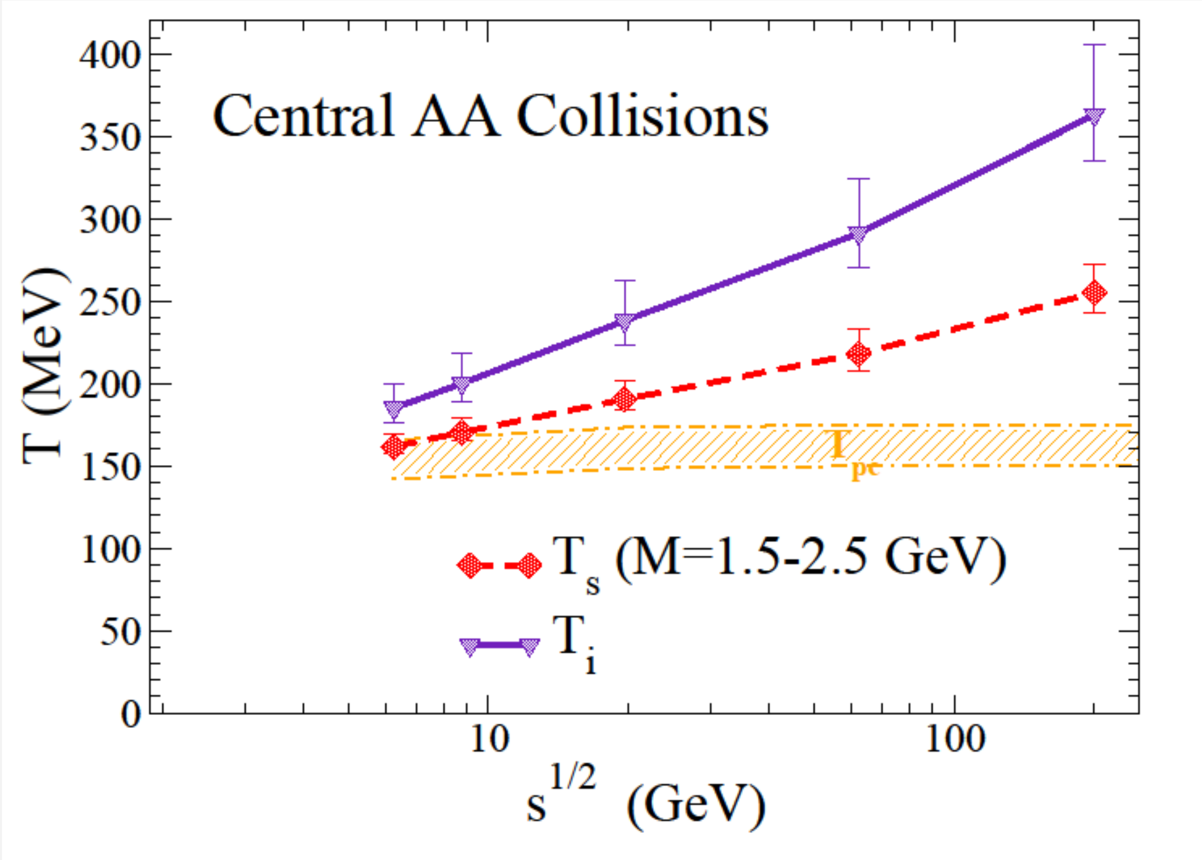
m_T -Slopes



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

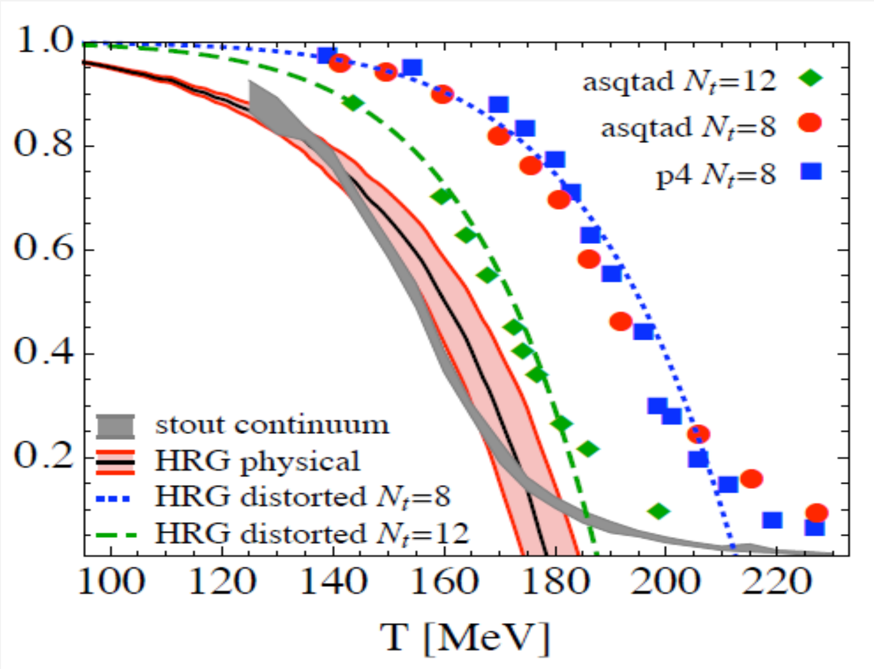
4.2 Fireball Temperature

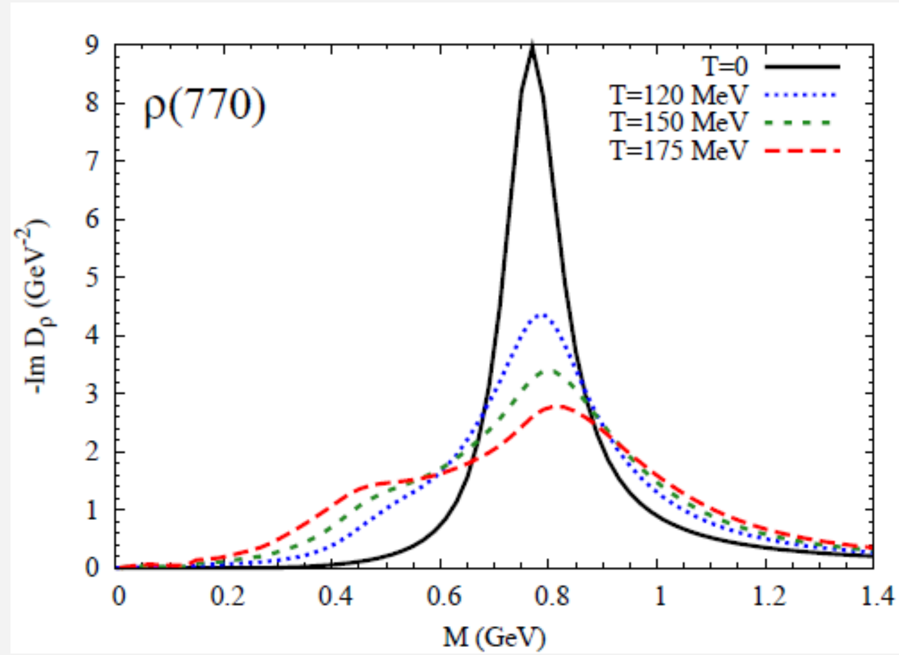
Slope of Intermediate-Mass Excess Dileptons



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

2.2 Chiral Condensate + ρ-Meson Broadening



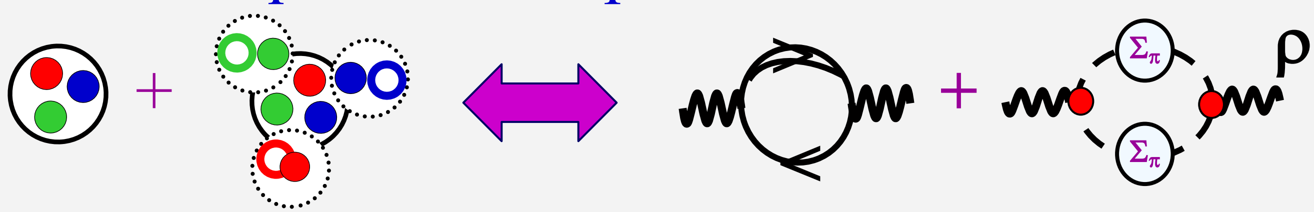


$$\frac{\langle\langle \bar{q}q \rangle\rangle(T,\mu_B)}{\langle \bar{q}q \rangle} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$$

⟺ effective hadronic theory

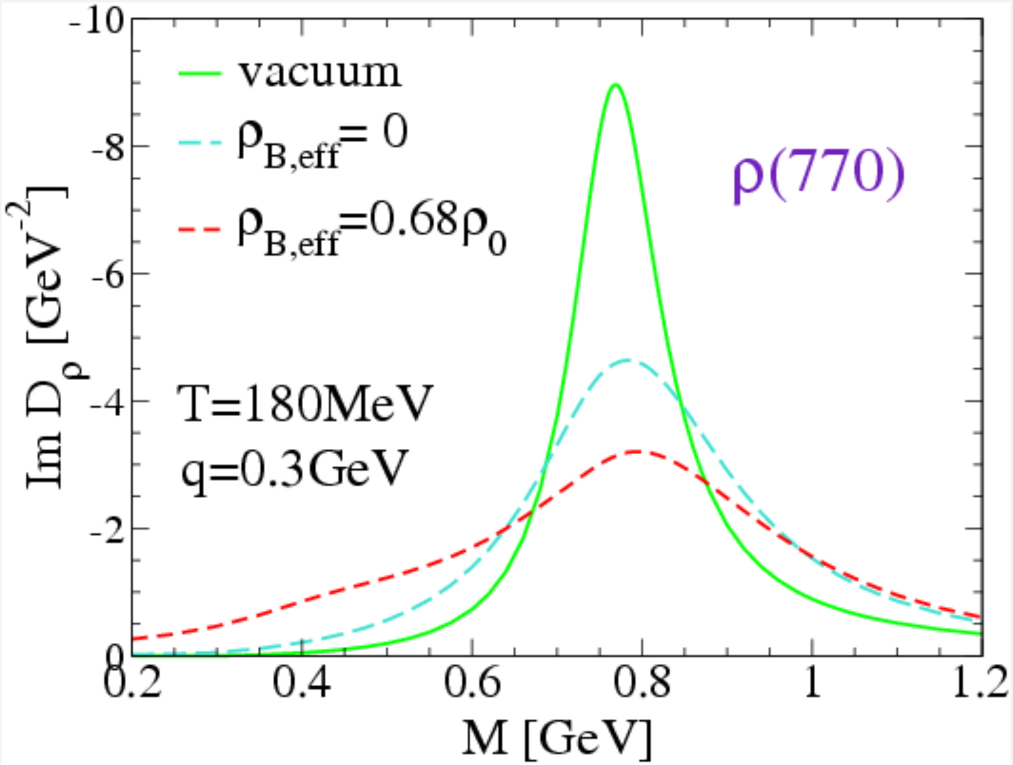
- $\Sigma_h = m_q \langle h|\bar{q}q|h\rangle > 0$ contains quark core + pion cloud

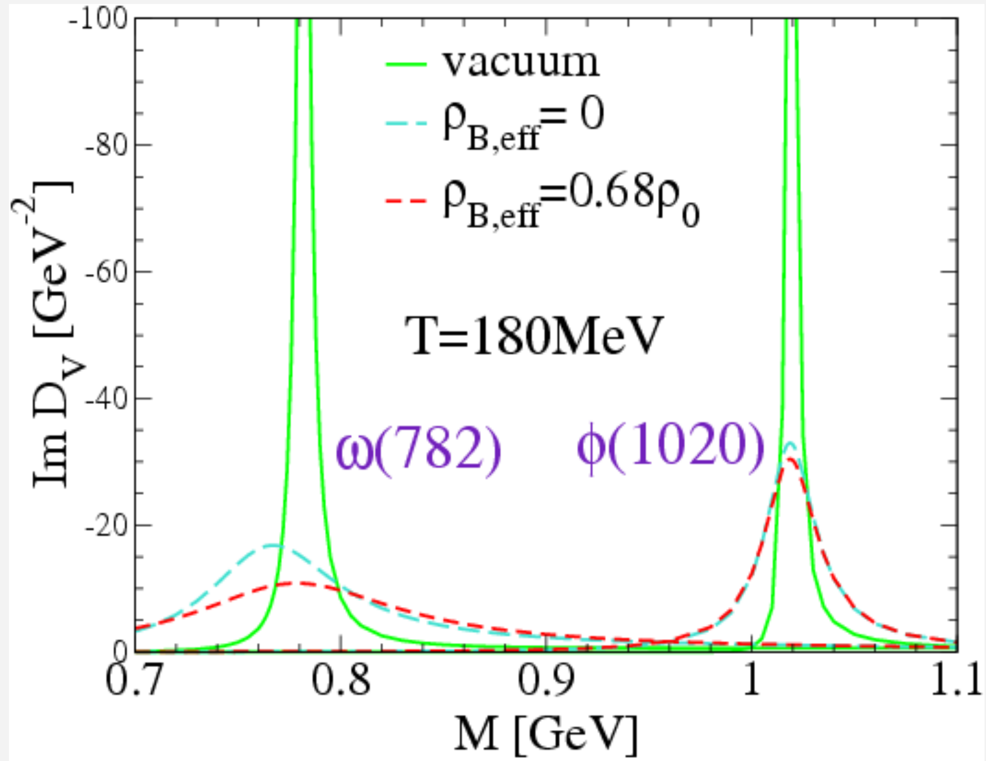
$= \Sigma_h^{core} + \Sigma_h^{cloud}$ ~



- **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

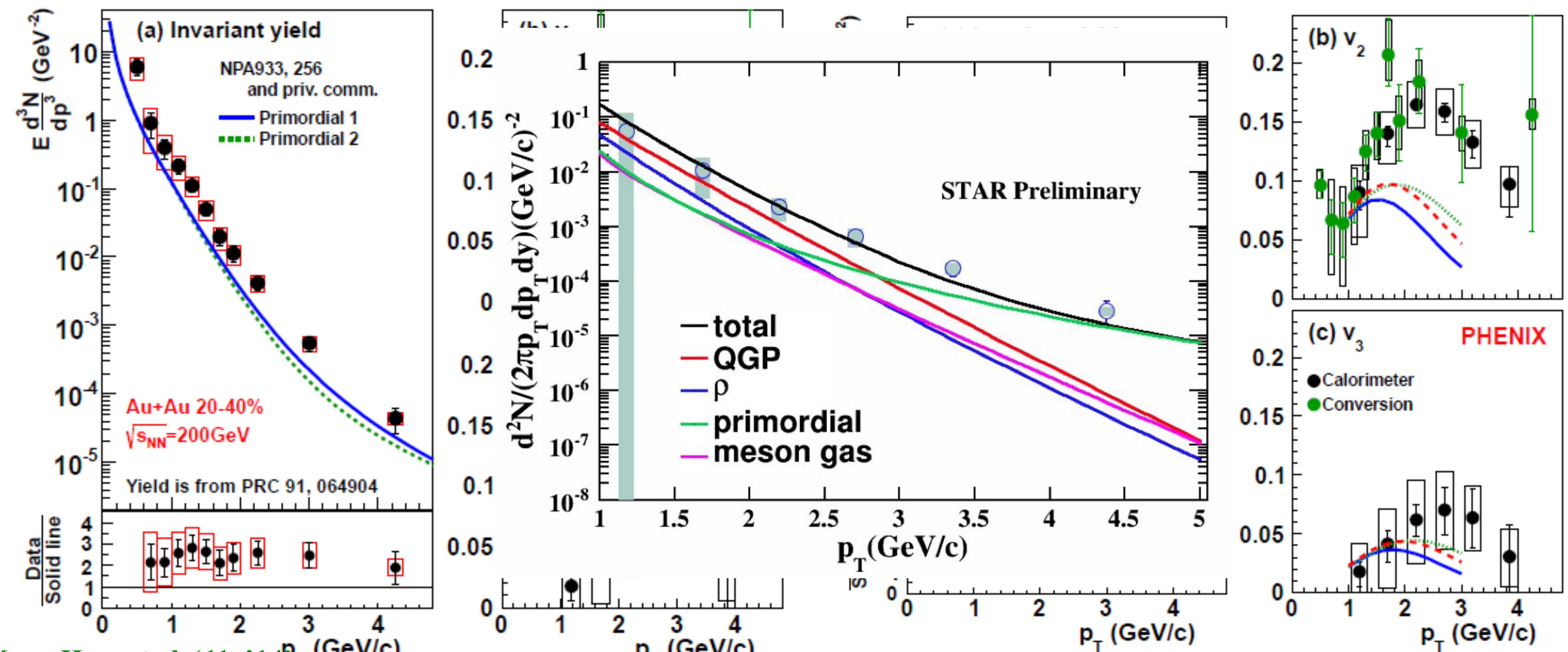




- Anti-/baryon effects melt the ρ meson
- ω also melts, ϕ more robust ↔ OZI

4.3 Comparison to Data: RHIC

Ideal Hydro **Viscous Hydro**



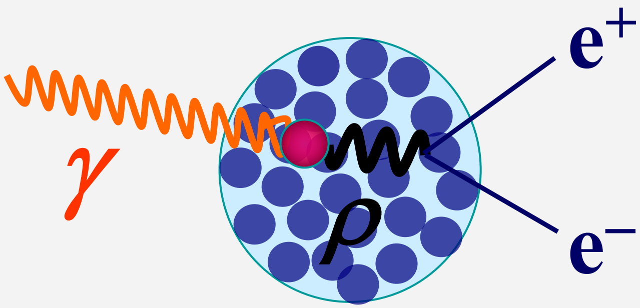
[van Hees et al, ‘11, ’14]

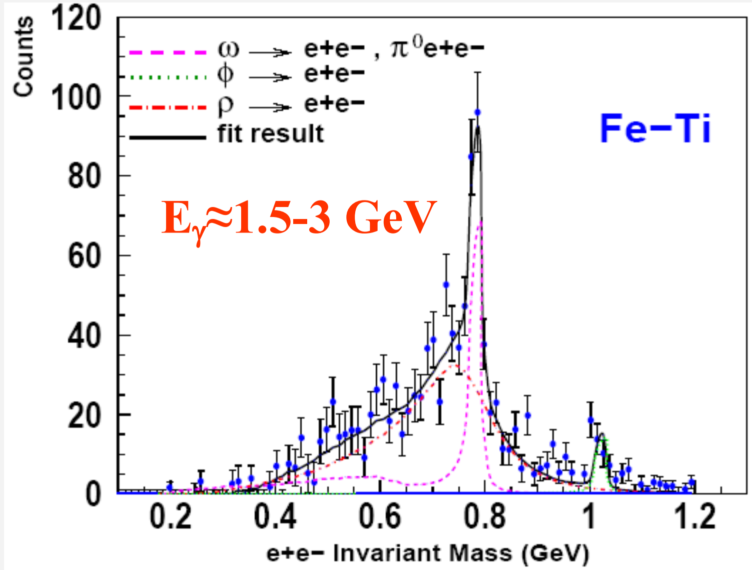
[Paquet et al ’16]

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

3.2 Nuclear Photoproduction: ρ Meson in Cold Matter

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



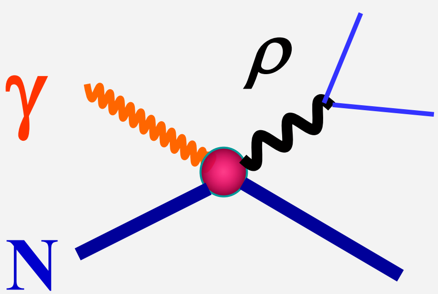


- extracted "in-med" ρ-width $\Gamma_\rho \approx 220$ MeV

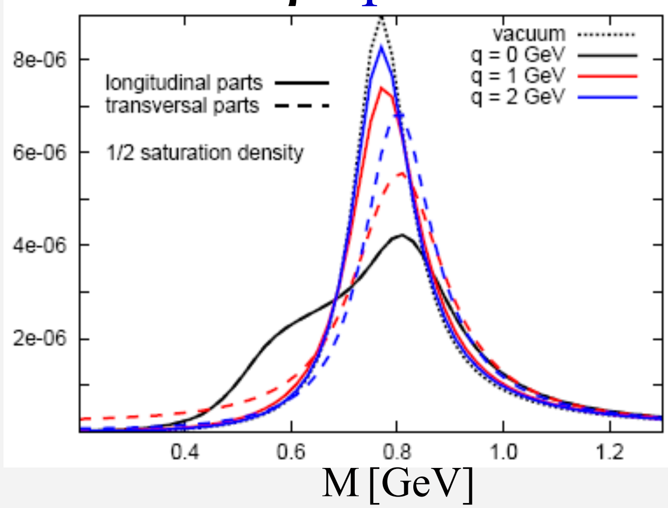
[CLAS+GiBUU '08]

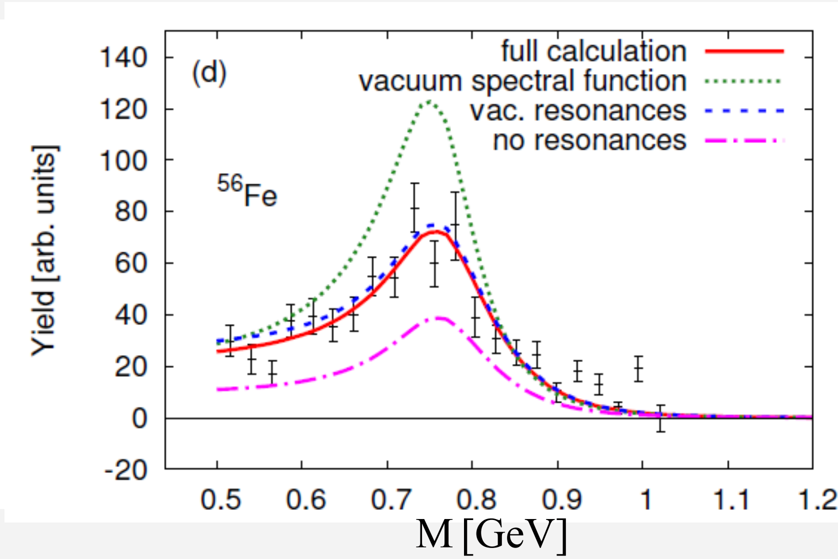
- **Microscopic Approach:**

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 Vaccum

- Gauge ρ + **a_1** into chiral pion lagrangian:

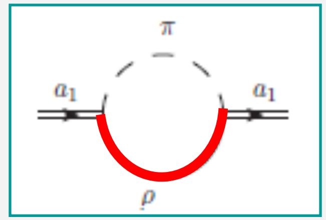
$$\mathcal{L}_{\mathrm{MYM}} = \frac{\tilde{f}_\pi^2}{8}\left(\mathrm{Tr}[D_\mu U^\dagger D^\mu U] + \tilde{m}_\pi^2 \mathrm{Tr}[U + U^\dagger - 2]\right) - \frac{1}{2}\mathrm{Tr}[F_L^2 + F_R^2] + m_0^2 \mathrm{Tr}[A_L^2 + A_R^2] - i\xi\, \mathrm{Tr}[D_\mu U D_\nu U^\dagger F_L + D_\mu U^\dagger D_\nu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

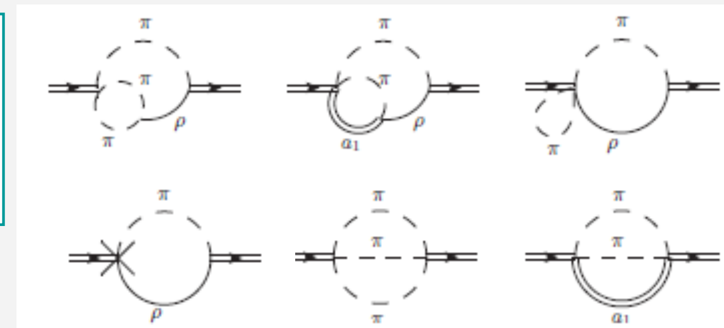
- problems with vacuum phenomenology

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

- Recent progress:
  - **full** ρ propagator in **a_1** selfenergy
  - **vertex corrections** to preserve **PCAC:**

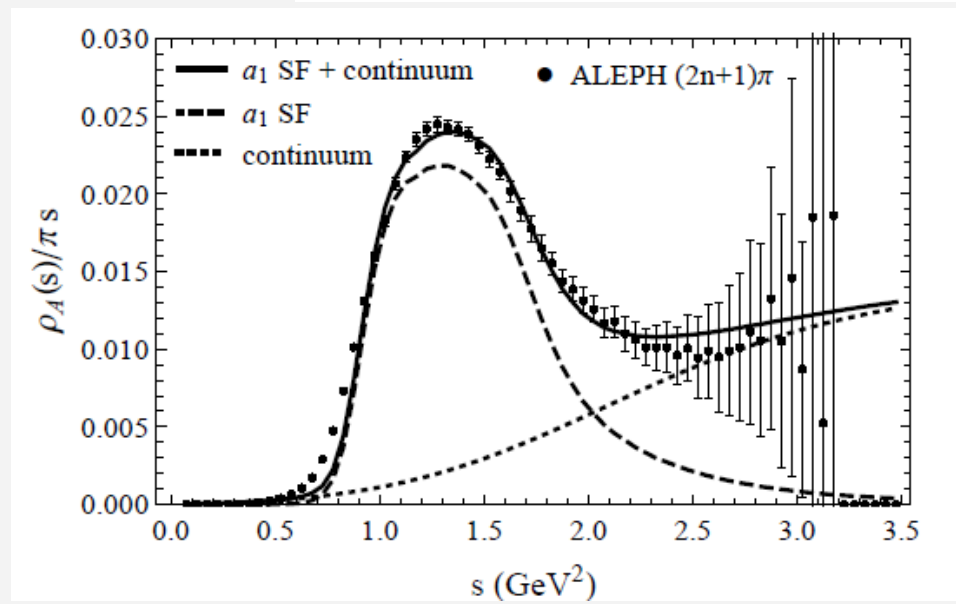
$$\int \frac{(-\mathrm{Im}\Pi_A^L)}{\pi s} ds = \frac{F_\pi^2}{2}$$



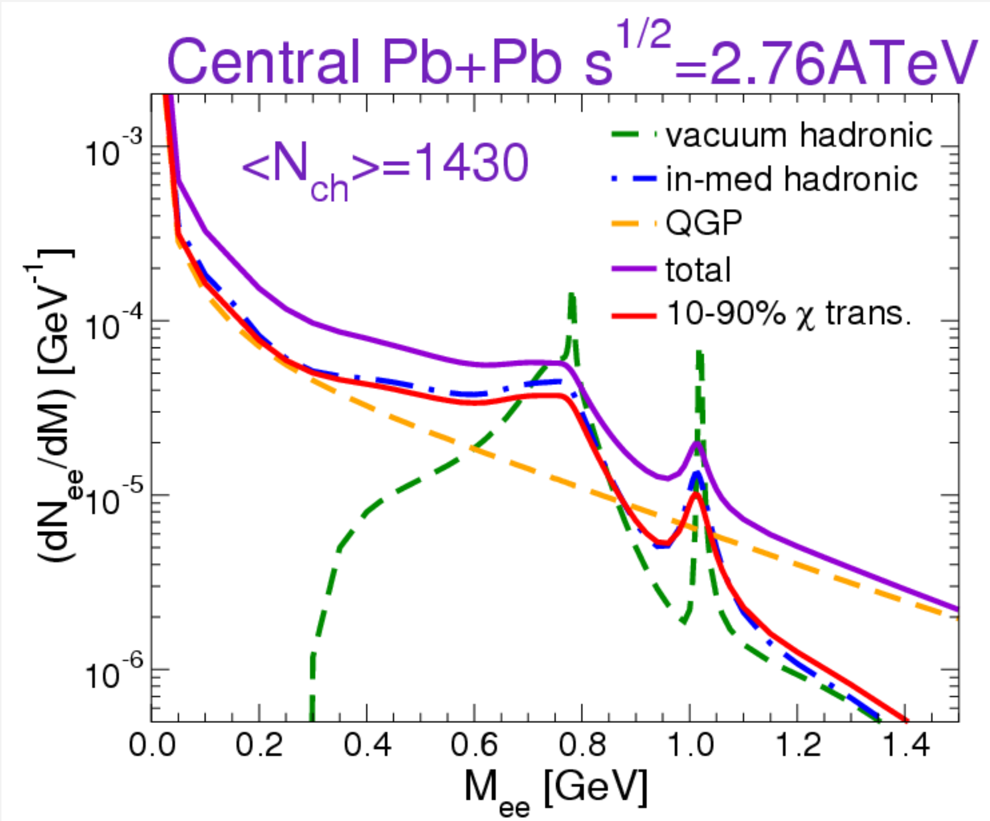


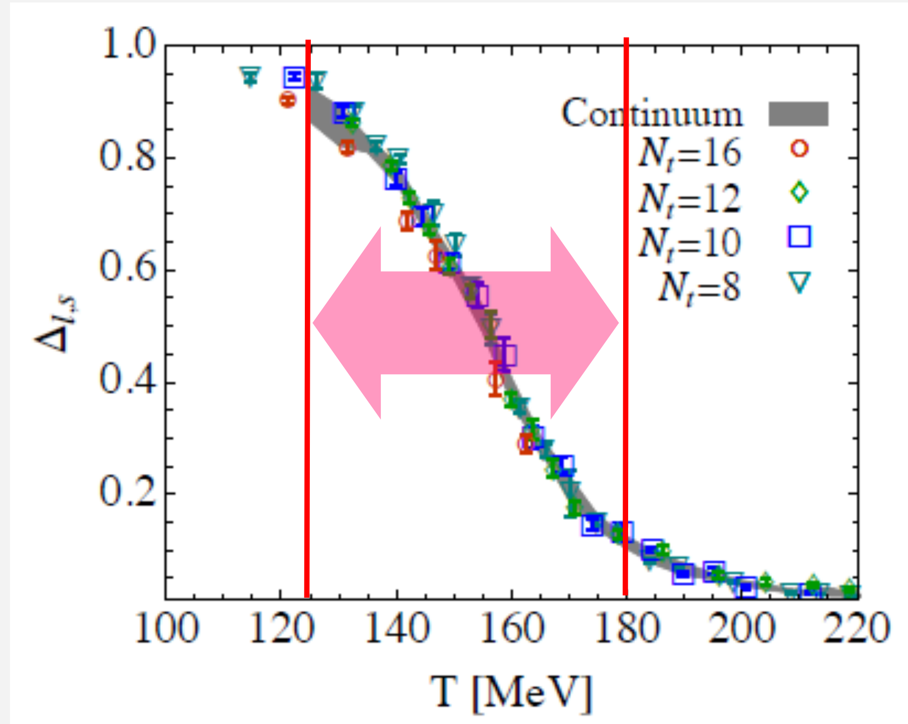
[Hohler +RR '14]

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



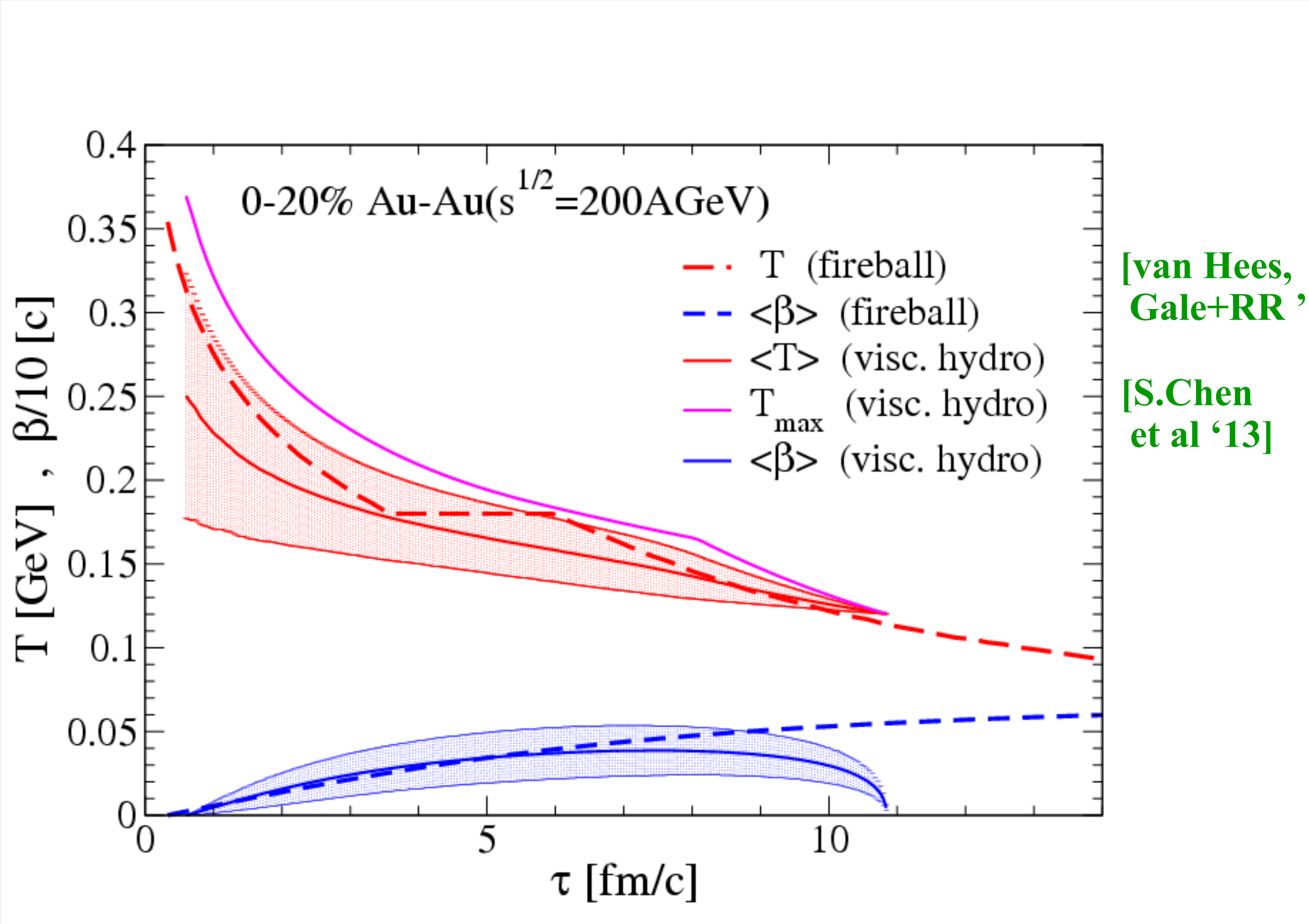
5.2 Chiral Restoration Window at LHC





- 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



[van Hees, Gale+RR '11]

[S.Chen et al '13]

- very similar!