Theory of Soft Electromagnetic Emission in Heavy-Ion Collisions

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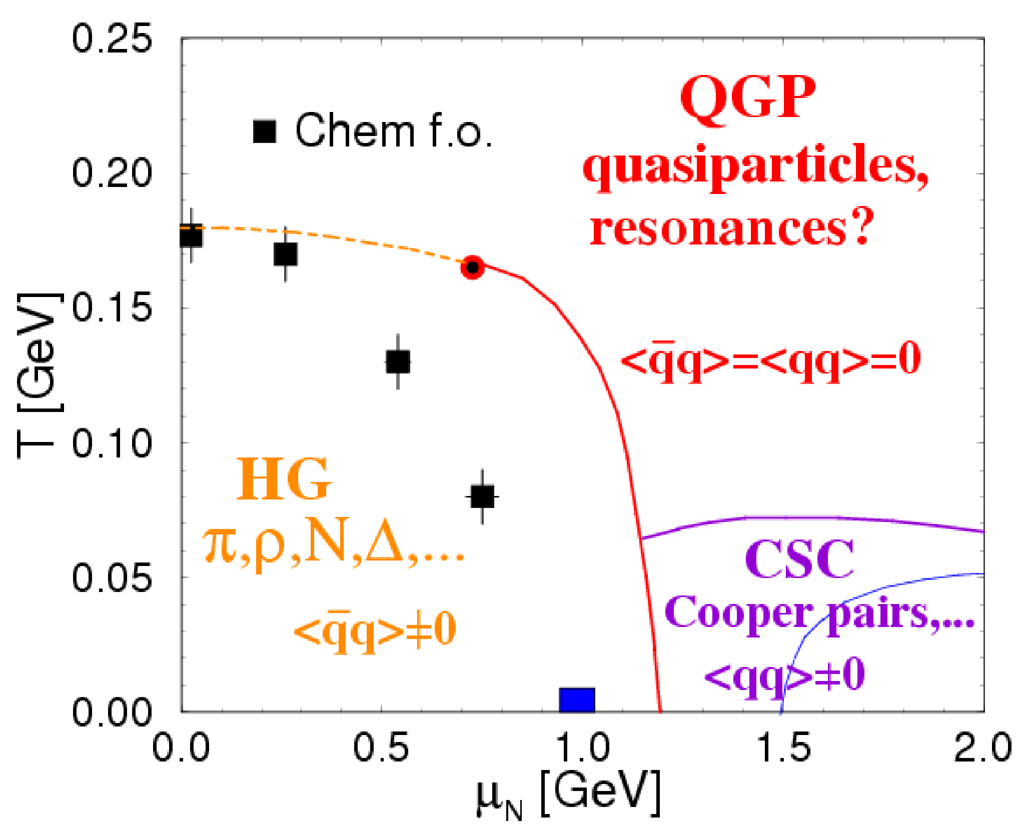
1.) Intro-I: Probing Strongly Interacting Matter

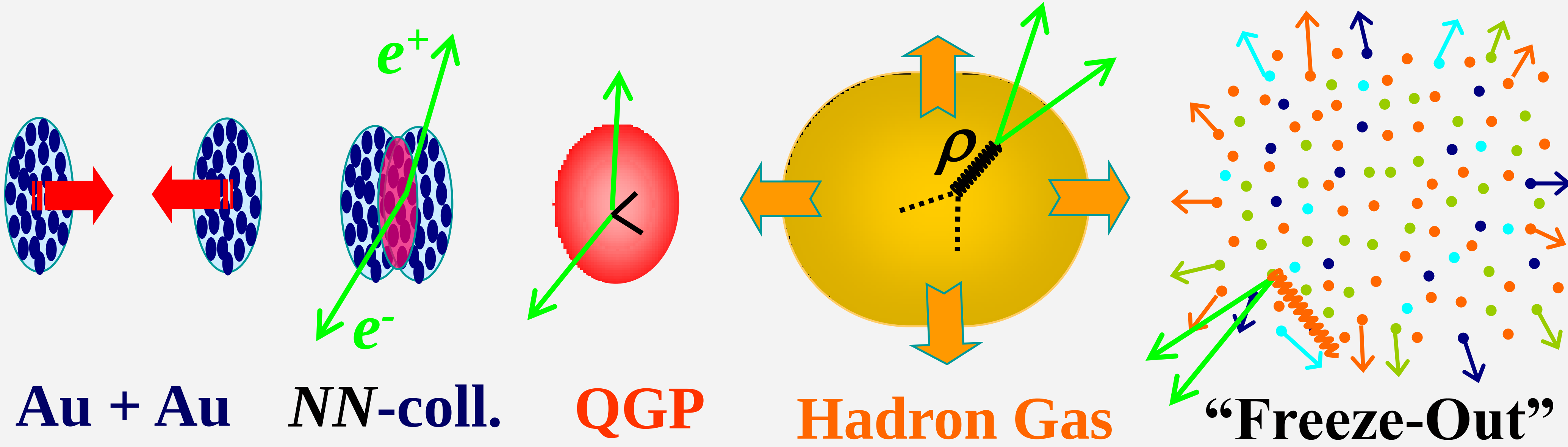


- **Bulk Properties:**
  Equation of State
- **Microscopic Properties:**
  - Degrees of Freedom
  - Spectral Functions
- **Phase Transitions:**
  (Pseudo-) Order Parameters

⇒ **Would like to extract from Observables:**

- **temperature + transport properties of the matter**
- **in-medium modifications of excitations (spectral functions)**
- **signatures of deconfinement + chiral symmetry restoration**

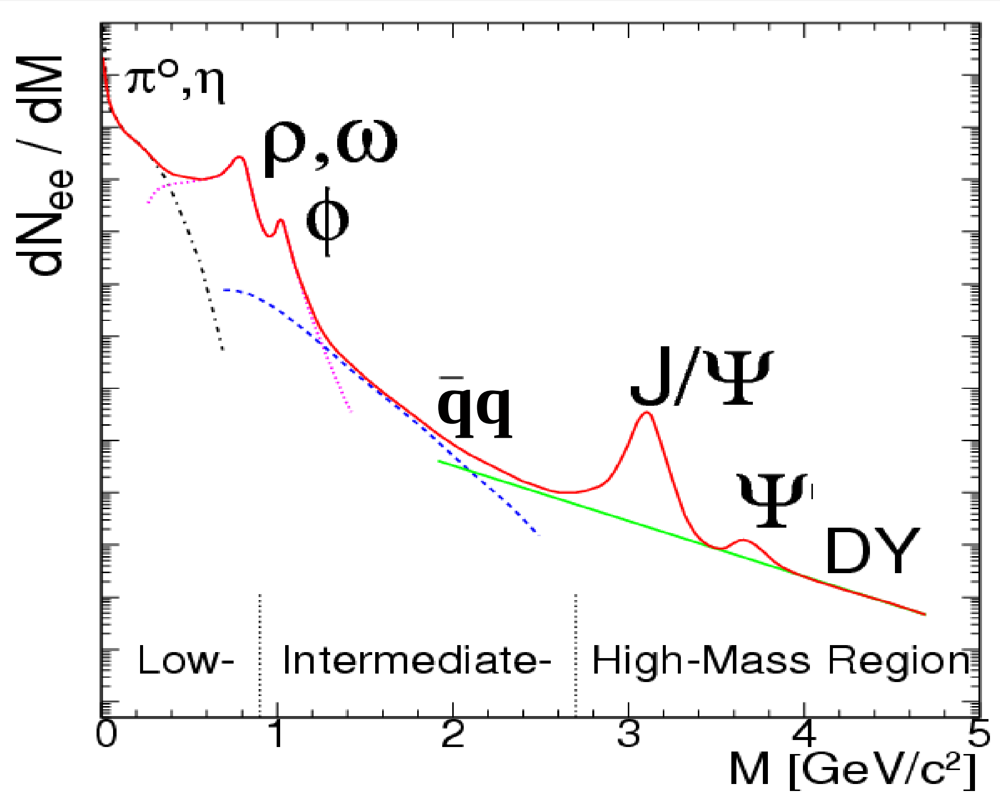
Creating Strong-Interaction Matter in the Laboratory



Sources of Dilepton Emission:

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

1.2 A Schematic Dilepton Spectrum in HICs



Characteristic regimes in invariant e^+e^- mass, $M^2=(p_{e+}+p_{e-})^2$

- **Drell-Yan: primordial, power law ~ M^{-n}**
- **thermal radiation:**
  - **entire evolution**
  - **Boltzmann ~ $exp(-M/T)$**

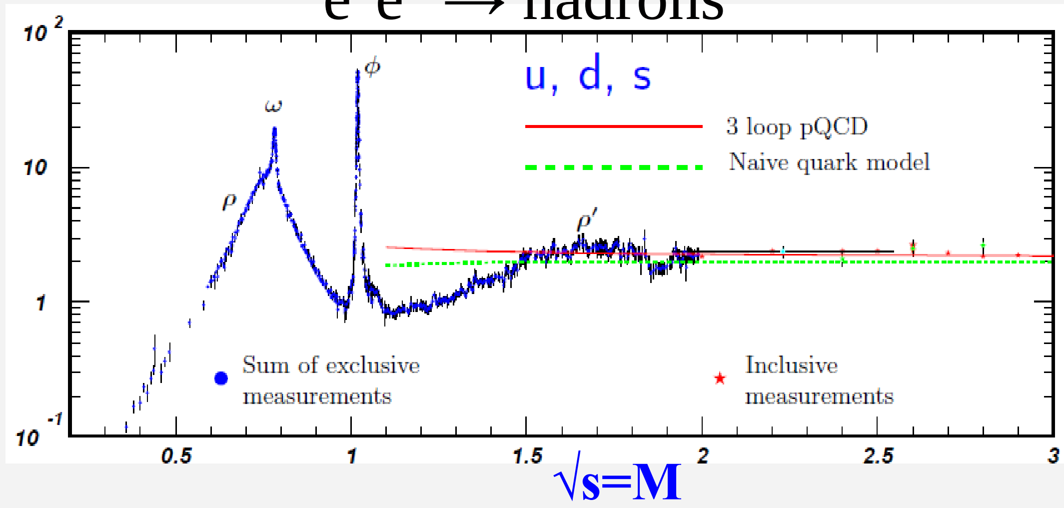
Thermal rate:

$$\frac{dN_{ee}}{dMd\tau} \approx V_{FB}\frac{dR_{ee}}{dM} \propto \frac{1}{T^3}\,e^{-q_0/T}\,Im\,\Pi_{em}(M)$$

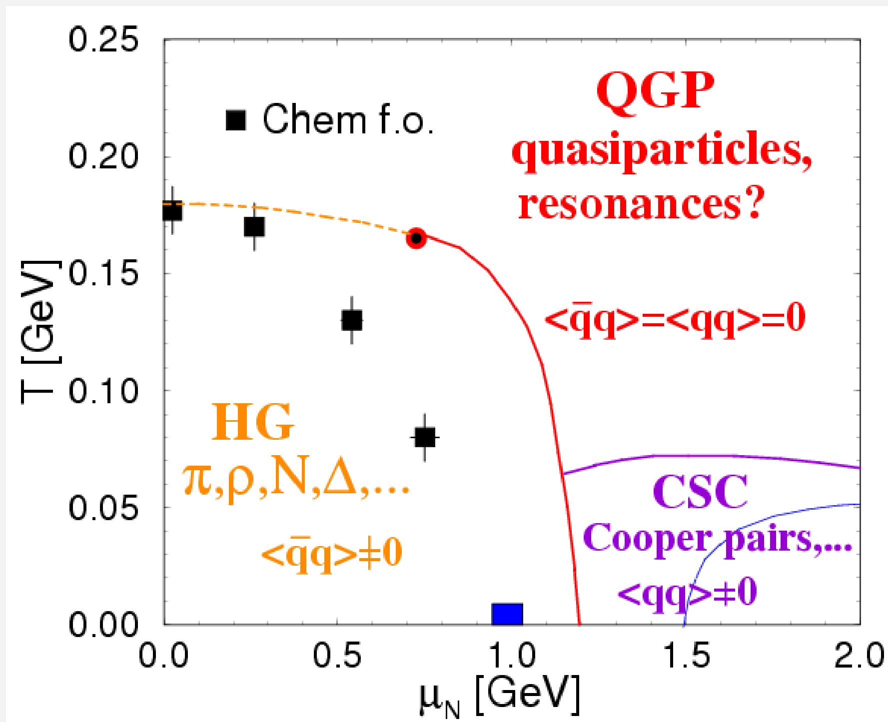
$q_0 \approx 0.5GeV \Rightarrow T_{max} \approx 0.17GeV$, $q_0 \approx 1.5GeV \Rightarrow T_{max} \approx 0.5GeV$

1.3 EM Spectral Function + QCD Phase Structure

- **Electromagn. spectral function**
  - $\sqrt{s} \leq 1$ GeV : non-perturbative
  - $\sqrt{s} \geq 2$ GeV : pertubative ("dual")



- **Disappearance of resonances**
  ↔ phase structure changes:
  - hadron gas → Quark-Gluon Plasma
  - realization of transition?



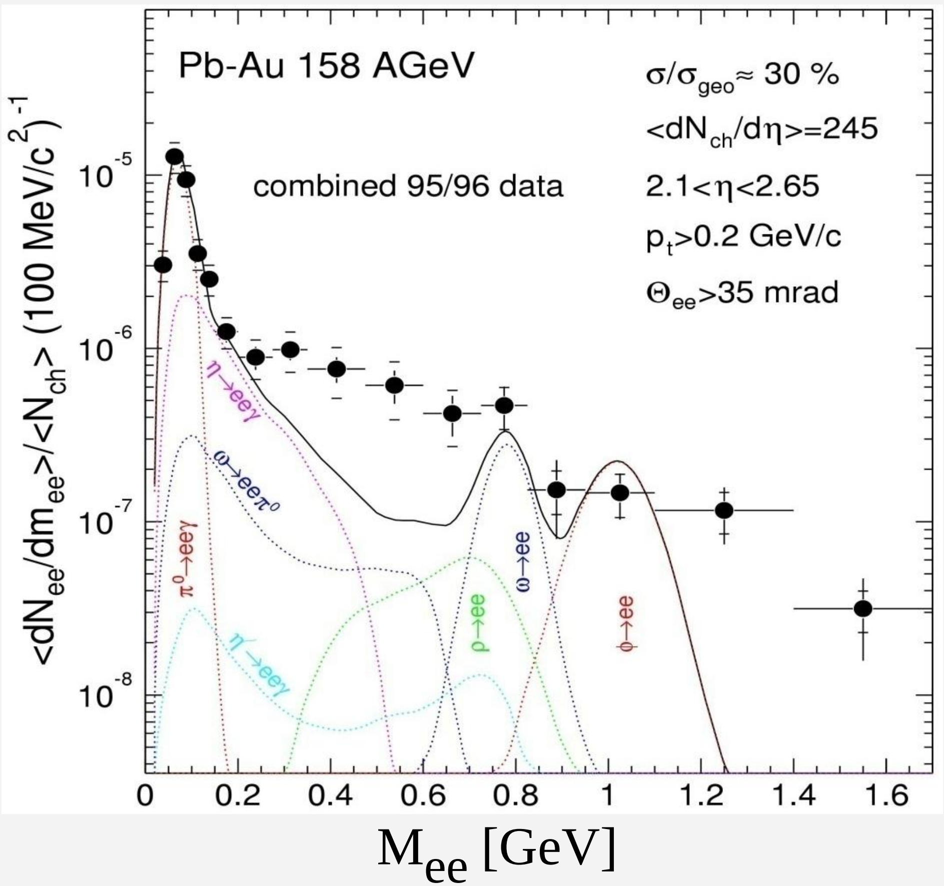
- **Thermal e^+e^- emission rate from hot/dense matter ($\lambda_{em} >> R_{nucleus}$)**

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

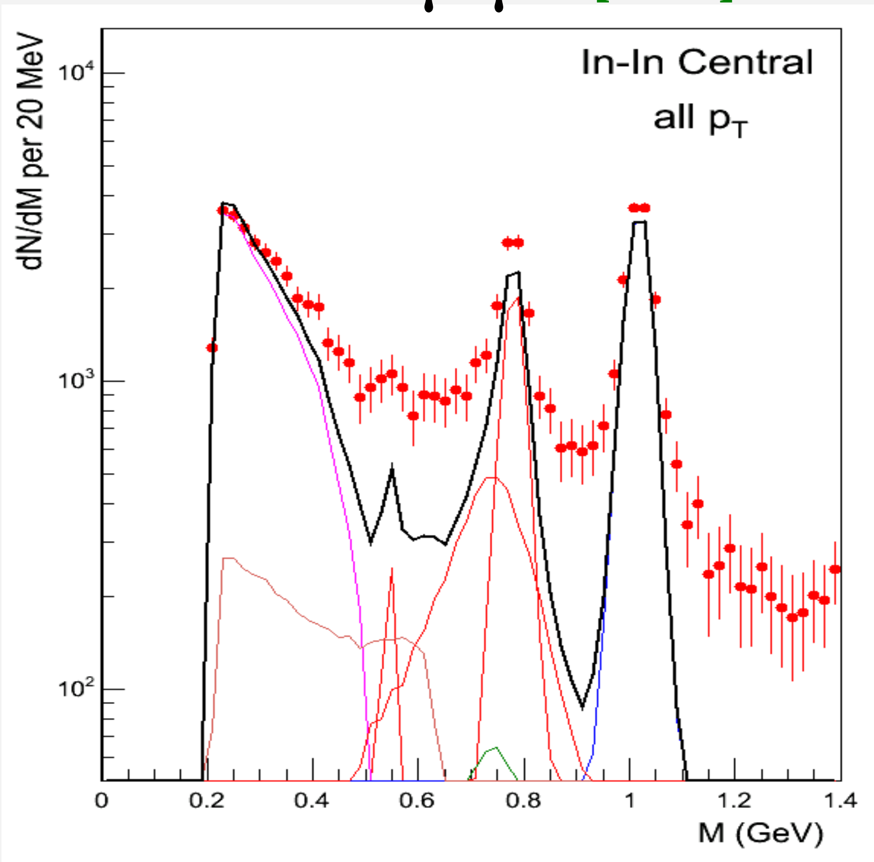
- **Temperature? Degrees of freedom?**
- **Deconfinement? Chiral Restoration?**

1.4 Low-Mass Dileptons at CERN-SPS

CERES/NA45 e^+e^- **[2000]**



NA60 $\mu^+\mu^-$ **[2005]**



- strong excess around ***M ≈ 0.5GeV , M > 1GeV***
- little excess in ρ, ω, ϕ region

Outline

2.) Chiral Symmetry in QCD

- Nonperturbative QCD, Chiral Breaking + Hadron Spectrum

3.) Thermal Electromagnetic Emission Rates

- EM Spectral Function: Hadronic vs. Partonic Regimes

4.) Vector Mesons in Medium

- Many-Body Theory, Spectral Functions + Chiral Partners (ρ-a_1)

5.) Quark-Gluon Plasma Emission

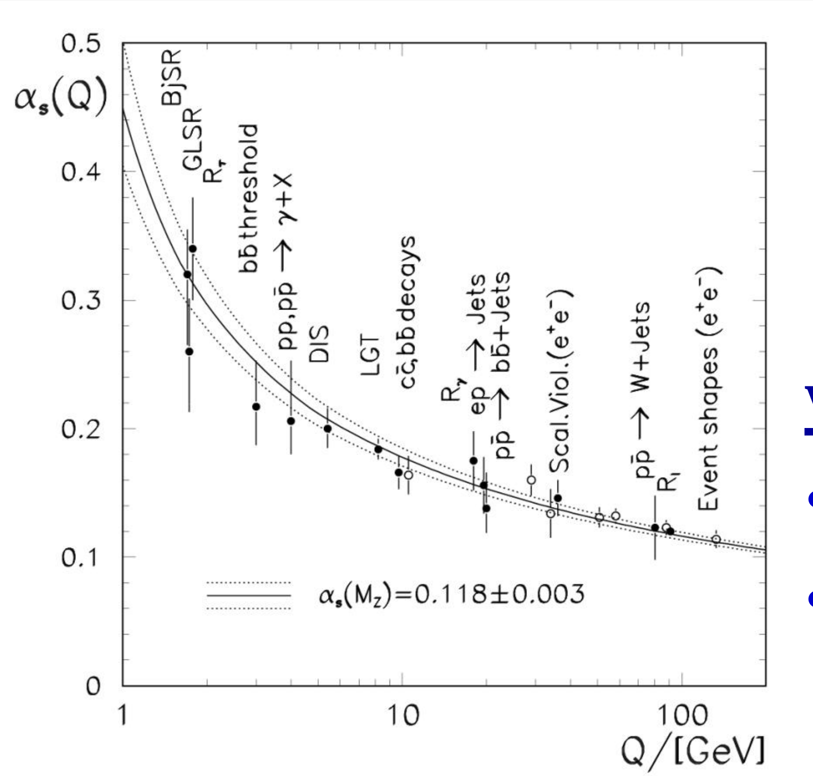
- Perturbative vs. Lattice-QCD Rates, "Quark-Hadron-Duality"

6.) Dilepton + Photon Spectra in Heavy-Ion Collisions

- Space-Time Evolution, Phenomenology + Interpretation

7.) Summary and Conclusions

2.1 Nonperturbative QCD



$$\mathcal{L}_{QCD} = \bar{q}\,(i\partial\!\!\!/ + gA\!\!\!/ - \hat{m}_q\,)\,q - \frac{1}{4} G^2_{a\mu\nu}$$

well tested at high energies, **$Q^2 > 1\,\text{GeV}^2$:**

- perturbation theory ($\alpha_s = g^2/4\pi << 1$)
- degrees of freedom = quarks + gluons

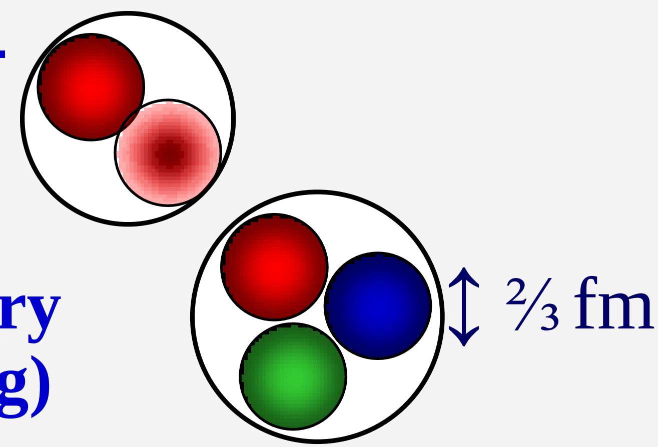
($m_u \approx m_d \approx$ 5-10MeV)

$Q^2 \leq 1\,\text{GeV}^2$ → transition to "strong" QCD:

- effective d.o.f. = hadrons (**Confinement**)
- massive "constituent quarks"

$m_q^* \approx$ 350 MeV ≈ ⅓ M_p **(Chiral Symmetry Breaking)**

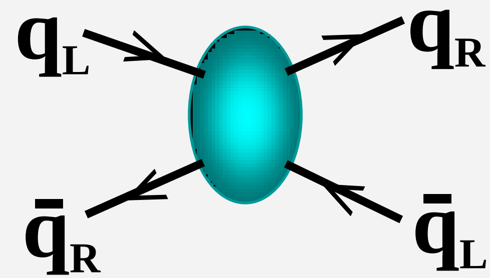
$\sim \langle 0|\bar{q}q|0\rangle$ condensate!



2.2 Chiral Symmetry + QCD Vacuum

$\mathcal{L}_{\mathrm{QCD}}(m_{u,d} \approx 0)$: **flavor + "chiral" (left/right) invariant**

"Higgs" Mechanism in Strong Interactions:



- **$\bar{q}q$ attraction $\Rightarrow$ condensate fills QCD vacuum!**

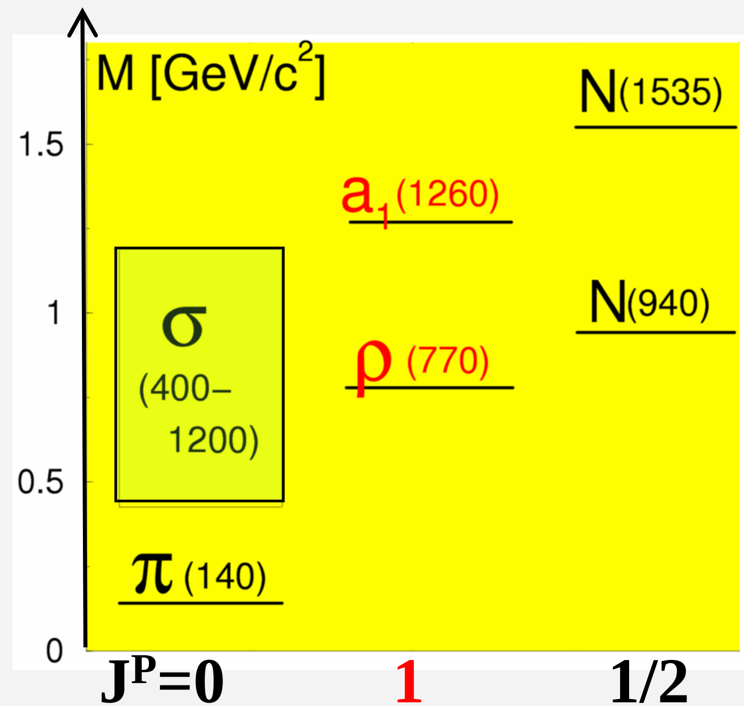
$$\langle 0|\bar{q}q|0\rangle = \langle 0|\bar{q}_L q_R + \bar{q}_R q_L|0\rangle \approx 5\, fm^{-3}$$

Spontaneous Chiral Symmetry Breaking

Profound Consequences:

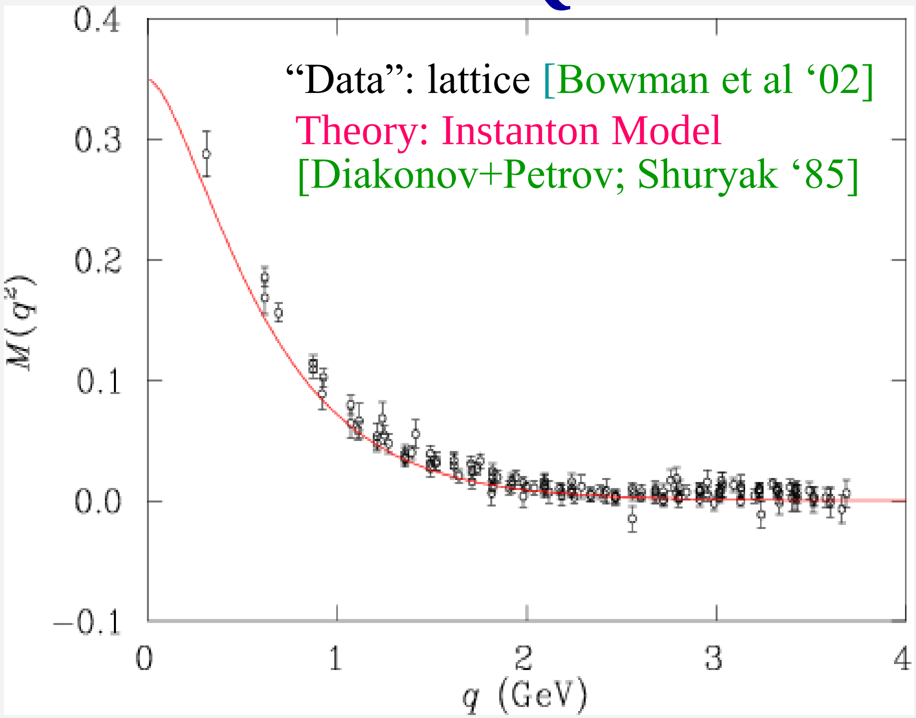
- **effective quark mass:** $m_q^* \propto \langle 0|\bar{q}q|0\rangle$

  $\leftrightarrow$ **mass generation!**
- **near-massless Goldstone bosons** $\pi^{0,\pm}$
- **"chiral partners" split,** $\Delta M \approx 0.5 GeV$



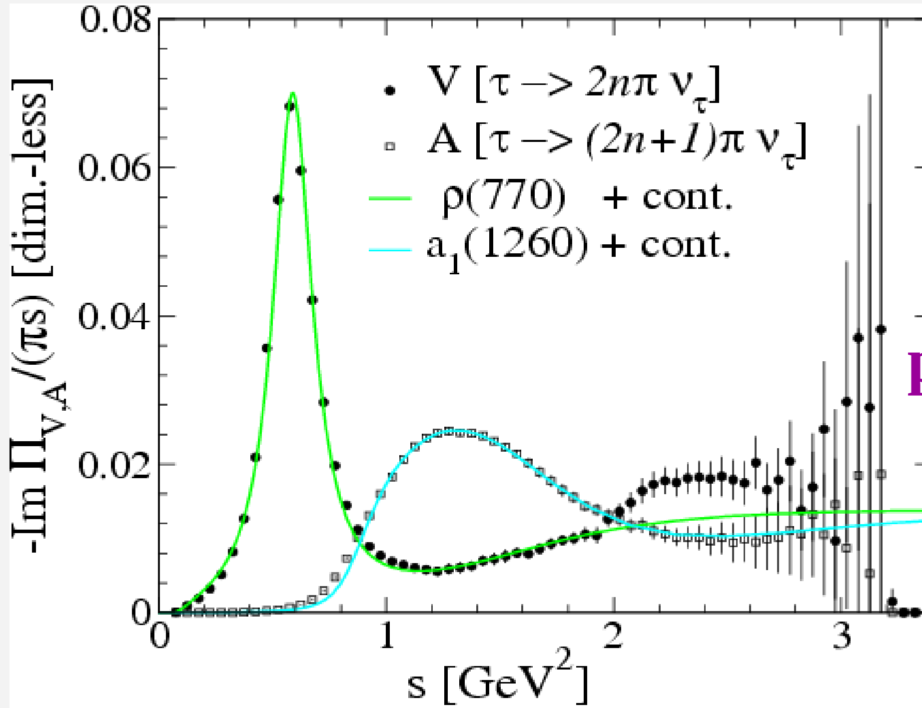
2.2.2 Hadron Spectra + Chiral Symm. Breaking

Constituent Quark Mass



chiral breaking: $|q^2| \leq 1\ GeV^2$

Axial-/Vector Correlators



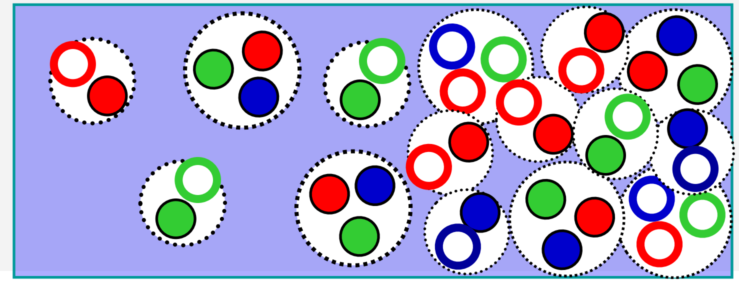
pQCD cont.

- Weinberg Sum Rule(s)

$$f_\pi^2 = -\int \frac{ds}{\pi s} (Im\,\Pi_V^{I=1} - Im\,\Pi_A^{I=1})$$

2.3 Quark-Gluon Plasma

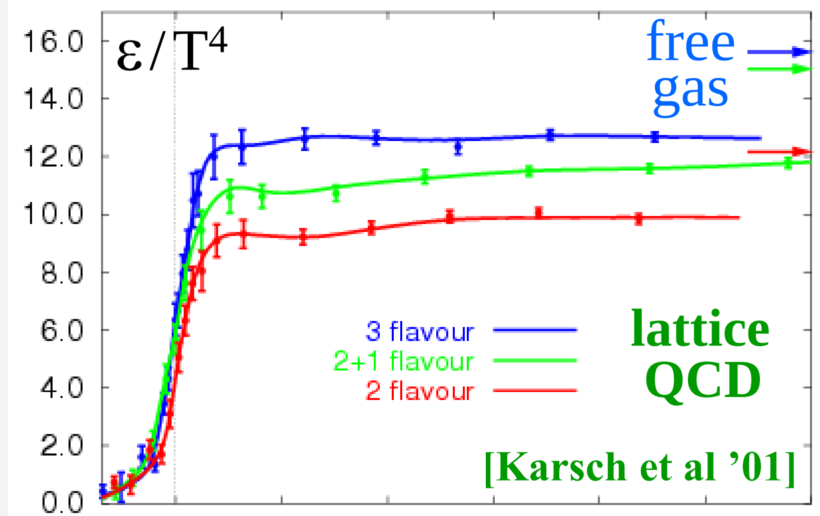
Excite vacuum (hot+dense matter)



- hadrons overlap, **quarks liberated**

  ⇒ **Deconfinement** (**$T_c \approx 170$MeV**)

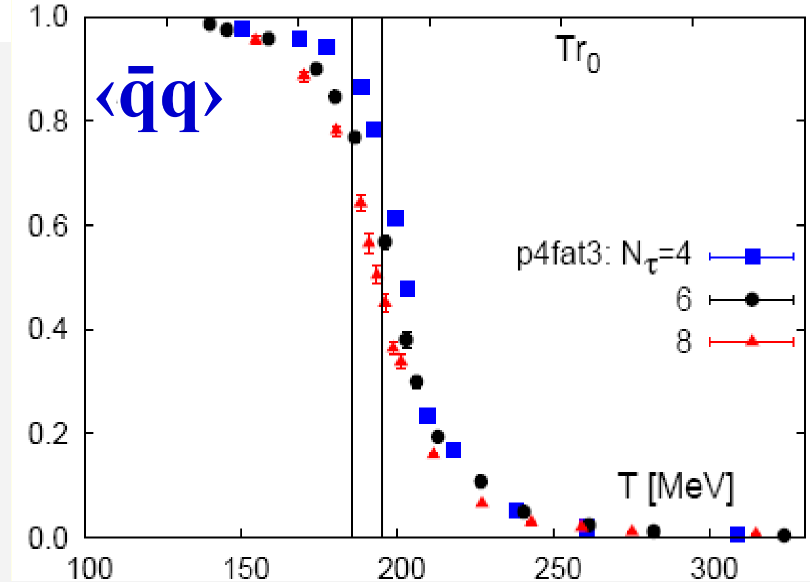
  energy density $\varepsilon \sim$ (# d.o.f)T^4



- **$\langle \bar{q}q \rangle$ condensate "melts"**

  ⇒ **Chiral Symmetry Restoration**

  dissolution of mass: $m_q^* \rightarrow \sim 0$



⇒ **clear indications for phase transition!**

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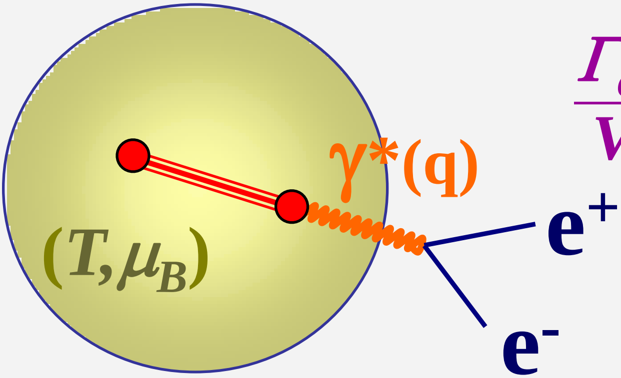
3.1 E.M. Correlator + Thermal Dilepton Emission



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

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

← photon selfenergy

E.M. Correlation Fct.: $\Pi_{em}^{\mu\nu}(q) = -i \int d^4x \, e^{iqx} \langle j_{em}^\mu(x) j_{em}^\nu(0) \rangle_T$

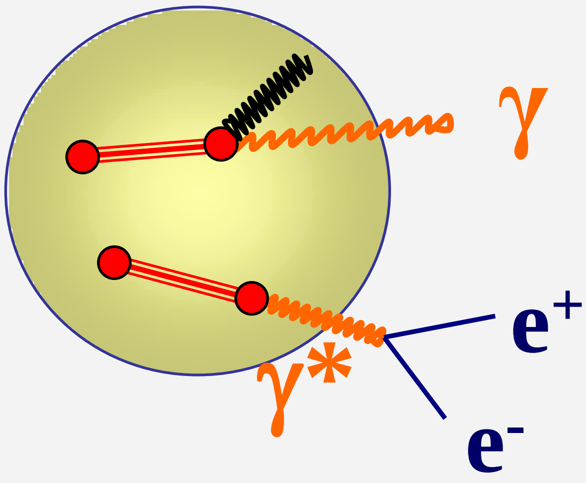
quark basis: $j_{em}^\mu = \frac{2}{3} \bar{u}\gamma^\mu u - \frac{1}{3} \bar{d}\gamma^\mu d - \frac{1}{3} \bar{s}\gamma^\mu s$

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

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

3.1.2 Versatility of EM Correlation Function

- **Photon Emission Rate**



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

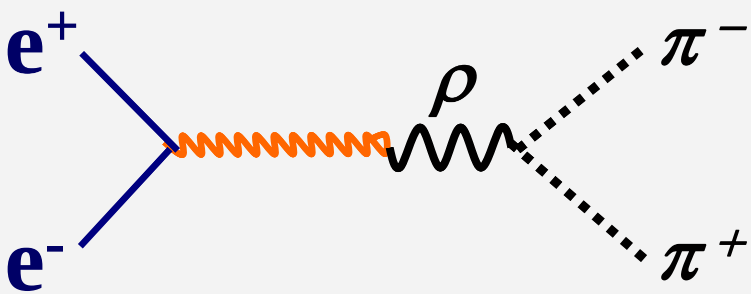
$$\frac{dR_{ee}}{d^4q} = \frac{-\alpha^2}{\pi^3 M^2} f^B(q_0,T)\ \mathrm{Im}\,\Pi_{em}(M,q) \qquad \sim O(1)$$

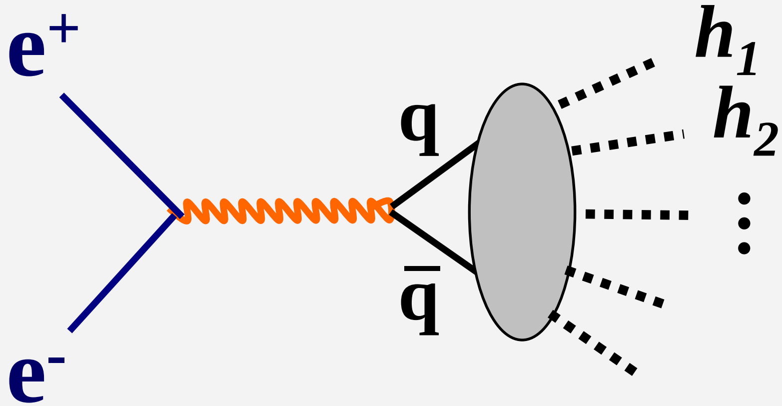
same correlator!

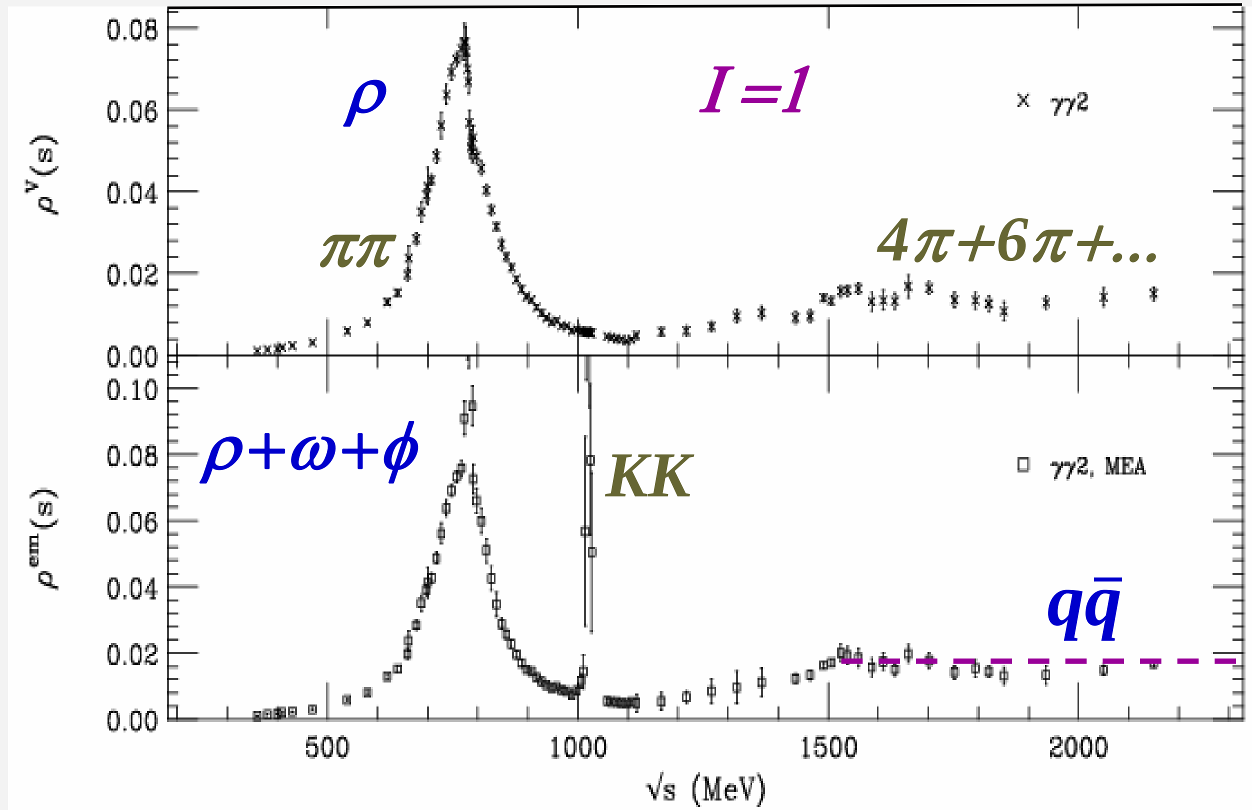
- **E.M. Susceptibility (→ charge fluctuations):**

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

3.2 EM Correlator in Vacuum: $\sigma(e^+e^- \to hadrons)$







$$Im\,\Pi_{em}(s) = \begin{cases} \dfrac{-s}{12\pi} N_c \sum\limits_{u,d,s} (e_q)^2 \left[1 + \dfrac{\alpha_S(s)}{\pi} + \cdots\right] & s \geq s_{dual} \sim (1.5\,GeV)^2 : \\ \sum\limits_{\rho,\omega,\phi} \left[\dfrac{m_V^2}{g_V}\right]^2 Im\,D_V(s) & s < s_{dual} : \end{cases}$$

$s \geq s_{dual} \sim (1.5GeV)^2$: **pQCD continuum**

$s < s_{dual}$: **Vector-Meson Dominance**

3.3 The Role of Light Vector Mesons in HICs

Contribution to invariant mass-spectrum:

$$\frac{dN_{V\to ee}}{dM} = \int d^3q\, d^4x \frac{dR_{ee}}{d^4q} \propto N_V(M) \frac{\Gamma_{V\to ee}}{M} \Delta\tau$$

thermal emission
$\tau_{FB} \sim 10fm/c$

after freezeout
$\tau_V \sim 1/\Gamma_V^{tot}$

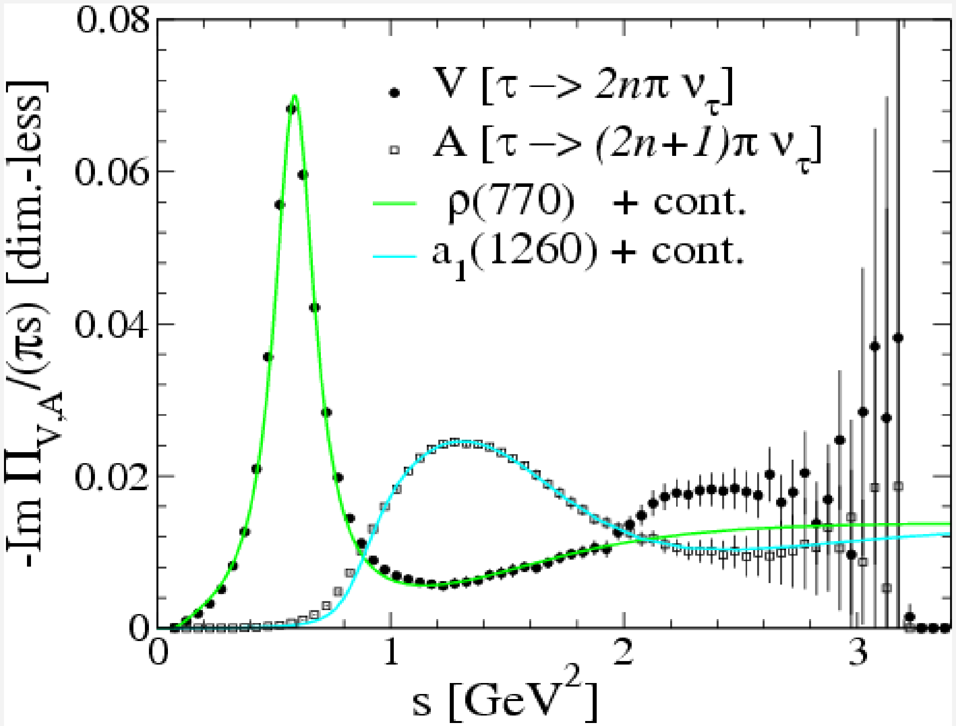
	Γ_{ee} [keV]	Γ_{tot} [MeV]	$(N_{ee})^{thermal}$	$(N_{ee})^{cocktail}$	ratio
$\rho(770)$	6.7	150 (1.3fm/c)	1	0.13	7.7
$\omega(782)$	0.6	8.6 (23fm/c)	0.09	0.21	0.43
$\phi(1020)$	1.3	4.4 (44fm/c)	0.07	0.31	0.23

$\Rightarrow$ **In-medium radiation dominated by ρ -meson!**

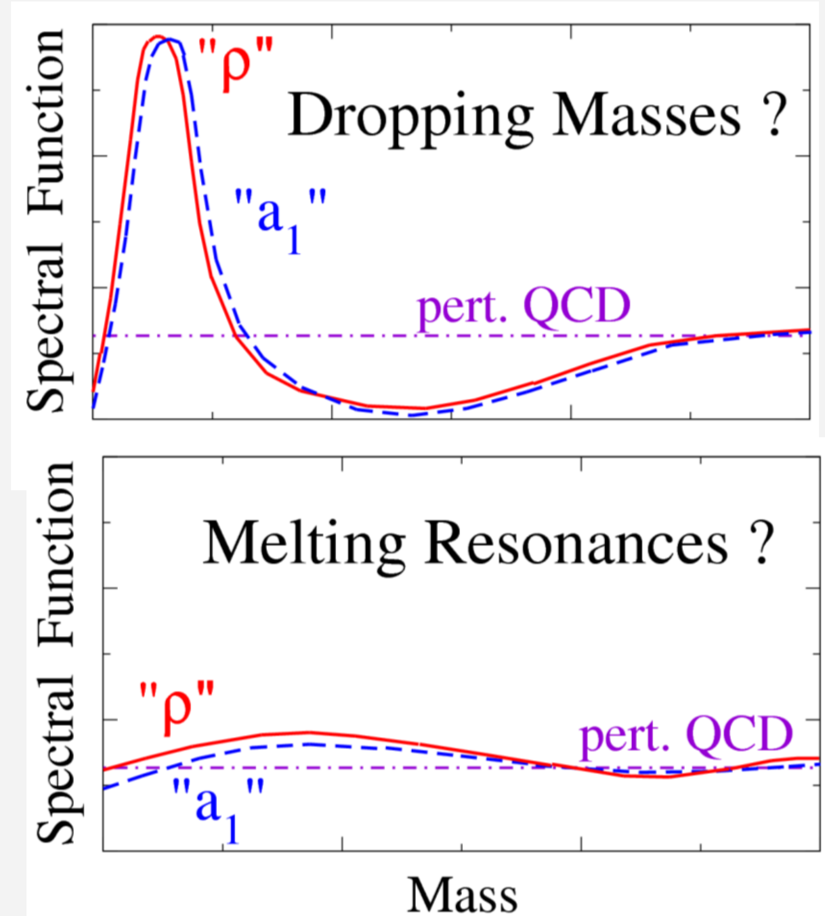
Connection to chiral symmetry restoration?!

3.4 Low-Mass Dileptons + Chiral Symmetry

Vacuum



$T > T_c$: Chiral Restoration



- **How is the degeneration realized?**
- **“measure” vector with e^+e^-, axialvector?**

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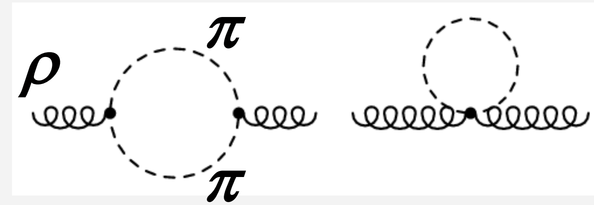
4.1 Axial/Vector Mesons in Vacuum

Introduce ρ, a_1 as gauge bosons into free $\pi + \rho + a_1$ Lagrangian $\Rightarrow$

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



ρ-propagator:

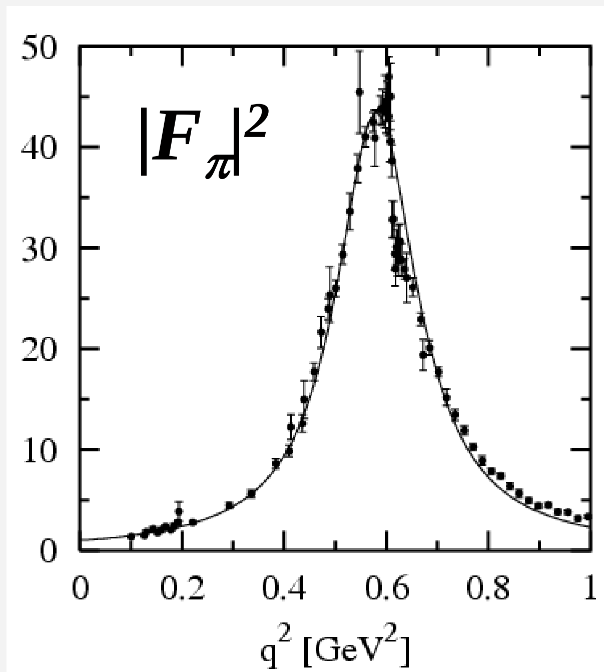
$$D_\rho(M) = [M^2 - (m_\rho^{(0)})^2 - \Sigma_{\rho\pi\pi}(M)]^{-1}$$

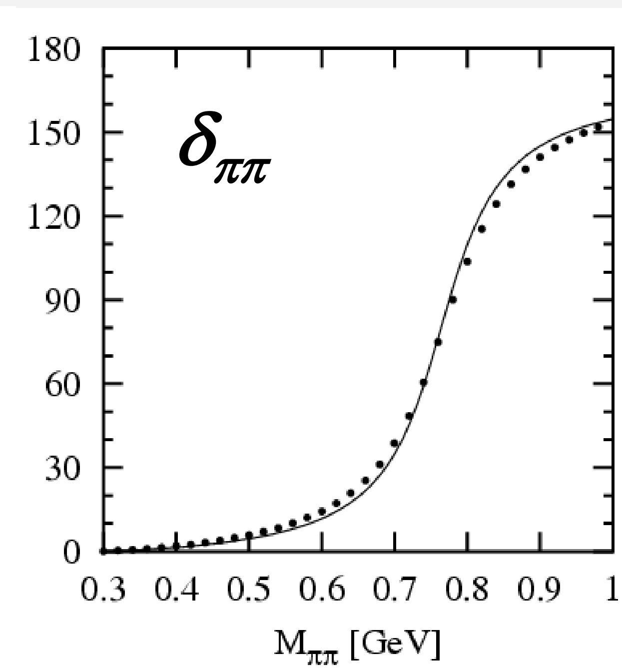
π EM formfactor

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

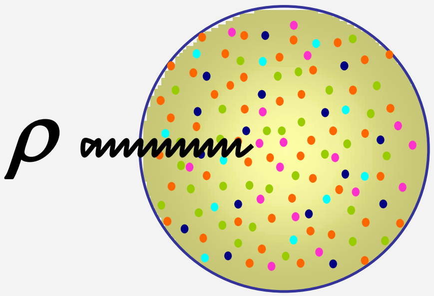
$\pi\pi$ scattering phase shift

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





4.2 ρ-Meson in Hot + Dense Matter



interactions with hadrons from heat bath

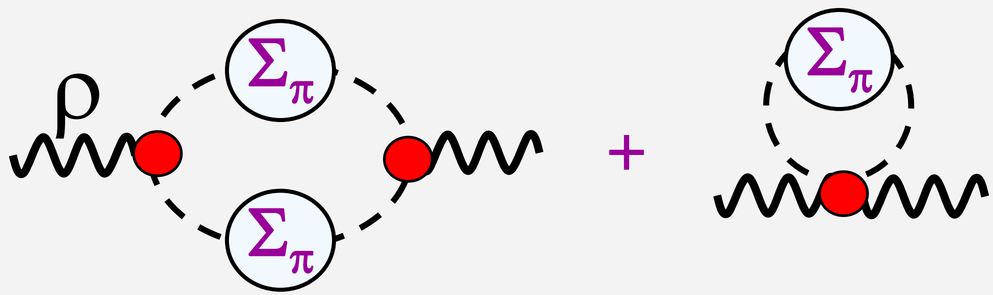
$\Rightarrow$ **In-Medium ρ-Propagator**

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

- **In-Medium Pion Cloud**

[Chanfray et al, Herrmann et al, Urban et al, Weise et al, Oset et al, …]

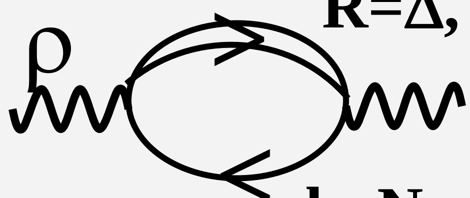
$\Sigma_{\rho\pi\pi}$ =



- **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…

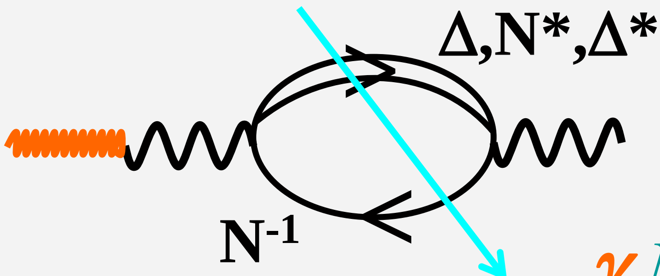
h=N, π, K …

- estimate coupling constants from **R→ ρ + h**, but more comprehensive constraints desirable

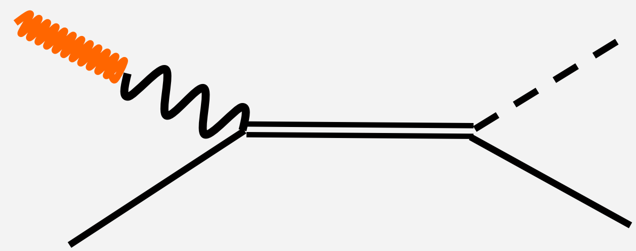
4.3 Constraints I: Nuclear Photo-Absorption

total nuclear γ-absorption cross section ⟷ in-medium ρ-spectral function at photon point

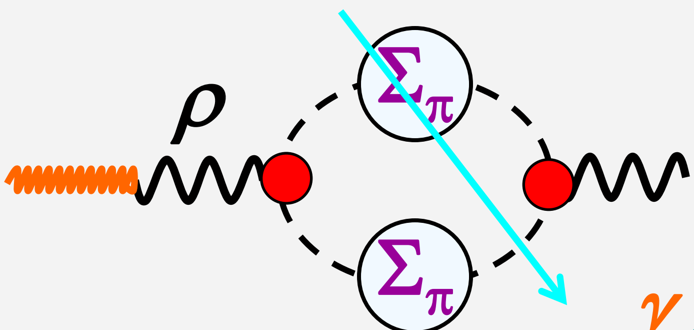
$$\frac{\sigma^{abs}_{\gamma A}(q_0)}{A} = -\frac{4\pi\alpha}{q_0\rho_N}\, Im\,\Pi_{em}(q_0=q) = -\frac{4\pi\alpha}{q_0\rho_N}\,\frac{m_\rho^4}{g_\rho^2}\, Im\,D_\rho^{med}(M=0,q)$$



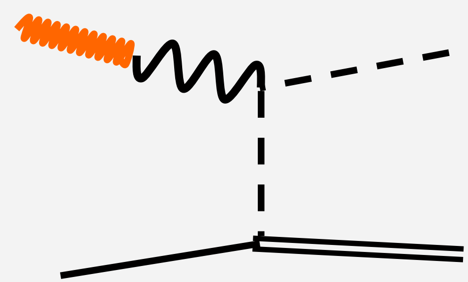
$\gamma N \rightarrow B^*$



direct resonance!



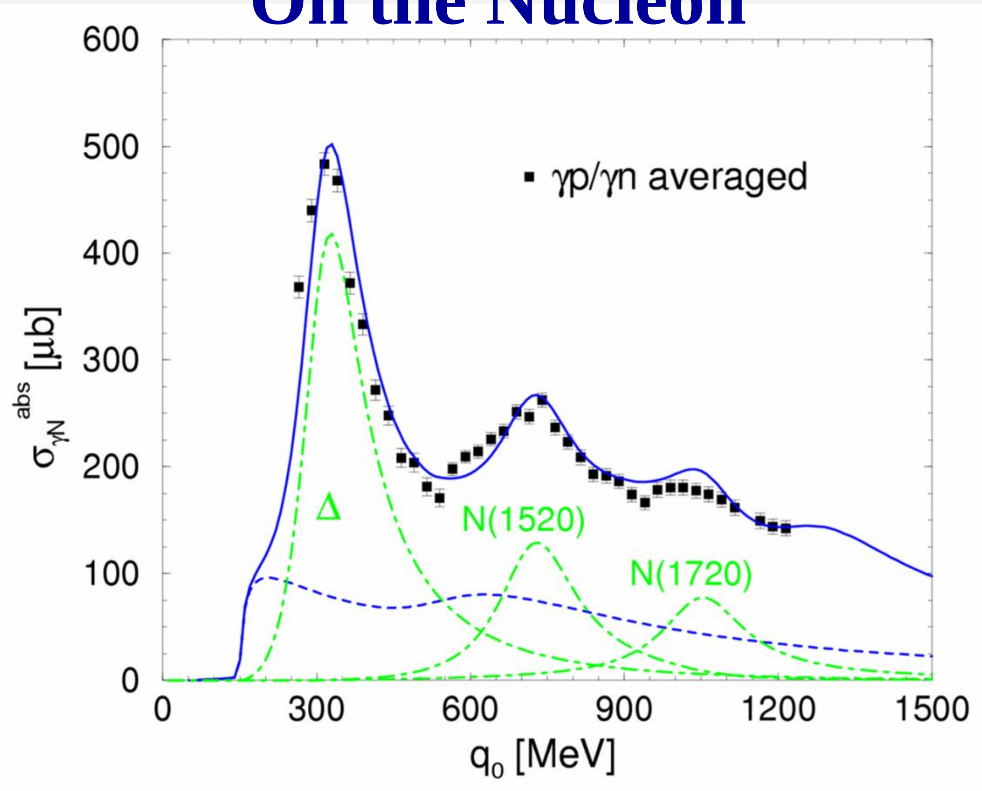
$\gamma N \rightarrow \pi N, \Delta$



meson exchange!

Light-like ρ-Spectral Function: $Im\ D_\rho(q_0=q)$ + Nuclear Photo-Absorption

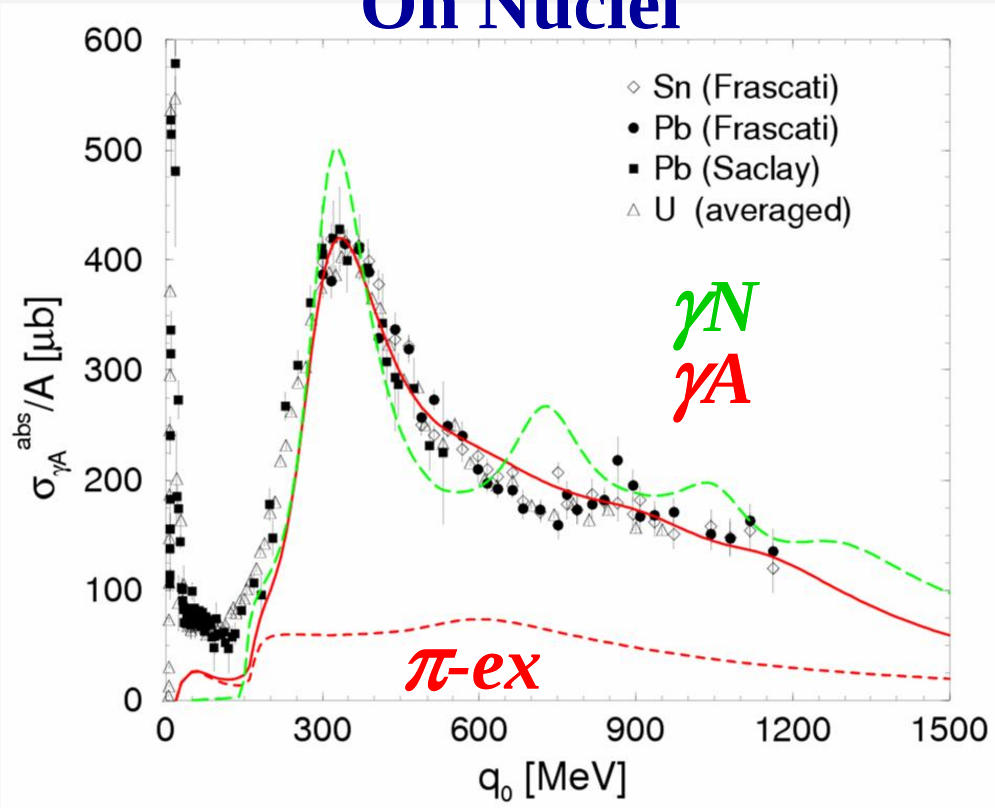
On the Nucleon



- fixes coupling constants and formfactor cutoffs for ρNB

[Urban,Buballa,RR+Wambach '98]

On Nuclei



- 2.+3. resonance melt (selfconsistent $N(1520)\rightarrow N\rho$)

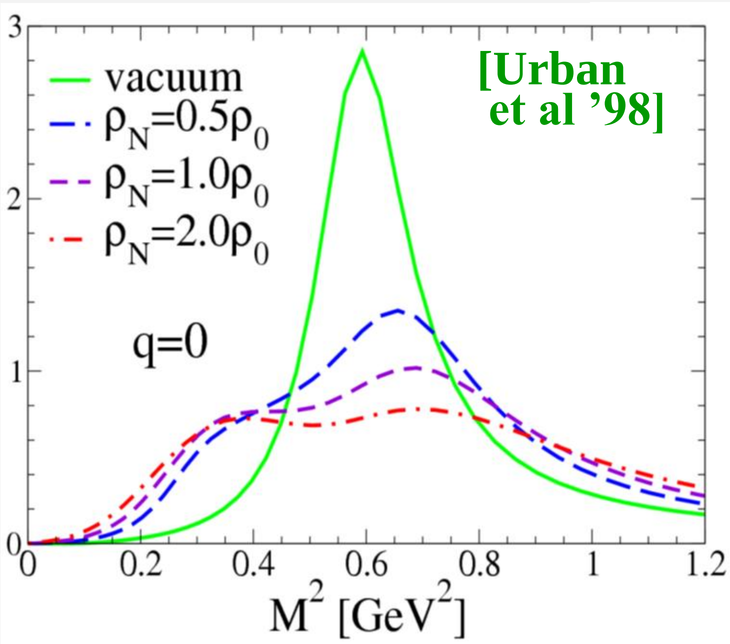
[Peters,Mosel et al '98]

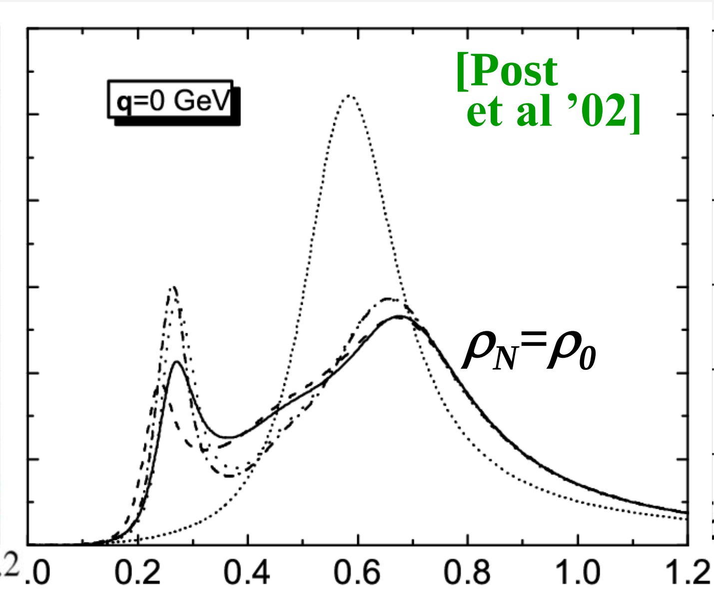
4.4 ρ Spectral Function in Nuclear Matter

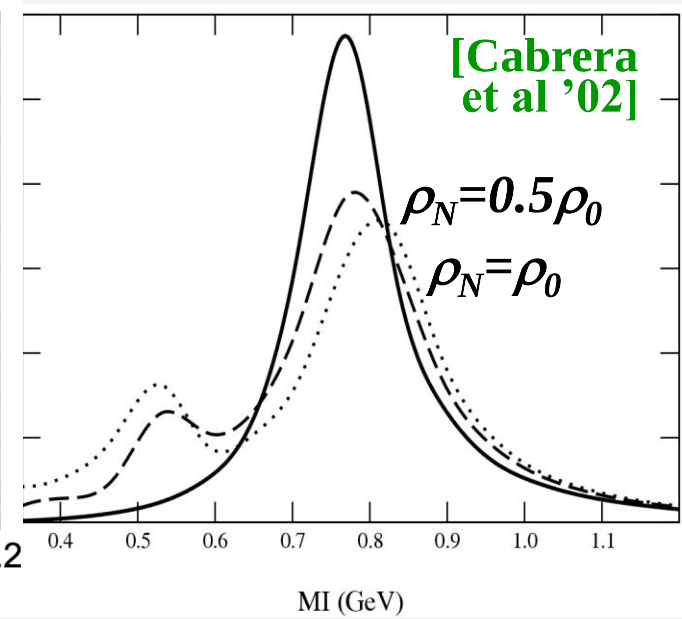
In-med. π-cloud +
ρ+N→B* resonances

ρ+N→B* resonances
(low-density approx.)

In-med π-cloud +
ρ+N → N(1520)







Constraints: γN , γA

$\pi N \rightarrow \rho N$ PWA

- Consensus: strong broadening + slight upward mass-shift
- Constraints from (vacuum) data important quantitatively

4.5 QCD Sum Rules for ρ(770) in Nuclear Matter

dispersion relation for correlator:

$$\frac{\Pi_\alpha(Q^2)}{Q^2} = \int_0^\infty \frac{ds}{s} \frac{Im\,\Pi_\alpha(s)}{Q^2+s}$$

[Shifman,Vainshtein +Zakharov '79]

- ***lhs:*** OPE (spacelike Q^2):

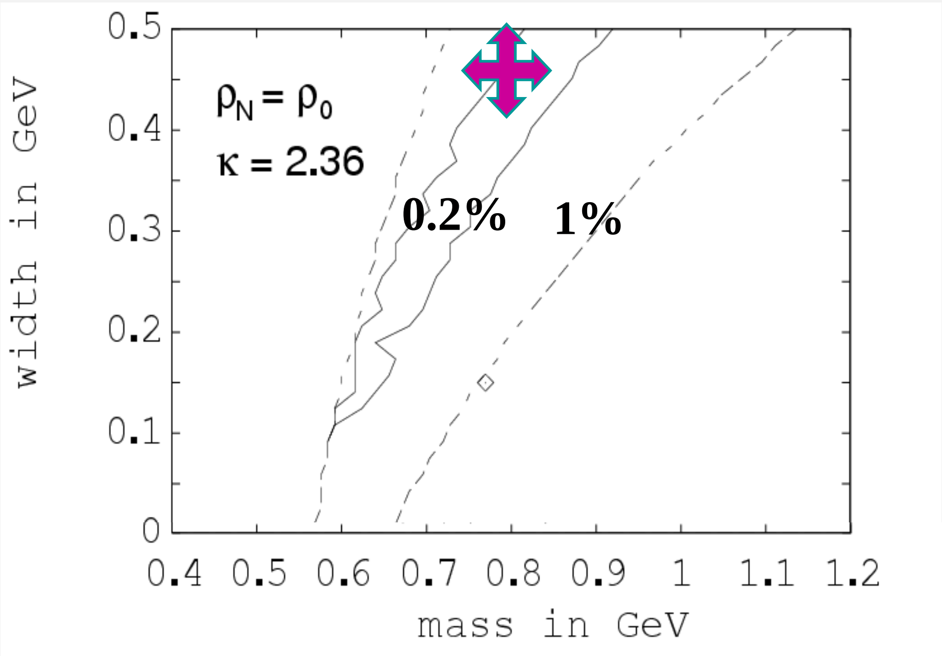
$$\Pi_\alpha(Q^2) = \sum_n \frac{c_n}{Q^{2n}}$$

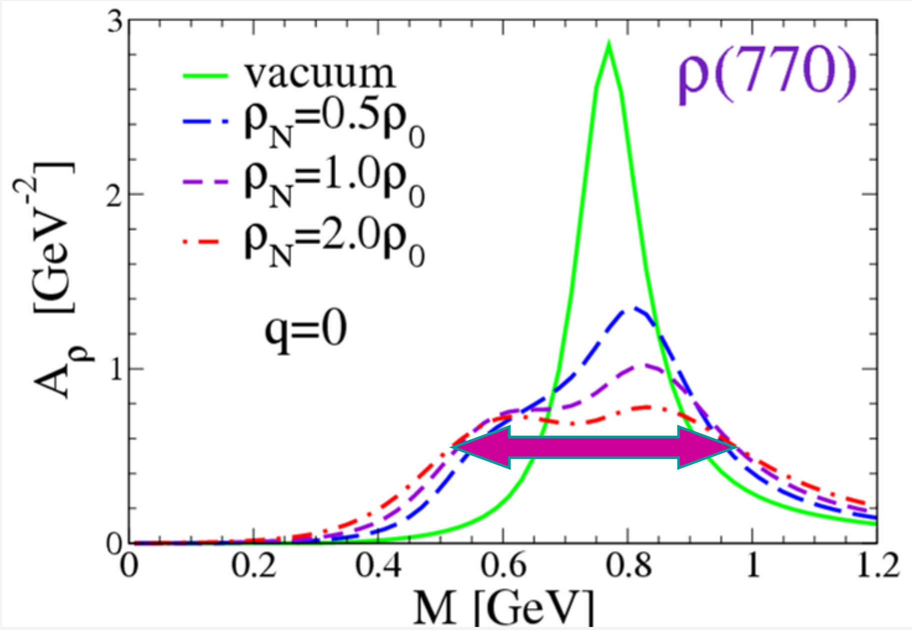
← Nonpert. Wilson coeffs (**condensates**)

- ***rhs:*** hadronic model ($s>0$):

$$Im\,\Pi_\rho(s) = \frac{m_\rho^4}{g_\rho^2} Im\,D_\rho(s) - \frac{s}{8\pi}\left(1+\frac{\alpha_s}{\pi}\right)\Theta(s-s_{dual})$$

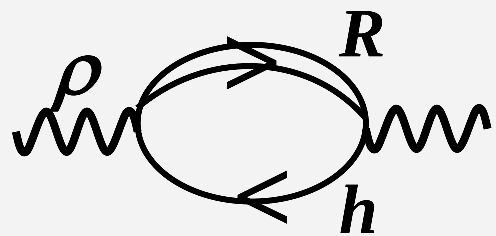
[Hatsuda+Lee'91, Asakawa+Ko '92, Klingl et al '97, Leupold et al '98, Kämpfer et al '03, Ruppert et al '05]





4.6 ρ -Hadron Interactions in Hot Meson Gas

resonance-dominated: $\rho + h \rightarrow R$, **selfenergy:**



$$\Sigma_{\rho hR} = \int \frac{d^3k}{(2\pi)^3} D_R(k+q)\, v^2_{\rho hR}\, [\, f^h(\omega_k) \pm f^R(\omega_R)]$$

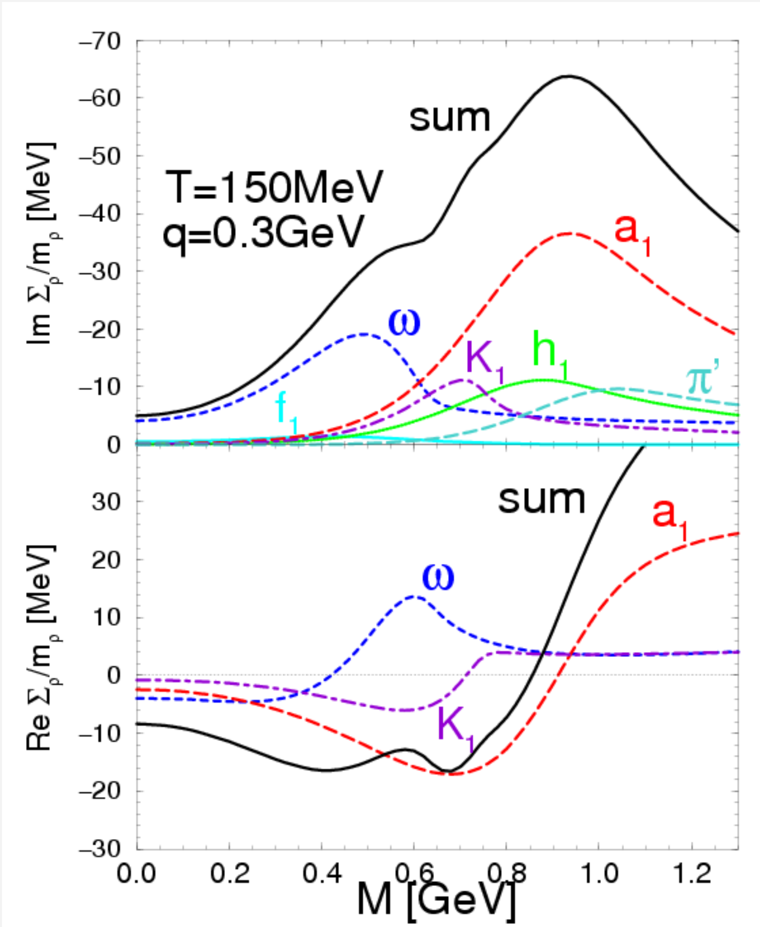
Effective Lagrangian ($h = \pi, K, \rho$)

e.g. $\mathcal{L}_{\pi\rho A} = G\, A^{\mu}\, (\partial^{\nu} \pi)\, \rho_{\mu\nu}$, $A = a_1, h_1$

fix G via $\Gamma(a_1 \rightarrow \rho\pi) \sim G^2 v^2\, PS \approx 0.4 GeV$, …

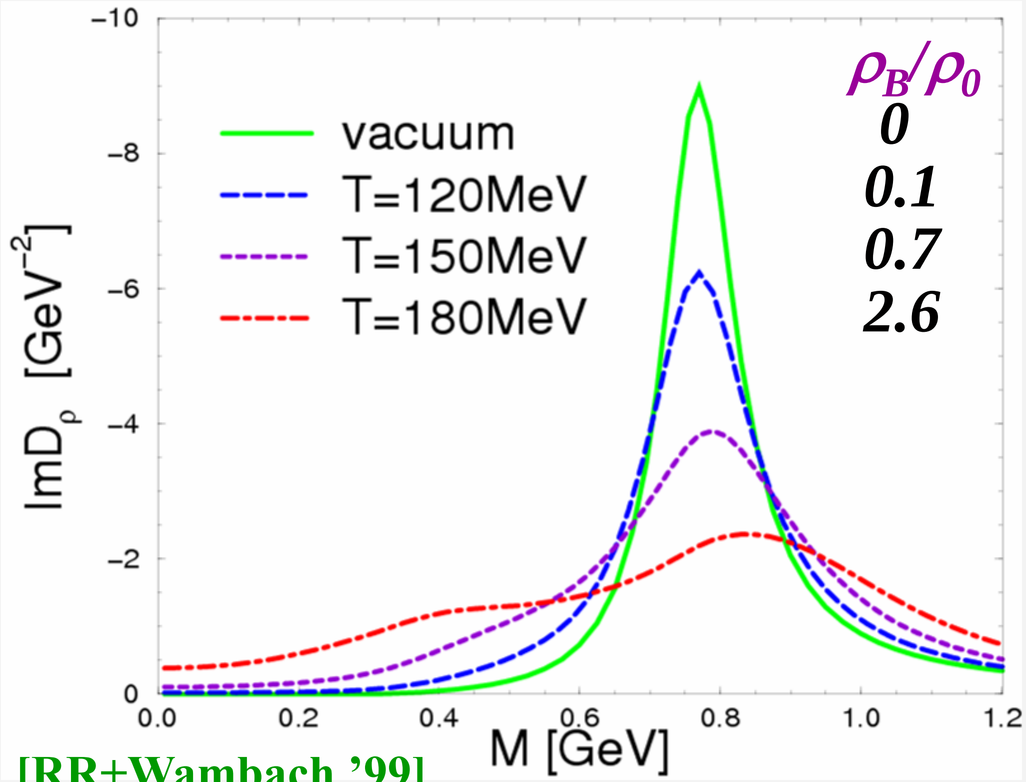
Generic features:

- **cancellations in real parts**
- **imaginary parts strictly add up**



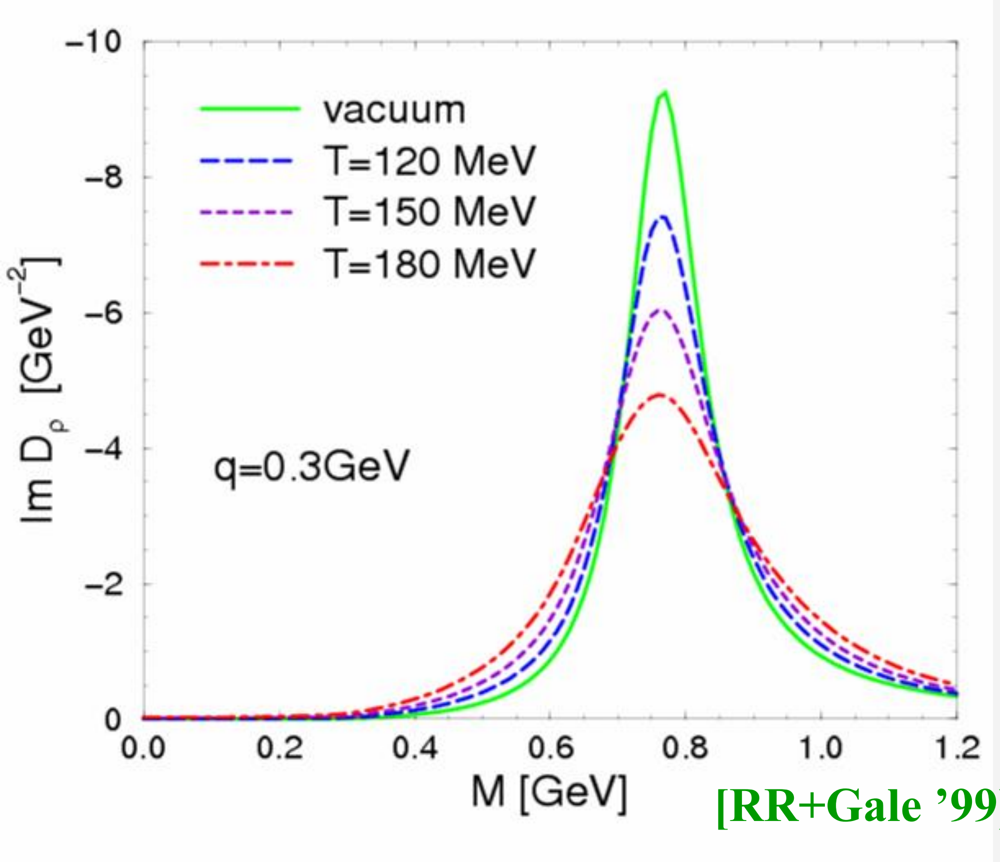
4.7 ρ-Meson Spectral Functions "at SPS"

Hot + Dense Matter



[RR+Wambach '99]

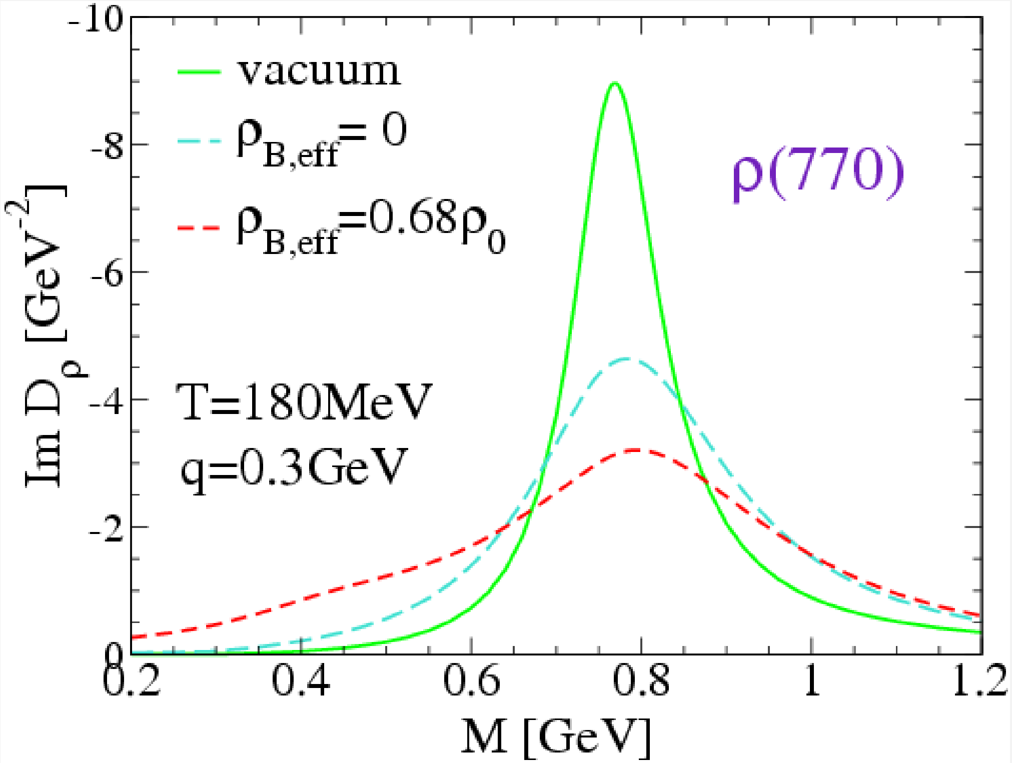
Hot Meson Gas

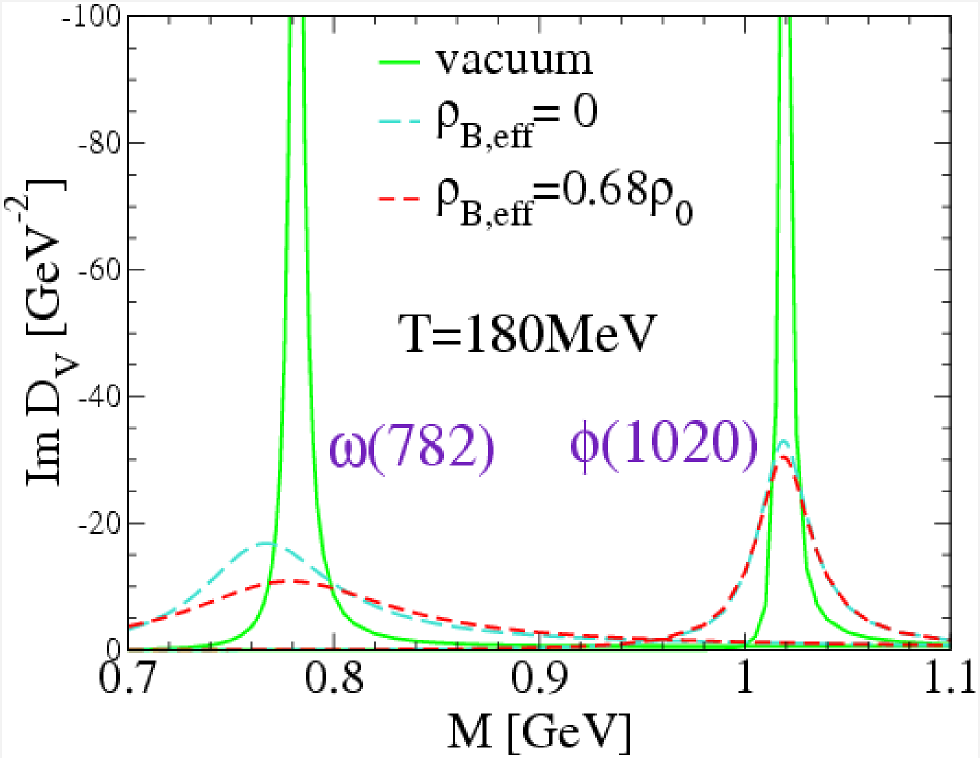


[RR+Gale '99]

- **ρ-meson "melts" in hot + dense matter close to T_c**
- **baryon density ρ_B more important than temperature**

4.7.2 Light Vector Mesons at RHIC + LHC

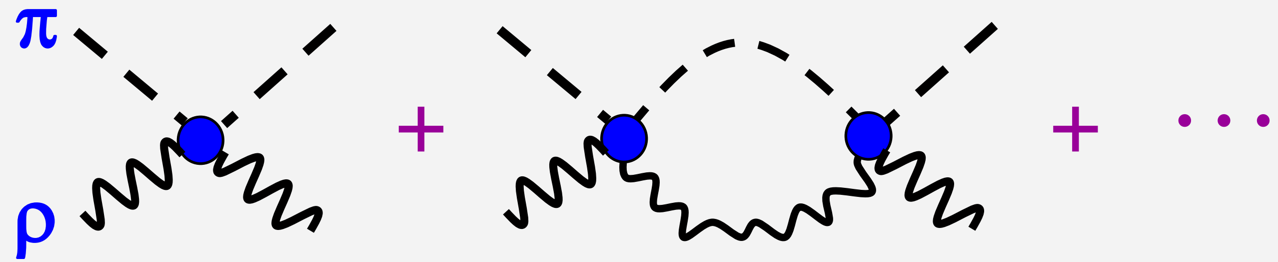




- **baryon effects important even at $\rho_{B,tot} = 0$:**
  sensitive to $\rho_{Btot} = \rho_B + \rho_{\bar{B}}$ (ρ-N and ρ-$\bar{N}$ interactions identical)
- **ω also melts, ϕ more robust ↔ OZI**

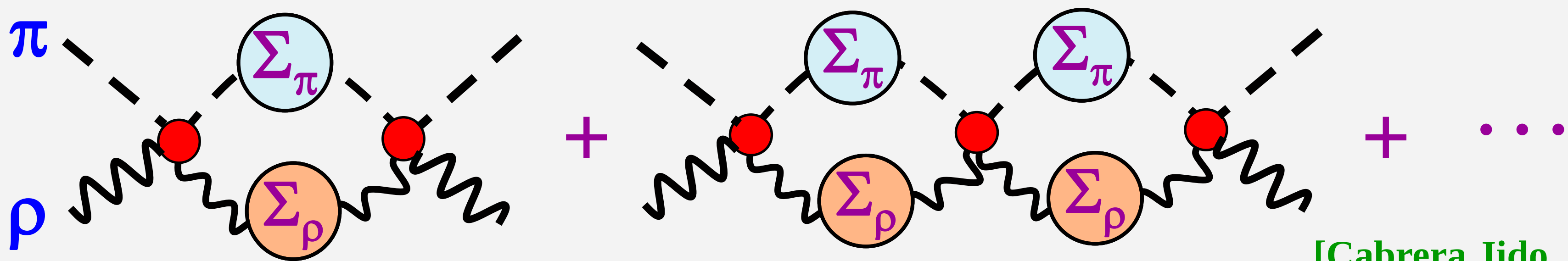
4.8 Axialvector in Medium: Dynamical $a_1(1260)$

Vacuum:

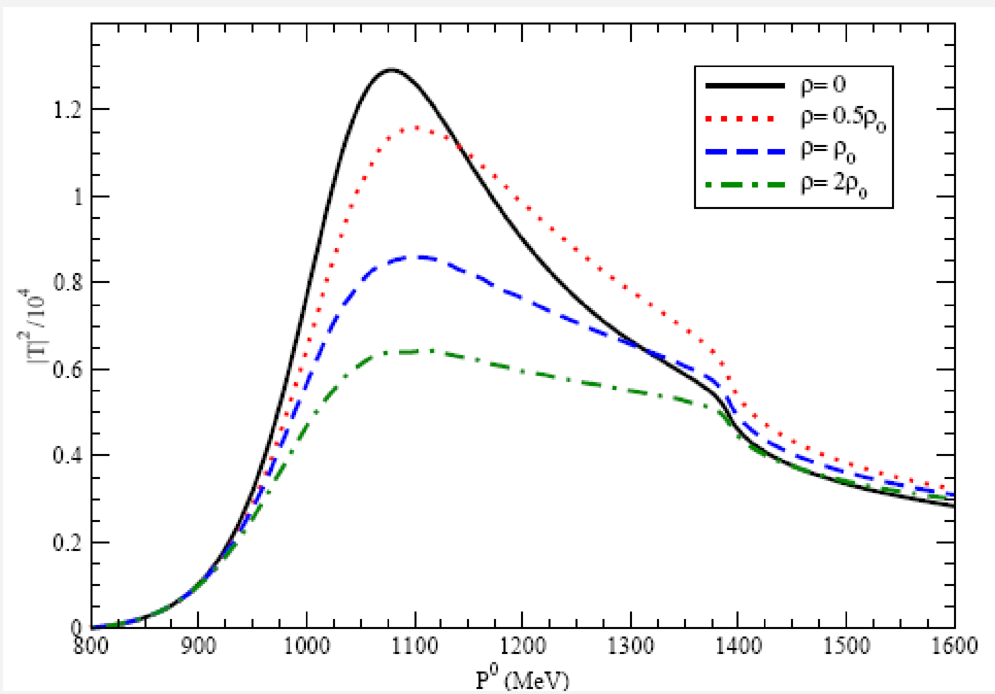


= a_1 resonance

In Medium:



[Cabrera,Jido, Roca+RR ’09]



- in-medium **π** + **ρ** propagators
- broadening of **π-ρ** scatt. Amplitude
- pion decay constant in medium:

ρ/ρ_0	present work (π-selfenergy A)	present work (π-selfenergy B)
0	93	93
1/2	100-108	91-101
1	65-86	66-93

Upshot of Chapters 2 - 4

Chiral Symmetry:

spontaneously broken in vacuum, $M_q^* \sim \langle \bar{q}q \rangle \neq 0$ (low q^2)

hadronic spectrum: chiral partners split (π-σ, ρ-a_1, …)

excite vacuum → condensate melts → chiral restoration

→ chiral partners degenerate

EM Emission Rates + Medium Effects:

imaginary part of el.mg. current correlator (photon selfenergy)

perturbative ($q\bar{q}$) - nonpert. (ρ,ω,ϕ); "duality scale" $s_{dual} \sim (1.5 GeV)^2$

in-med radiation: low-mass ↔ ρ-meson, high-mass ↔ QGP

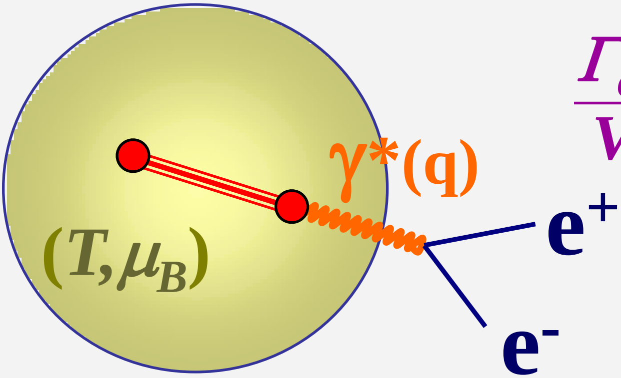
many-body theory: eff. Lagrangian + constraints; broadening!

Theory of Soft Electromagnetic Emission in Heavy-Ion Collisions

Ralf Rapp
Cyclotron Institute
+ Physics Department
Texas A&M University
College Station, Texas
USA

51. Cracow School of Theoretical Physics on
"Soft Side of the LHC"
Zakopane (Poland), June 11-19, 2010

E.M. Correlator + Thermal Dilepton Emission



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

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

E.M. Correlation Fct.: $$\Pi_{em}^{\mu\nu}(q)=-i\int d^4x\, e^{iqx}\langle j_{em}^\mu(x)\,j_{em}^\nu(0)\rangle_T$$

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

hadron basis: $$j_{em}^\mu=\frac{1}{2}(\bar{u}\gamma^\mu u-\bar{d}\gamma^\mu d)+\frac{1}{6}(\bar{u}\gamma^\mu u+\bar{d}\gamma^\mu d)-\frac{1}{3}\bar{s}\gamma^\mu s$$
$$=\frac{1}{\sqrt{2}}j_\rho^\mu+\frac{1}{3\sqrt{2}}j_\omega^\mu-\frac{1}{3}j_\phi^\mu$$

Outline

2.) Chiral Symmetry in QCD

- Nonperturbative QCD, Chiral Breaking + Hadron Spectrum

3.) Thermal Electromagnetic Emission Rates

- EM Spectral Function: Hadronic vs. Partonic Regimes

4.) Vector Mesons in Medium

- Many-Body Theory, Spectral Functions + Chiral Partners (ρ-a_1)

5.) Quark-Gluon Plasma Emission

- Perturbative vs. Lattice-QCD Rates, "Quark-Hadron-Duality"

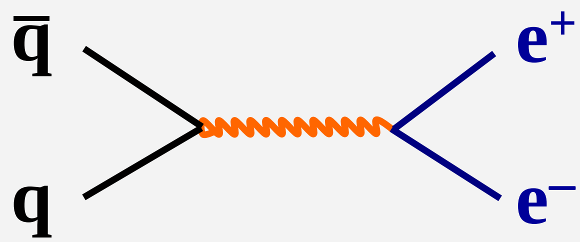
6.) Dilepton + Photon Spectra in Heavy-Ion Collisions

- Space-Time Evolution, Phenomenology + Interpretation

7.) Summary and Conclusions

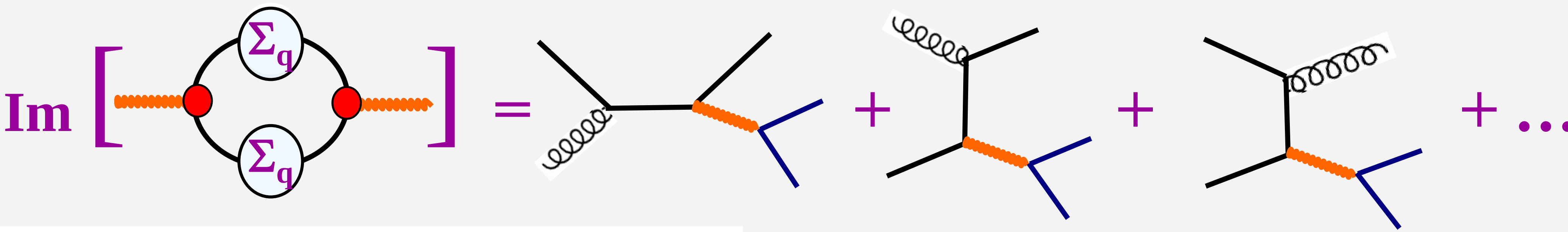
5.1 QGP Emission: Perturbative vs. Lattice QCD

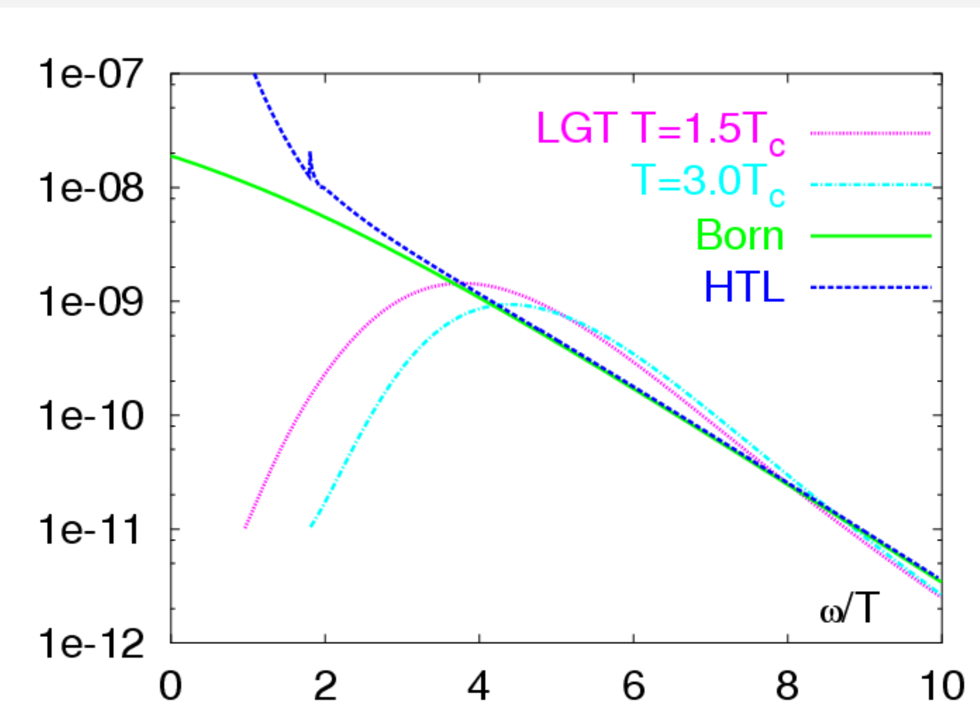
Baseline:



But: small *M* → resummations
finite-*T* perturbation theory (HTL)

[Braaten,Pisarski+Yuan '91]



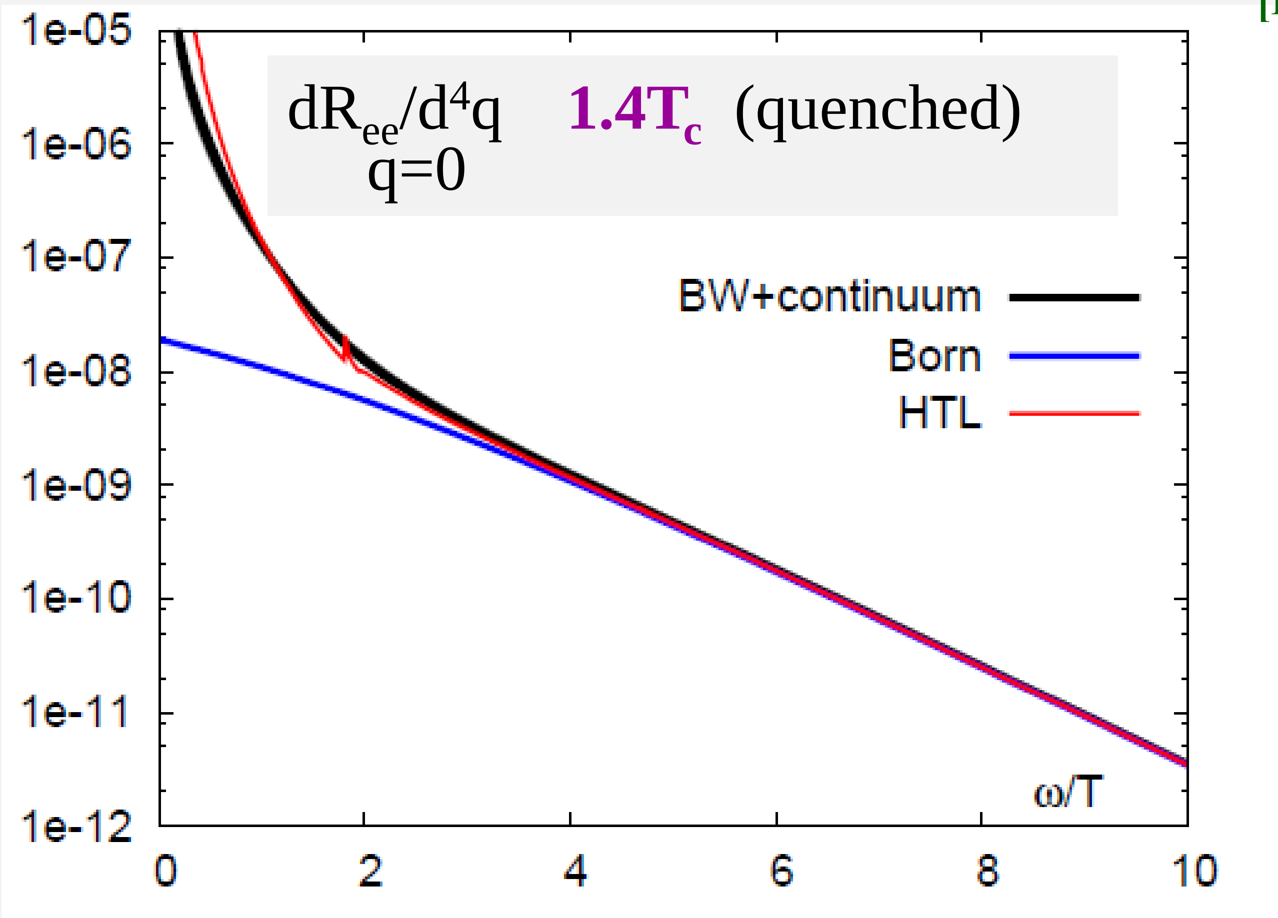


collinear enhancement:
$D_{q,g}=(t-m_D^2)^{-1} \sim 1/\alpha_s$

- large enhancement at low *M*
- not shared by lattice calculations at the time **[Bielefeld Group '02]**

5.2 Updated Dilepton Rate from Lattice QCD

[Kaczmarek et al ’10]



- low-mass enhancement in lattice rate!
- similar to hard-thermal-loop resummed perturbation theory

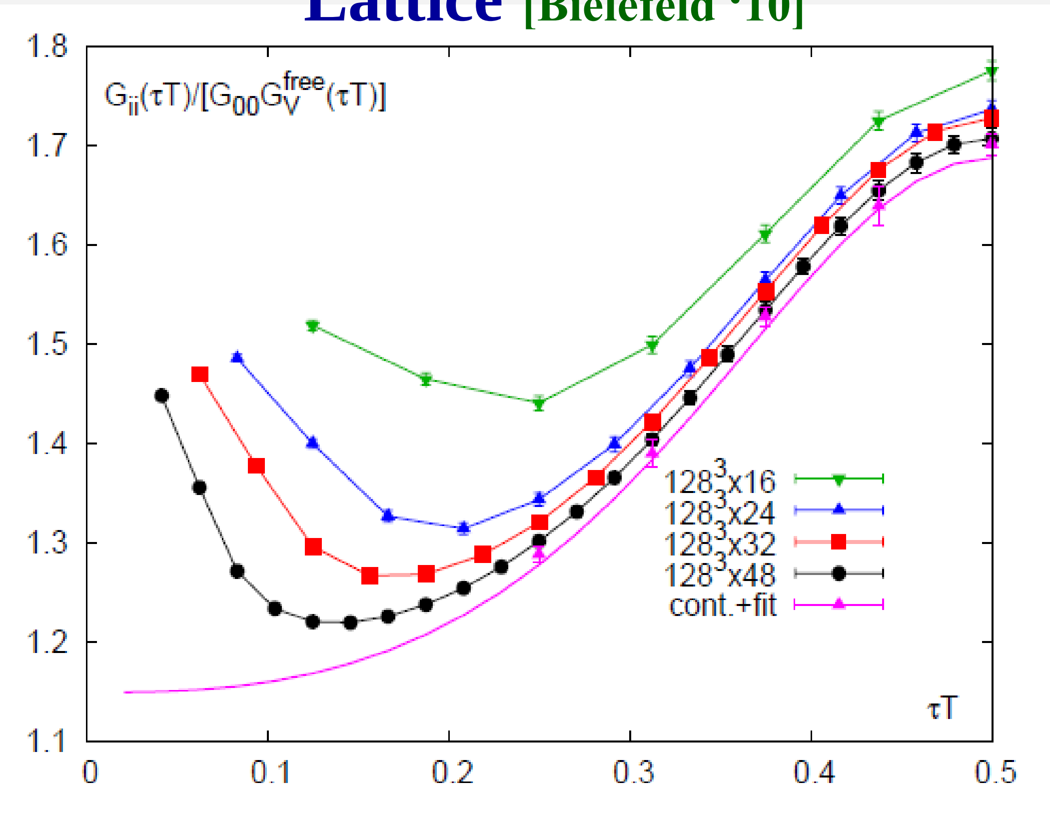
[Braaten,Pisarski+Yuan ‘90]

5.2.2 Euclidean Correlators: Lattice vs. Hadronic

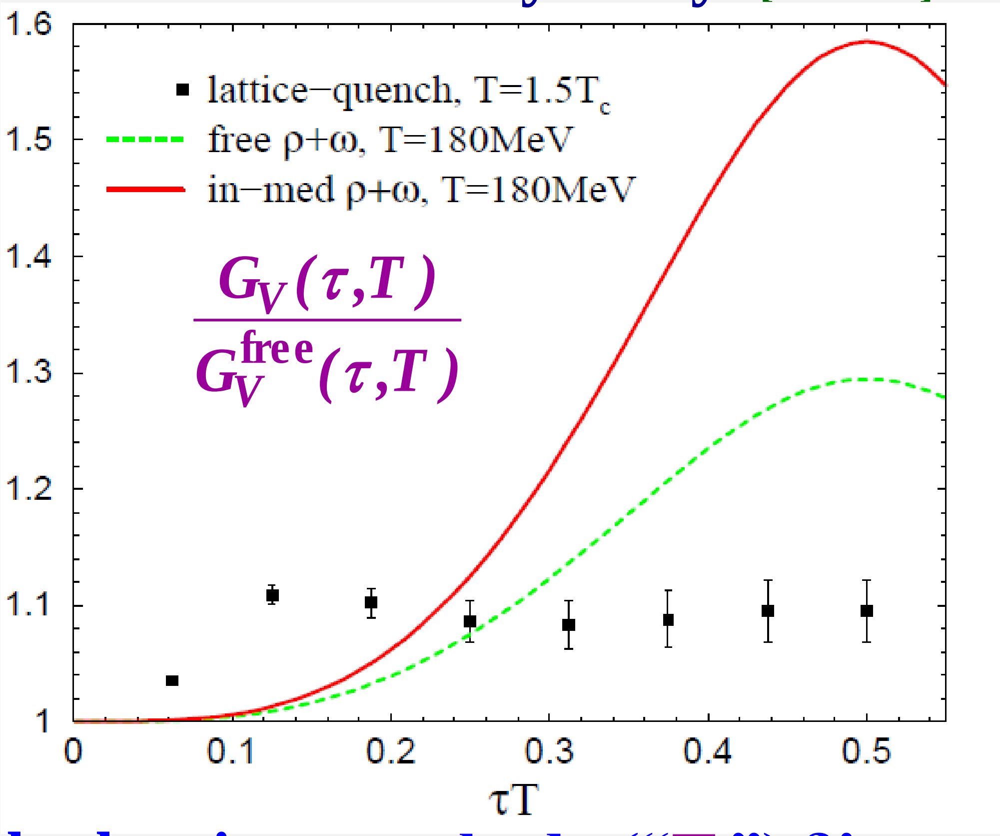
- **Euclidean Correlation fct.**

$$G_V(\tau,q;T) = \int_0^\infty \frac{dq_0}{2\pi}\, \rho_V(q_0,q;T)\, \frac{\cosh[q_0(\tau-1/2T)]}{\sinh[q_0/2T]}$$

Lattice [Bielefeld '10]

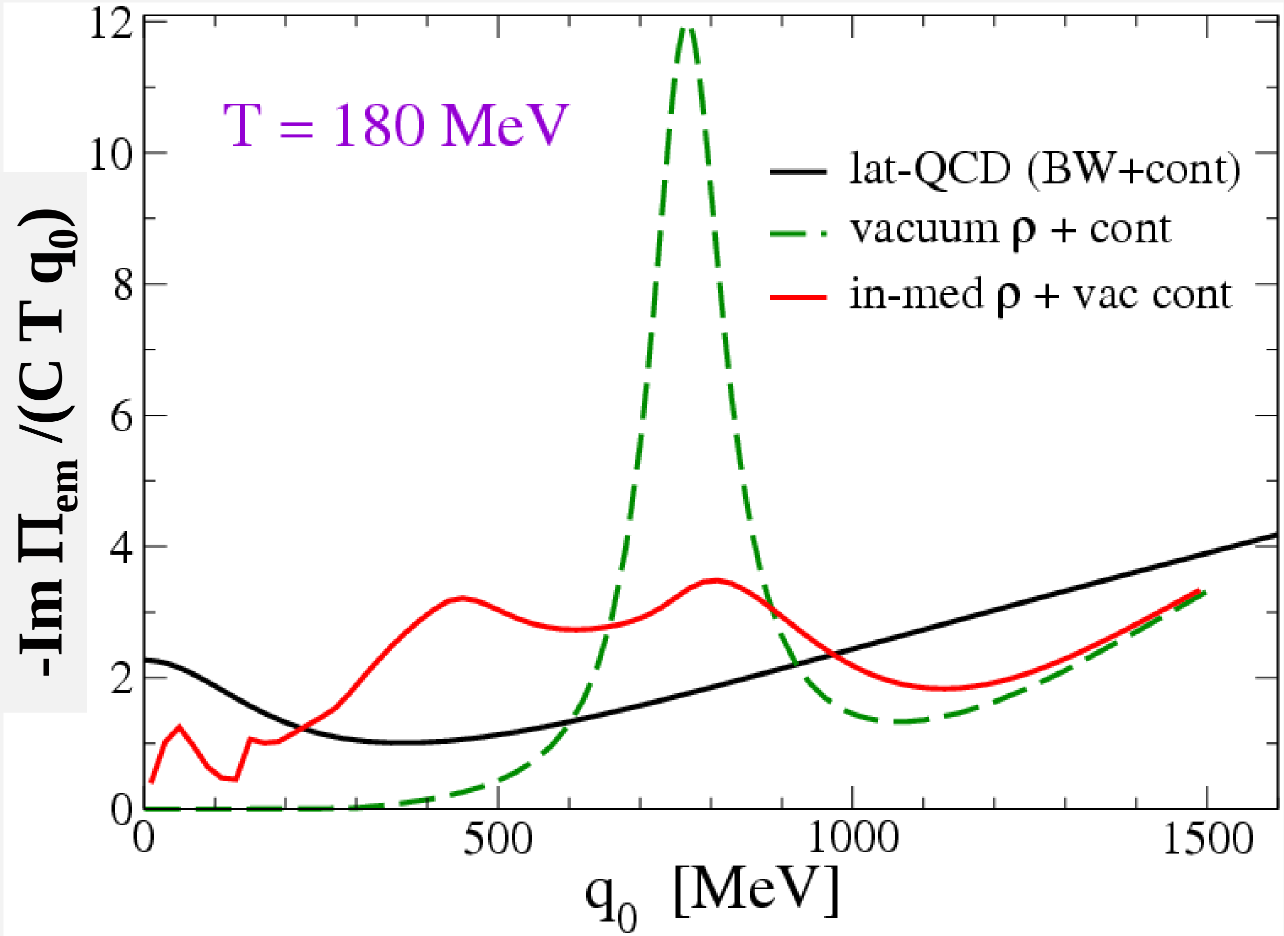


Hadronic Many-Body [RR '02]



- **"Duality" of lattice (1.5 T_c) with hadronic many-body ("T_c") ?!**
- discrimination power vacuum vs. in-medium ρ/ω

5.2.3 Back to Spectral Function

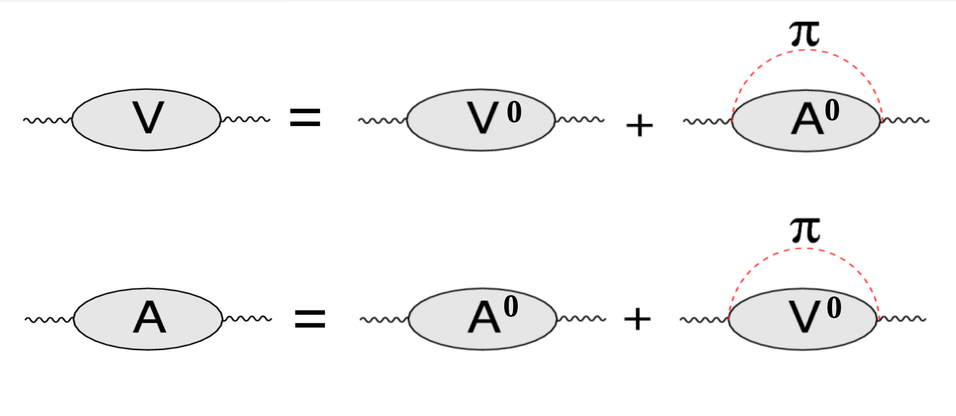


• **suggestive approach to chiral restoration and deconfinement !?**

5.3 Intermediate Mass Emission: "Chiral Mixing"

[Dey, Eletsky +Ioffe '90]

- low-energy pion interactions fixed by chiral symmetry



$$\Pi_V^{\mu\nu}(q) = (1-\varepsilon)\,\Pi_V^{0,\mu\nu}(q) + \varepsilon\,\Pi_A^{0,\mu\nu}(q)$$

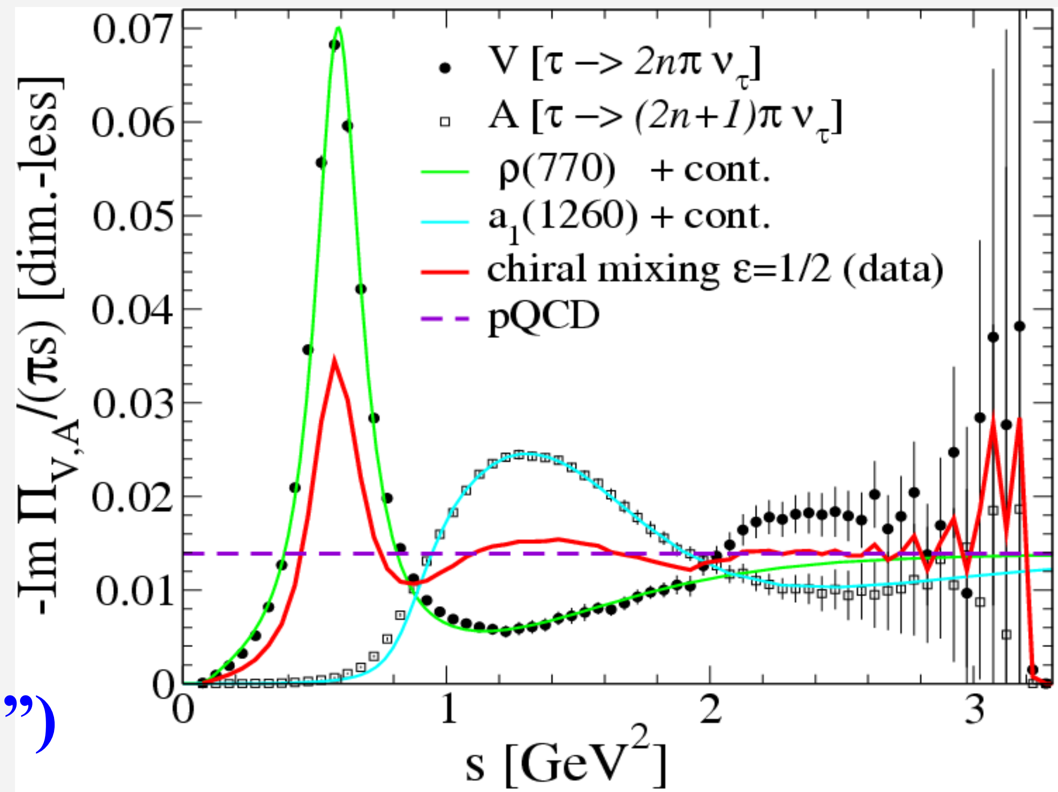
$$\Pi_A^{\mu\nu}(q) = (1-\varepsilon)\,\Pi_A^{0,\mu\nu}(q) + \varepsilon\,\Pi_V^{0,\mu\nu}(q)$$

- mixing parameter

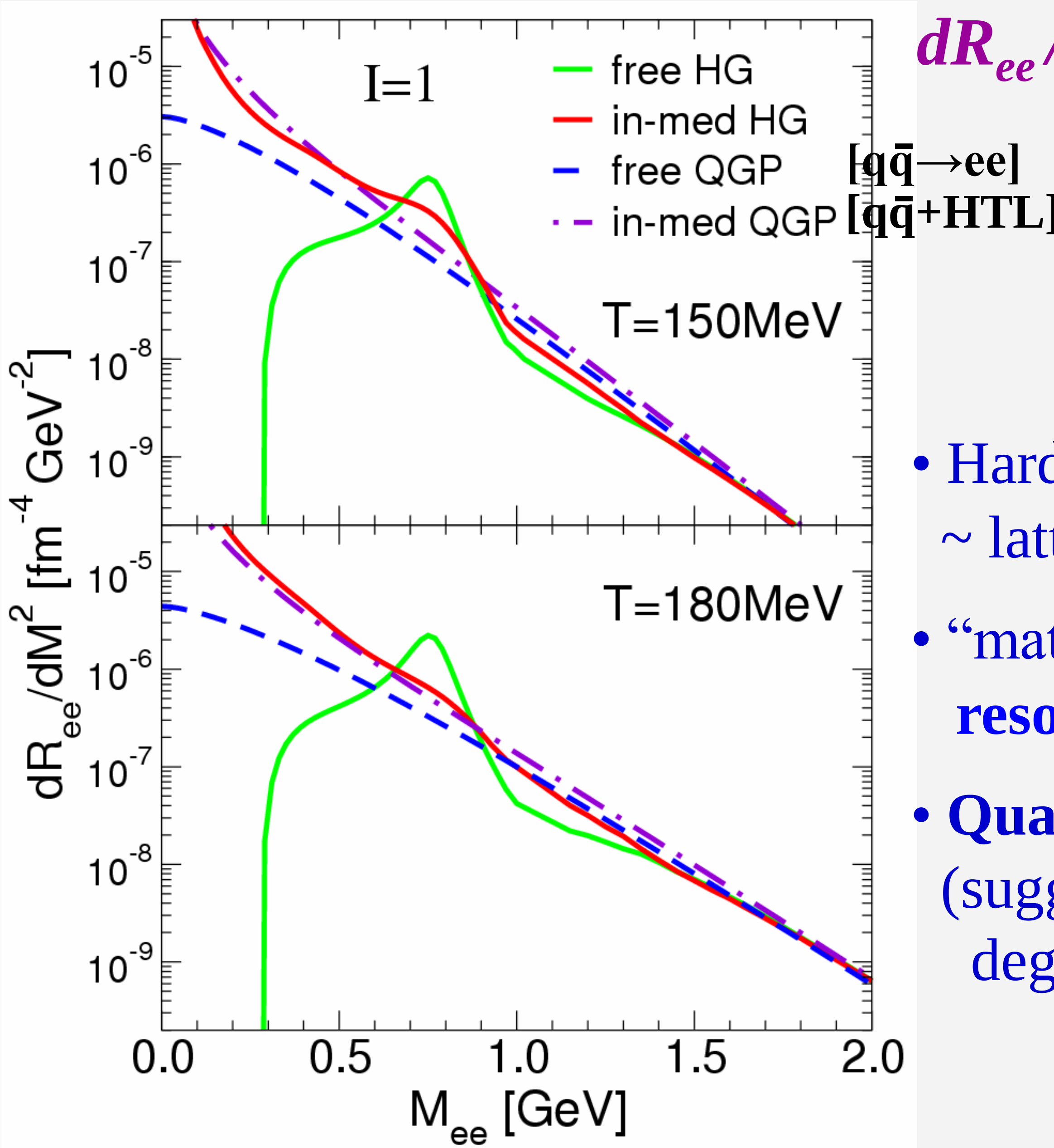
$$\varepsilon = \frac{4}{f_\pi^2}\int \frac{d^3k}{(2\pi)^3 2\omega_k}\, f^\pi(\omega_k) \;\approx \frac{T^2}{6 f_\pi^2}$$

- degeneracy with perturbative spectral fct. down to M~1GeV

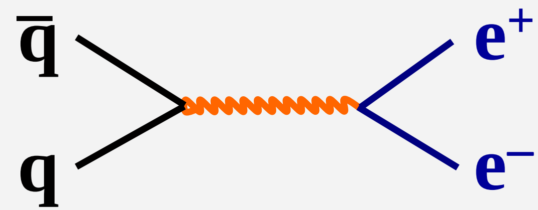
- physical processes at M≥ 1GeV: $\pi a_1 \rightarrow e^+e^-$ etc. ("4π annihilation")



5.4 Summary of Dilepton Rates: HG vs. QGP



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



- Hard-Thermal-Loop ~ lattice-QCD rate
- "matching" **HG - QGP** at $\sim T_{c}$: **resonance melting + chiral mixing**
- **Quark-Hadron Duality** at all M_{ee}?! (suggestive for chiral restoration: degenerate axialvector SF!)

Outline

2.) **Chiral Symmetry in QCD**

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5.) **Quark-Gluon Plasma Emission**

- Perturbative vs. Lattice-QCD Rates, "Quark-Hadron-Duality"

6.) **Dilepton + Photon Spectra in Heavy-Ion Collisions**

- Space-Time Evolution, Phenomenology + Interpretation

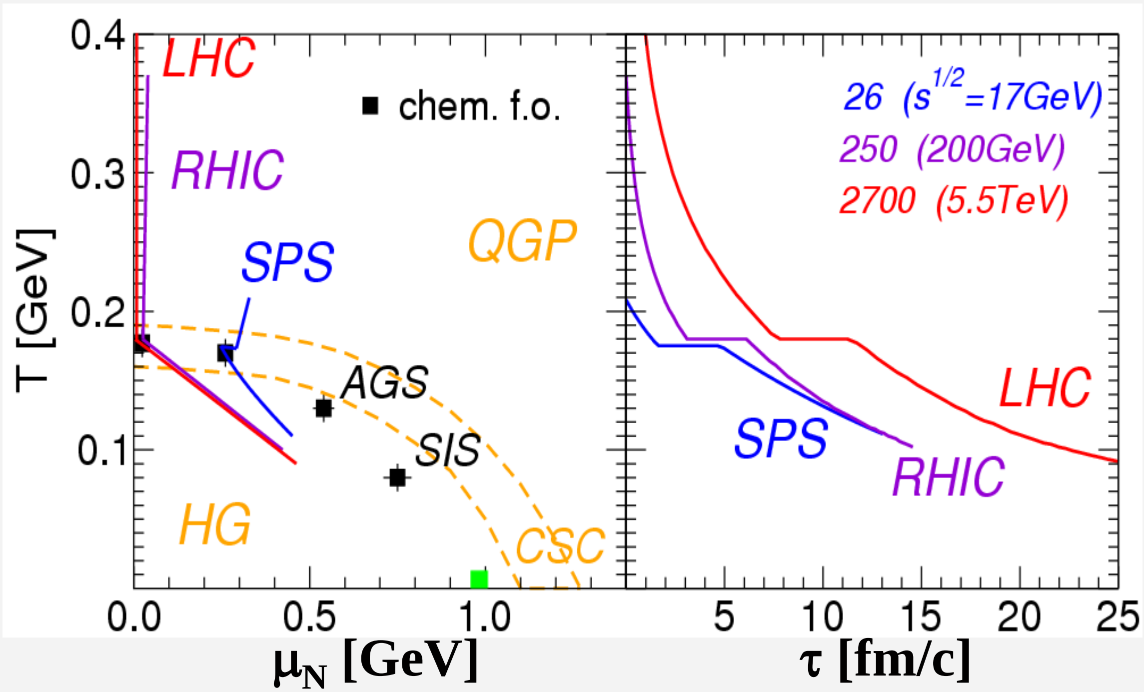
7.) **Summary and Conclusions**

6.1 Fireball Evolution in Heavy-Ion Collisions

Thermal Dilepton Spectrum:

$$\frac{dN_{ee}^{therm}}{dM} = \int_{\tau_0}^{\tau_{fo}} d\tau V_{FB}(\tau) \int \frac{M\, d^3q}{q_0} \frac{dN_{ee}^{therm}}{d^4x d^4q}(M,q;T,\mu_i)\; Acc(M,y)$$

Isentropic Trajectories in the Phase Diagram



- "chemical" freezeout $T_{chem} \sim T_c \sim$ **170MeV**, "thermal" freezeout $T_{fo} \sim$ **120MeV**
- conserve entropy + baryon no.: $T_i \rightarrow T_{chem} \rightarrow T_{fo}$
- time scale: hydrodynamics, fireball $V_{FB}(\tau) = (z_0+v_z\,\tau)\;\pi\,(r_0 + 0.5a_\perp\,\tau^2)^2$

6.1.2 Emission Profile of Thermal EM Radiation

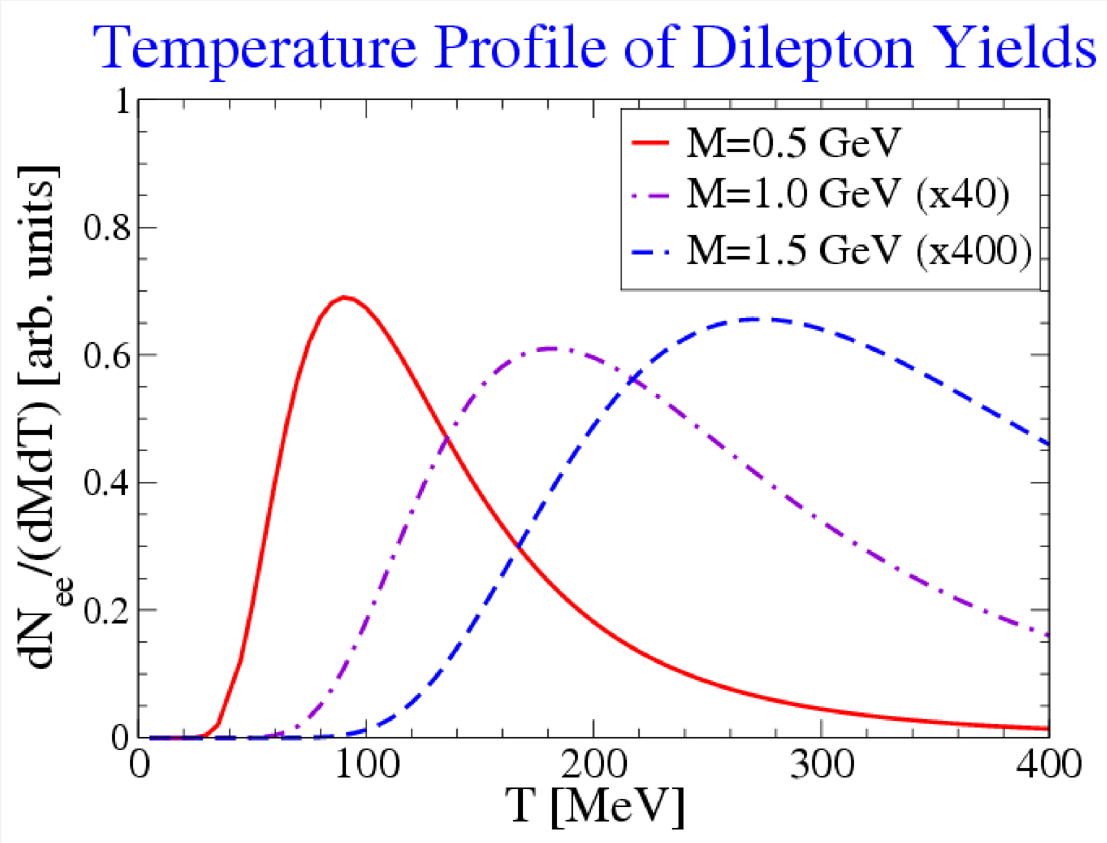
- generic space-time argument:

$$\frac{dN_{ee}}{dMd\tau} = \frac{M}{q_0}\int d^3x d^3q \frac{dN_{ee}}{d^4x d^4q} \propto V_{FB}(T)\frac{Im\Pi_{em}}{M} e^{-M/T}(MT)^{3/2}$$

$$\Rightarrow \quad \frac{dN_{ee}}{dM\,dT} \propto Im\Pi_{em}(M,T)\ e^{-M/T}\ T^{-5.5}$$

$\Rightarrow$ $T_{max} \approx M / 5.5$
(for $Im\Pi_{em}$ =const)

- Additional **T**-dependence from EM spectral function
- Latent heat at T_c not included (penalizes $T > T_c$, i.e. QGP)



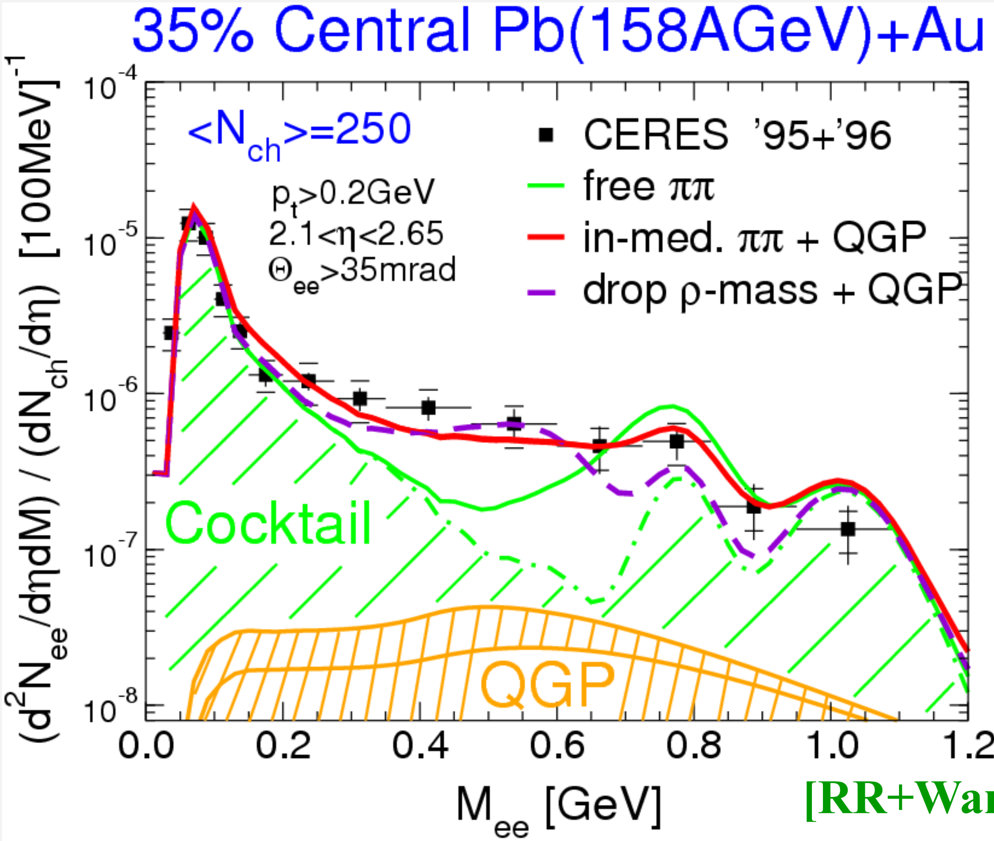
6.2 Low-Mass Di-Electrons: CERES/NA45

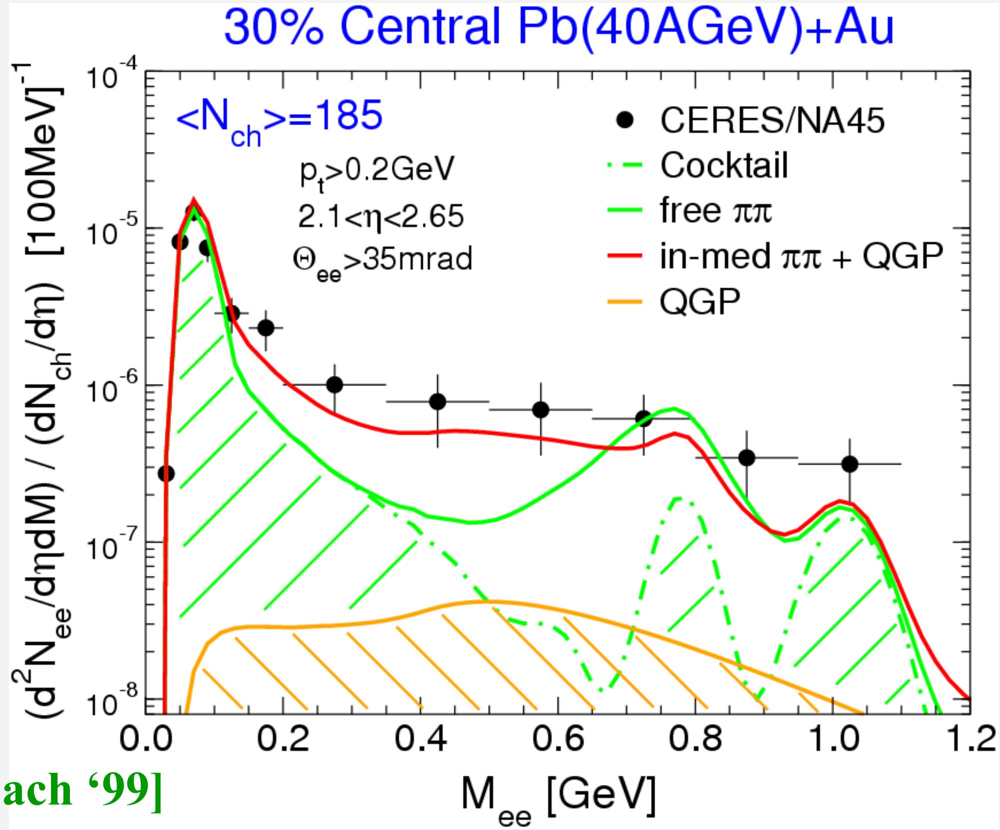
Top SPS Energy

($T_i \sim 200$MeV $\rightarrow$ T_{fo}~110 MeV)

Lower SPS Energy

($T_i \sim 170$MeV$\rightarrow$ T_{fo}~100MeV)





[RR+Wambach '99]

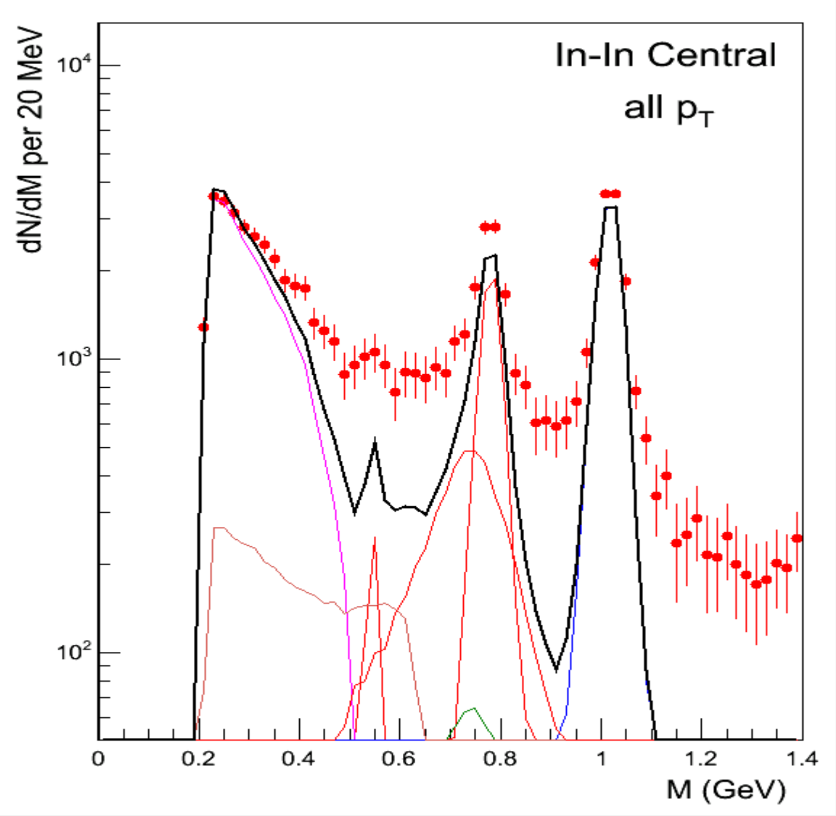
- QGP contribution small
- **medium effects!**
- drop. mass or broadening?!

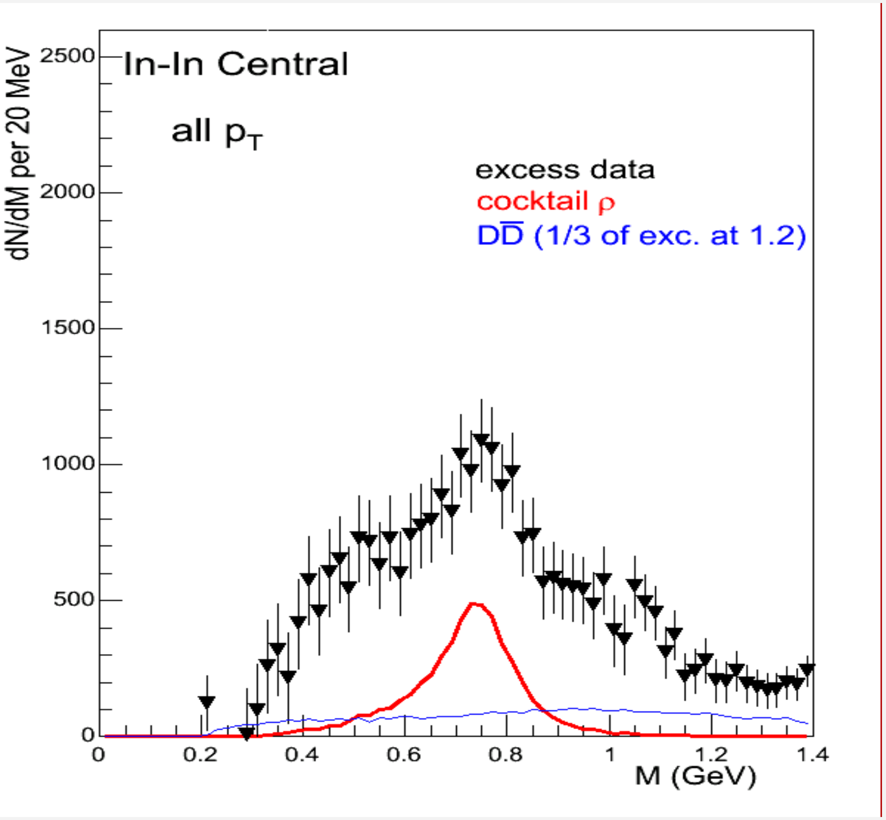
- enhancement increases!?
- supports importance of baryonic effects

6.3 In-In at SPS: Dimuons from NA60

[Damjanovic et al. PRL '06]

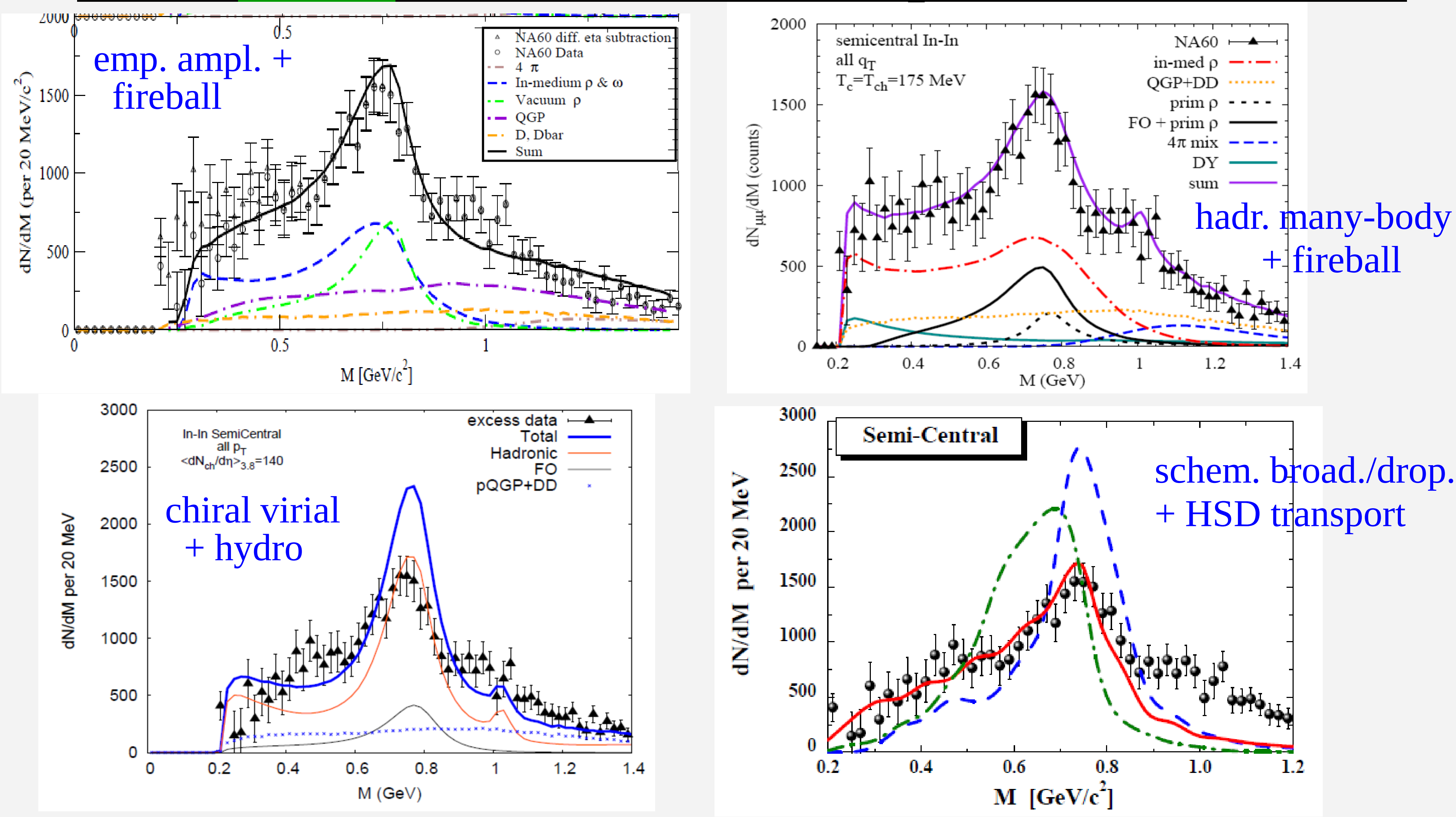
- excellent mass resolution and statistics
- for the first time, dilepton excess spectra could be extracted!





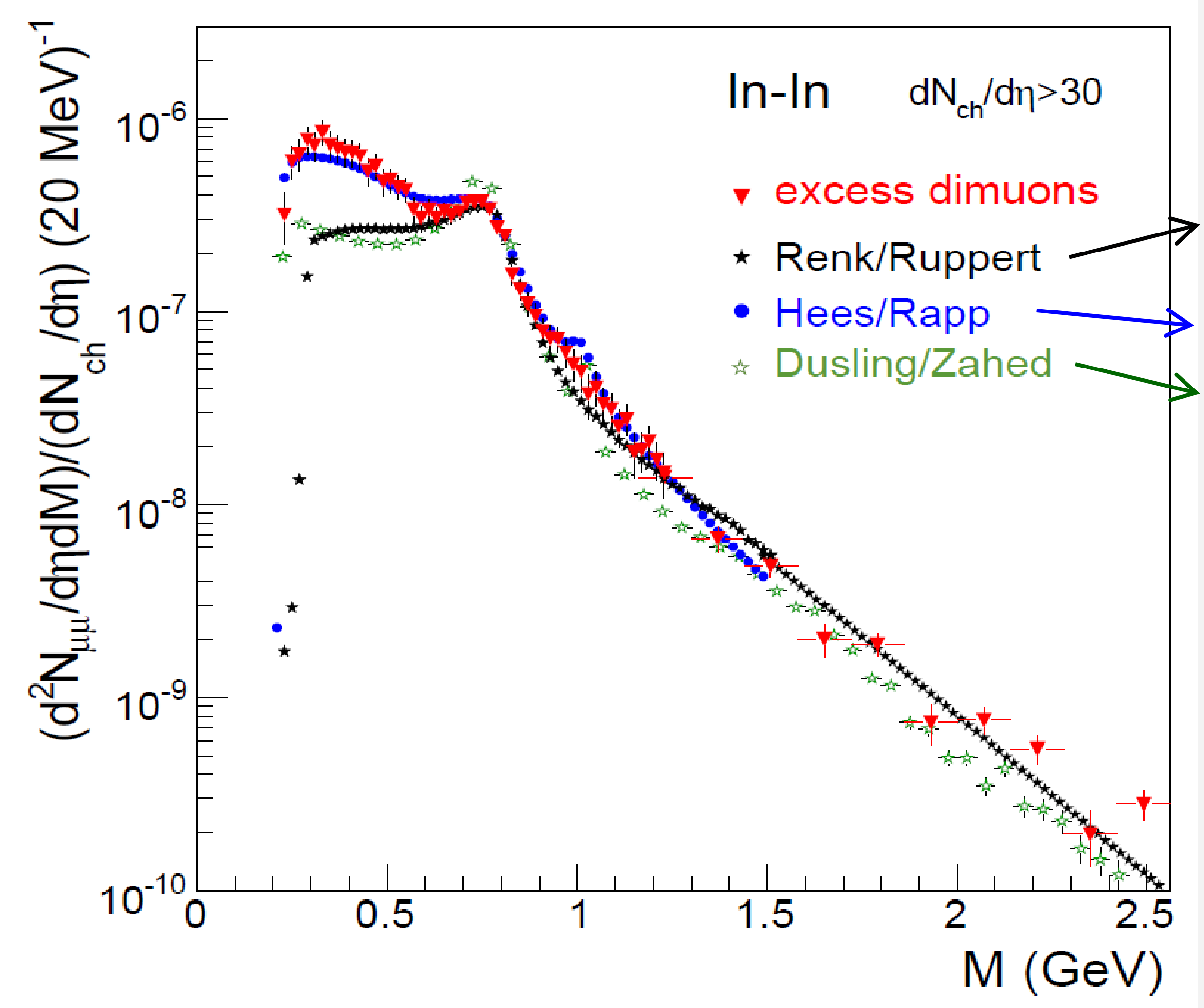
- quantitative theory?

6.3.2 NA60 Data Before Acceptance Correction



- **Discrimination power of model calculations improved, but limited**
- can compensate spectral “deficit” by larger flow: lift pairs into acceptance

6.3.3 NA60 II: Acceptance-Corrected Mass Spectra



Emp. scatt. ampl. + T-ρ approximation

Hadronic many-body

Chiral virial expansion

[CERN Courier Nov. 2009]

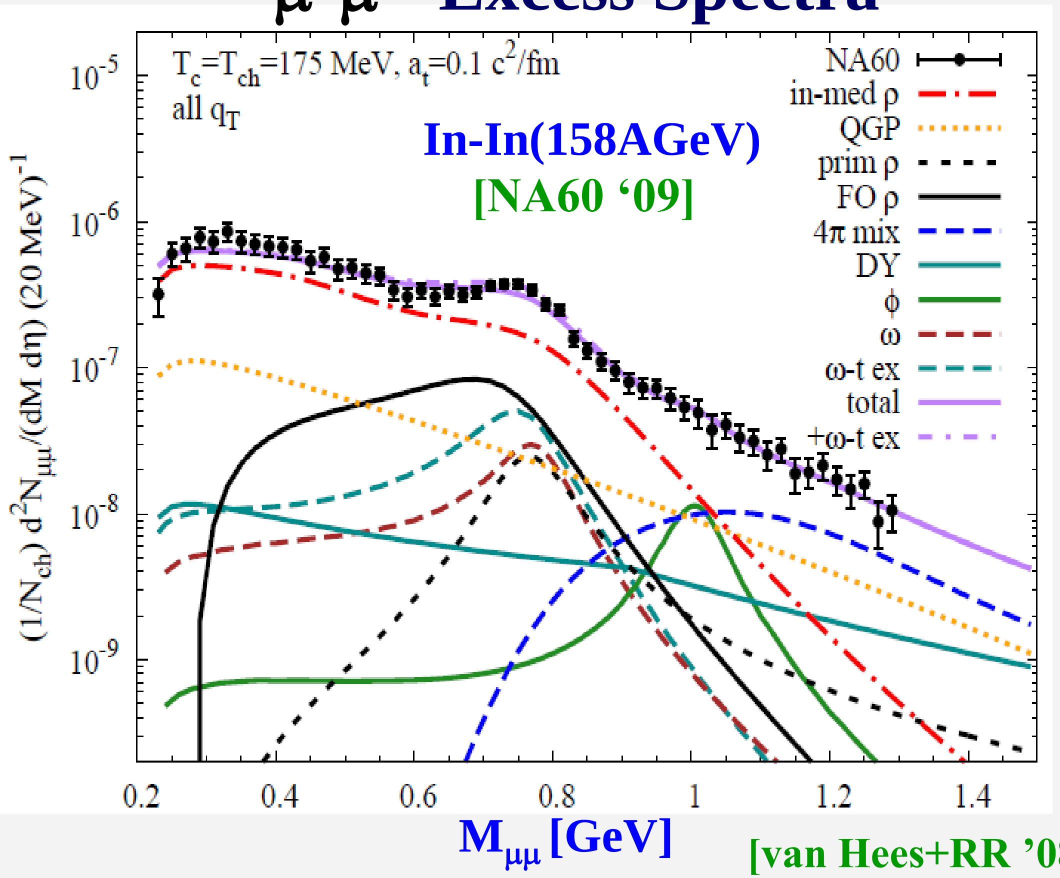
- **Thermal source** does well overall (isotropic!)
- Low-mass: **good sensitivitiy to medium effects (ΔT~130-170MeV)**
- Intermediate-mass: **decomposition varies, but ΔT~160-210MeV**

6.3.4 NA60 III: “Spectrometer” at SPS

- **Evolve rates over fireball expansion:**

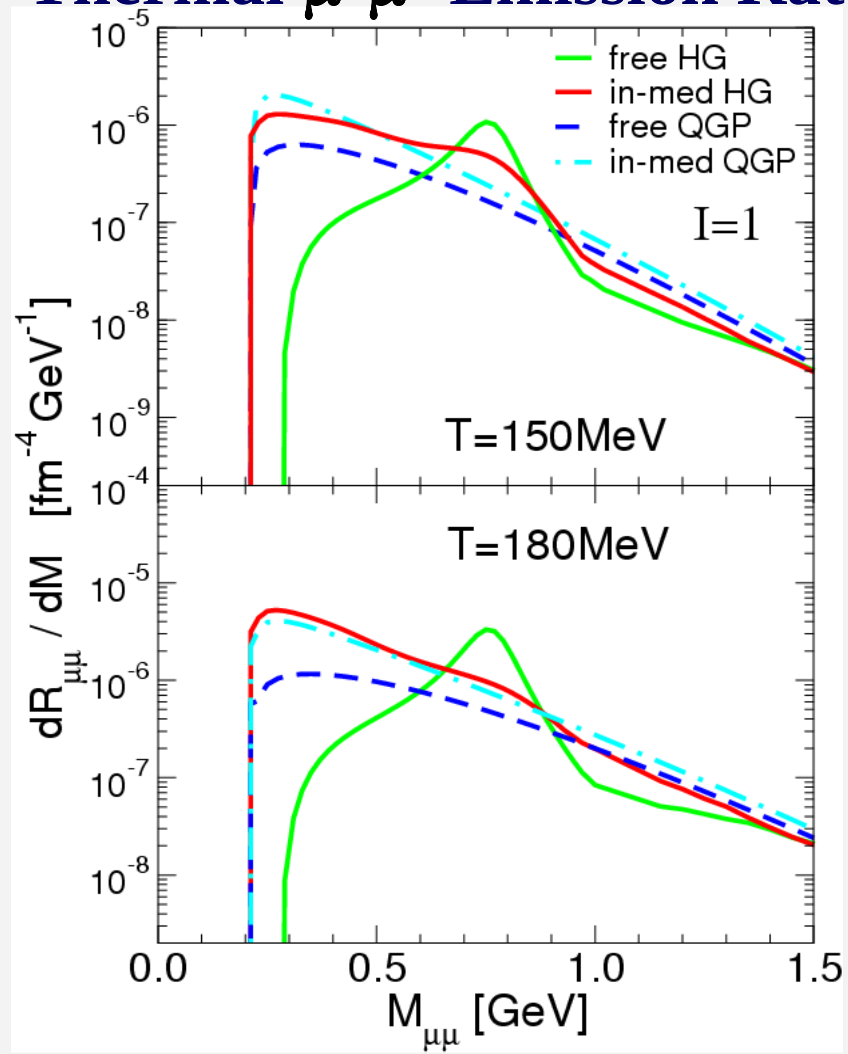
$$\frac{dN_{ee}^{therm}}{dM^2} = \int_{\tau_0}^{\tau_{fo}} d\tau V_{FB}(\tau) \int \frac{d^3q}{2q_0} \frac{dR_{ee}^{therm}}{d^4q}$$

$\mu^+\mu^-$ Excess Spectra



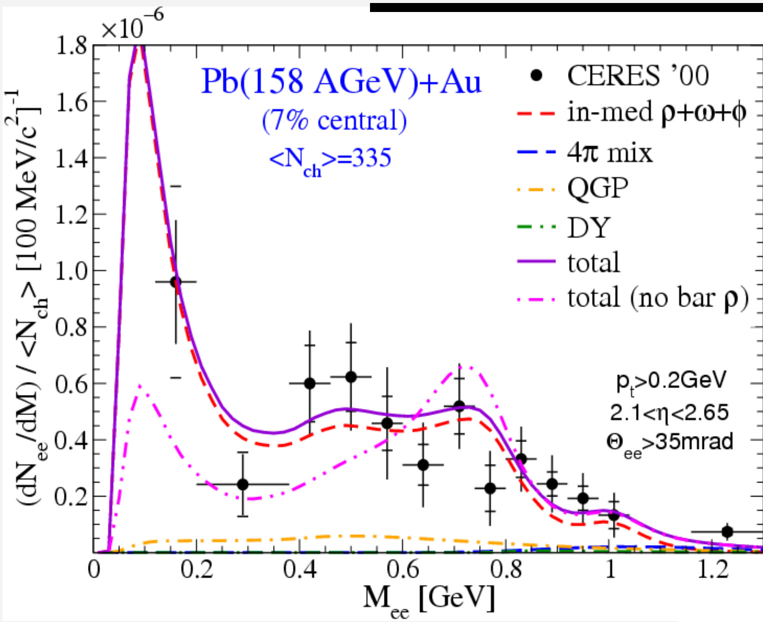
[van Hees+RR ’08]

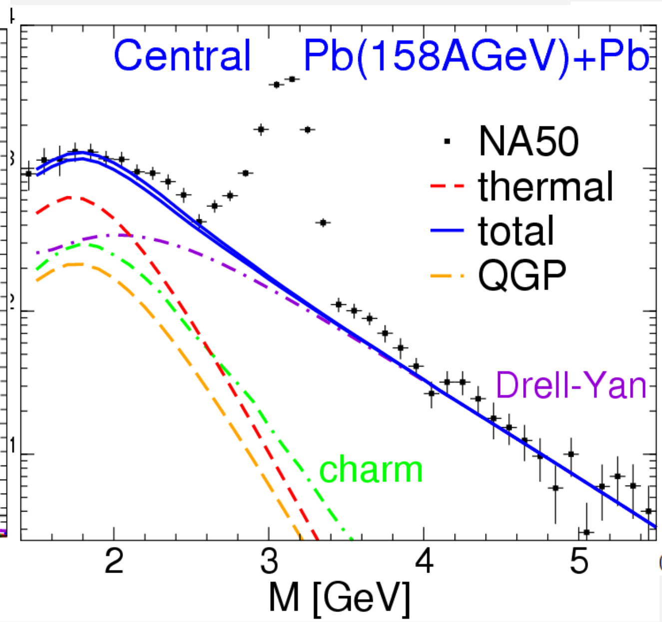
Thermal $\mu^+\mu^-$ Emission Rate

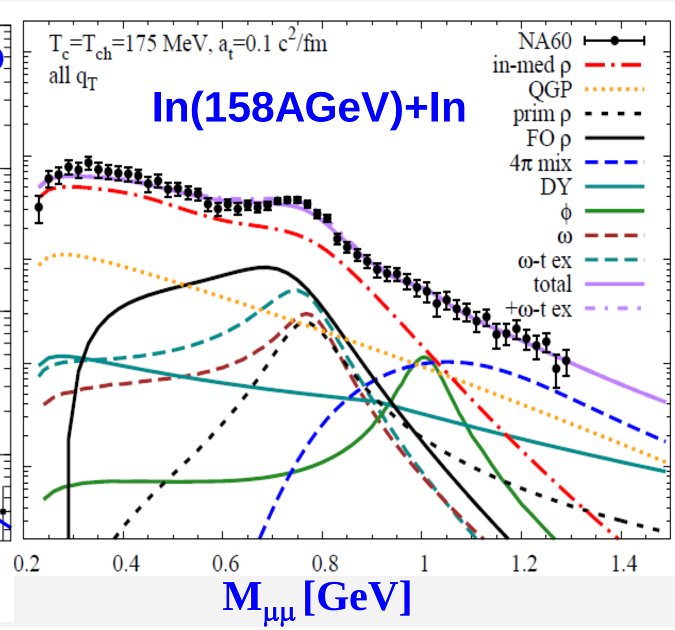


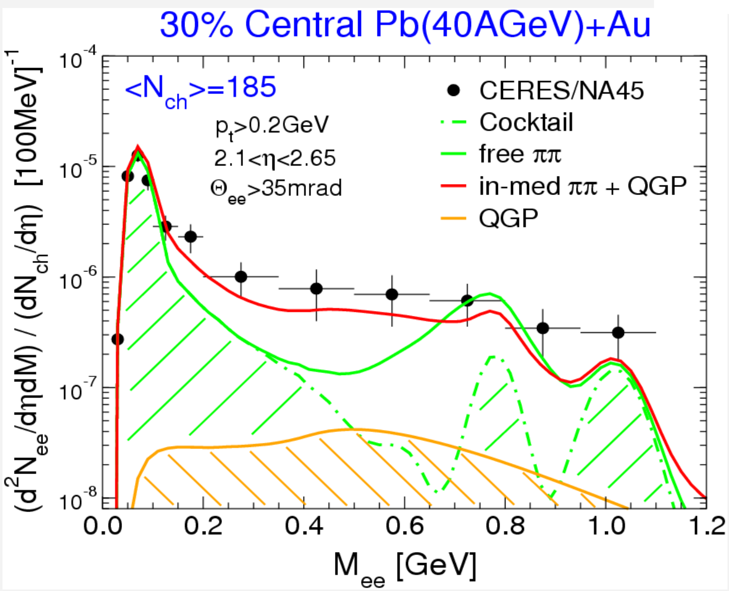
- **thermal radiation, τ_{FB} ~ (6.5 1) fm/c**
- **invariant-mass spectrum directly reflects thermal emission rate!**

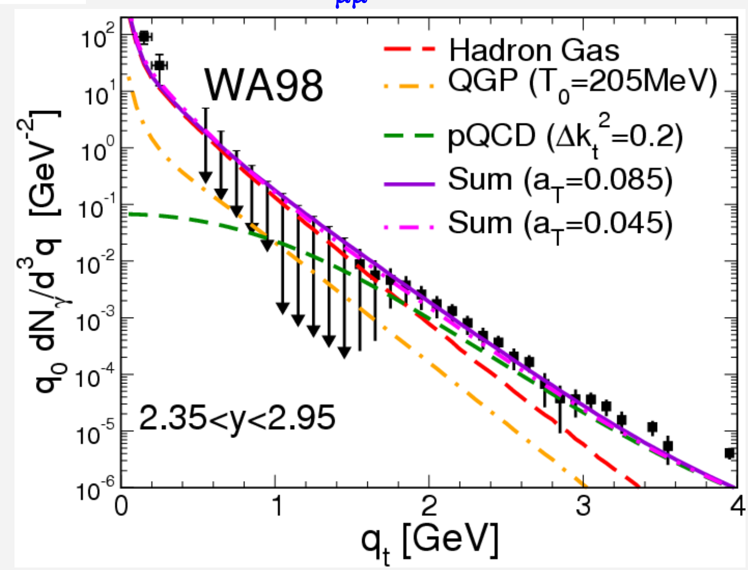
6.4 Summary of EM Probes at SPS











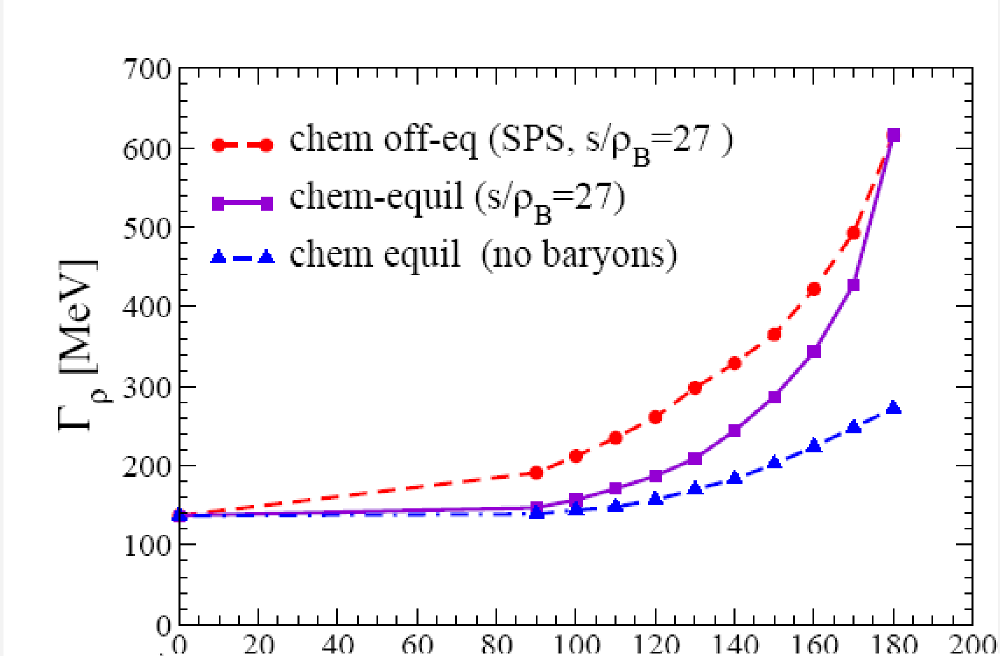
- calculated with the **same e.m. spectral function**!

- thermal source: **$T_i \approx$ 210MeV**, HG-dominated, **ρ-meson melting**!

6.5 Conclusions from Dilepton "Excess" Spectra

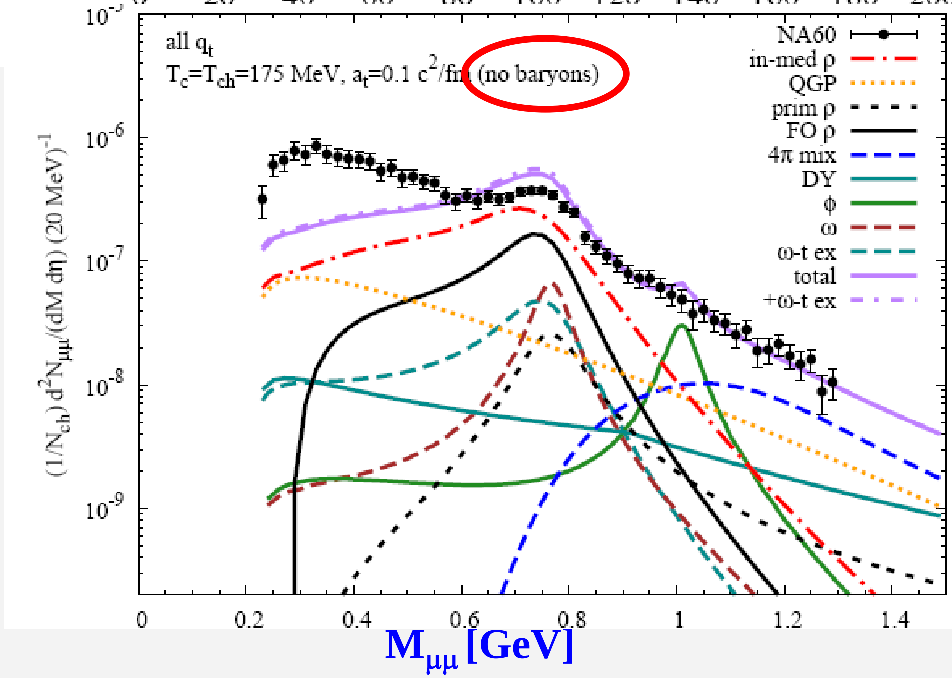
- thermal source (**T~120-210MeV**)
- **M<1GeV**: in-medium ρ meson
  - no significant mass shift
  - avg. Γ_ρ **(T~150MeV) ~ 350-400 MeV**

    $\Rightarrow$ **Γ_ρ (T~T$_c$) ≈ 600 MeV** $\rightarrow$ **m_ρ**
  - driven by baryons, good sensitivity



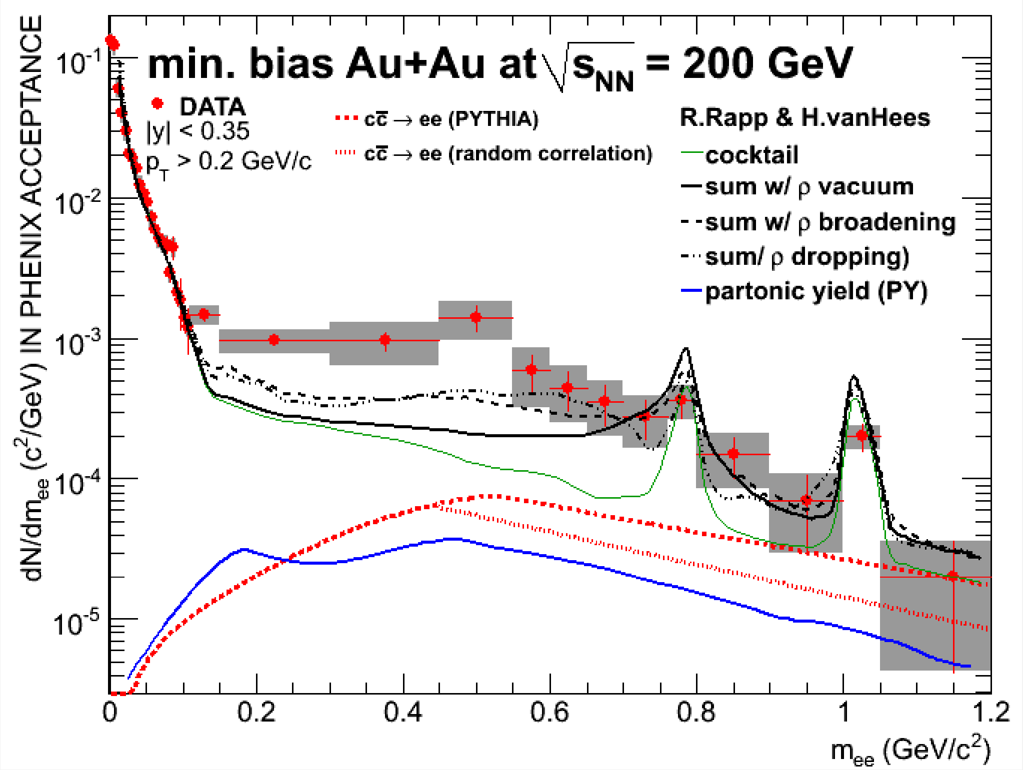
- **M>1GeV**: radiation around **T$_c$**
- fireball lifetime "measurement":

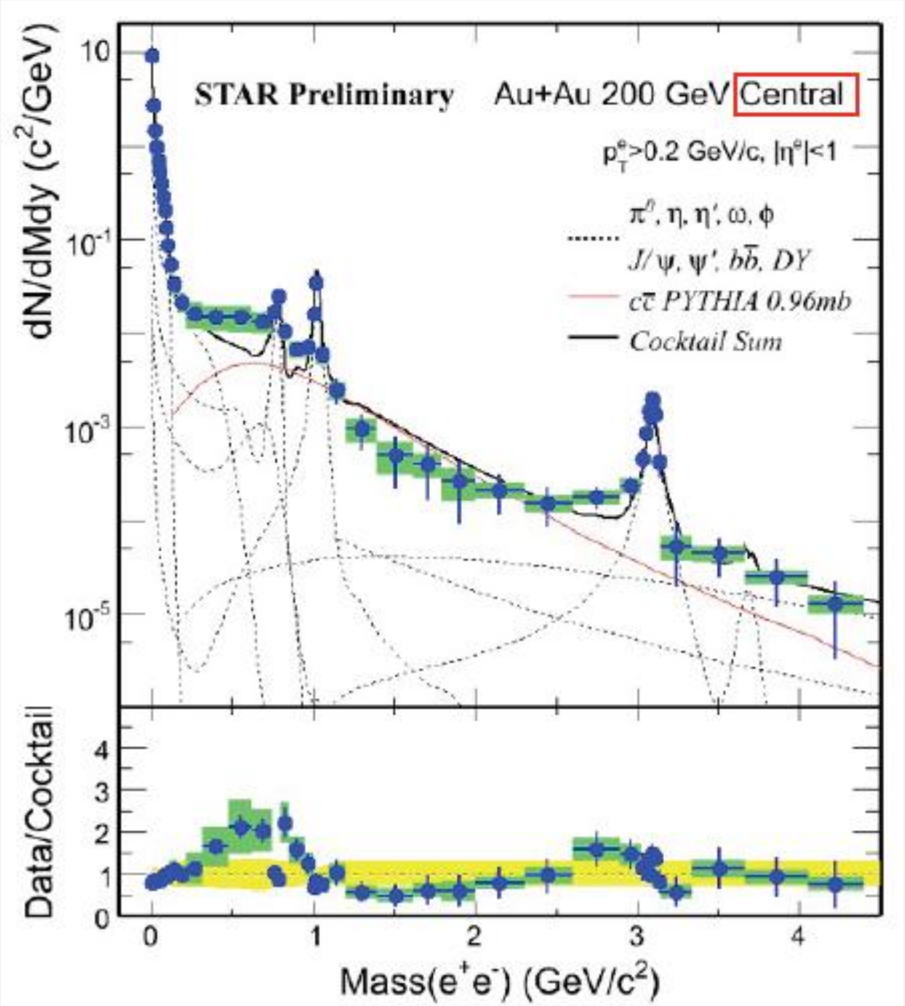
  τ_{FB} ~ (6.5 1) fm/c (semicentral In-In)



[van Hees+RR '06, Dusling et al '06, Ruppert et al '07, Bratkovskaya et al '08]

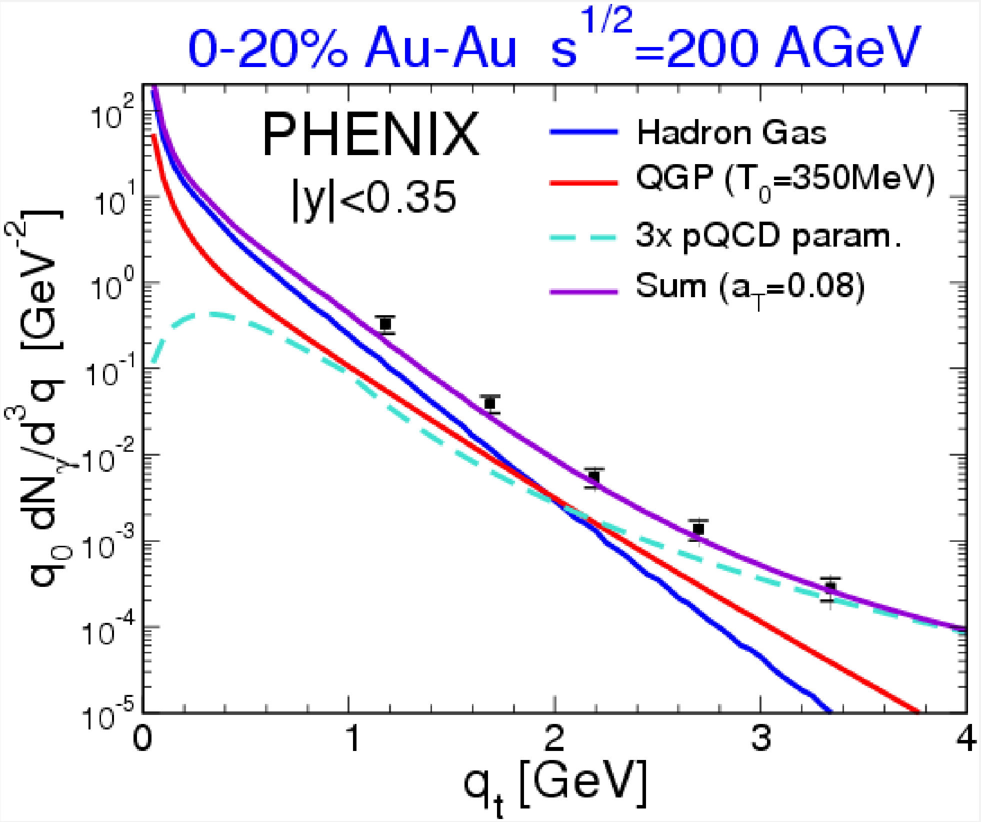
6.6 Low-Mass Dileptons at RHIC: PHENIX Puzzle

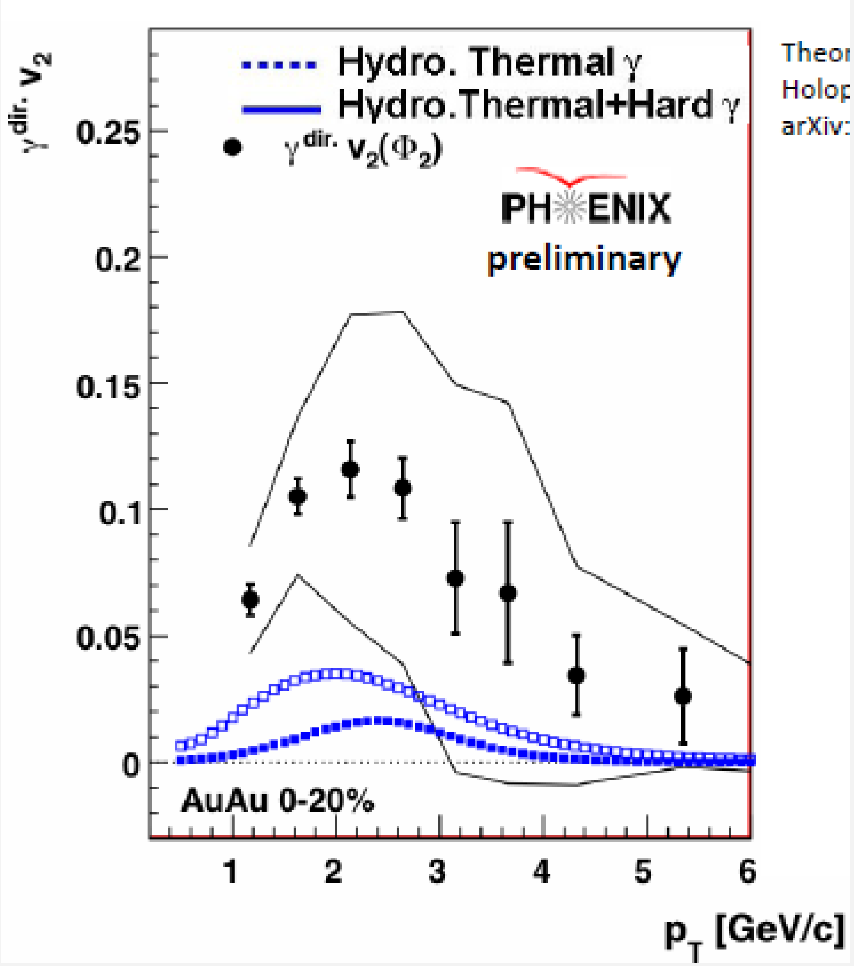




- "anomalous" **PHENIX** excess, concentrated at:
  low mass (**M=0.15-0.5GeV**), low **p_T** (**T_{eff} ~ 100 MeV**), central collisions
- not confirmed by preliminary **STAR** data

6.7 Thermal Photons at RHIC





- "expected" **thermal source** accounts for enhancement over **p-p**: **T_i ~350-400MeV**, **T_{av} ~225MeV**, QGP + hadron-gas sources (blue-shift)
- **unexpectedly large elliptic flow**: dominant HG radiation?

7.) Conclusions

• Spontaneous Chiral Symmetry Breaking in QCD Vacuum:

- $\langle \bar{q}q \rangle \sim m_q^* \neq 0$, chiral partners split **(π-σ, ρ-a_1**, …)
- low-mass EM emission dominated by ρ, "dual" above **M>1.5GeV**

• Hadronic Medium Effects (Many-Body Theory):

- "melting" of ρ (empirical + theoretical constraints!)
- connection to chiral restoration: QCD/chiral sum rules (**a_1**!)

• Extrapolate EM Emission Rates to **T=160-190MeV**

$\Rightarrow$ **in-med HG** and **QGP** shine **equally** bright ("duality") !?

• Phenomenology for **URHICs**:

- precision data + theory essential for definite conclusions
- CERN-SPS (**NA45,NA60**) ok,
  RHIC (**PHENIX**) unclear, LHC (**ALICE**) future

2.4.4 Weinberg (Chiral) Sum Rules + Order Parameters

- **Moments Vector–Axialvector**

$$I_n = -\int \frac{ds}{\pi} s^n \left(Im\,\Pi_V - Im\,\Pi_A\right)$$

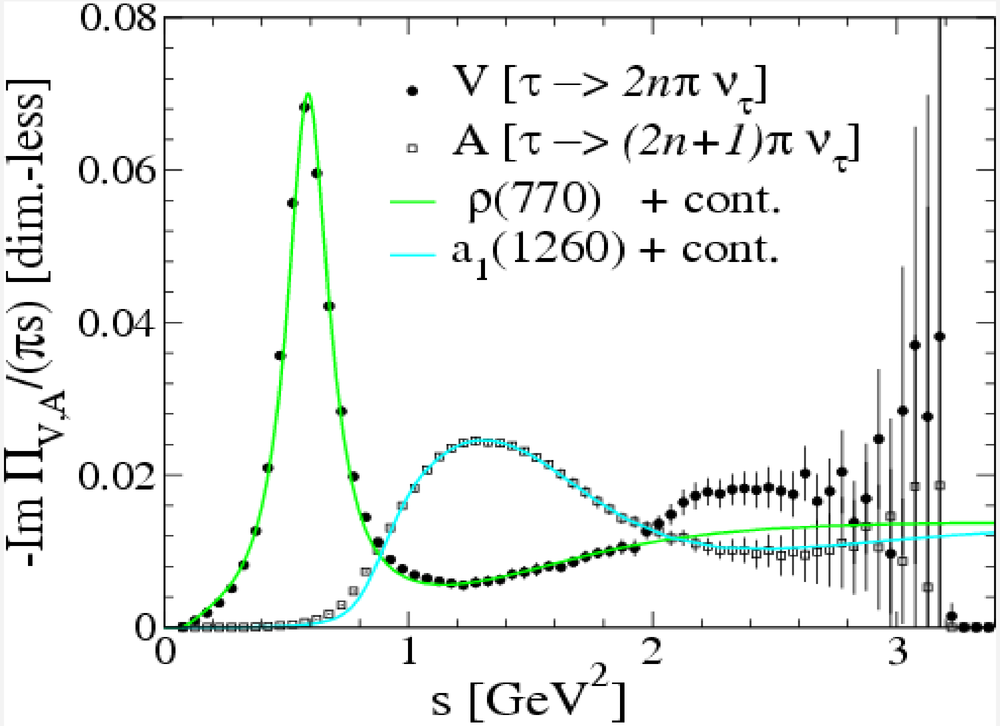
$$I_{-2} = \frac{1}{3} f_\pi^2 \left\langle r_\pi^2 \right\rangle - F_A$$

$$I_{-1} = f_\pi^2$$

$$I_0 = 0$$

$$I_1 = c\,\alpha_s \left\langle (\bar{q}q)^2 \right\rangle$$

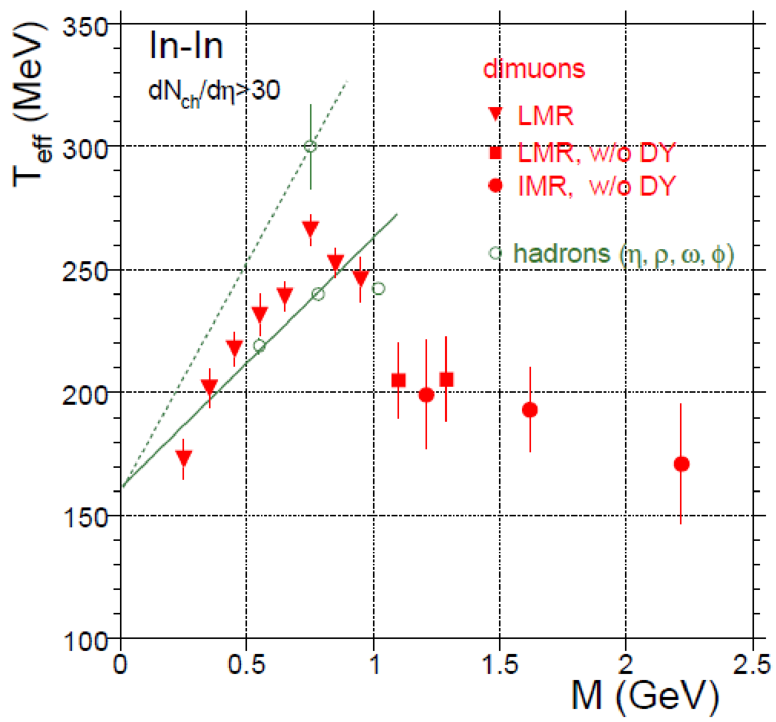
[Weinberg '67, Das et al '67]

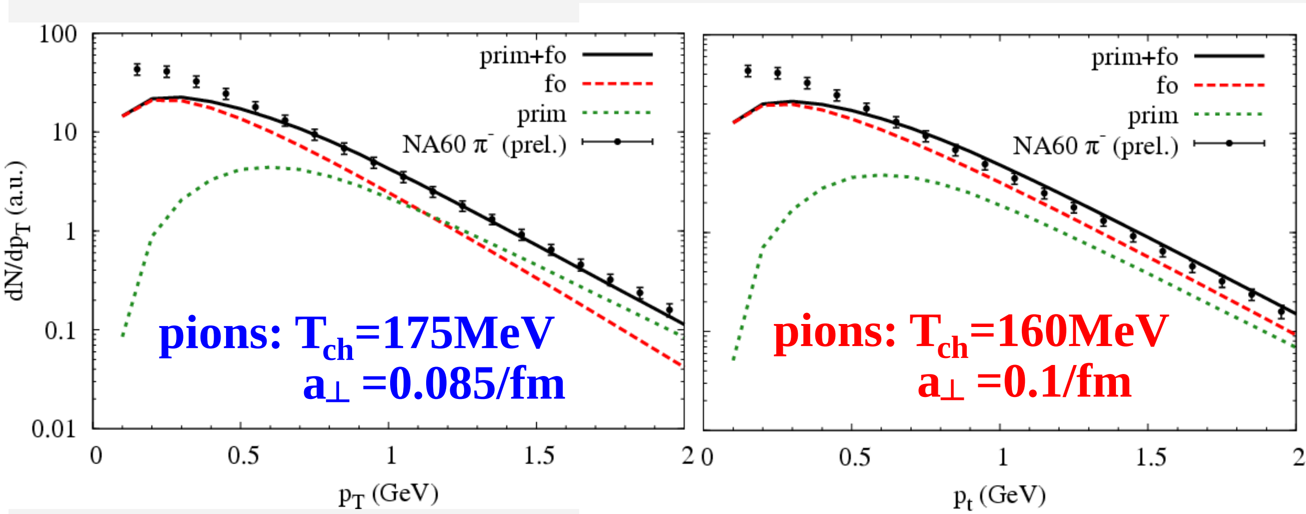


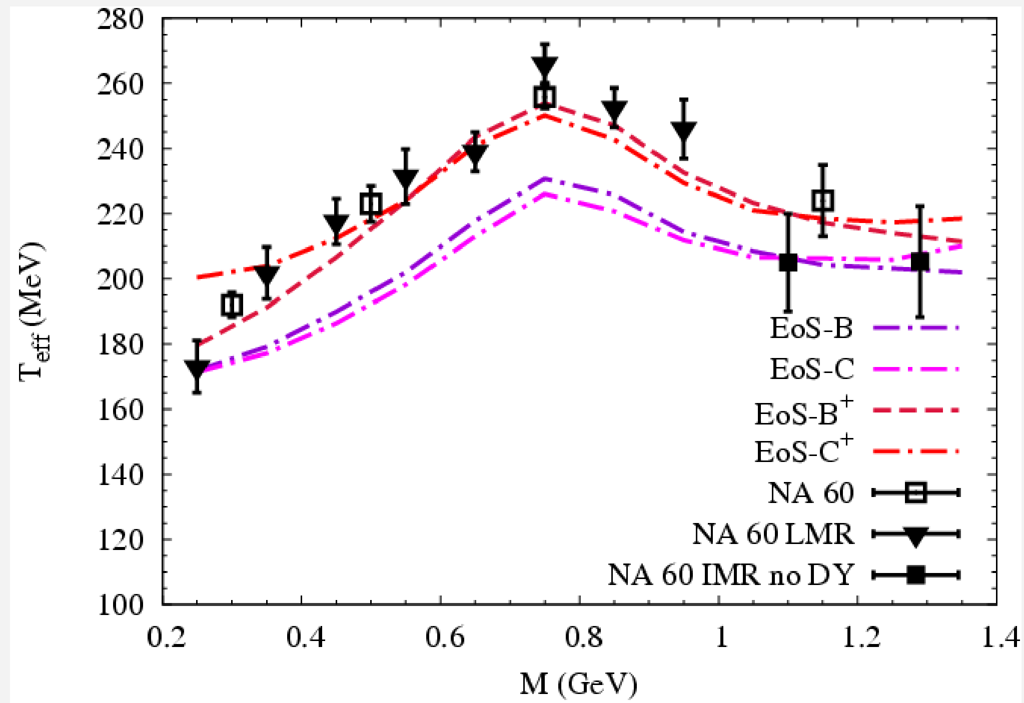
- **In Medium:** energy sum rules at fixed **q** [Kapusta+Shuryak '93]
- **correlators (rhs): effective models (+data)**
- **order parameters (lhs): lattice QCD**

} **promising synergy!**

2.5 Dimuon p_t-Spectra and Slopes: Barometer

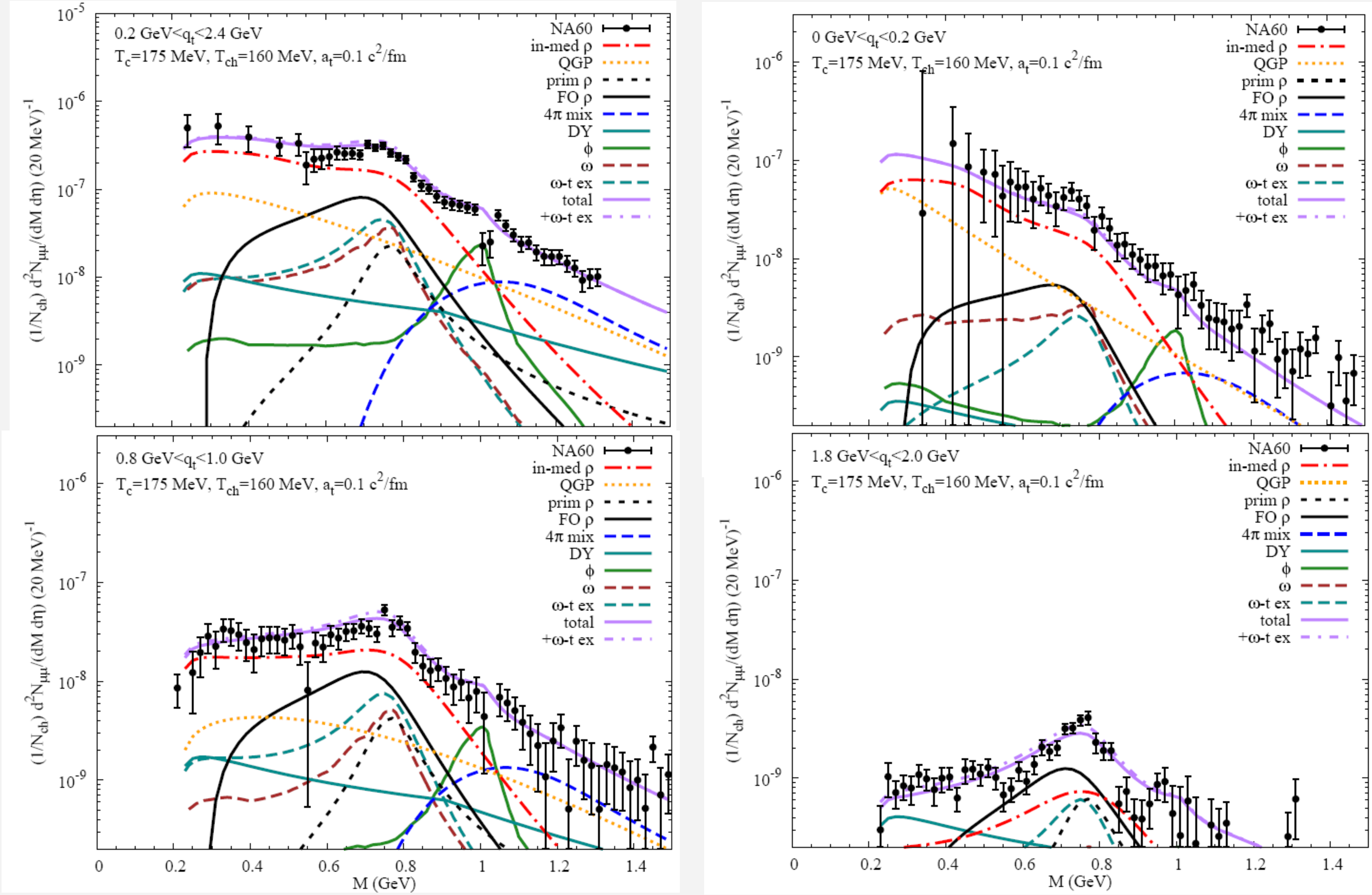






- vary fireball evolution:
  e.g. $a_\perp$ = 0.085/fm → 0.1/fm
- both large and small T_c compatible with excess dilepton slopes

4.3.3 Acceptance-Corrected NA60 Spectra

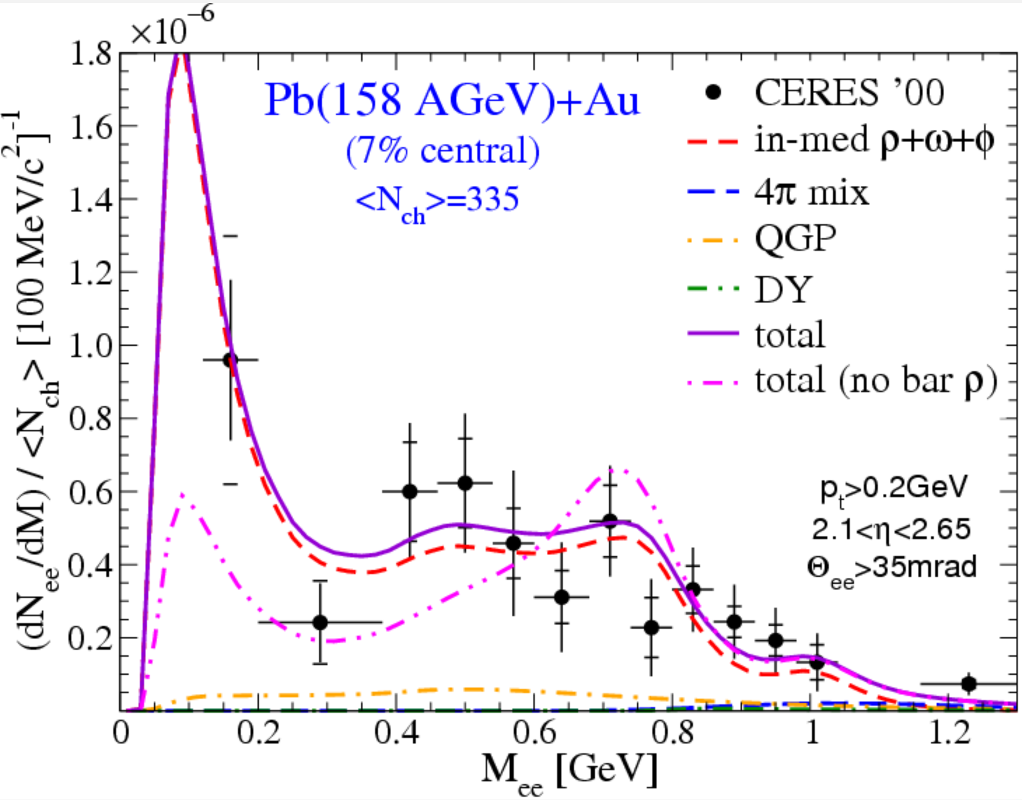


[van Hees + RR '08]

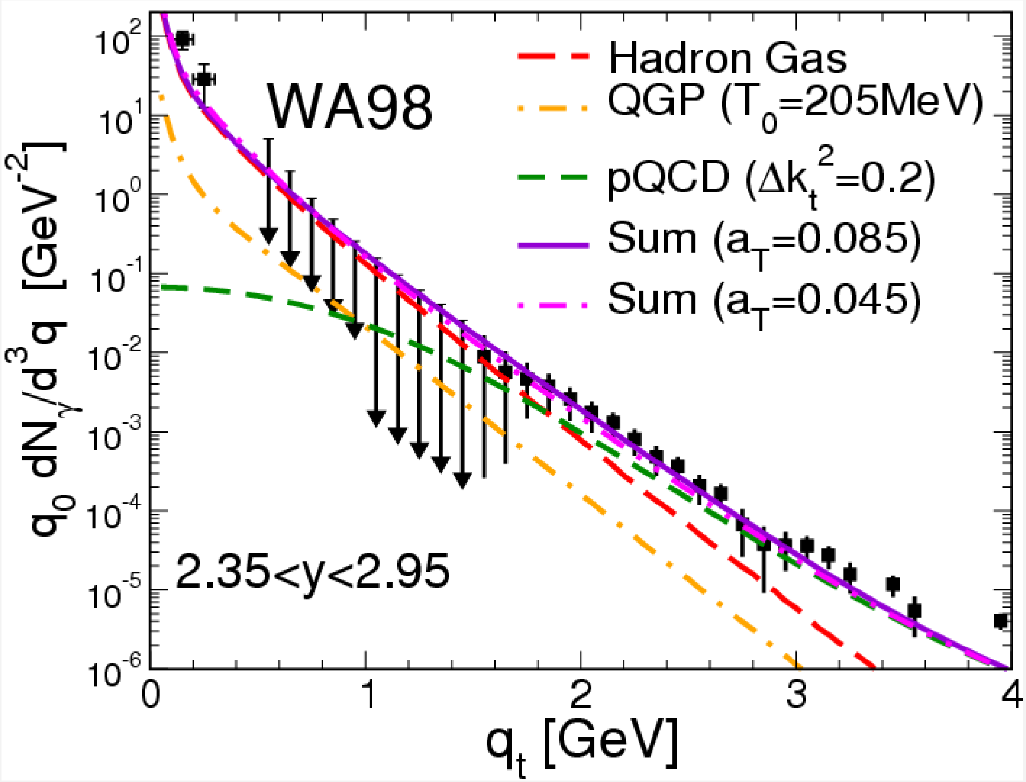
- rather involved at p_T>1.5GeV: Drell-Yan, primordial/freezeout ρ , …

4.5 EM Probes in Central Pb-Au/Pb at SPS

Di-Electrons [CERES/NA45]



Photons [WA98]



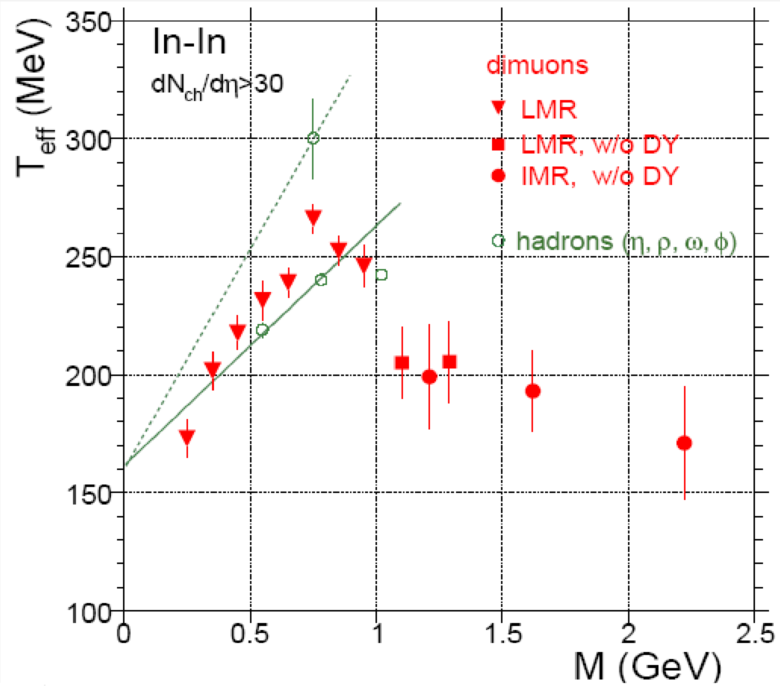
- consistent description with updated fireball (a_T=0.045→0.085/fm)

[van Hees+RR '07]

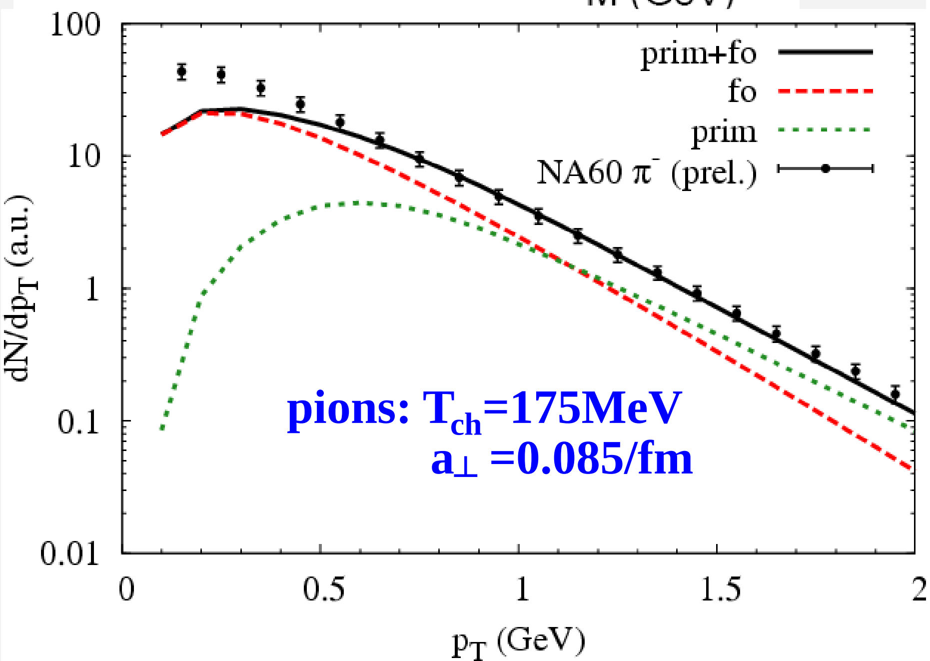
- very low-mass di-**electrons** ↔ (low-energy) photons

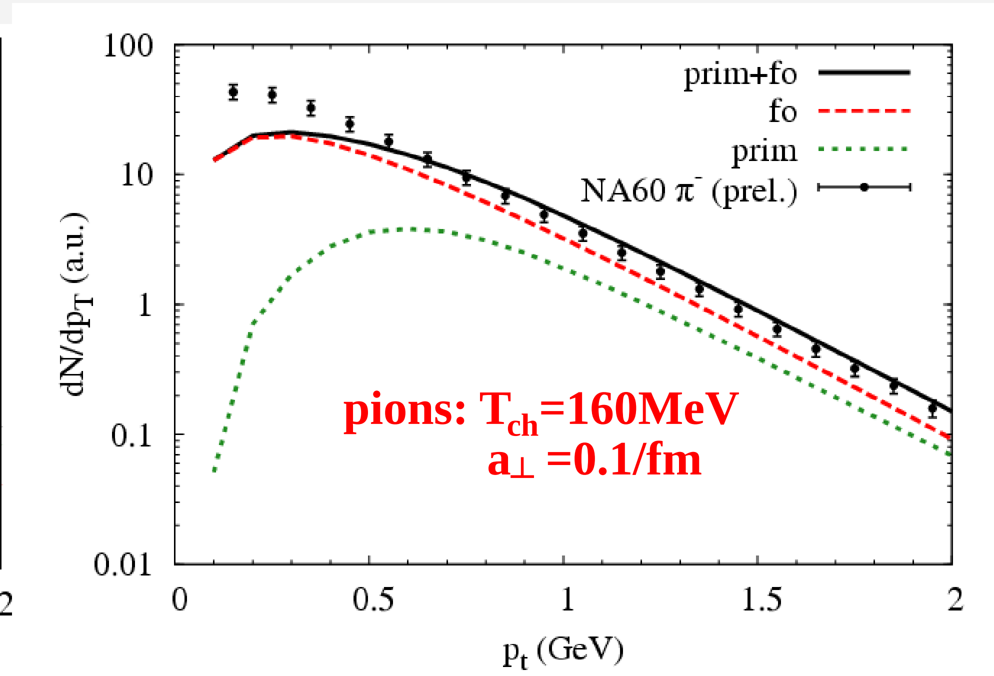
[Liu+RR '06, Alam et al. '01]

5.2.5 NA60 Dimuons: p_t-Slopes



- in-medium radiation “harder” than hadrons at freezeout?!
  (thermal radiation softer by Lorentz-**1/γ**)
- smaller **T_{ch}** helps (larger **T_{fo}**)
- non-thermal sources (DY, …)?
- additional transverse acceleration?
- hadron spectra (pions)?

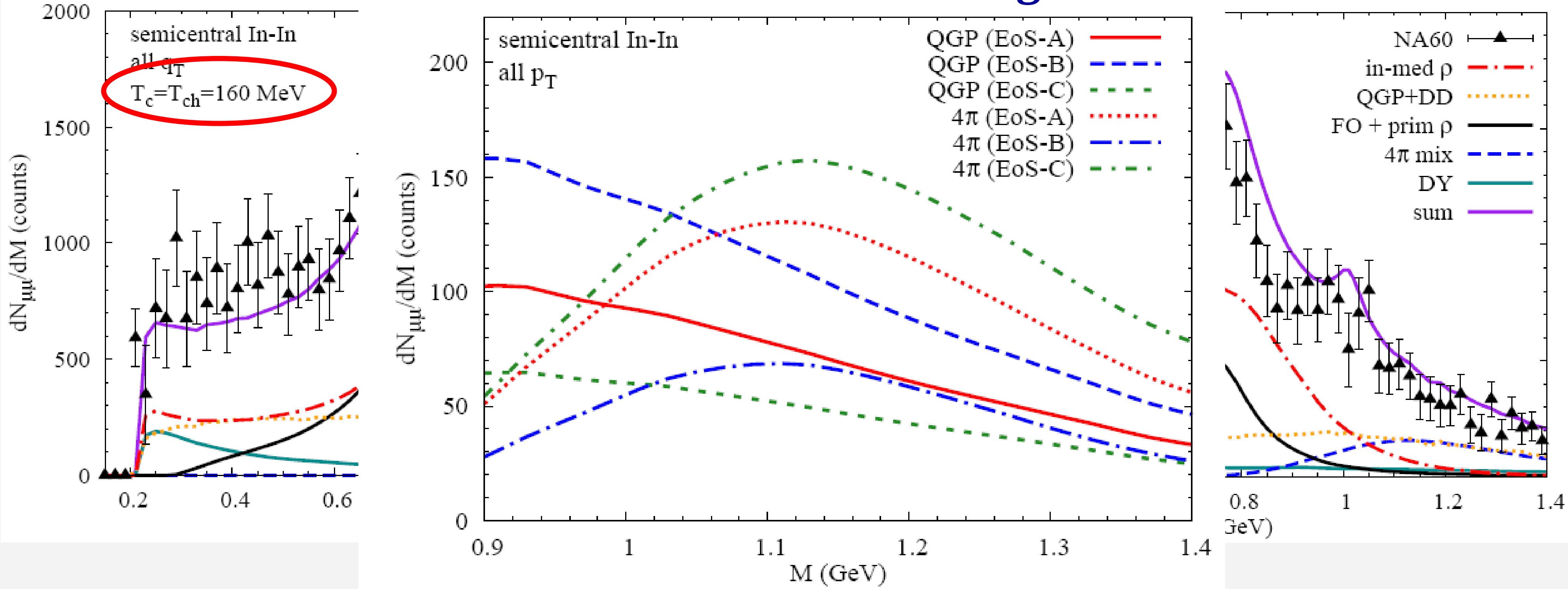




5.2.3 NA60 Dimuons: Sensitivity to QGP and T_c

• vary critical and chemical-freezeout temperature (**T_{fo}** fix)

"EoS-B" **Intermediate Mass Region** **"EoS-C"**



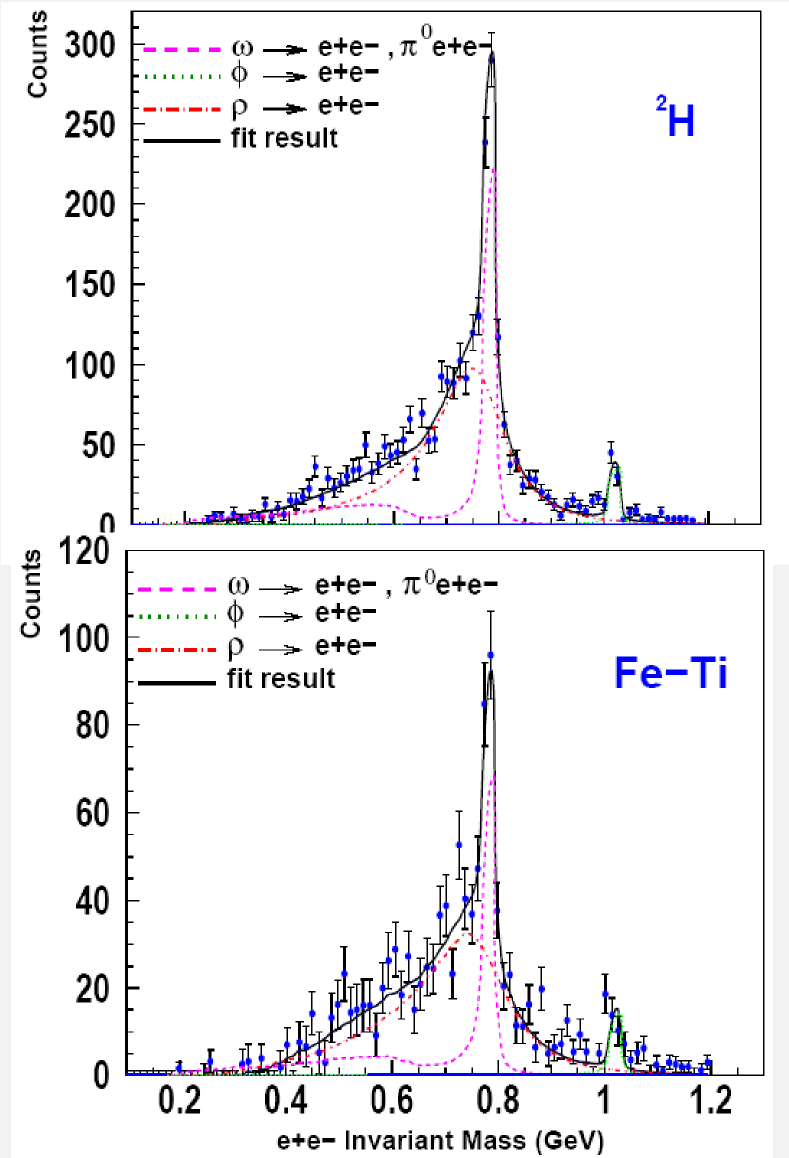
• overall shape of spectra robust: "duality" of dilepton rate around "**T_c**"!

• yields slightly larger for large **T_c** (hadronic volume larger), **$|\Delta\tau|<1fm/c$**

• intermediate mass (**M>1GeV**): QGP vs. hadronic depends on **T_c**

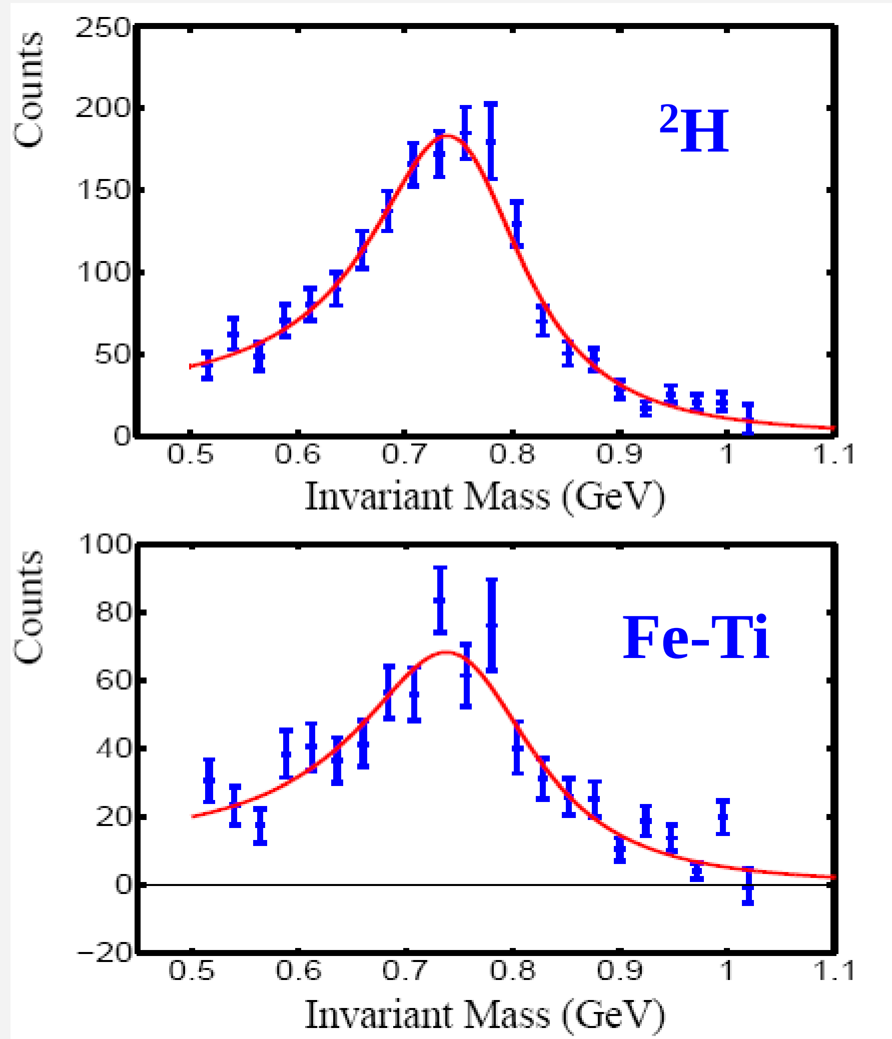
3.6 ρ-Mesons in Nuclei: Photo-Production

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



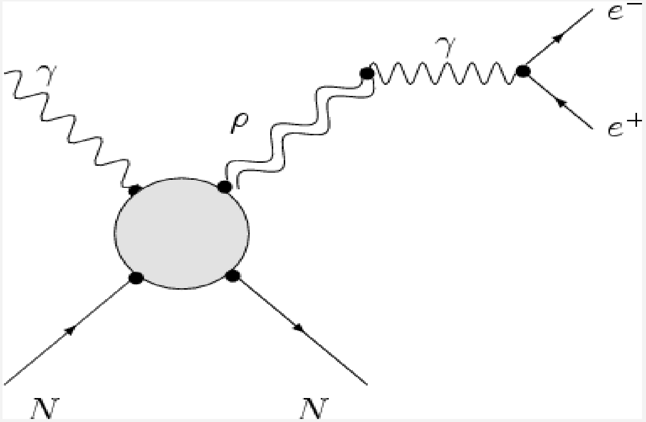
[CLAS+GiBUU Collab. '08]

“Excess” Spectra

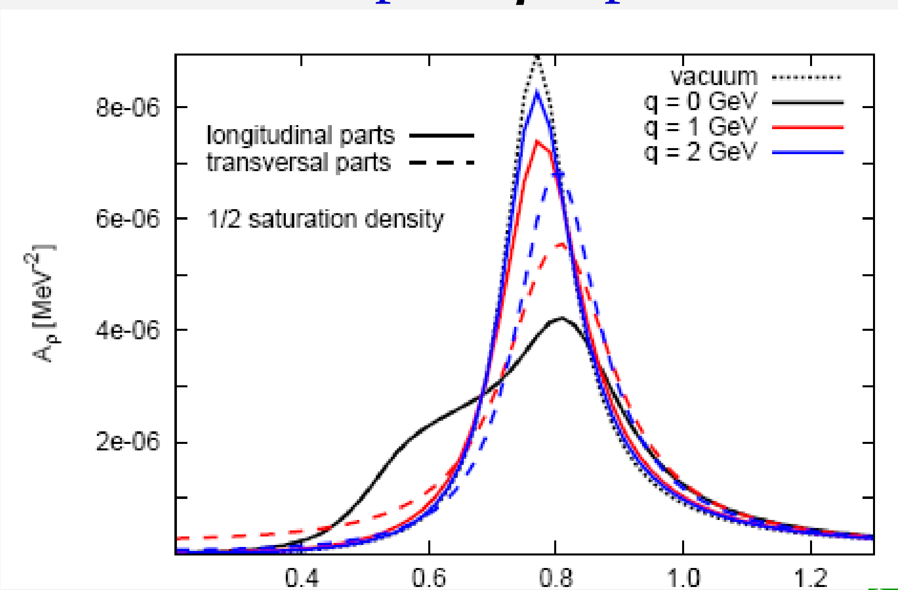


- ρ meson moderately broadened

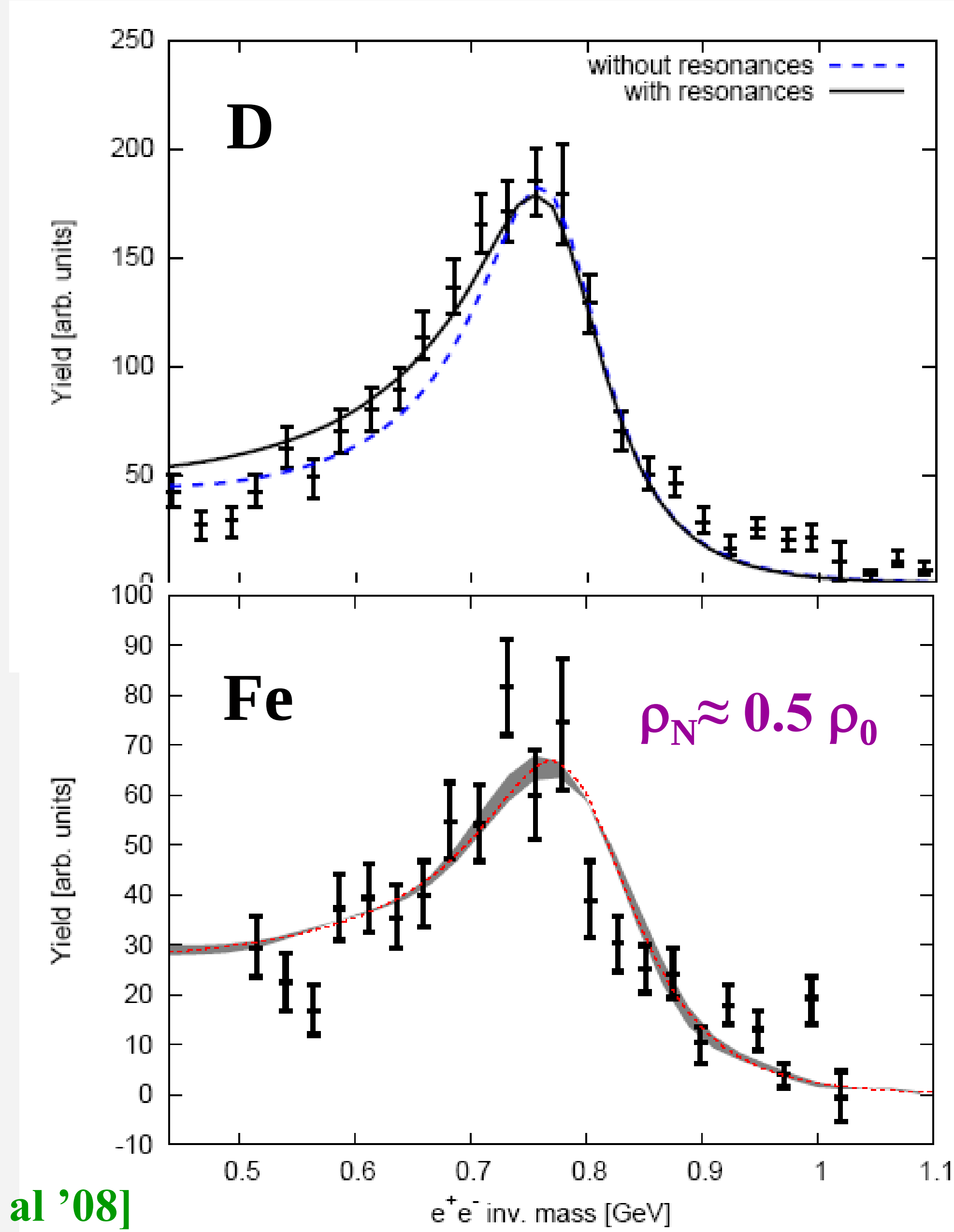
3.6.2 ρ-Meson Spectral Fct. in Photoproduction



- photon energy **E_γ=1.5-3 GeV**
- 3-Mom. Dep. of ρ Spec. Function



M [GeV]



[Riek et al '08]