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Dileptons and Medium Effects in Heavy-Ion Collisions

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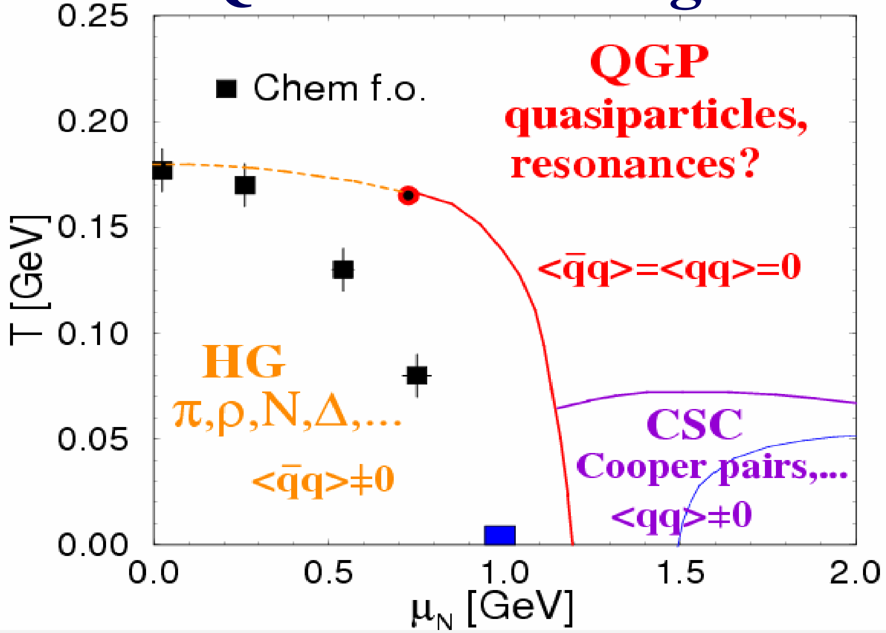
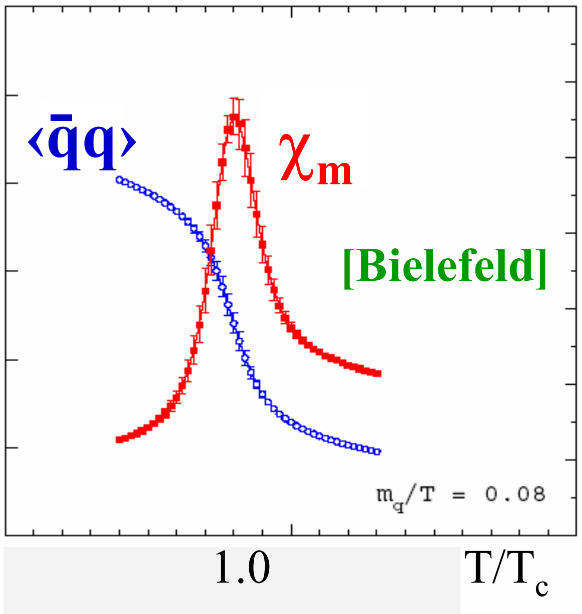
ICTP Trieste, 24.05.06

Introduction: EM-Probes -- Basic Questions

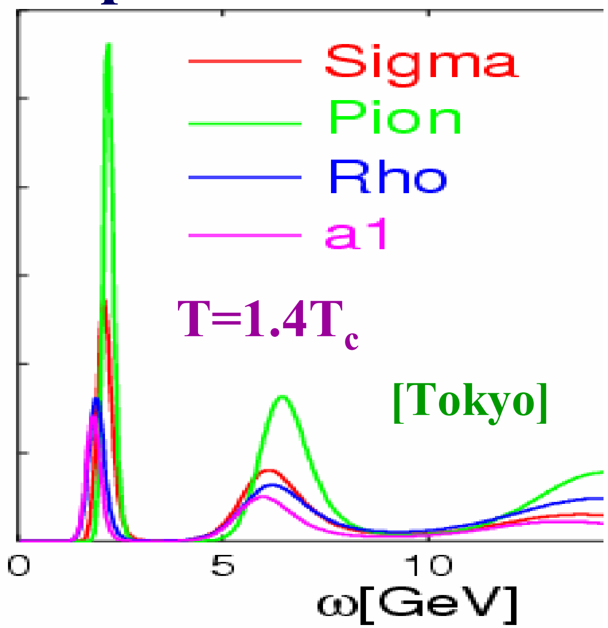
QCD Phase Diagram



Chiral Condensate



Spectral Functions



Thermalization $\Rightarrow$ study the phase diagram:

- **(highest) temperature of the matter**
- **chiral symmetry restoration (mass generation!)**
- **in-medium spectral properties below + above T_c**

Inevitable consequences of QGP, link to lattice QCD

Outline

2.) Electromagnetic Emission and Chiral Symmetry

- EM Thermal Rates
- Axial-/Vector Correlators and Chiral Sum Rules

3.) Medium Effects and Thermal Dileptons

- Vector Mesons in Medium: Hadronic Many-Body Theory
- Experimental and Theoretical Constraints
- Dilepton Rates: Hadronic vs. QGP

4.) Dileptons at SPS

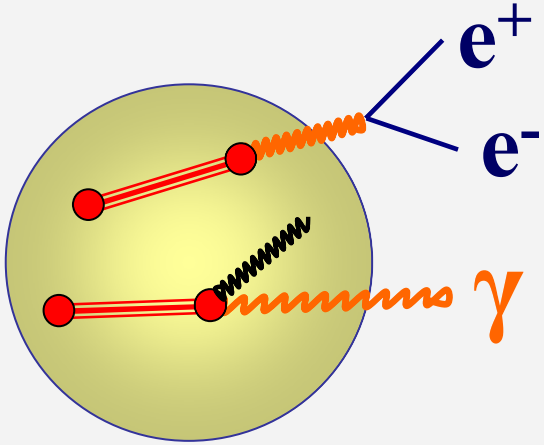
- CERES and NA60 Data
- Interpretation + Open Issues

5.) Conclusions

2.) EM Emission Rates and Chiral Symmetry

E.M. Correlation Function:

$$\Pi^{\mu\nu}_{em}(q) = -i \int d^4x\, e^{iqx} \left\langle j^{\mu}_{em}(x)\, j^{\nu}_{em}(0) \right\rangle_T$$

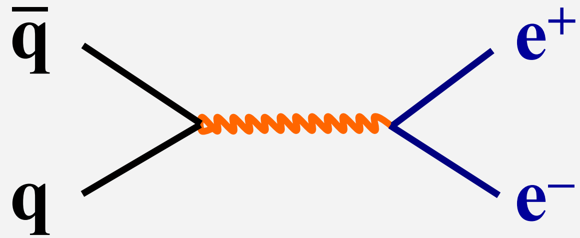


$$\frac{dN_{ee}}{d^4x\, d^4q} = \frac{-\alpha^2}{\pi^3 M^2}\, f^B(q_0,T)\ \mathrm{Im}\, \Pi_{em}(M,q;\mu_B,T)$$

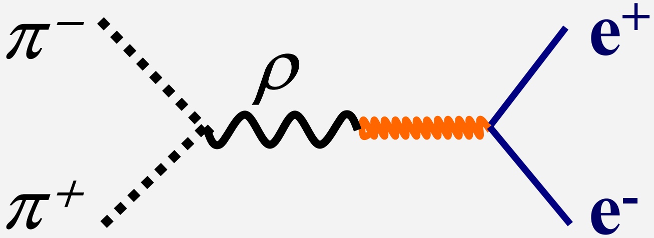
$$q_0 \frac{dN_\gamma}{d^4x\, d^3q} = \frac{-\alpha}{\pi^2}\, f^B(q_0,T)\ \mathrm{Im}\, \Pi_{em}(q_0=q;\ \mu_B,T)$$

Radiation Sources:

- **Quark-Gluon Plasma:**
  $q\bar{q} \to e^+e^-$, …



- **Hot + Dense Hadron Gas:**
  $\pi^+\pi^- \to e^+e^-$, …



Relevance:

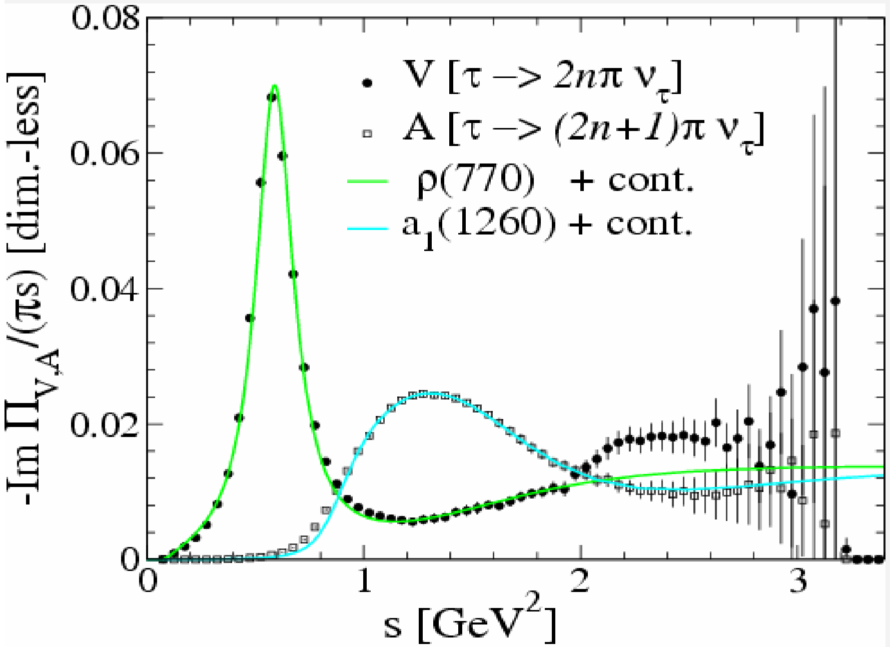
high mass + temp.
$M > 1.5 GeV$, $T > T_c$

$M \leq 1\ GeV$
$T \leq T_c$

2.2 Chiral Symmetry Breaking and Restoration

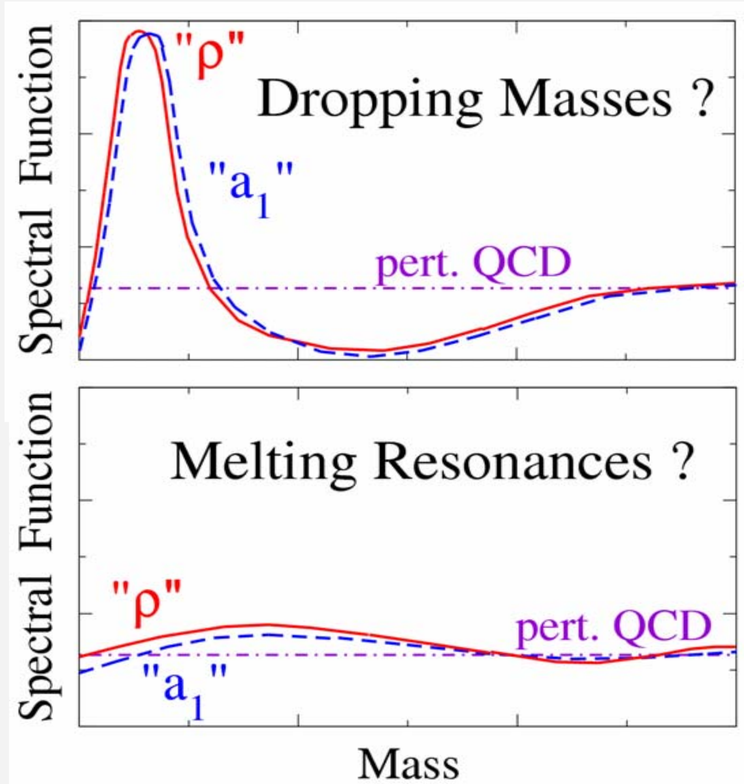
Splitting of "chiral partners" ρ - $a_1(1260)$ $\Rightarrow$ Chiral Symmetry Breaking

Axial-/Vector in Vacuum



at T_c: Chiral Restoration

pQCD cont.



- **Low-Mass Dilepton Rate:**

$$\frac{dN_{ee}}{d^4x\,d^4q} = \frac{-\alpha^2}{\pi^3 M^2} f^B(T)\; Im\Pi_{em} \sim [ImD_\rho + ImD_\omega/10 + ImD_\phi/5]$$

ρ -meson dominated!

- **Axialvector Channel:** $\pi^\pm\gamma$ invariant mass-spectra $\sim Im\ D_{a1}(M)$?!

2.3 Chiral Sum Rules and the a_1(1260)

- Energy-weighted moments of difference ***vector – axialvector***:

$$I_0 = -\int \frac{ds}{\pi s^2}(Im\Pi_V - Im\Pi_A) = \frac{1}{3} f_\pi^2 \langle r_\pi^2 \rangle - F_A$$

[Das etal '67]

$$\boxed{I_1(s_0) = -\int_0^{s_0} \frac{ds}{\pi s}(Im\Pi_V - Im\Pi_A) = f_\pi^2}$$

[Weinberg '67]

$$\boxed{I_2(s_0) = -\int_0^{s_0} \frac{ds}{\pi}(Im\Pi_V - Im\Pi_A) = 0}$$

$$I_3 = -\int \frac{s\,ds}{\pi}(Im\Pi_V - Im\Pi_A) = c\,\alpha_s \langle (\bar{q}q)^2 \rangle$$

- explicit link:

V – A spectral fcts. (models) $\leftrightarrow$ order parameters (lattice QCD)

- extended to finite temperature **[Kapusta+ Shuryak '93]**

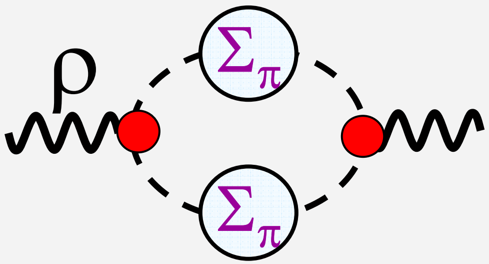
3.1 Medium Effects I: Hadronic Many-Body Theory

[Chanfray etal, Herrmann etal, RR etal, Weise etal, Post etal, Eletsky etal, Oset etal, …]

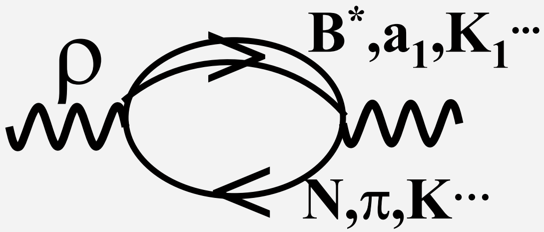
ρ-Propagator:

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

ρ-Selfenergies: $\Sigma_{\rho\pi\pi} =$

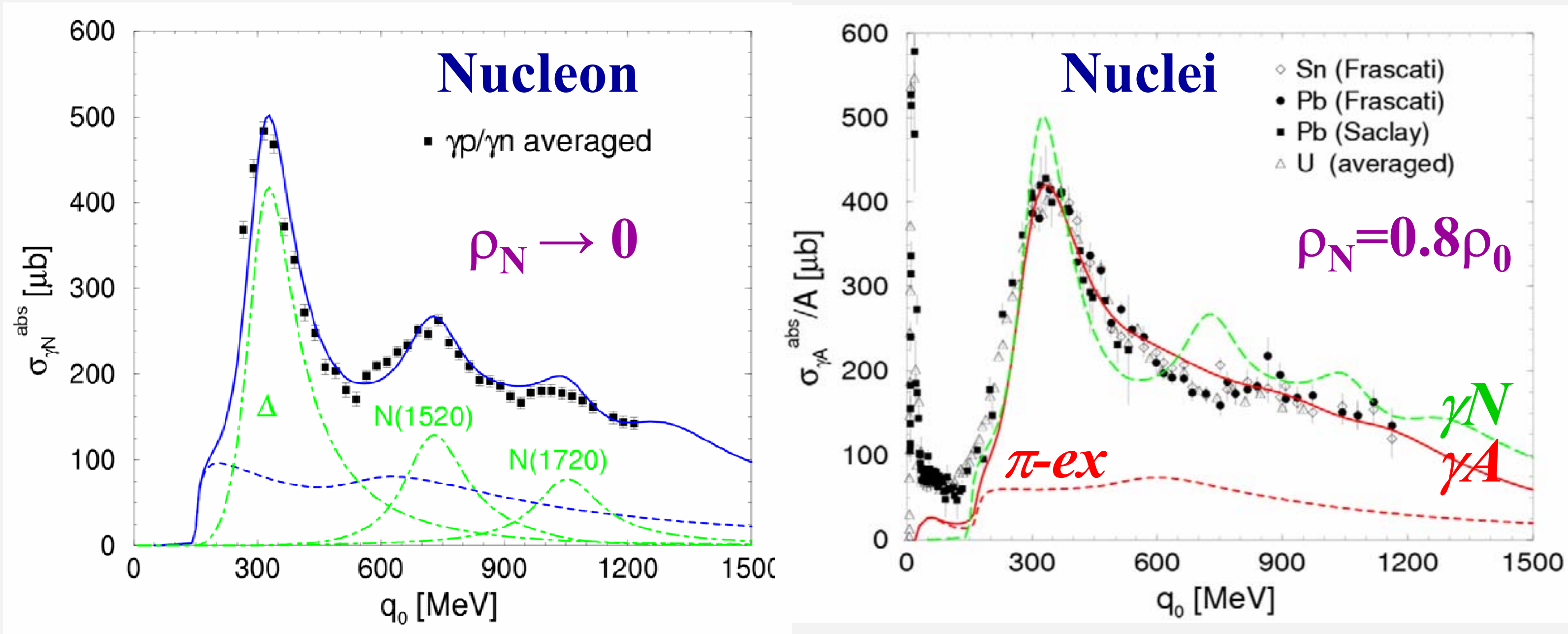


$\Sigma_{\rho B,M} =$



Constraints:

- vacuum decays:
  B,M→ ρN, ρπ
- scattering data:
  γN , γA ,
  πN→ρN

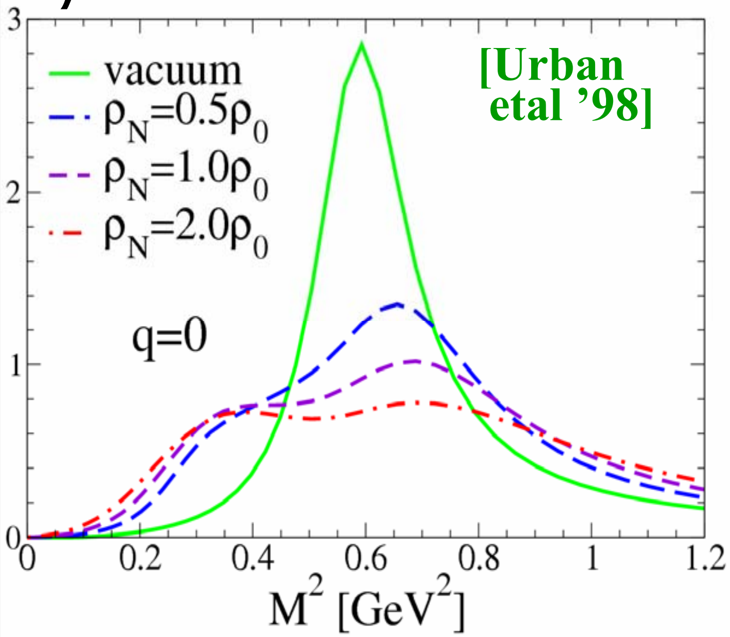


$$\sigma^{abs}_{\gamma A}(q_0)/\,A \;\propto\; ImD_\rho(q_0\!=\!q)$$

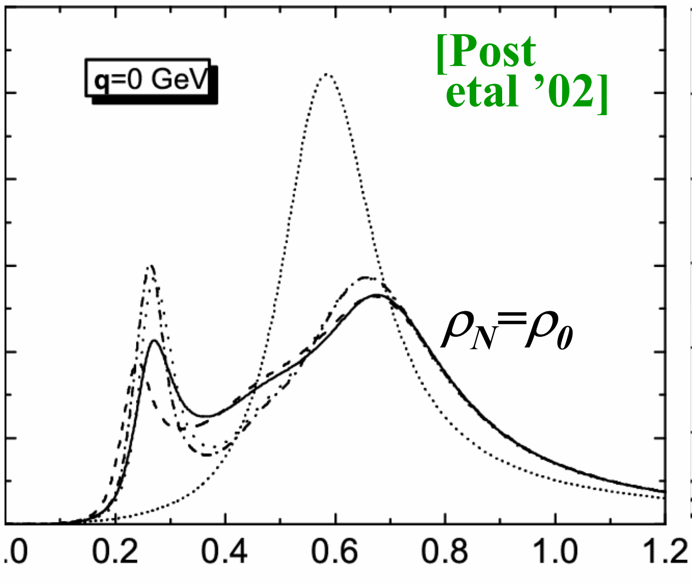
[Urban et al. '98]

3.1.2 ρ(770) Spectral Function in Nuclear Matter

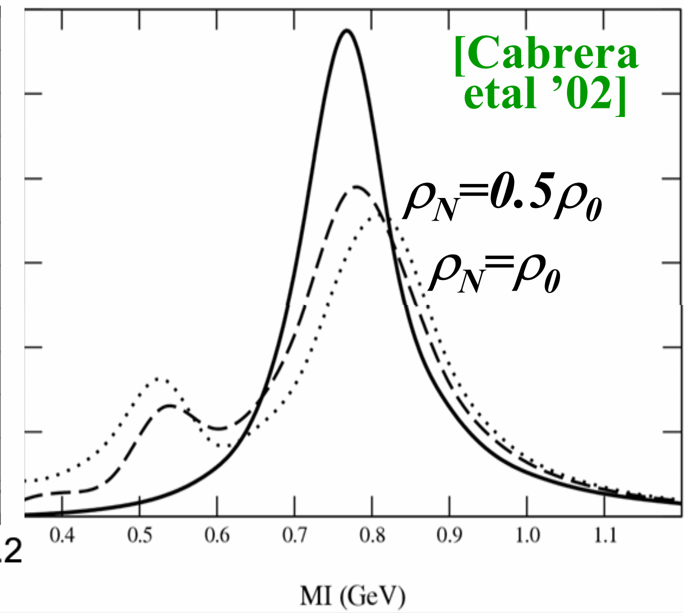
In-med π-cloud + ρ-$N \rightarrow B^*$ resonances



Relativist. ρ-$N \rightarrow B^*$ (low-density approx)



In-med π-cloud + ρ-$N \rightarrow N(1520)$



Constraints: γN, γA $\qquad$ $\pi N \rightarrow \rho N$ PWA

- good agreement: strong broadening + small mass-shift up
- constraints from (vacuum) data important quantitatively

3.1.3 QCD Sum Rules + ρ(770) in Nuclear Matter

dispersion relation for correlator:

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

[Shifman, Vainshtein +Zakharov '79]

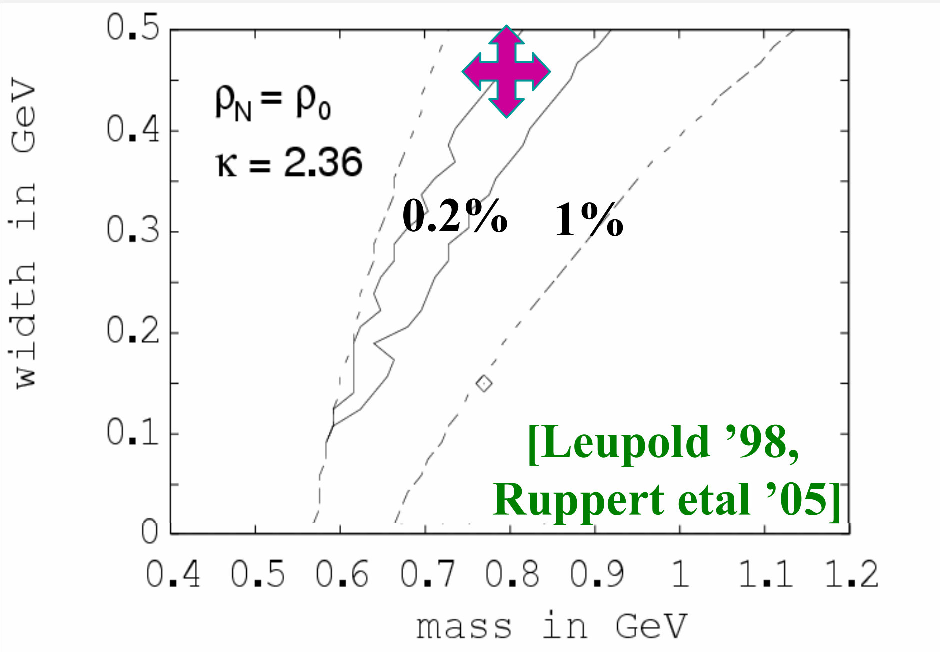
• ***lhs:*** OPE (spacelike Q^2):

$$\Pi_\rho = \frac{-1}{8\pi^2}\left[(1+\alpha_s)\ln\left(\frac{Q^2}{\Lambda^2}\right) + \frac{\pi^2}{3}\frac{\langle\alpha_s G^2/\pi\rangle}{Q^4} - C\frac{\alpha_s\langle(\bar{q}q)^2\rangle}{Q^6} + \ldots\right]$$

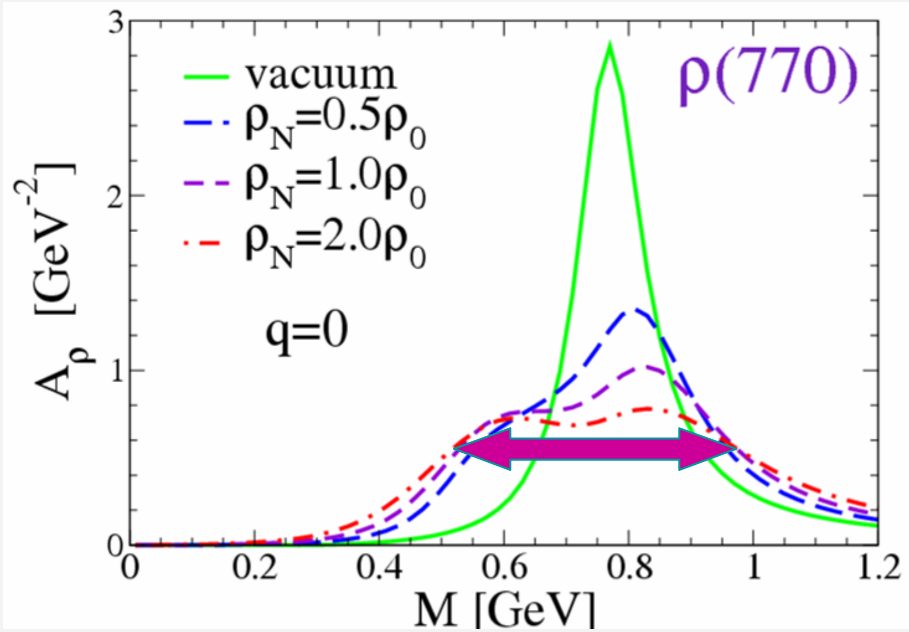
4-quark condensate!

• ***rhs:*** hadronic model ($s>0$):

$$Im\Pi_\rho(s) = \frac{m_\rho^4}{g_\rho^2} Im D_\rho(s) - \frac{s}{8\pi}\left(1+\frac{\alpha_s}{\pi}\right)\Theta(s-s_0)$$

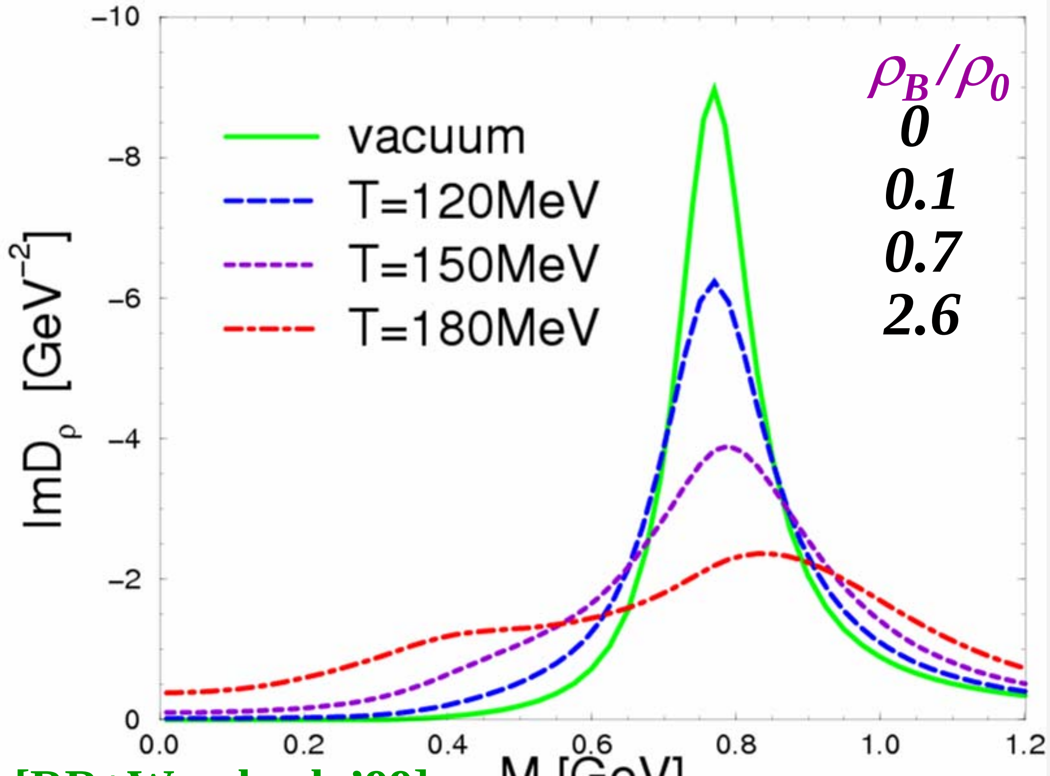


[Leupold '98, Ruppert etal '05]



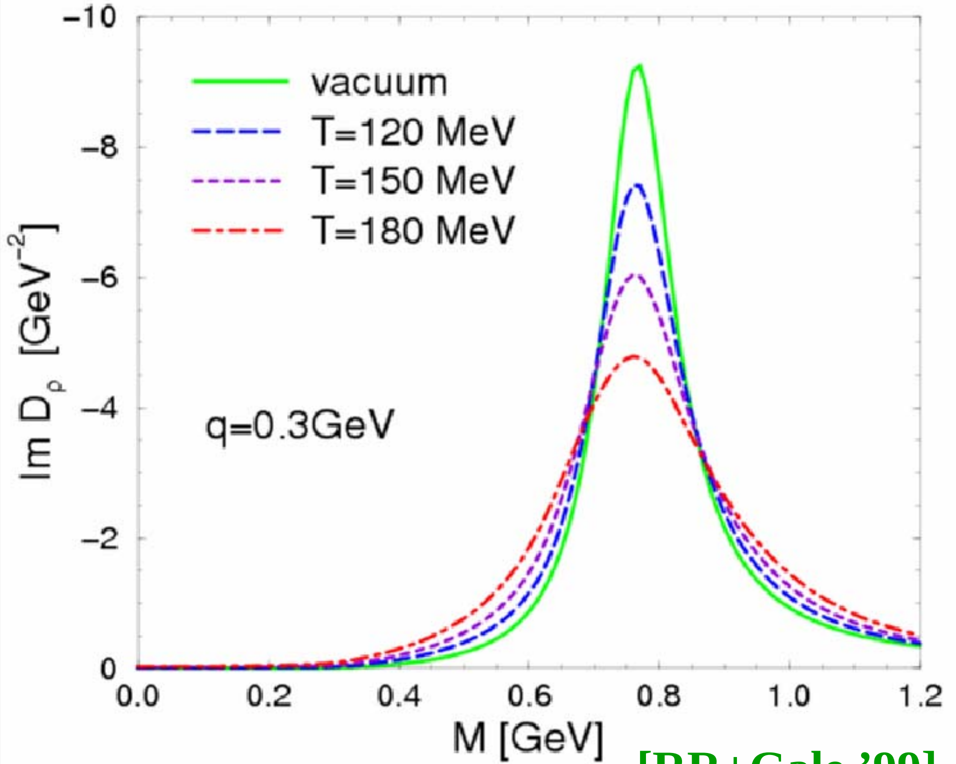
3.1.4 ρ-Meson Spectral Functions at SPS

Hot+Dense Matter



[RR+Wambach '99]

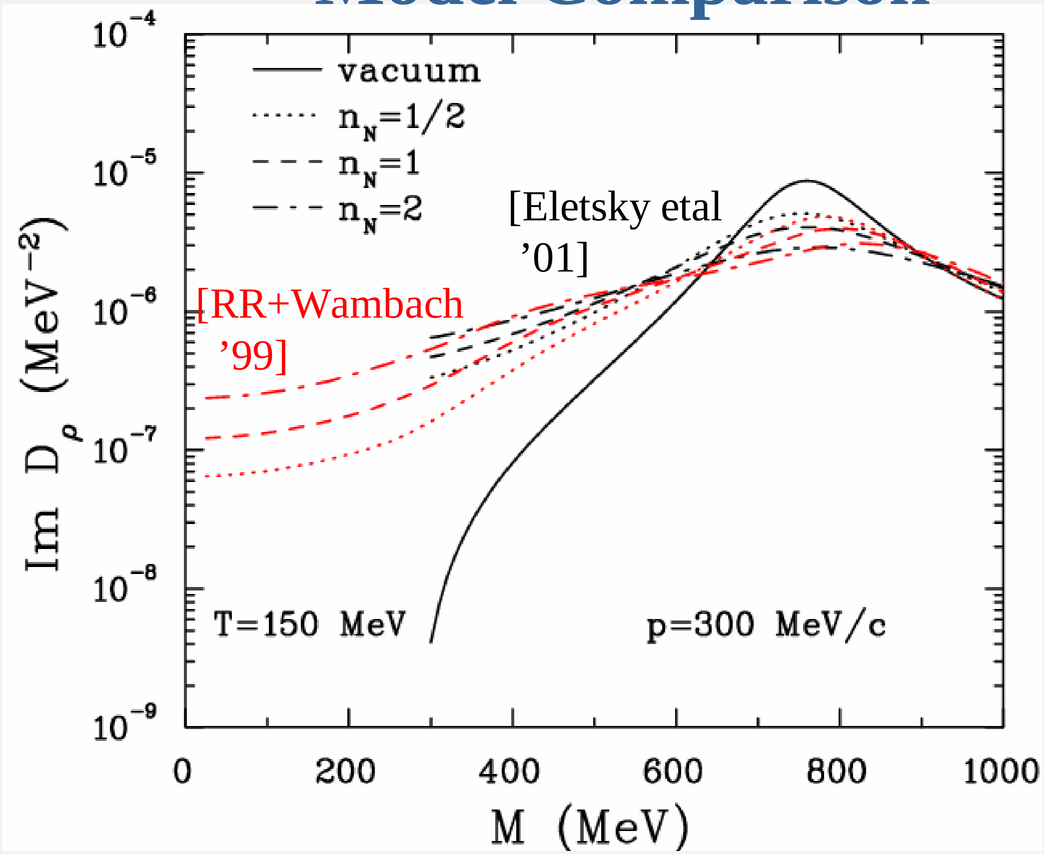
Hot Meson Gas



[RR+Gale '99]

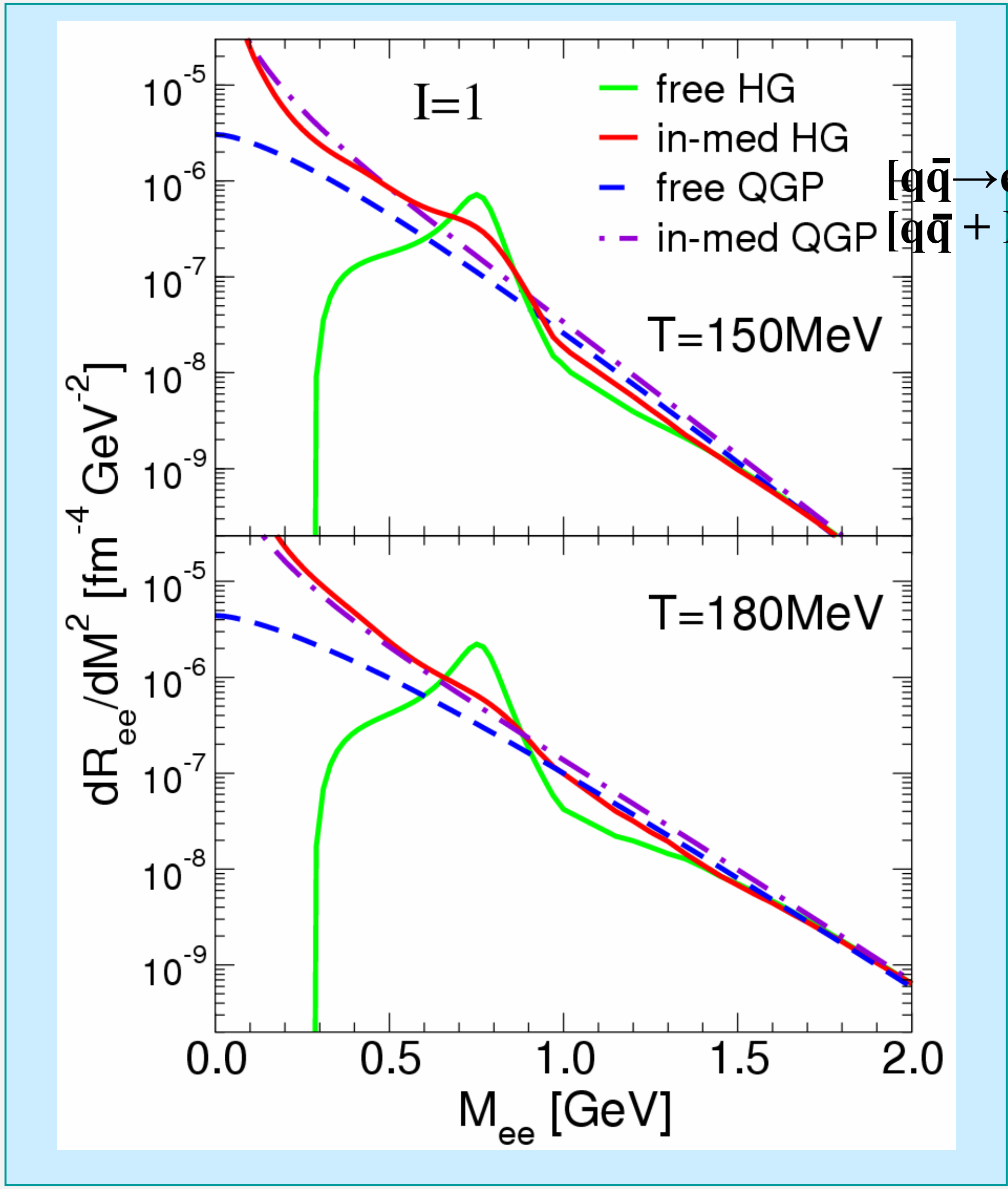
- ρ-meson "**melts**" in hot and dense matter
- baryon density ρ_B more important than temperature
- reasonable agreement between models

Model Comparison



3.2 Dilepton Emission Rate: Hadron Gas vs. QGP

$$\frac{dR_{ee}}{dM^2} = \frac{c\,\alpha^2}{M^2}\int\frac{d^3q}{q_0}\, f^B(T)\, Im\Pi_{em}(M,q)$$



[$q\bar{q}\to ee$]

[$q\bar{q}$ + HTL] [Braaten,Pisarski+Yuan '90]

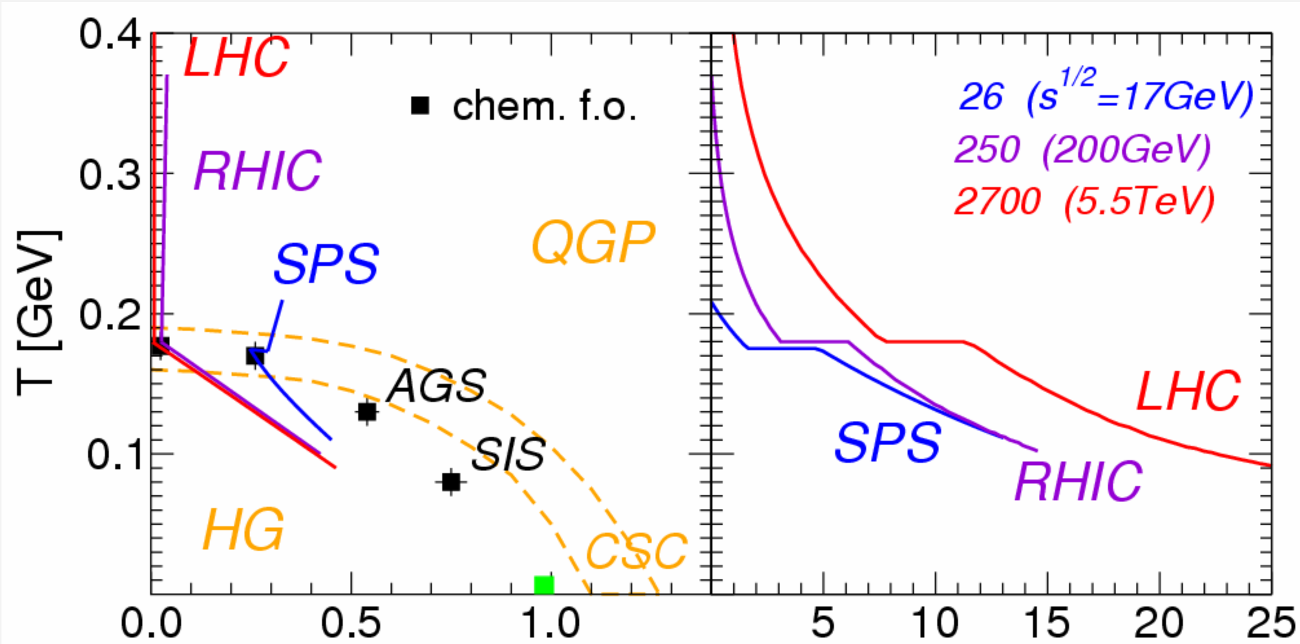
- Hard-Thermal-Loop QGP rate enhanced over Born rate
- **"matching" of HG and QGP in vicinity of T_c**
- **"Quark-Hadron Duality" ?!**

4.) Dilepton Spectra in Heavy-Ion Collisions

Thermal Emission:

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

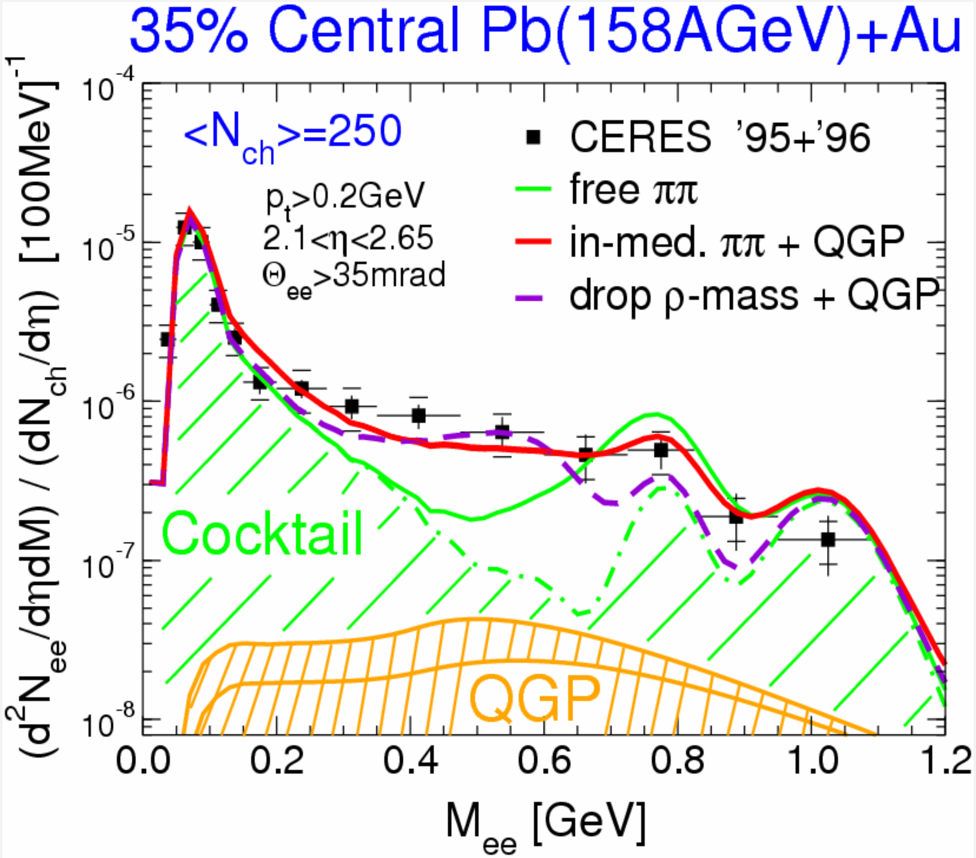
Pb-Pb Collisions: Trajectories in the Phase Diagram



μ_N [GeV] τ [fm/c]

- based on entropy (+baryon-number) conservation
- volume expansion: $V_{FB}(\tau) = (z_0+v_z\tau)\ \pi\ (R_\perp + 0.5a_\perp\tau^2)^2$

4.1 Pb-Au Collisions at SPS: CERES/NA45

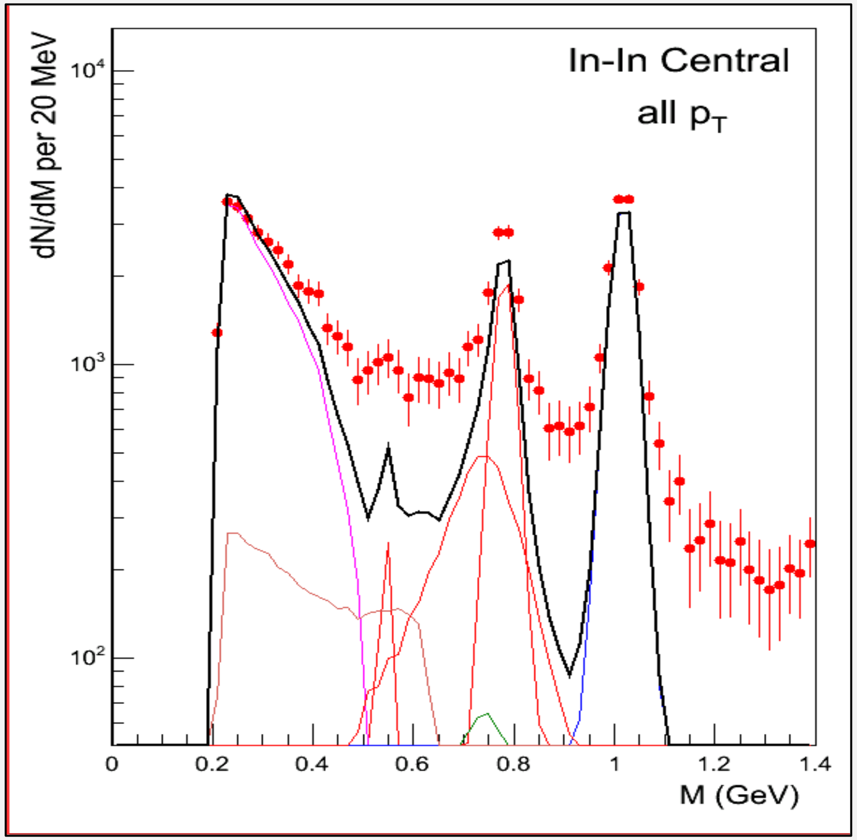


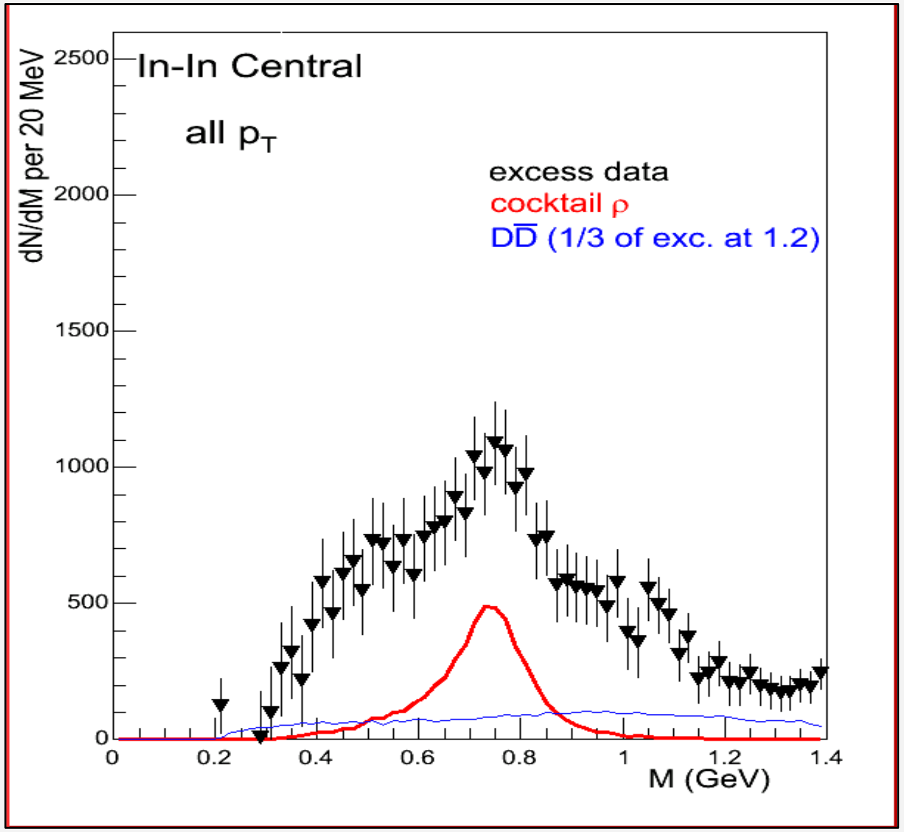
- QGP contribution small
- **medium effects on ρ-meson!**
- dropping mass or broadening?!

4.2 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!

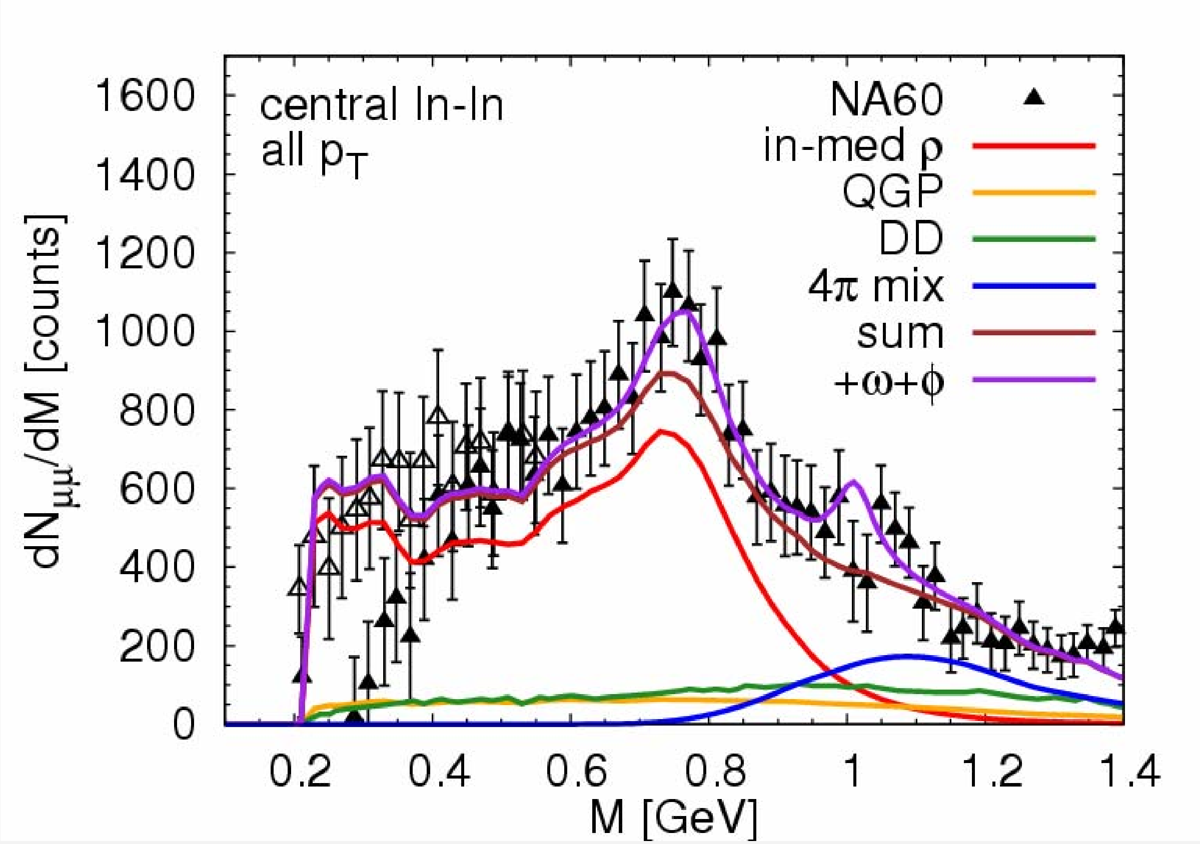




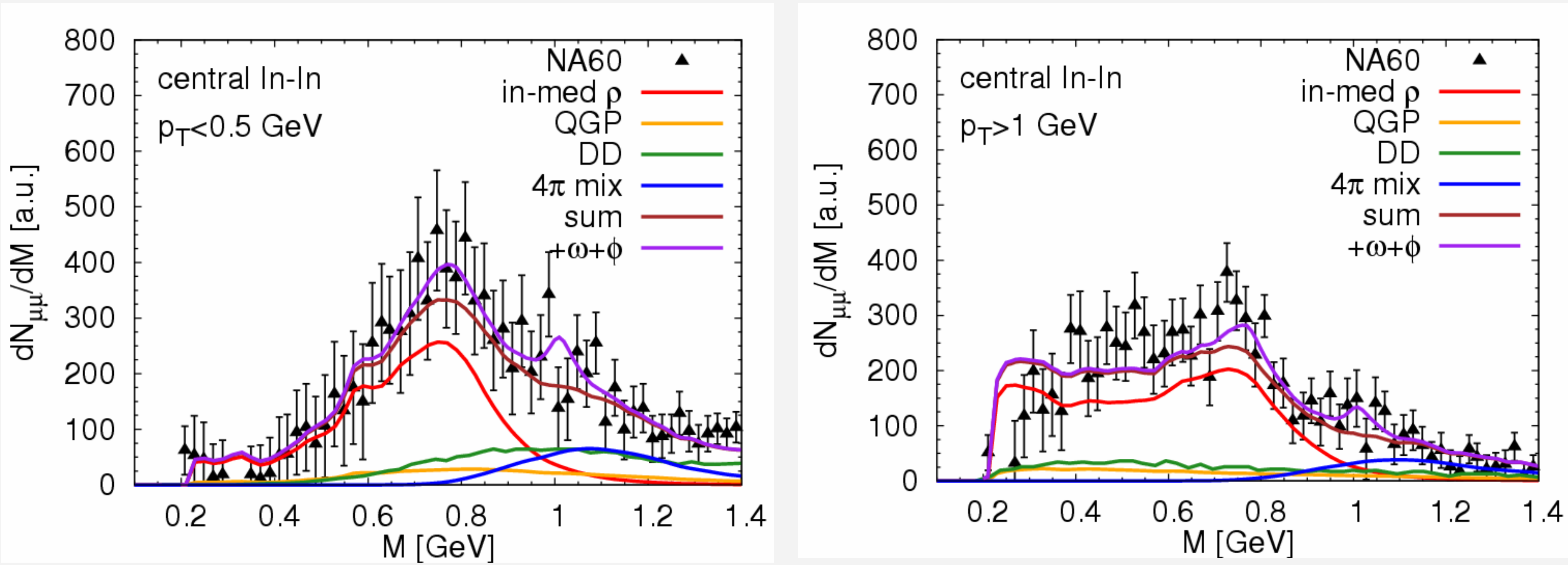
- **quantitative theory?**

4.2.2 In-In at SPS: Theory vs. NA60

- predictions based ρ-spectral function of **[RR+Wambach '99]**
- uncertainty in fireball lifetime (±25% norm.); or: infer **τ_{FB}≈7fm/c** !
- relative strength of thermal sources fix



- good agreement with ρ **melting**, including **p_t** dependence **[van Hees +RR '06]**



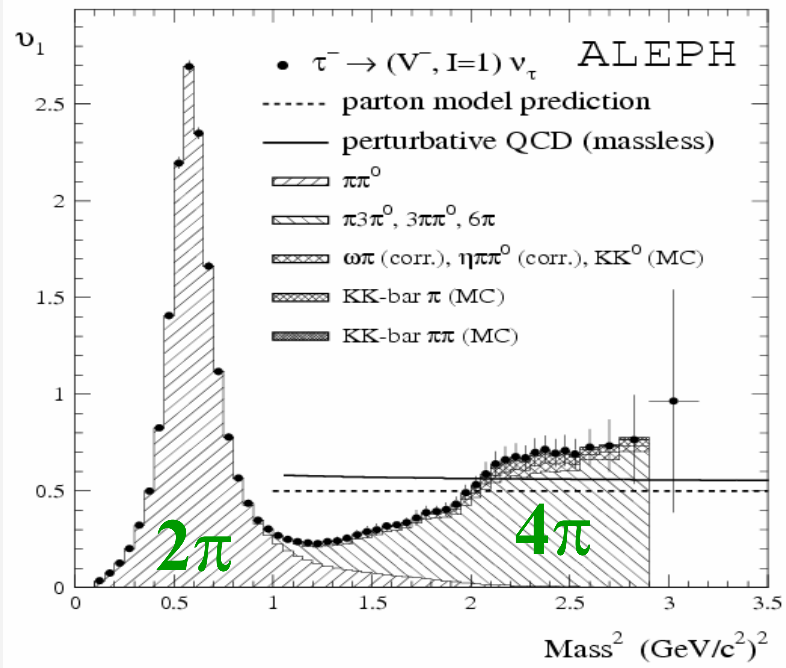
central In-In
p_T<0.5 GeV
NA60
in-med ρ
QGP
DD
4π mix
sum
+ω+φ
$dN_{\mu\mu}/dM$ [a.u.]
M [GeV]
central In-In
p_T>1 GeV
NA60
in-med ρ
QGP
DD
4π mix
sum
+ω+φ
$dN_{\mu\mu}/dM$ [a.u.]
M [GeV]

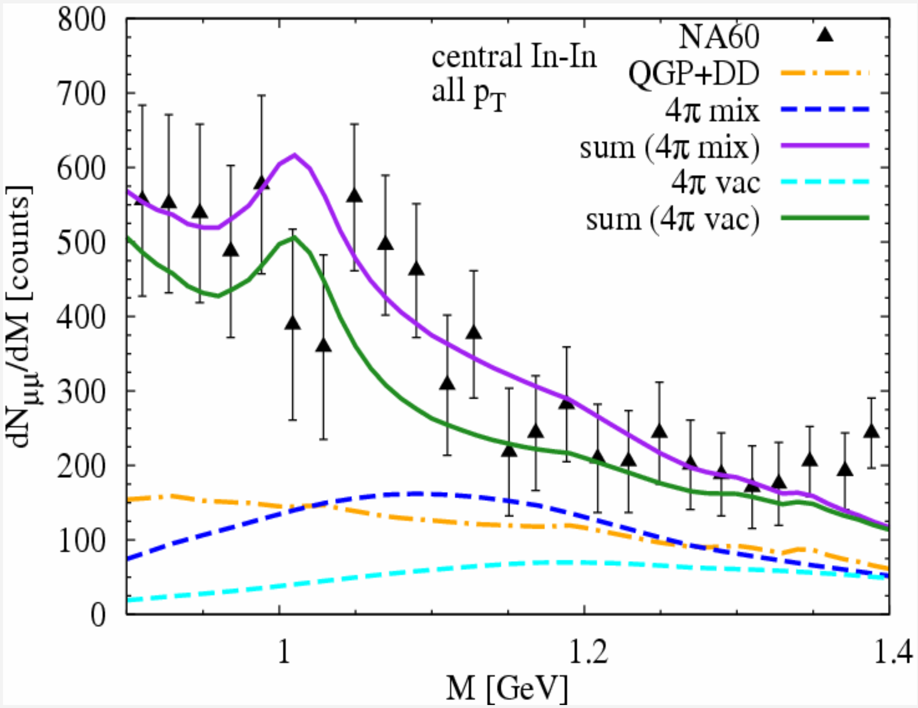
4.2.3 Intermediate-Mass Region

- "4π" states dominate in the vacuum e.m. correlator above **M ≈ 1.1GeV**
- **lower estimate:** use **vacuum** **4π** correlator
- **upper estimate:** **O(T^2)** medium effect → "chiral **V-A** mixing": **[Eletsky+Ioffe '90]**

$$\Pi_V(q) = (1-\varepsilon)\Pi_V^0(q) + \varepsilon\,\Pi_A^0(q)$$

with $\varepsilon(T_c) \equiv \frac{1}{2}$

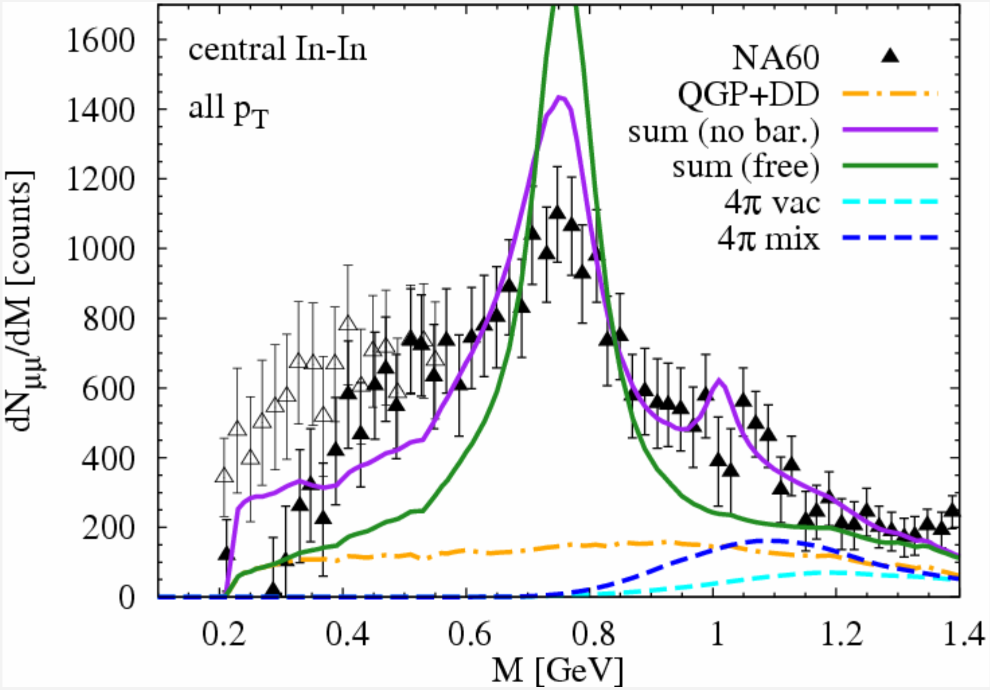


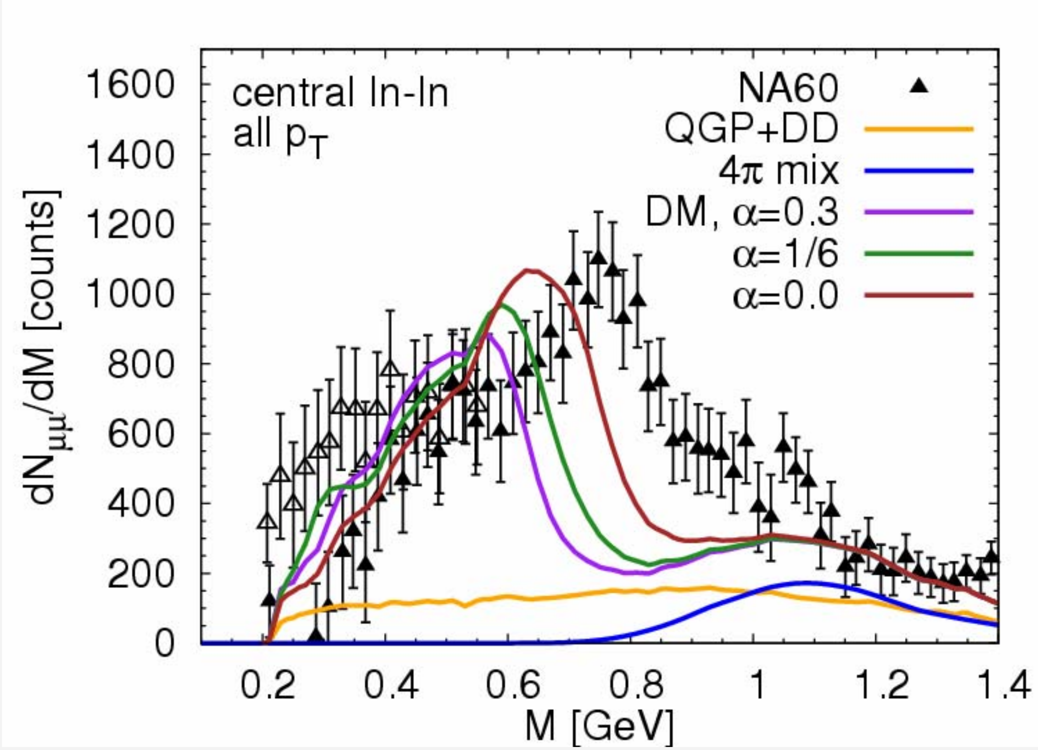


[van Hees+RR '06]

4.2.4 NA60 Data: Other ρ-Spectral Functions

- switch off medium modifications
- **T**-, ρ_B- dependence of bare parameters: **dropping mass** **[Brown+Rho '91, Hatsuda+Lee '92]**





- free spectral function ruled out
- meson gas insufficient either

- dropping mass as used for CERES disfavored (free ρ decays?)

4.2.5 (Some) Open Issues

- **Heavy-Ion Collisions** **[NA60]**
  - centrality dependence, free ρ's (surface vs. volume)
  - sensitivity to fireball evolution
  - quantitative ω and ϕ
  - thermal radiation at intermediate mass (**M=1.5-3 GeV**)
  - chiral restoration:
    - "duality" (hadron liquid → sQGP)
    - chiral sum rules
    - chiral mixing in the **M=1-1.5GeV** region

- **Cold Nuclei** **[CB/TAPS, KEK-E325]**
  - dropping ω-mass + broadening
  - dropping ρ-mass without broadening ?!

5.) Conclusions

- Strong medium effects in l^+l^- spectra
- new level of precision in NA60 → model discrimination
- ρ-melting at T_c, no apparent mass shift
- alternative models? (quality control)

- Chiral Restoration:
  - direct (exp.): measure axialvector
  - indirect (theo.): (1) effective model (constraints)
    (2) chiral sum rules (V-A moments) vs. lQCD
    (3) compatibility with dilepton/photon data
- HADES, RHIC, LHC, SPS-09, CBM, …, elementary reactions

In-medium V-meson spectroscopy has begun …

3.3 Medium Effects II: Dropping Mass

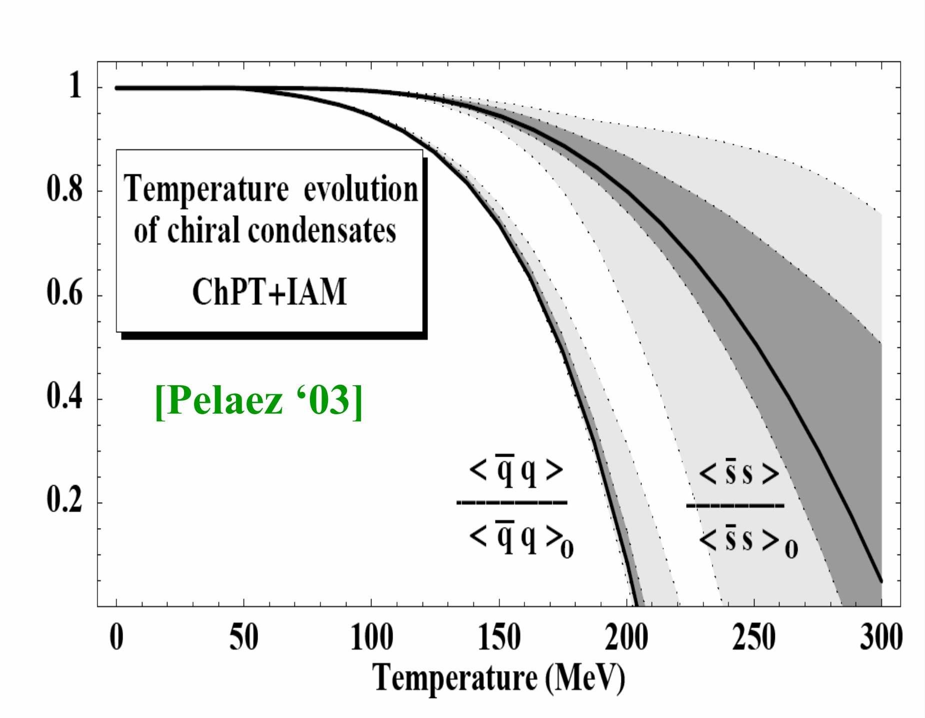
Scale Invariance of $\mathcal{L}_{QCD}$ → bare parameters change!?

[Brown+Rho '91, '02]

$$\langle\bar{q}q\rangle_T^{1/n} \big/ \langle\bar{q}q\rangle_{\rm vac}^{1/n} = f_\pi^* / f_\pi = m_N^* \big/ m_N = m_\rho^* \big/ m_\rho \quad = \left[1-\left(\frac{T}{T_c}\right)^2\right]^\alpha \left[1 - C\frac{\rho_B}{\rho_0}\right]$$

- density dependence:
  QCD sum rules: $C \approx 0.15$ [Hatsuda+ Lee '92]

- temperature dependence: α
  quark condensate from chiral perturbation theory: $\frac{\langle qq\rangle_T}{\langle qq\rangle_{vac}} \approx \left[1-\left(\frac{T}{T_c}\right)^2\right]^{\frac{1}{3}}$



- vector dominance coupling:

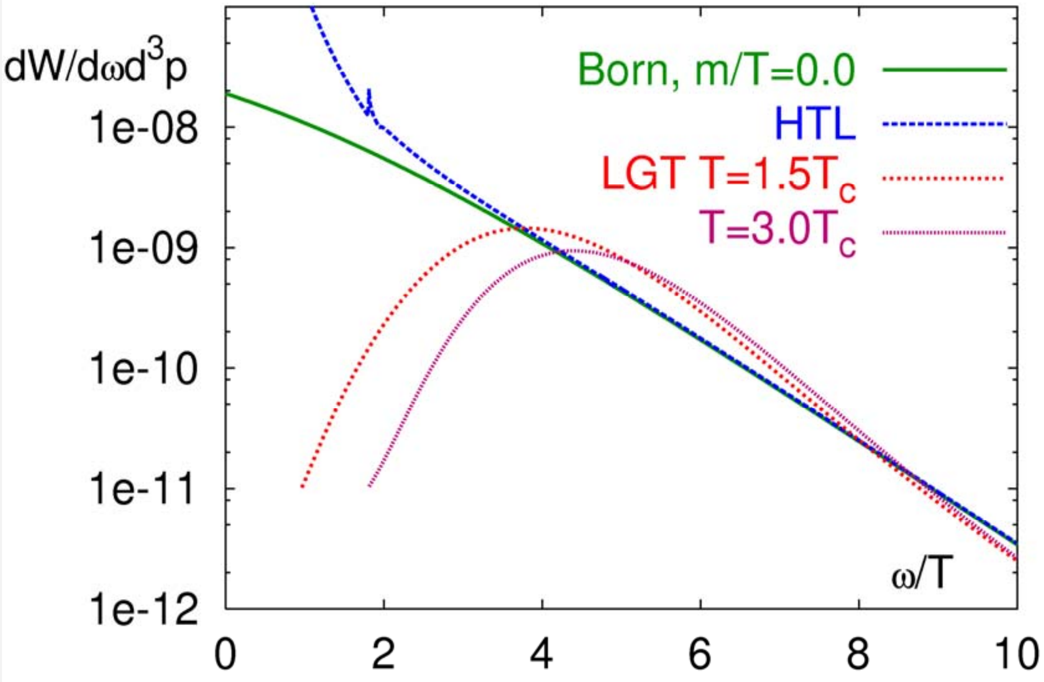
$$Im\,\Pi_\rho = \frac{(m_\rho^*)^4}{g_\rho^2} Im\,D_\rho(m_\rho^*)$$

(gauge invariance!)

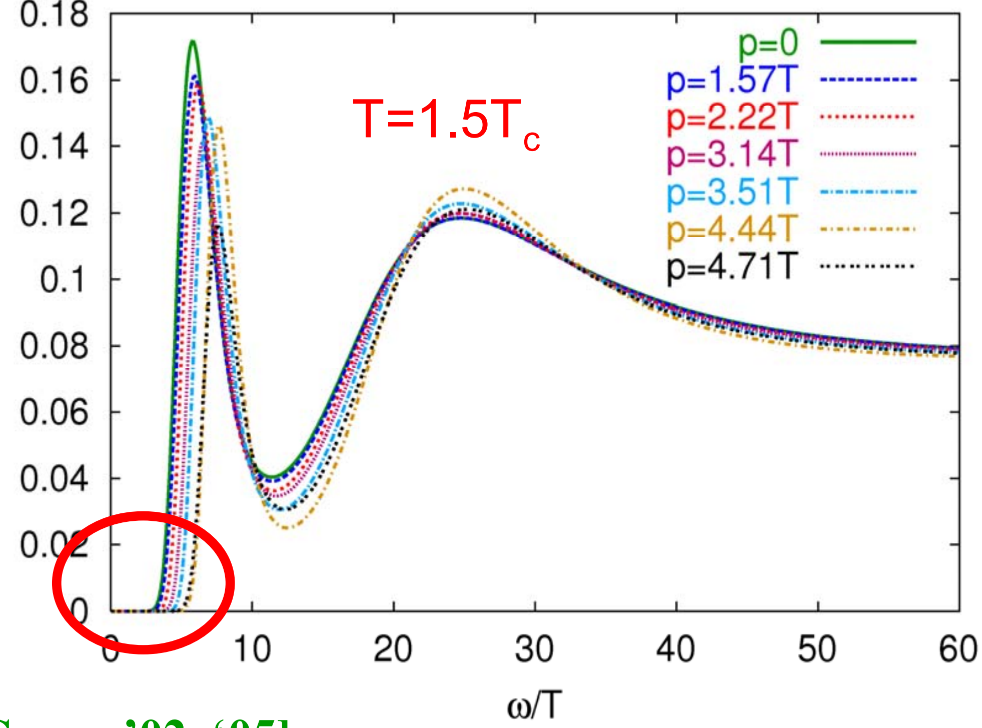
3.) Medium Effects and Thermal Dileptons

3.1 Lattice QCD (QGP)

Dilepton Rate ~ *ImΠ(ω,q=0)/ω²*



EM Correlator *ImΠ(ω,q)/ω²*



[Bielefeld Group '02, '05]

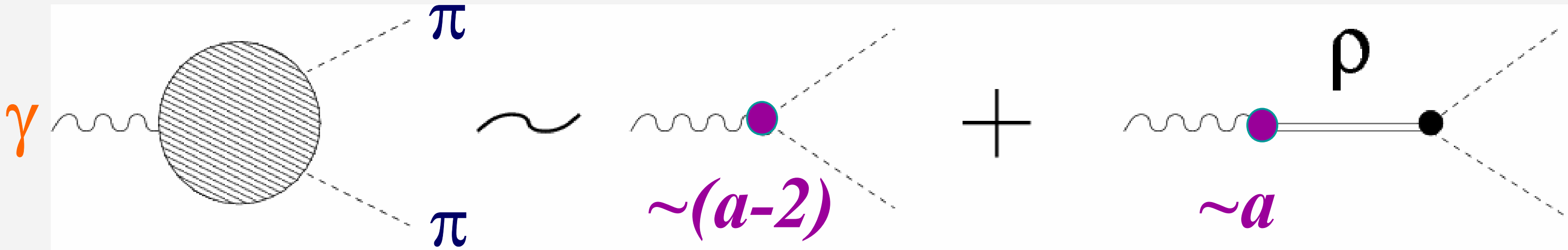
- **l**QCD << **p**QCD at low mass (finite volume?)
- currently no thermal photons from lQCD
- vanishing electric conductivity!? but: [Gavai '04]

3.4 In-Medium IV: Vector Manifestation of Chiral Symmetry

- Hidden Local Symmetry: ρ-meson introduced as gauge boson, "Higgs" mechanism generates ρ-mass
- **Vacuum**: $\rho_L \leftrightarrow \pi$, good phenomenology (loop exp. $\mathcal{O}(p/\Lambda_\chi, m_\rho/\Lambda_\chi, g)$)
- **In-Medium:** T-dep. $m_\rho^{(0)}$, g_ρ matched to OPE (spacelike), $\Lambda_{match} < \Lambda_\chi$, Renormalization Group running → on-shell

[Harada, Yamawaki etal, '01]

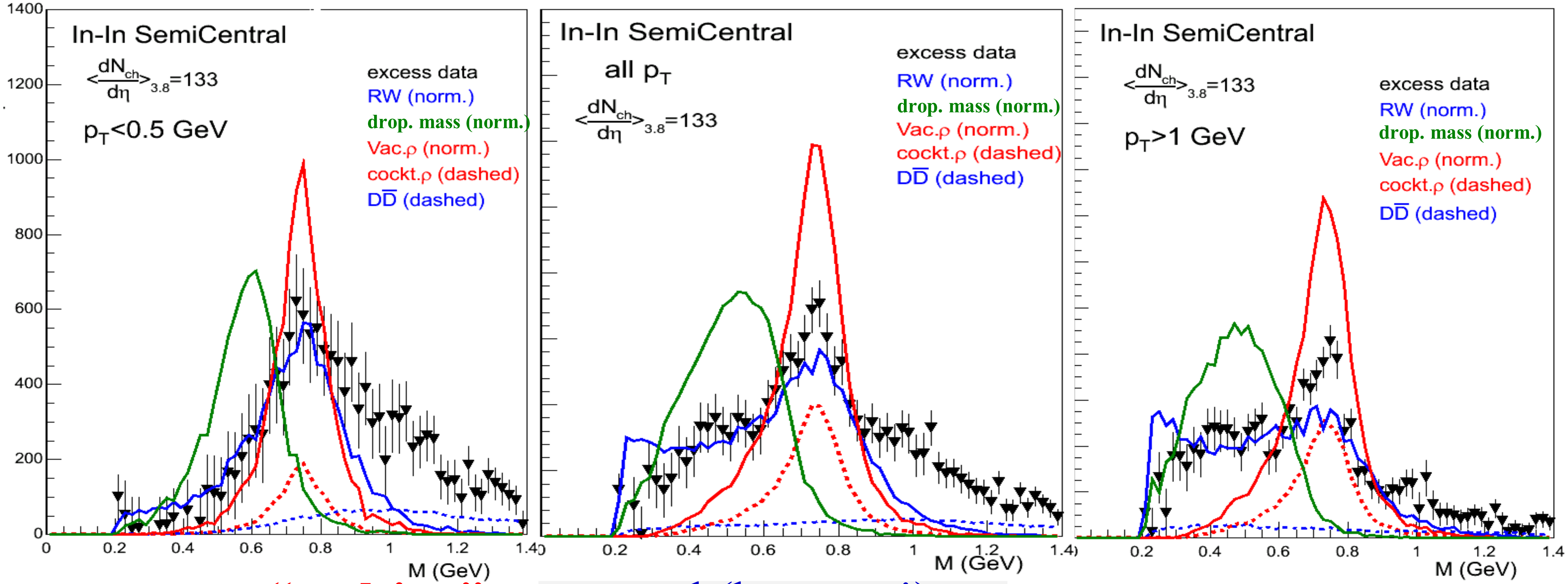
⇒ **- dropping ρ-mass → 0 (RG fixed point at T_c) ,**
- violation of vector dominance: $a = 2 \rightarrow 1$



e.m. spectral function? matching HG-QGP: massless mesons?

4.2 Recent Advances at SPS: Power of Precision

NA60 Data vs. Model Predictions [RR+Wambach '99; RR'03]



- ρ-meson "**melting**" supported (baryons!)
- dropping mass (as used to explain CERES data) ruled out
- open issues:

  (1) $M > 0.9 GeV$ ($4\pi \rightarrow \mu^+\mu^-$!?)

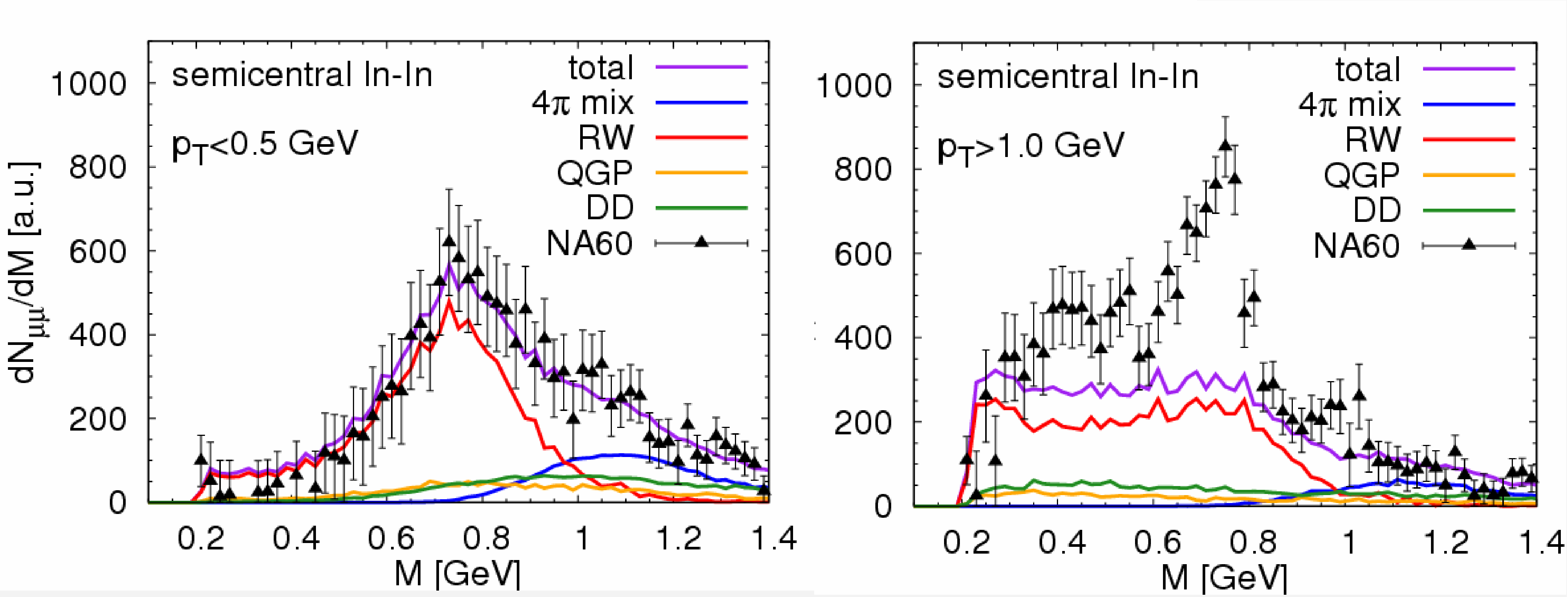
  (2) normalization: **0.6** (p_t <0.5GeV), **0.8** (all p_t), **~2** (p_t >1GeV)

  (3) other models (vector manifestation, chiral virial approach, …)

4.2.2 Modified Fireball and Absolute Normalization

- ρ-spectral function unchanged since **[RR+Wambach '99]**
- expanding fireball, fixed S ($\leftrightarrow N_{ch}$): $V_{FB}(\tau)=(z_0+v_z\tau)\ \pi\,(R_{\perp 0}+0.5a_\perp\tau^2)^2$

Increase $a_\perp \Rightarrow$ reduced lifetime ($\tau=9\rightarrow 6fm/c$), increased $v_\perp=0.4\rightarrow 0.5c$

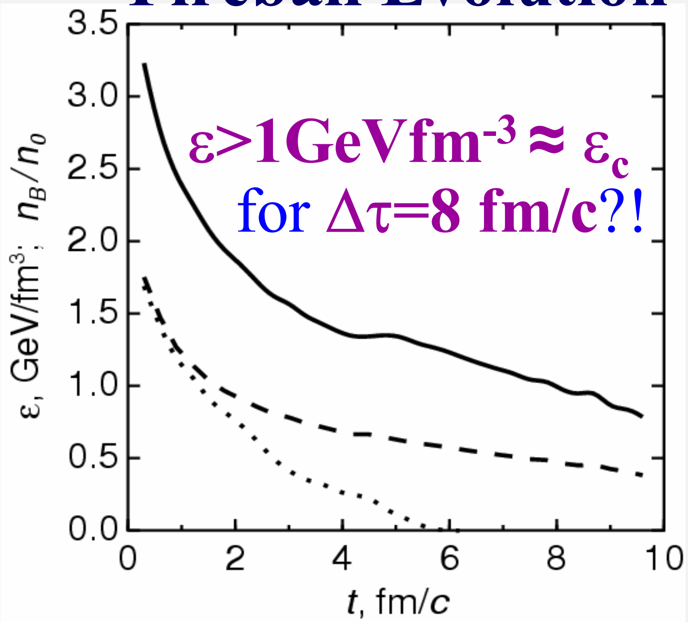


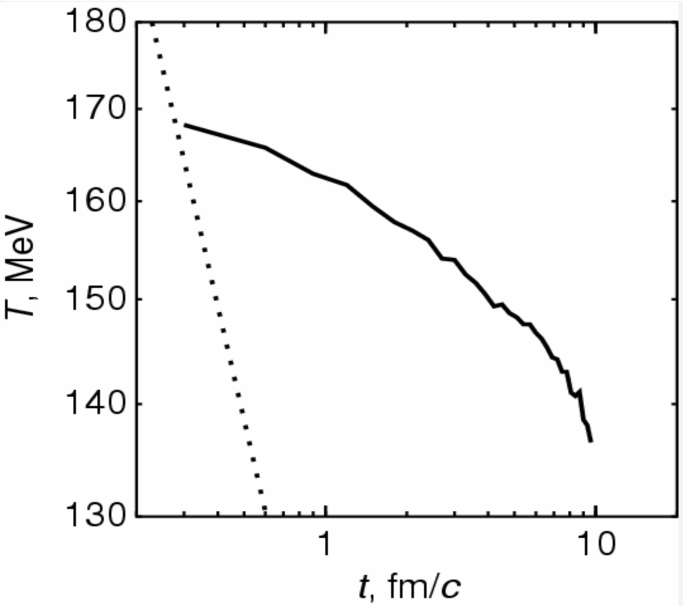
- reasonable agreement with absolute normalization, but …
- too little yield at high $\mathbf{p_t}$; "free ρ"? ω? check central …

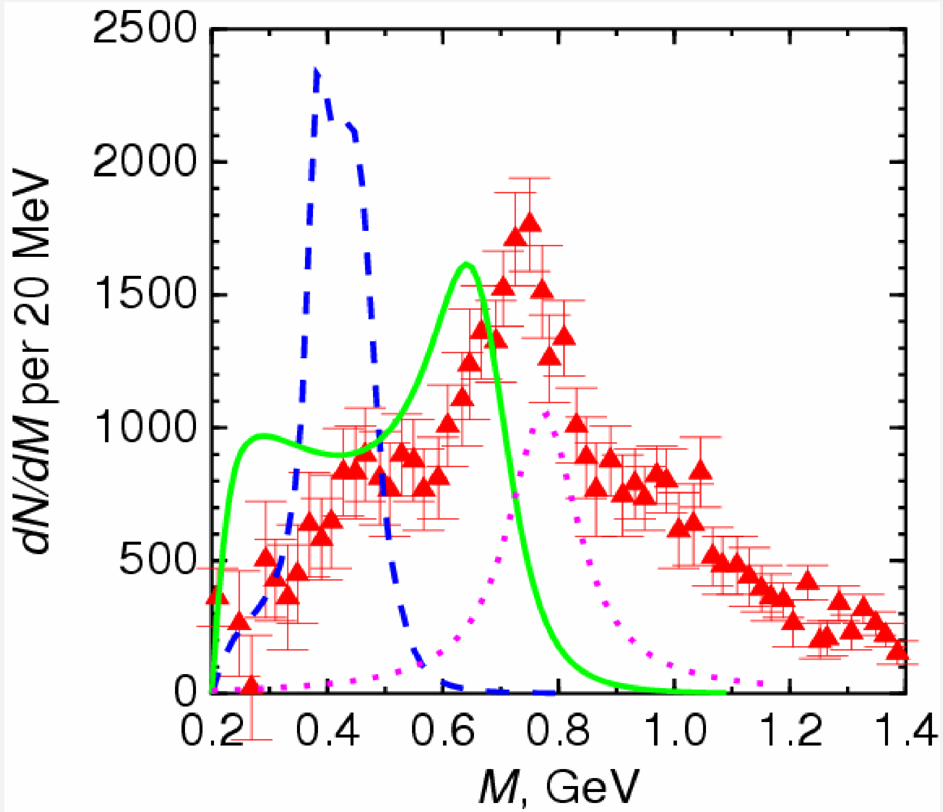
Revival Attempts for Dropping ρ-Mass

E.g., [Skokov+Toneev '05]

Fireball Evolution





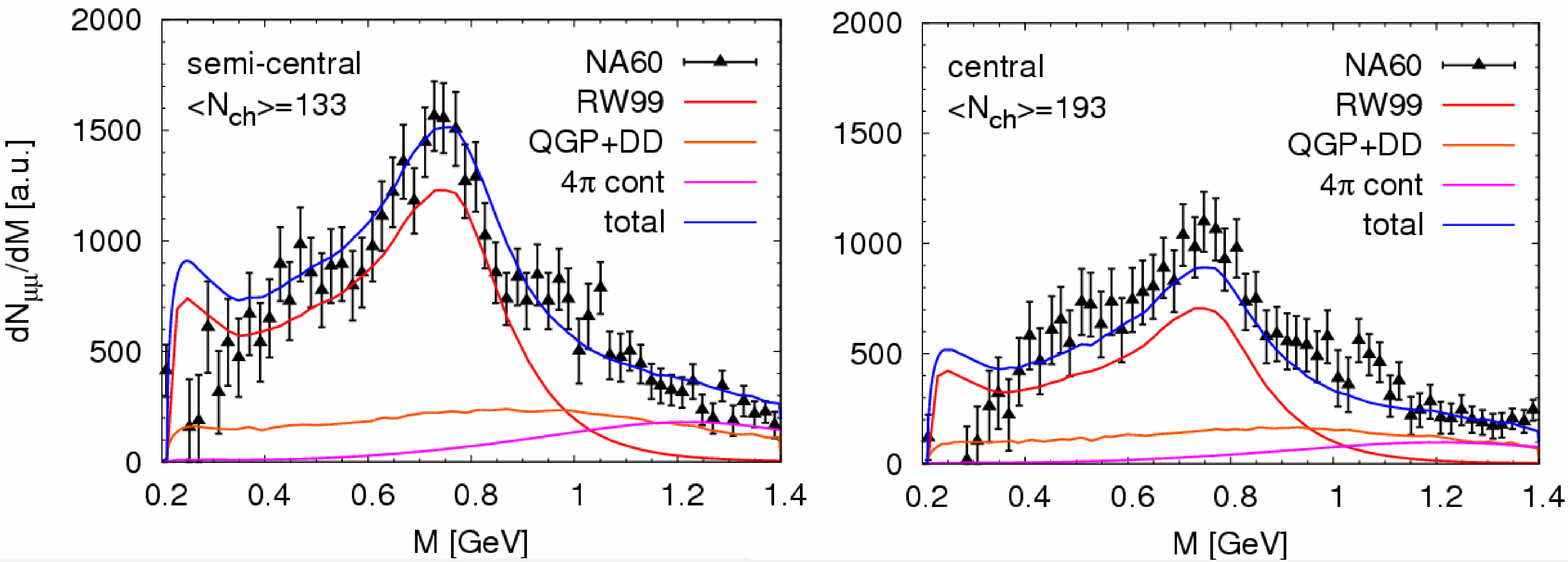


Bjorken regime:
τ_{FB}=0.5 fm/c?!

- Not compatible with gauge invariance (no $\mathbf{m}_\rho$* in VDM)
- acceptance?

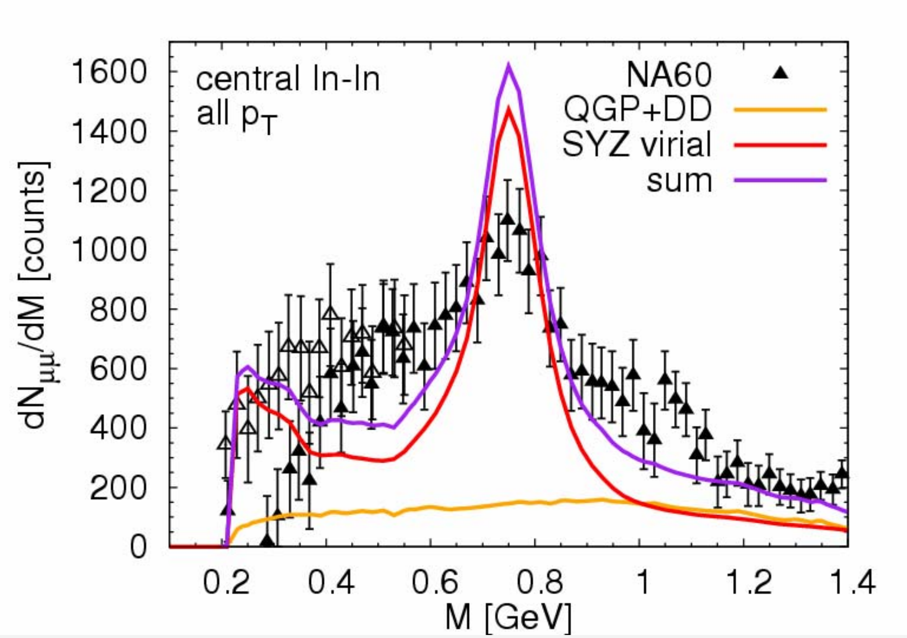
M ≥ 1GeV in NA60

[H. van Hess + RR, in prep.]



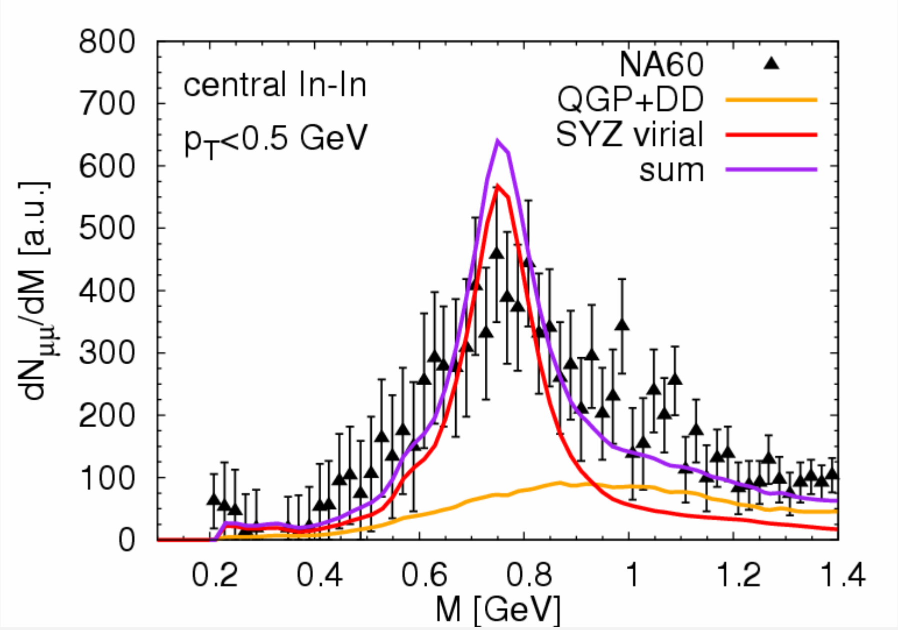
- combination of 4-π + QGP + charm?!
- (beware: schematic acceptance)

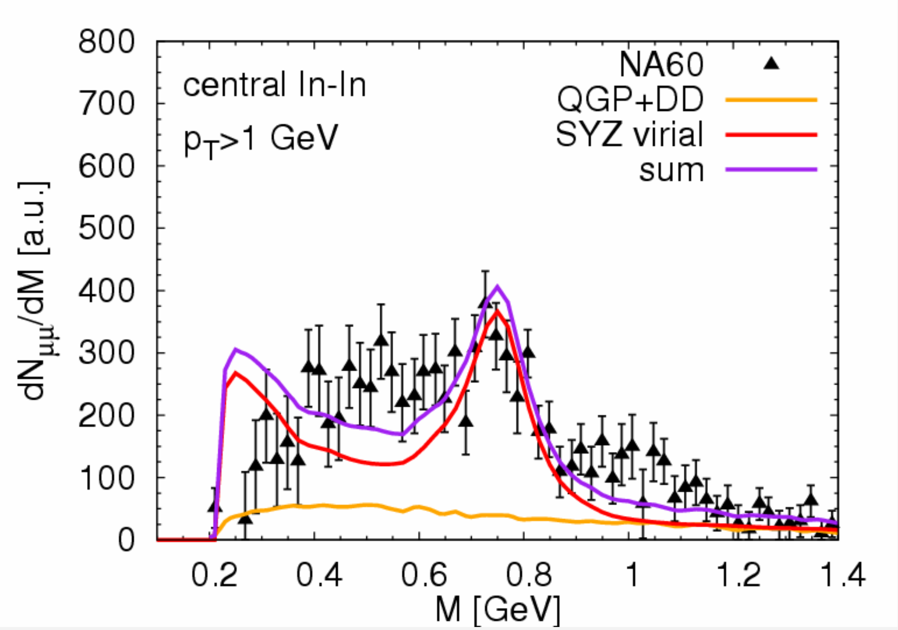
4.2.5 Chiral Virial Approach vs. NA60 (central)



[Steele,Yamagishi +Zahed '99]

[implementation van Hees+RR '05]

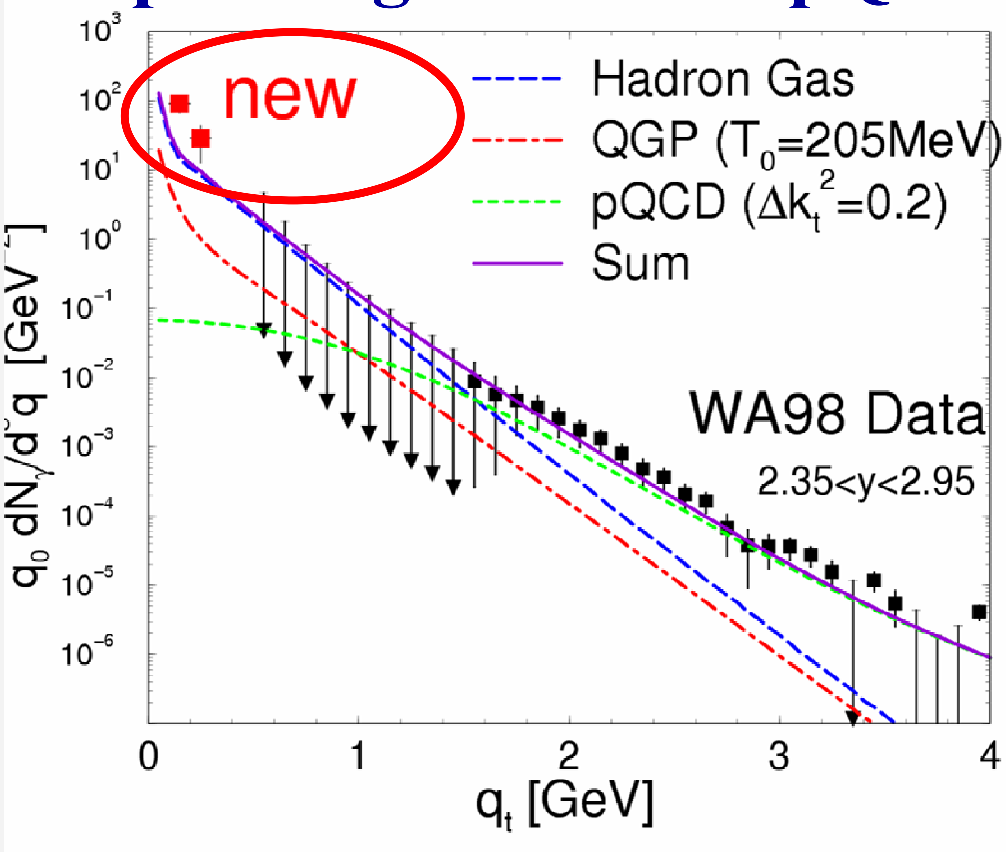




5.) Electromagnetic Probes

5.1.1 Thermal Photons I : SPS

Expanding Fireball + pQCD

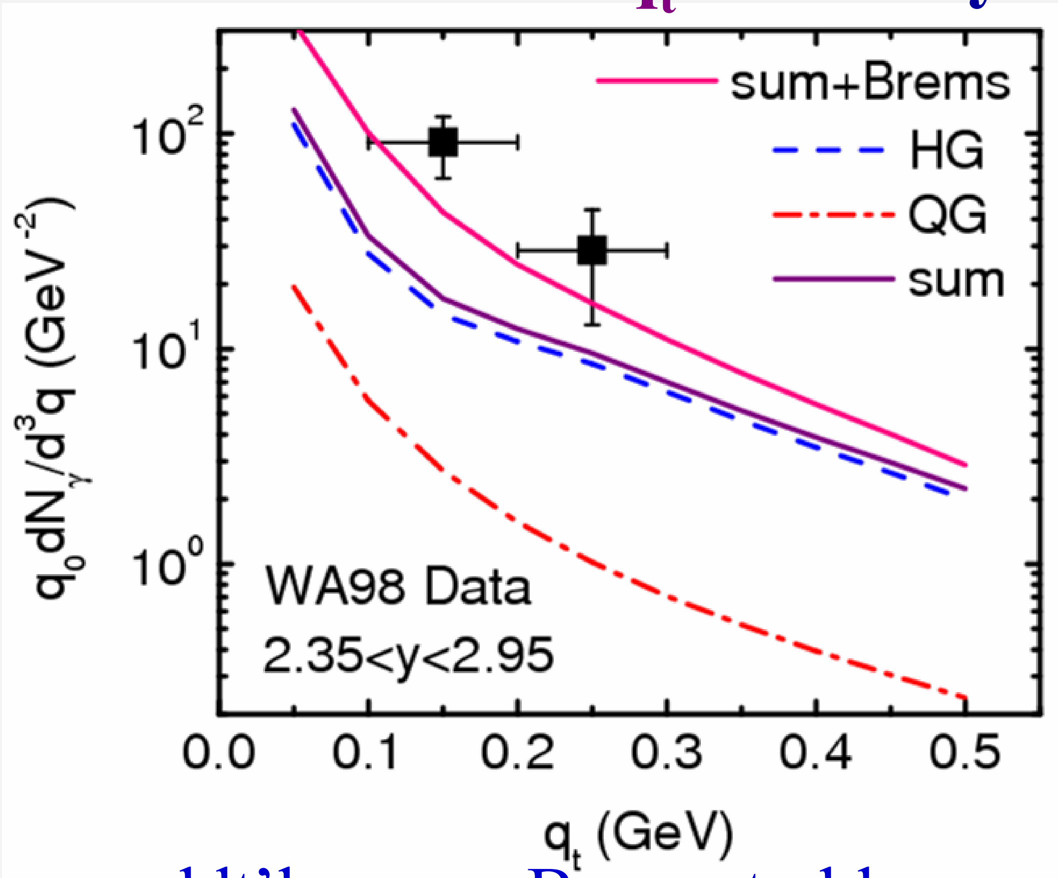


• pQCD+Cronin at q_t >1.6GeV

⇒ T_0=205MeV suff., HG dom.

[Turbide,RR+Gale'04]

WA98 "Low-q_t Anomaly"



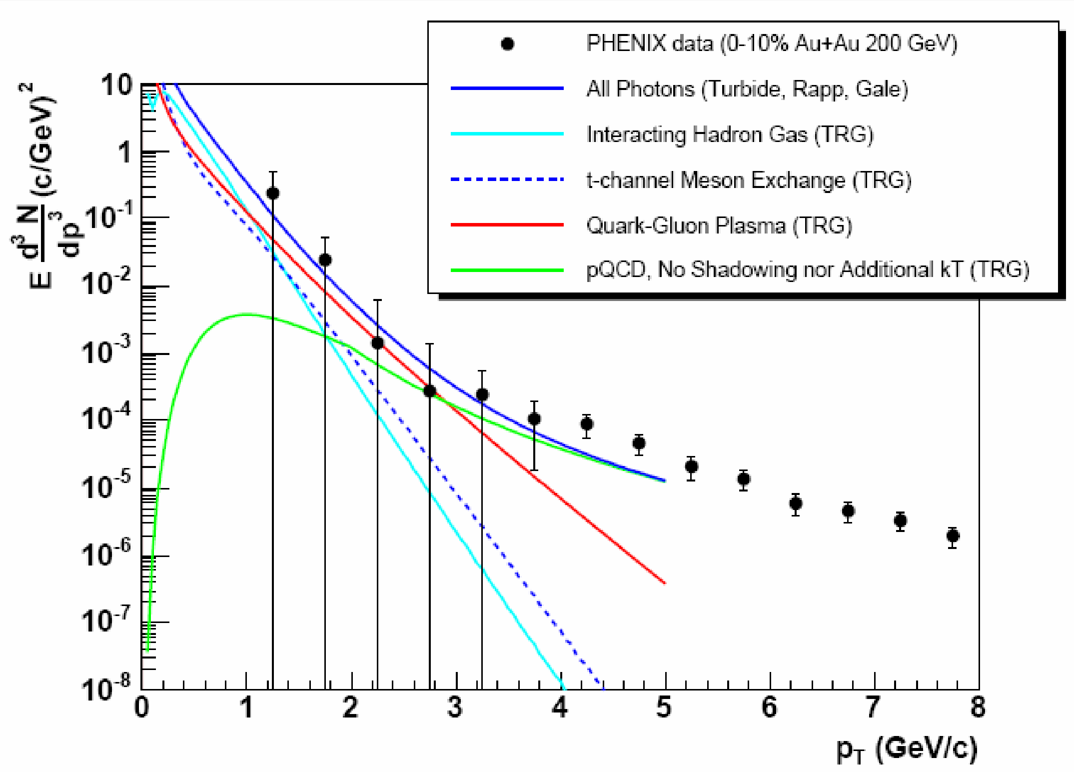
• addt'l meson-Bremsstrahlung

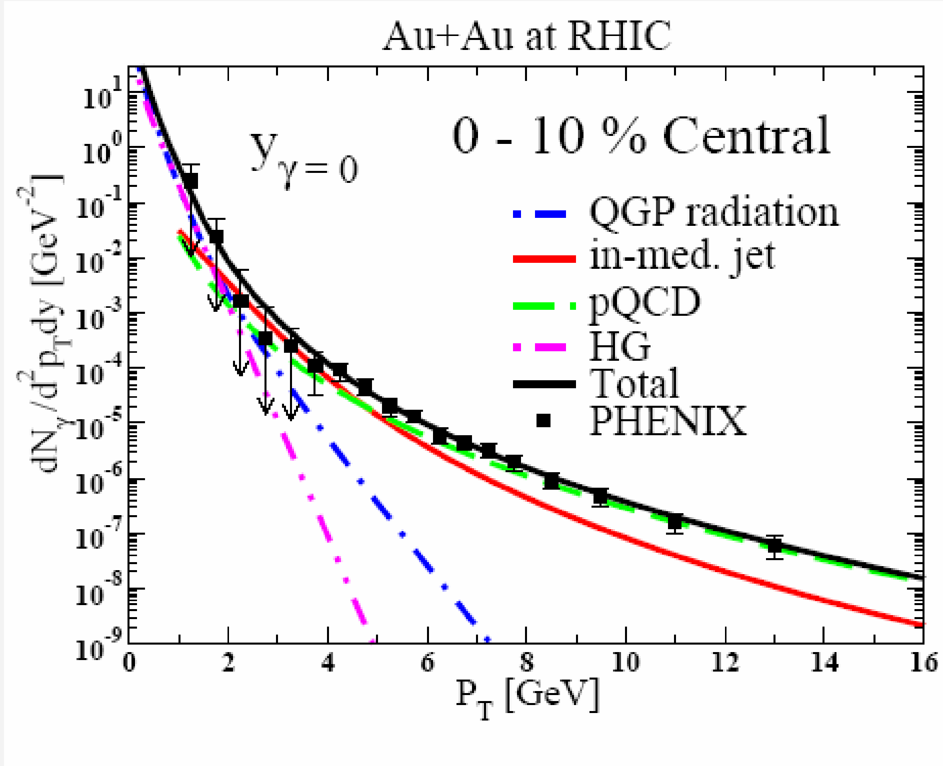
$\pi\pi \rightarrow \pi\pi\gamma \quad \pi K \rightarrow \pi K\gamma$

substantial at low q_t

[Liu+ RR'05]

5.1.2 Thermal Photons II: RHIC



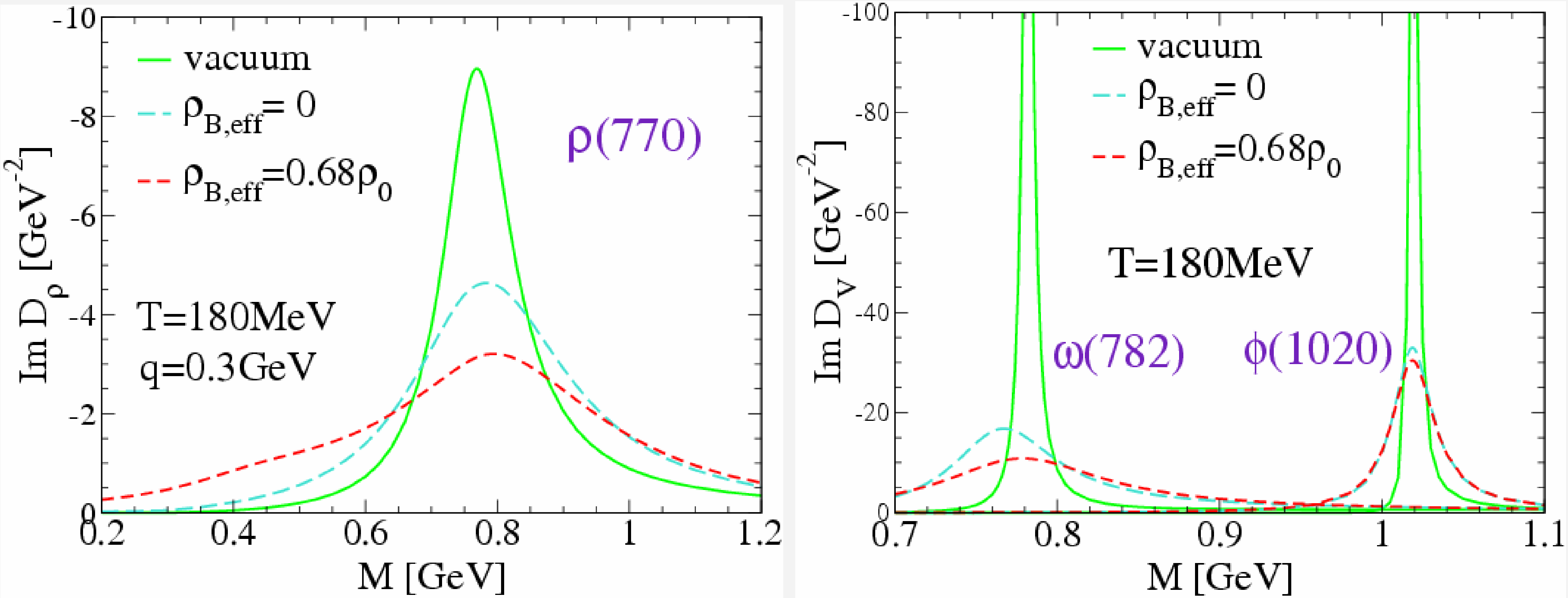


- thermal radiation ***q_t<3GeV*** ?!
- QGP window ***1.5<q_t<3GeV*** ?!
- also: γ-radiation off jets
- shrinks QGP window ***q_t<2GeV*** ?!

[Gale,Fries,Turbide,Srivastava '04]

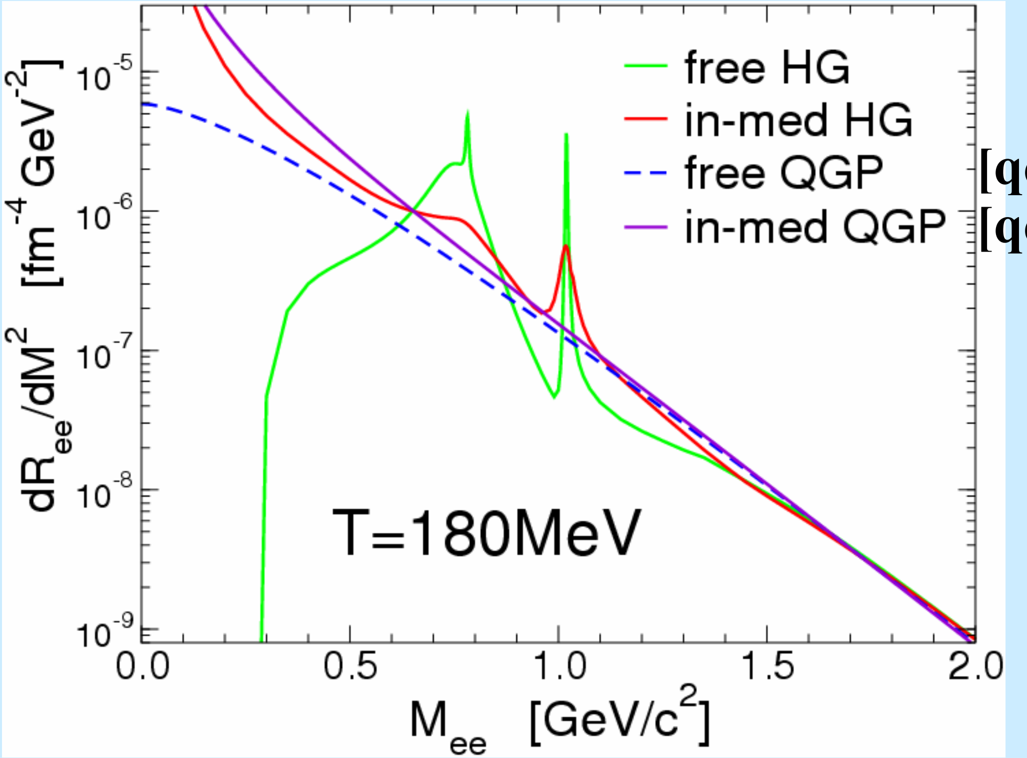
5.3.1 RHIC: Vector Mesons in Medium

Hadronic Many-Body Theory



- baryon effects important even at $\rho_{B,net}=0$:
  sensitive to $\rho_{B,tot}=\rho_B+\rho_{\bar{B}}$, most pronounced at low M
- ϕ more robust ↔ OZI

Dilepton Emission Rates



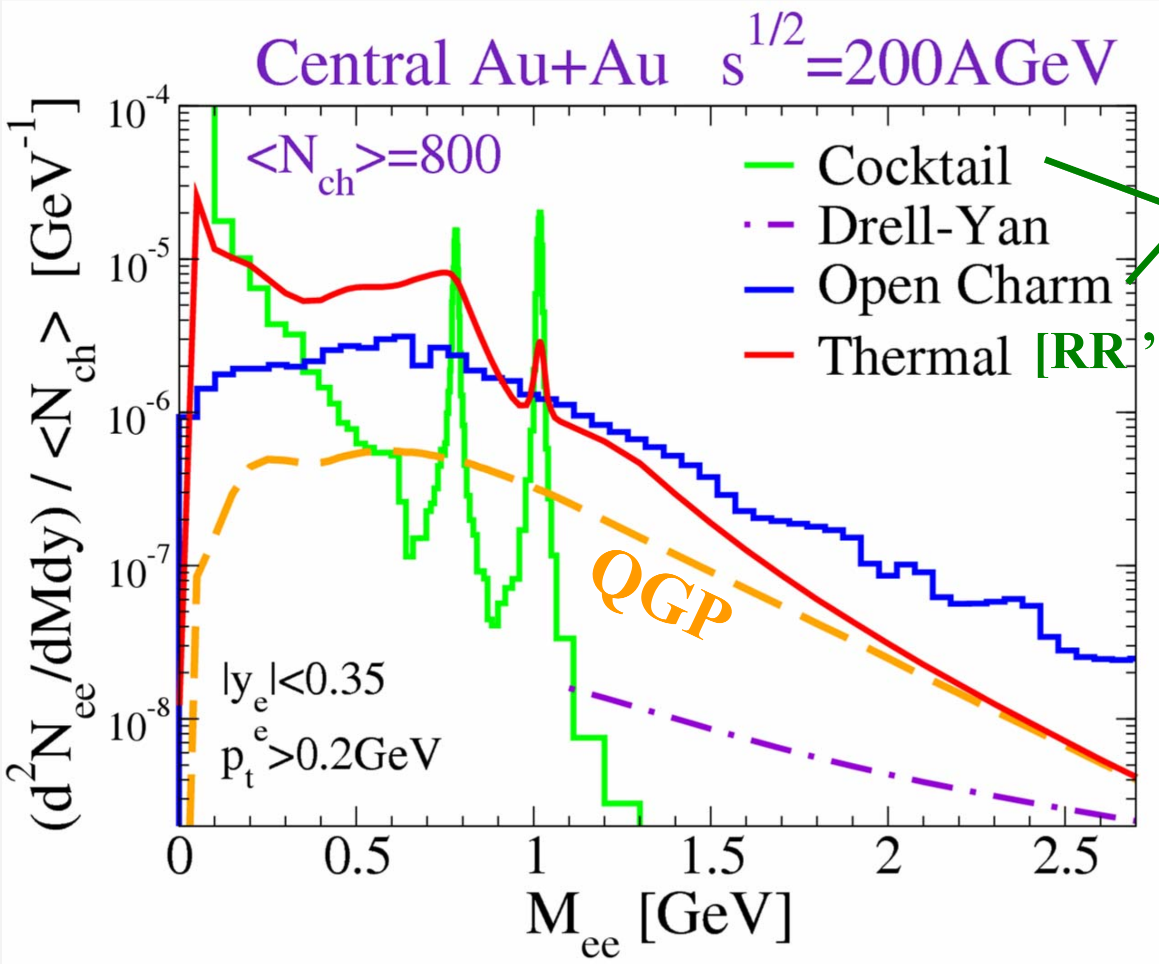
[$q\bar{q}\rightarrow ee$]

[$q\bar{q}+O(\alpha_s)$]

in-med HG ≈ in-med QGP !

Quark-Hadron Duality ?!

5.3.2 Dileptons II: RHIC



- low mass: thermal! (mostly in-medium ρ)
- **connection to Chiral Restoration:** $a_1(1260) \rightarrow \pi\gamma$, 3π
- int. mass: **QGP** (resonances?) vs. $c\bar{c} \rightarrow e^+e^-X$ (softening?)