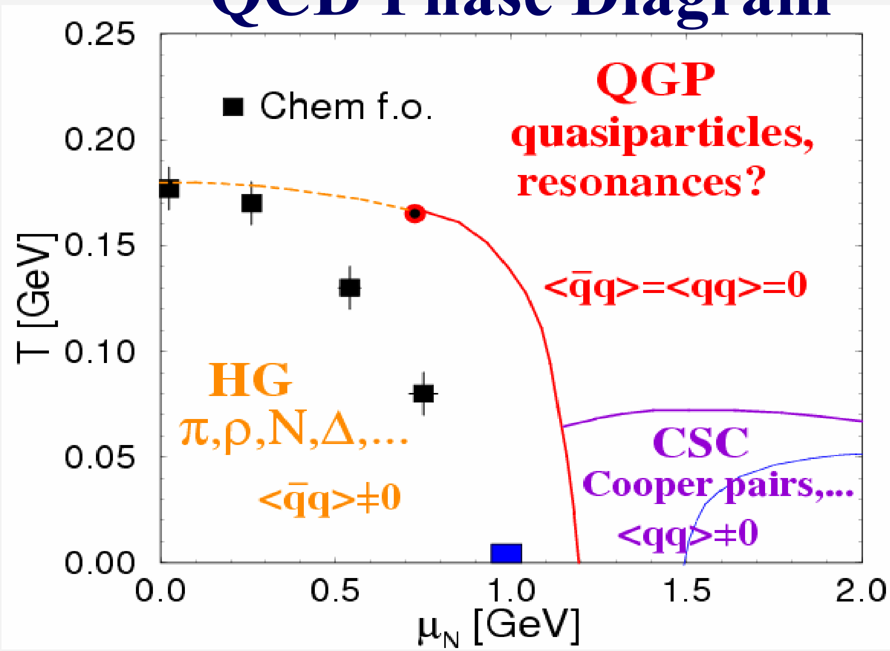
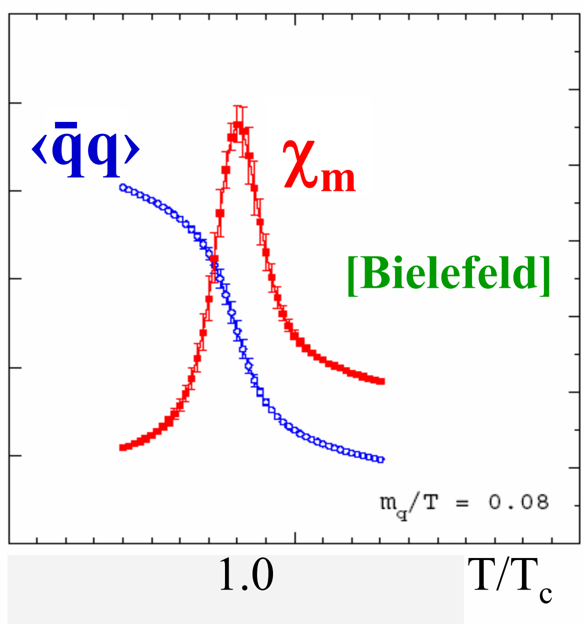
Phenomenology of Dilepton Production in Heavy-Ion Collisions

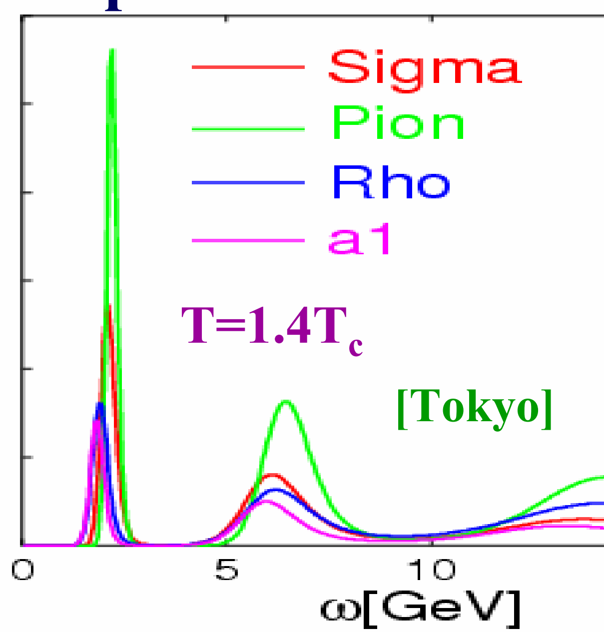
Ralf Rapp
Cyclotron Institute
+ Physics Department
Texas A&M University
College Station, USA

Compressed Baryonic Matter Workshop 2006
ECT* Trento, 30.05.06

Introduction: EM-Probes -- Basic Questions







Thermalization ⇒ 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

4.) Dileptons at SPS

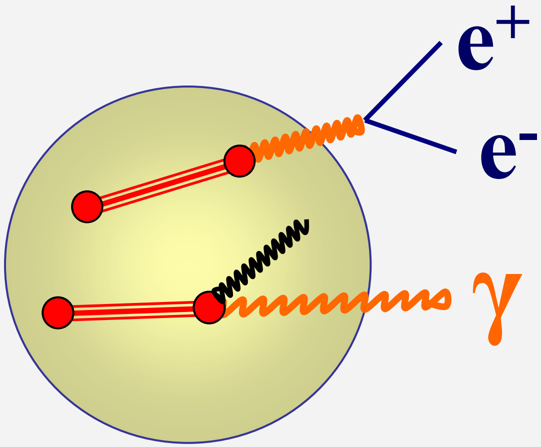
- CERES and NA60 Data
- Interpretation + Open Issues

5.) Conclusions

2.) EM Emission Rates and Chiral Symmetry

E.M. Correlation Function:

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



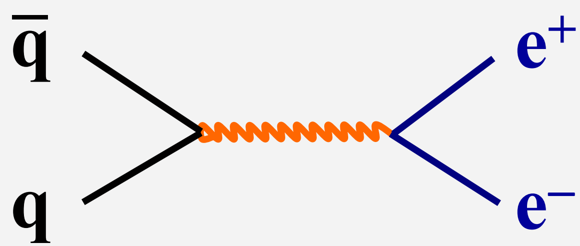
$$\frac{dN_{ee}}{d^4x\, d^4q} = \frac{-\alpha^2}{\pi^3 M^2} f^B(q_0,T) \; Im\, \Pi_{em}(M,q;\mu_B,T)$$

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

Radiation Sources:

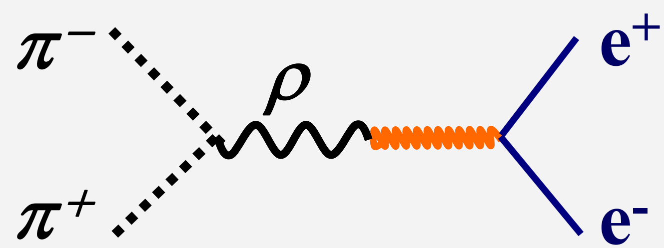
- **Quark-Gluon Plasma:**

  $q\bar{q} \to e^+e^-$, ...



- **Hot + Dense Hadron Gas:**

  $\pi^+\pi^- \to e^+e^-$, ...



Relevance:

high mass + temp.

$M > 1.5 GeV$, $T > T_c$

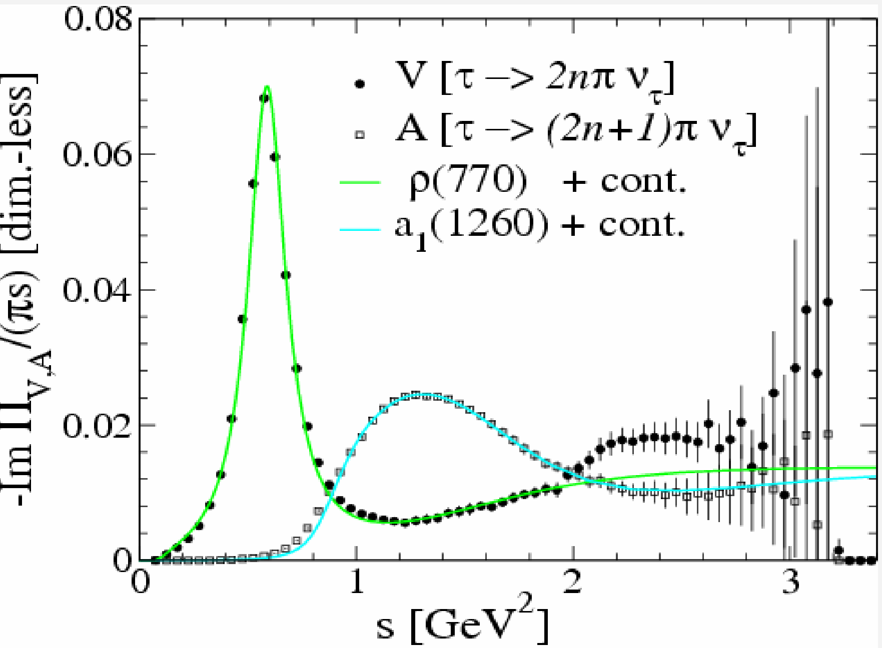
$M \leq 1\ GeV$

$T \leq T_c$

2.2 Chiral Symmetry Breaking and Restoration

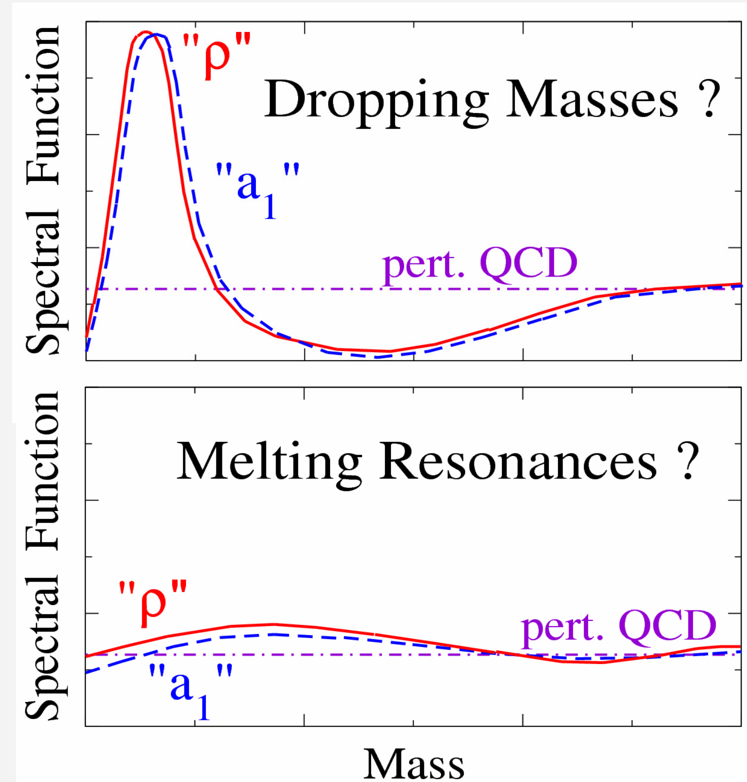
Splitting of "chiral partners" ρ - $a_1(1260)$ ⇒ Chiral Symmetry Breaking

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 ~ $Im\ D_{a1}(M)$?!

2.3 Chiral Sum Rules

• 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]

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

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

[Weinberg '67]

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

• **explicit link**:

V – A spectral fcts. (**models**) ↔ order parameters (**lattice QCD**)

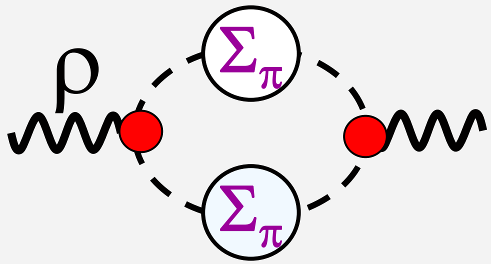
• extended to finite temperature [Kapusta+ Shuryak '93]

3.1 Medium Effects I: Hadronic Many-Body Theory

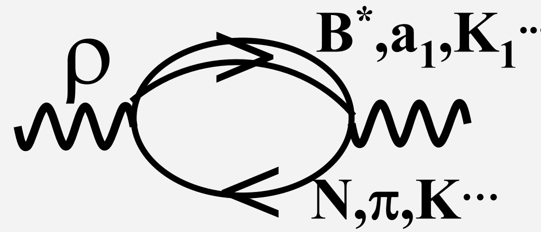
[Chanfray etal, Herrmann etal, RR etal, Weise etal, Post etal, Eletsky etal, Oset etal, …]

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



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

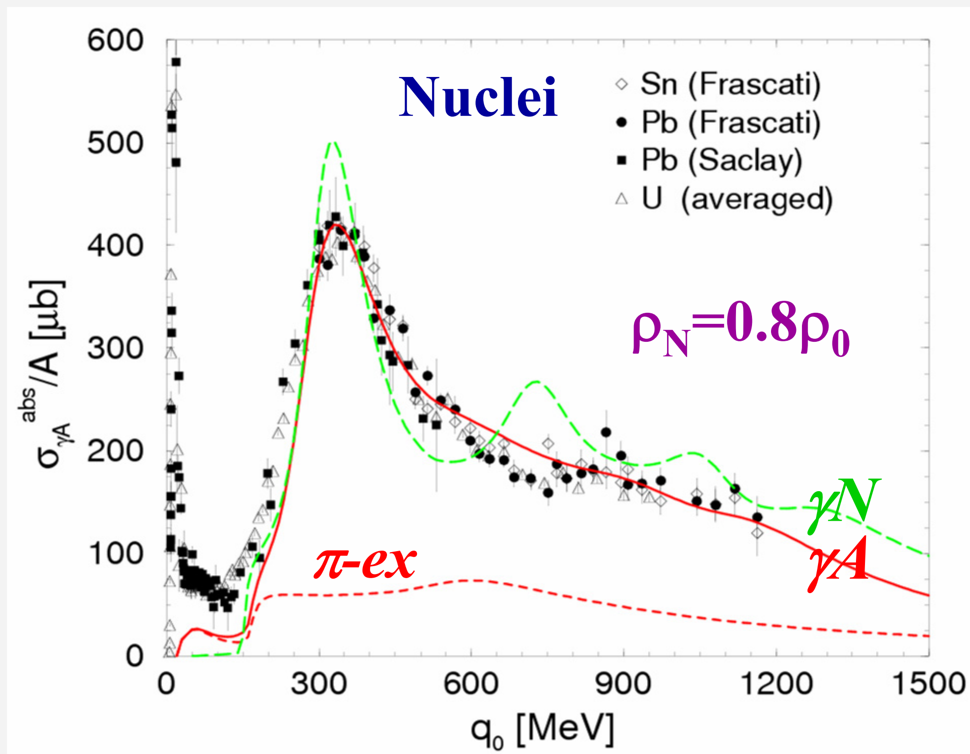


Constraints:

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

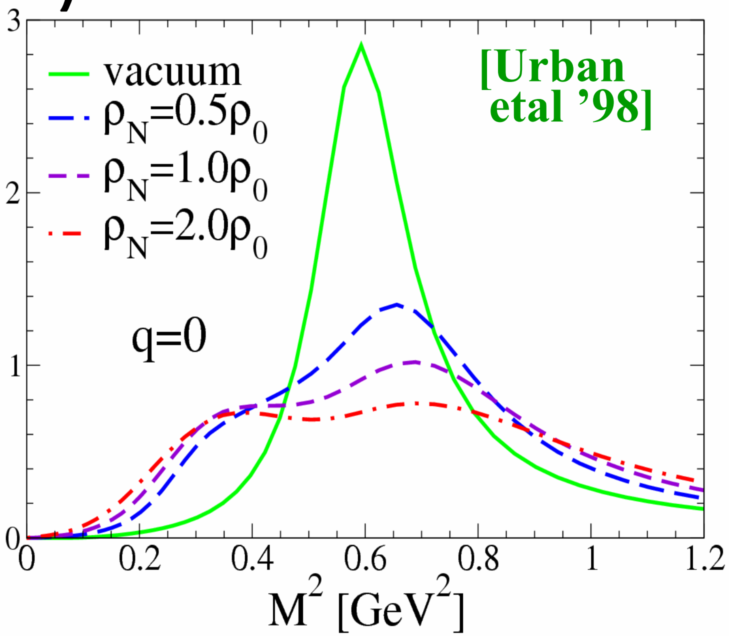
$$\sigma^{abs}_{\gamma A}(q_0)/A \propto ImD_\rho(q_0=q)$$

[Urban et al. '98]

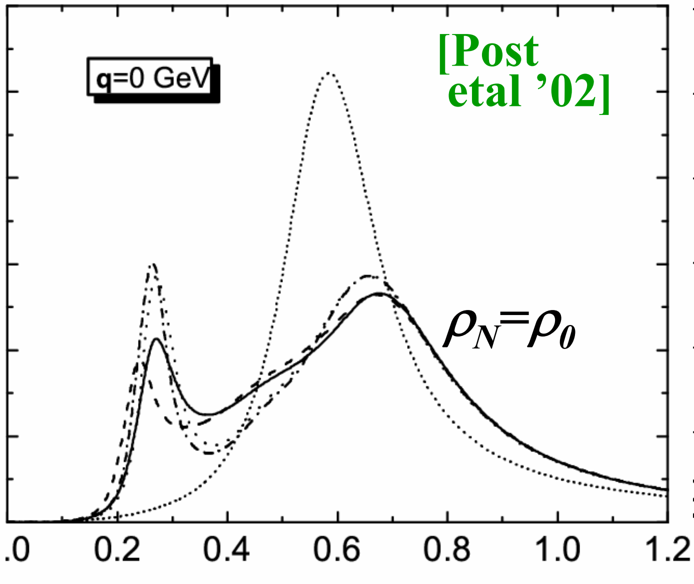


3.1.2 ρ(770) Spectral Function in Nuclear Matter

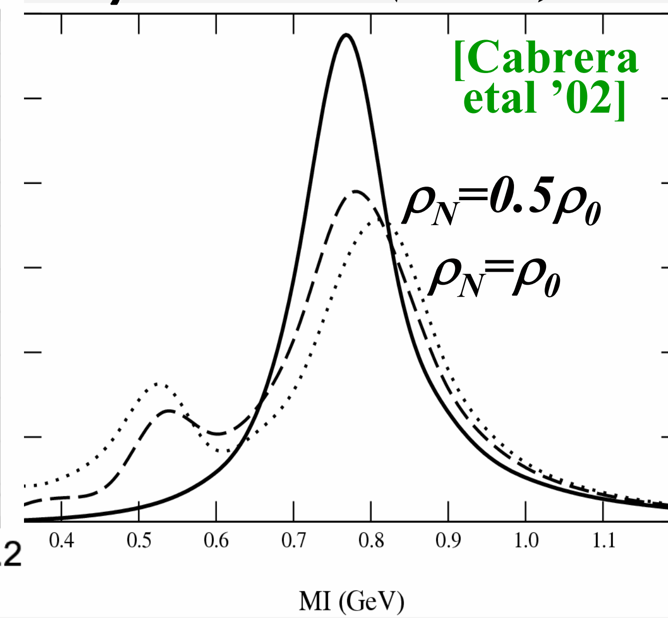
In-med π-cloud + ρ-$N \rightarrow B^*$ resonances



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



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

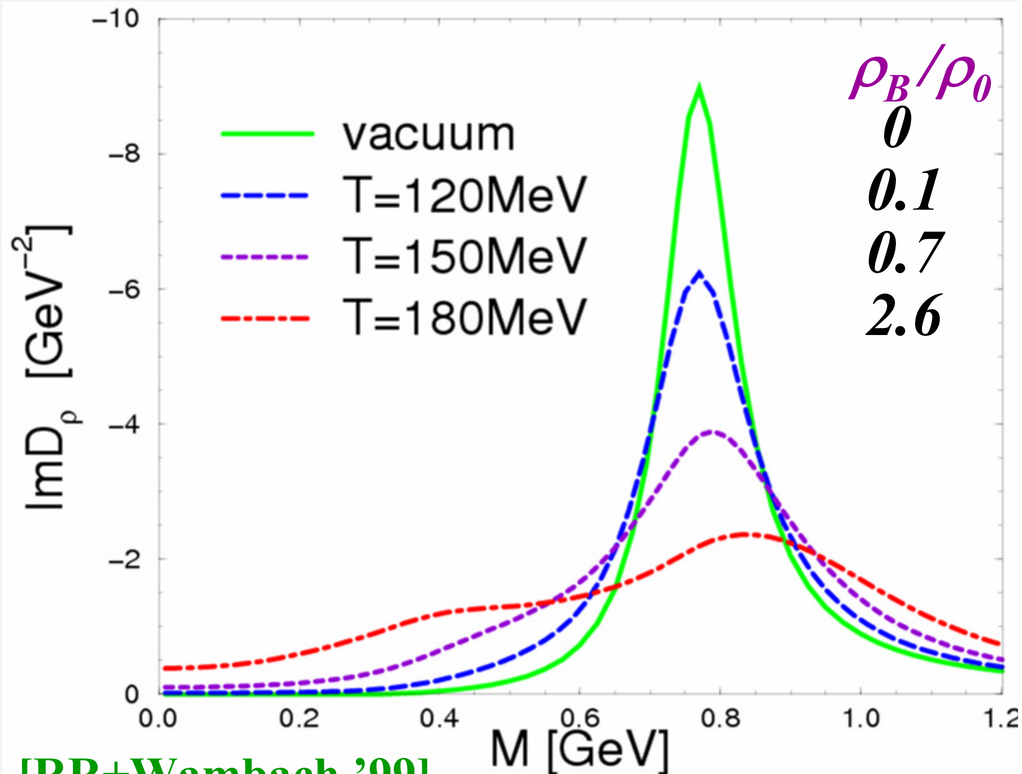


Constraints: γN, γA $\pi N \rightarrow \rho N$ PWA

- constraints from elementary reactions → model agreement!
- consistent with QCD sum rules

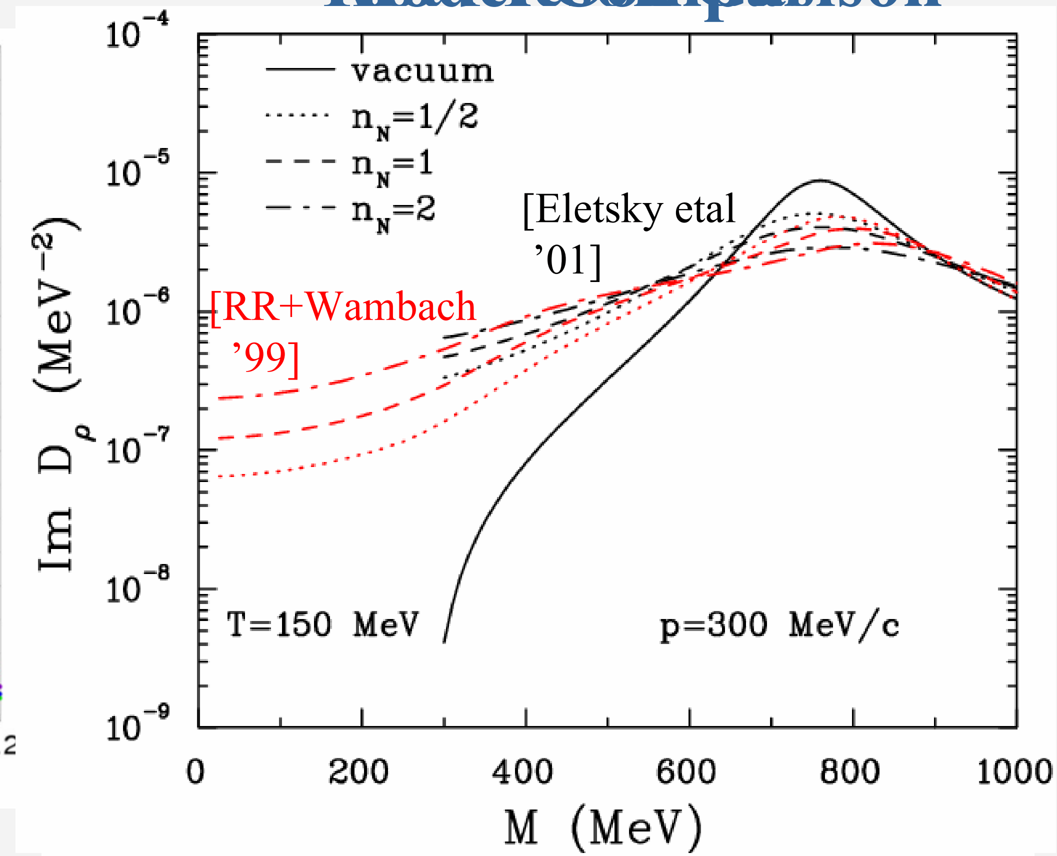
3.1.4 ρ-Meson Spectral Functions at SPS

Hot+Dense Matter



[RR+Wambach '99]

Model Comparison



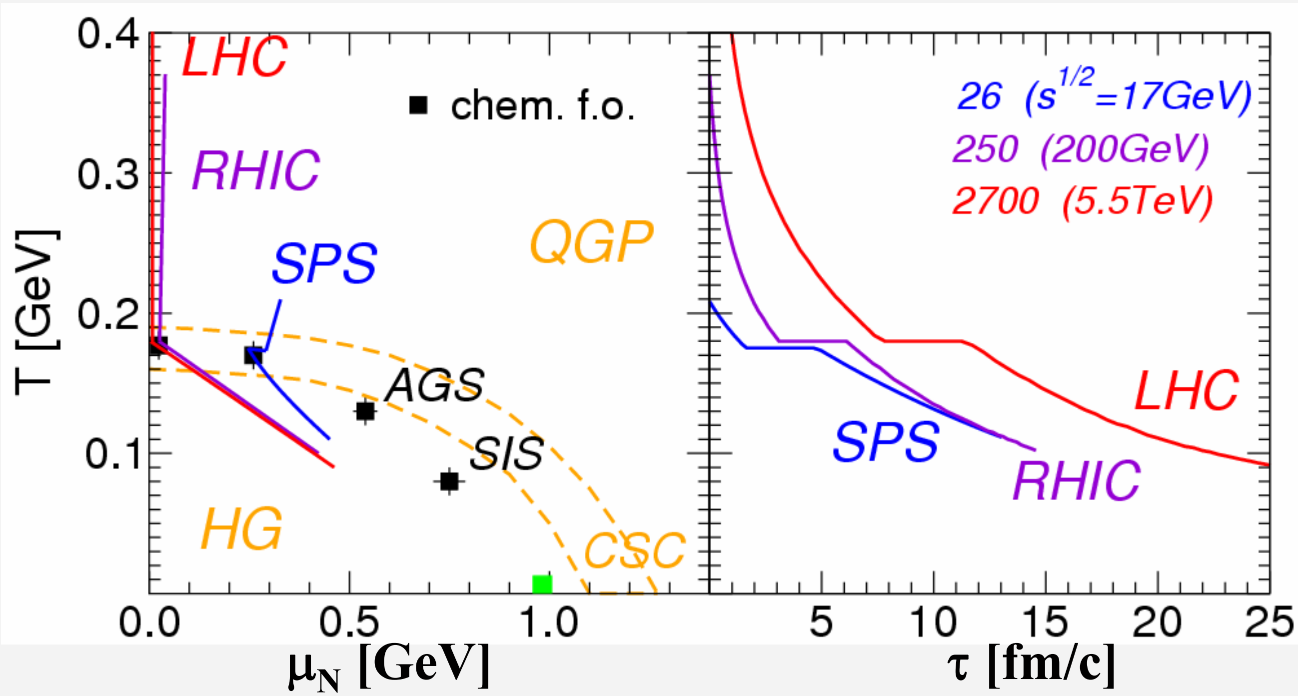
- ρ-meson **"melts"** in hot and dense matter
- baryon density ρ_B more important than temperature
- reasonable agreement between models

4.) Dilepton Spectra in Heavy-Ion Collisions

Thermal Emission:

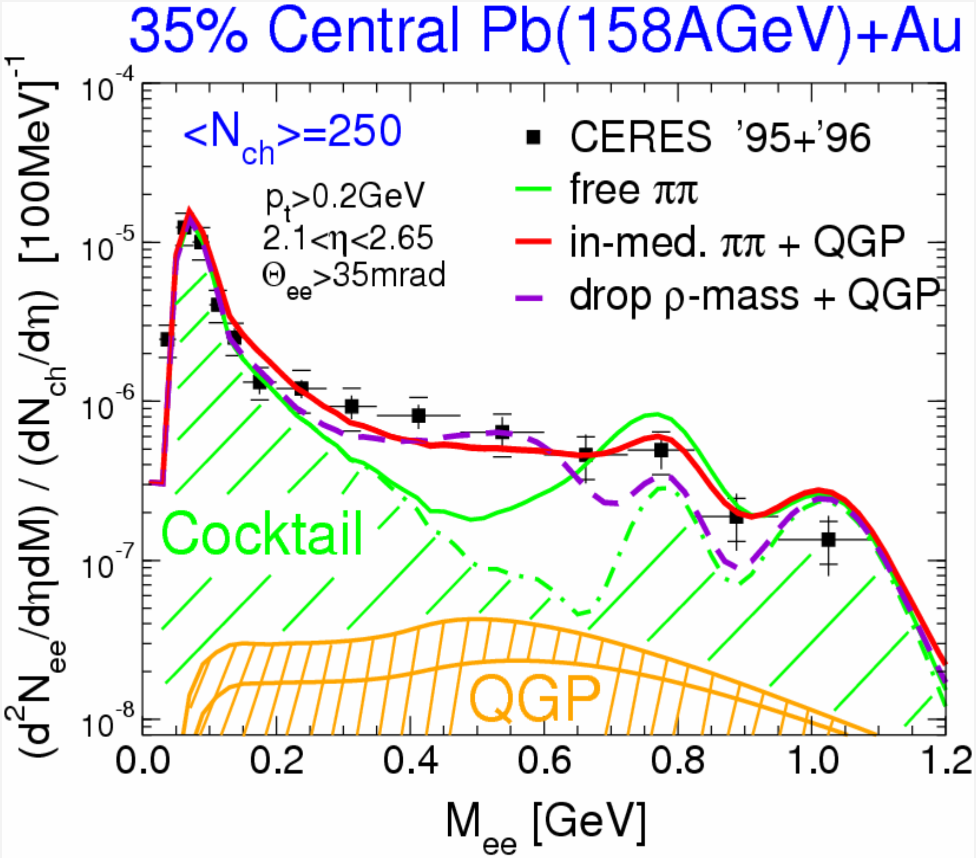
$$\frac{dN_{ee}^{therm}}{dM} = \int_{\tau_0}^{\tau_{fo}} d\tau V_{FB}(\tau) \int \frac{M d^3q}{q_0} \frac{dR_{ee}^{therm}}{d^4q}(M,q;T,\mu_i)\ e^{n\mu_\pi/T}\ Acc$$

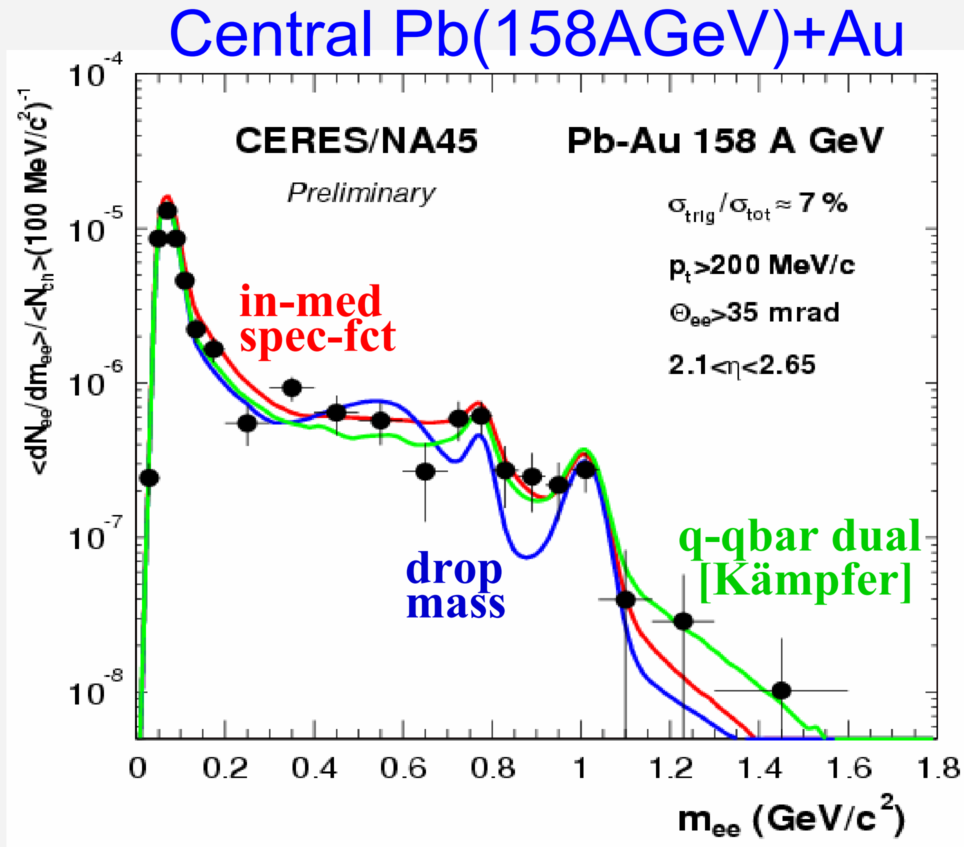
Pb-Pb Collisions: Trajectories in the Phase Diagram



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

4.1 Pb-Au Collisions at SPS: CERES/NA45



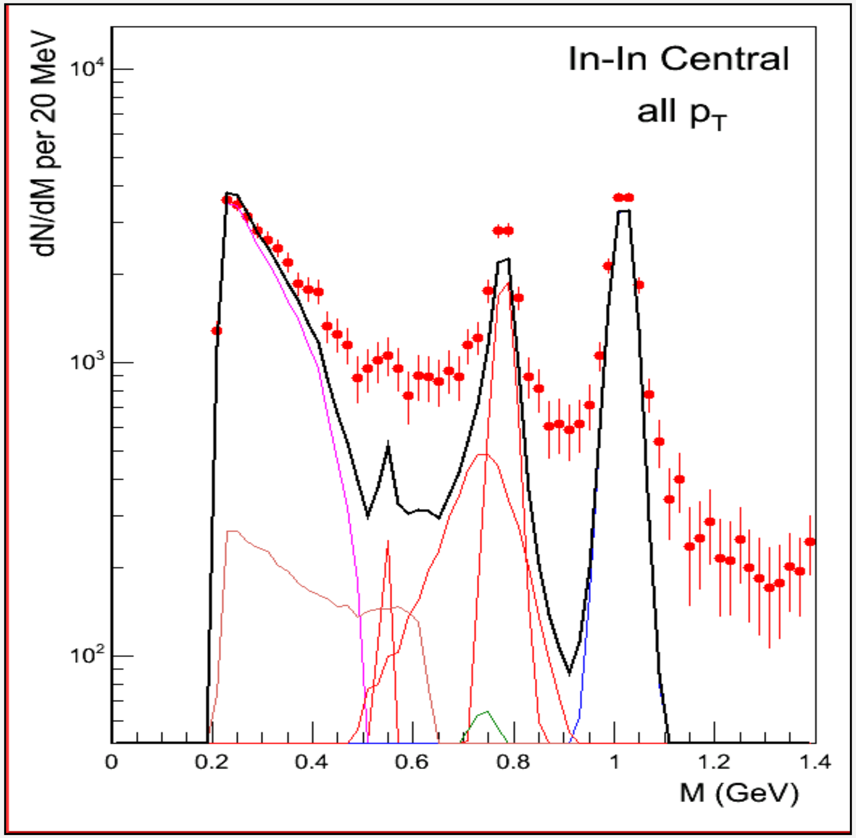


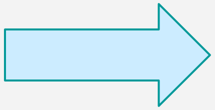
- QGP contribution small
- **medium effects on ρ-meson!**

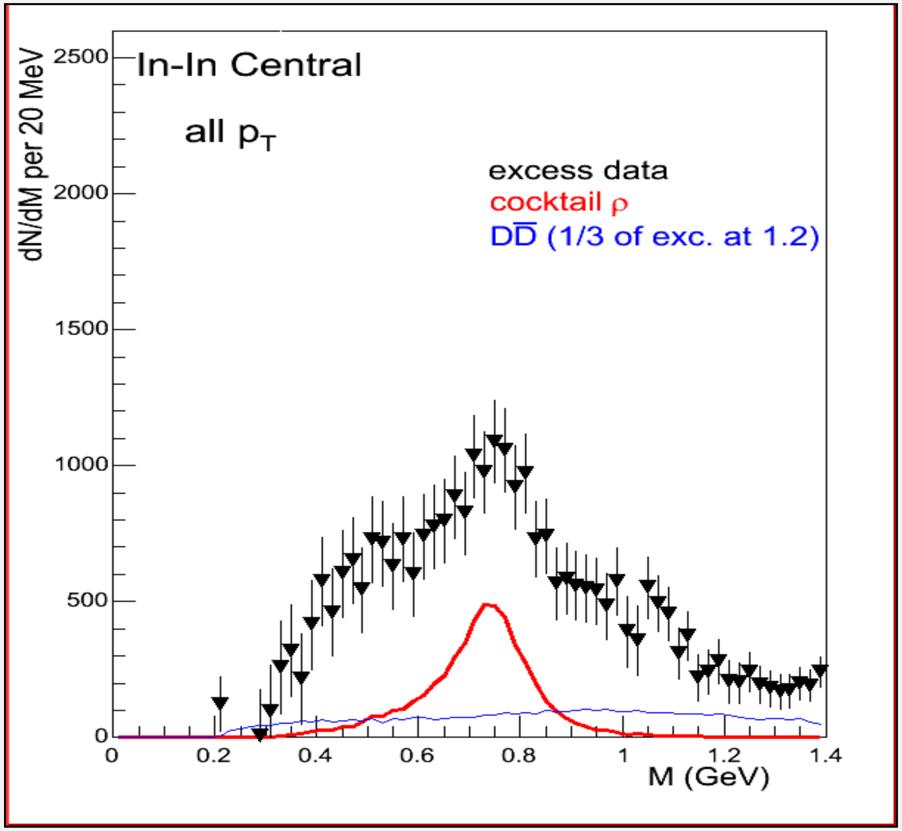
4.2 In-In at SPS: Dimuons from NA60

[Damjanovic et al. PRL '06]

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



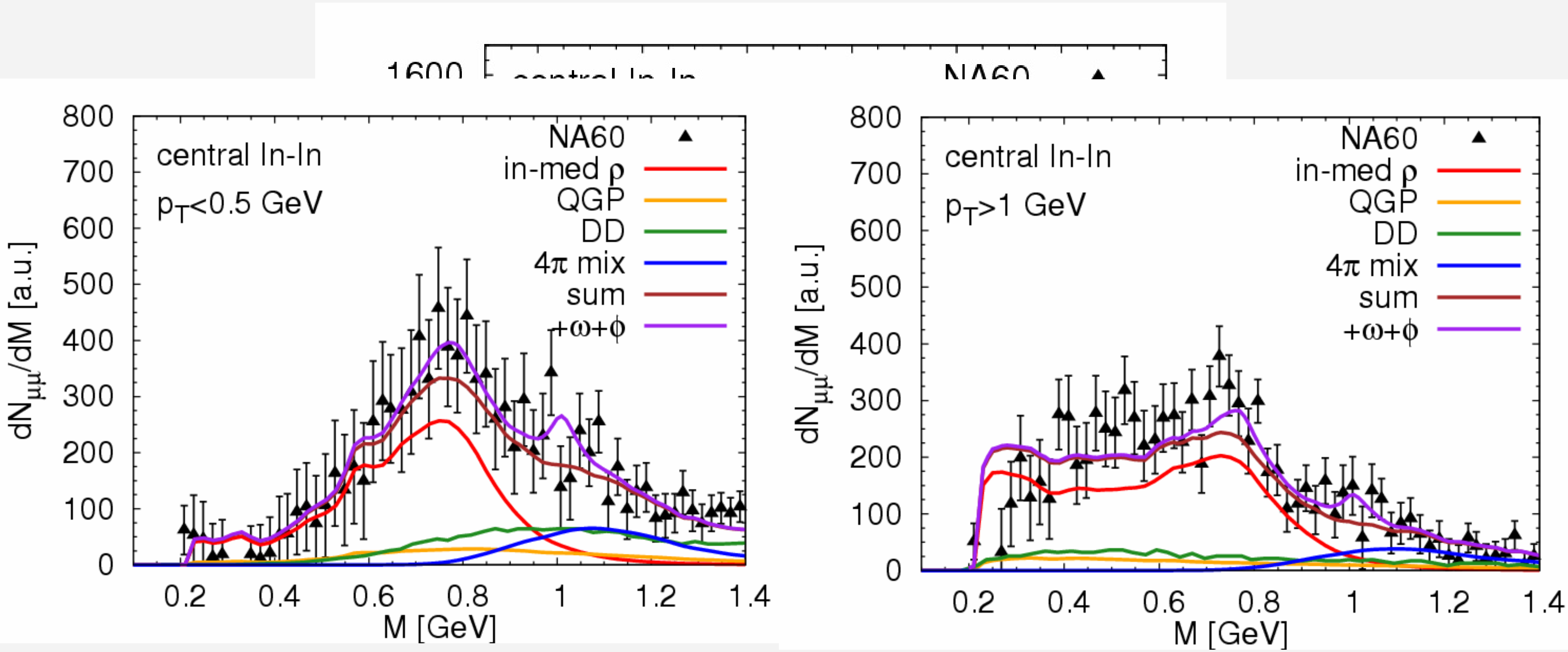




- **quantitative theory?**

4.2.2 In-In at SPS: Theory vs. NA60

- predictions: 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



- ρ **melting** confirmed, incl. **p_t** dependence; ω and φ ?!

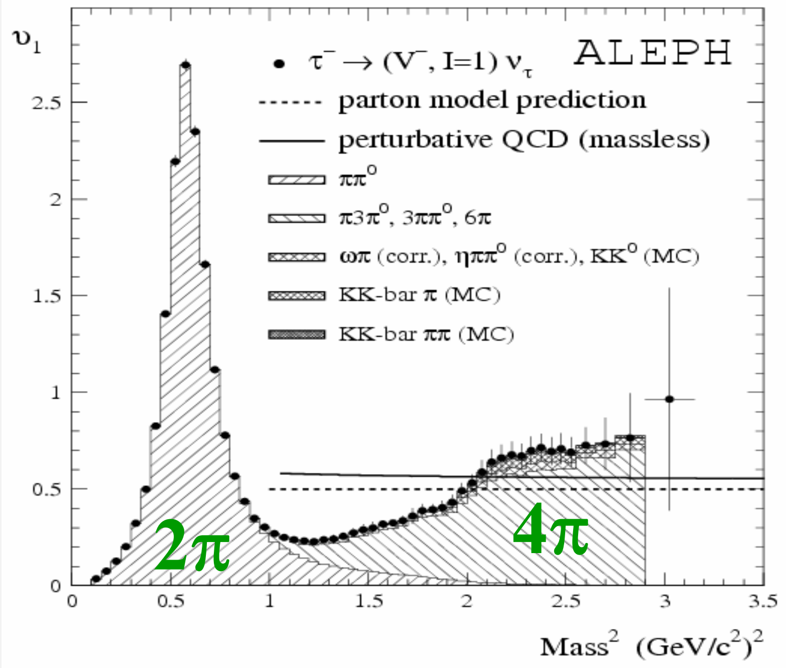
[van Hees +RR '06]

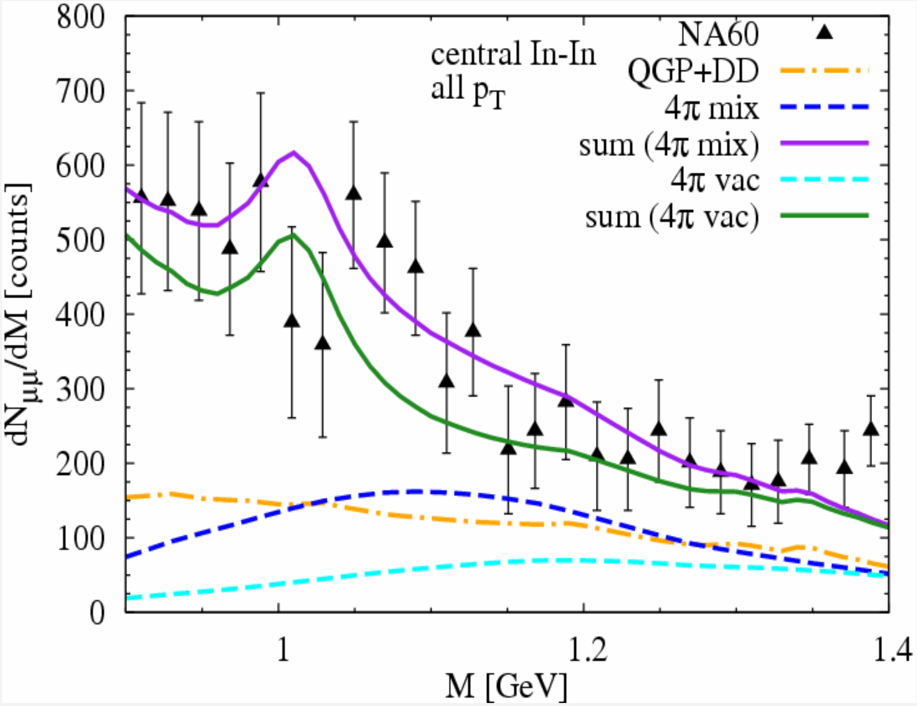
4.2.3 Intermediate-Mass Region

- **“4π“** states dominate in the vacuum e.m. correlator above **M ≈ 1.1GeV**
- **lower estimate:**
  use **vacuum 4π** correlator
- **upper estimate:**
  O(T²) medium effect → “chiral **V-A** mixing”: **[Eletsky+Ioffe ‘90]**

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

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



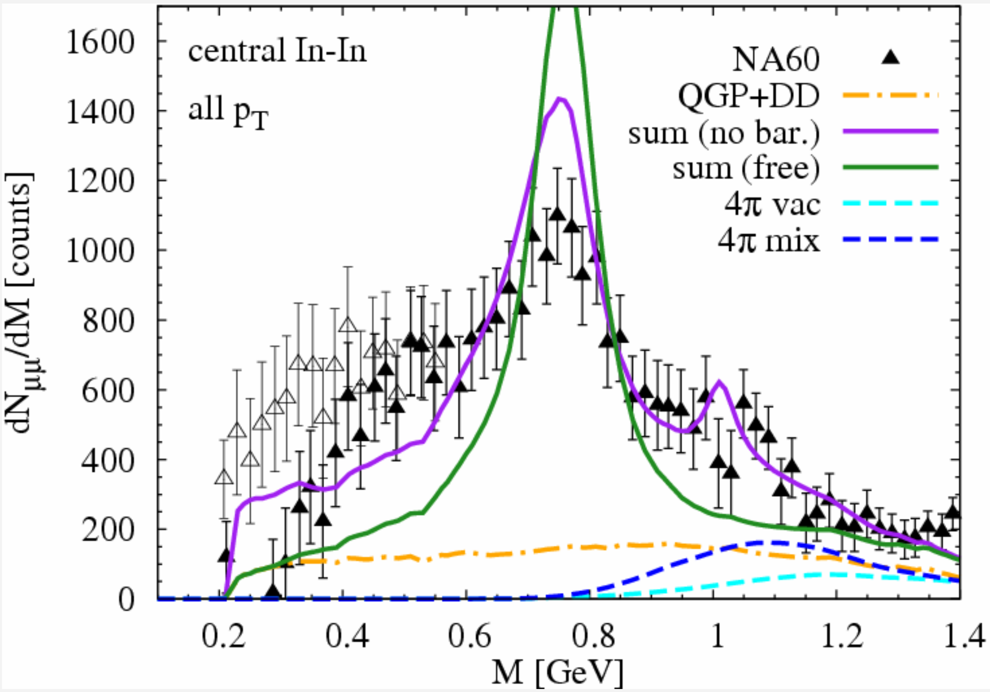


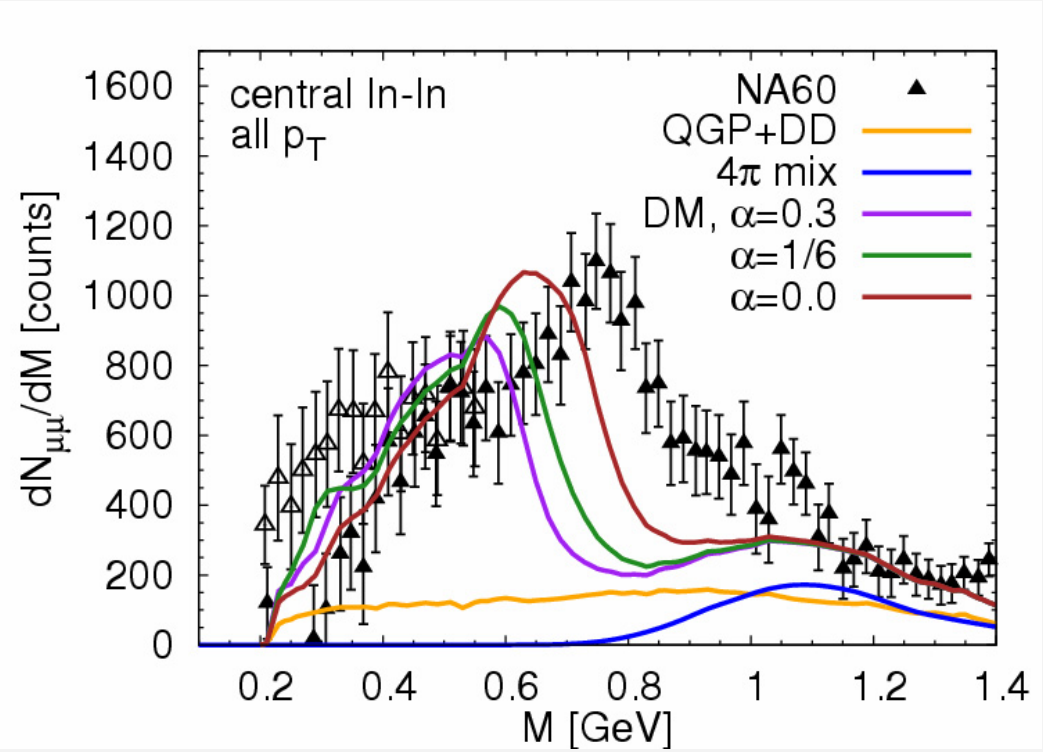
[van Hees+RR ‘06]

4.2.4 NA60 Data: Other ρ-Spectral Functions

- switch off medium modifications
- bare parameters: **dropping mass**
  [Brown+Rho '91,Hatsuda+Lee '92,…]

$$\frac{m_\rho(T,\rho_B)}{m_\rho^{\rm vac}} = \left[1-\left(\frac{T}{T_c}\right)^2\right]^\alpha \left[1-C\frac{\rho_B}{\rho_0}\right]$$

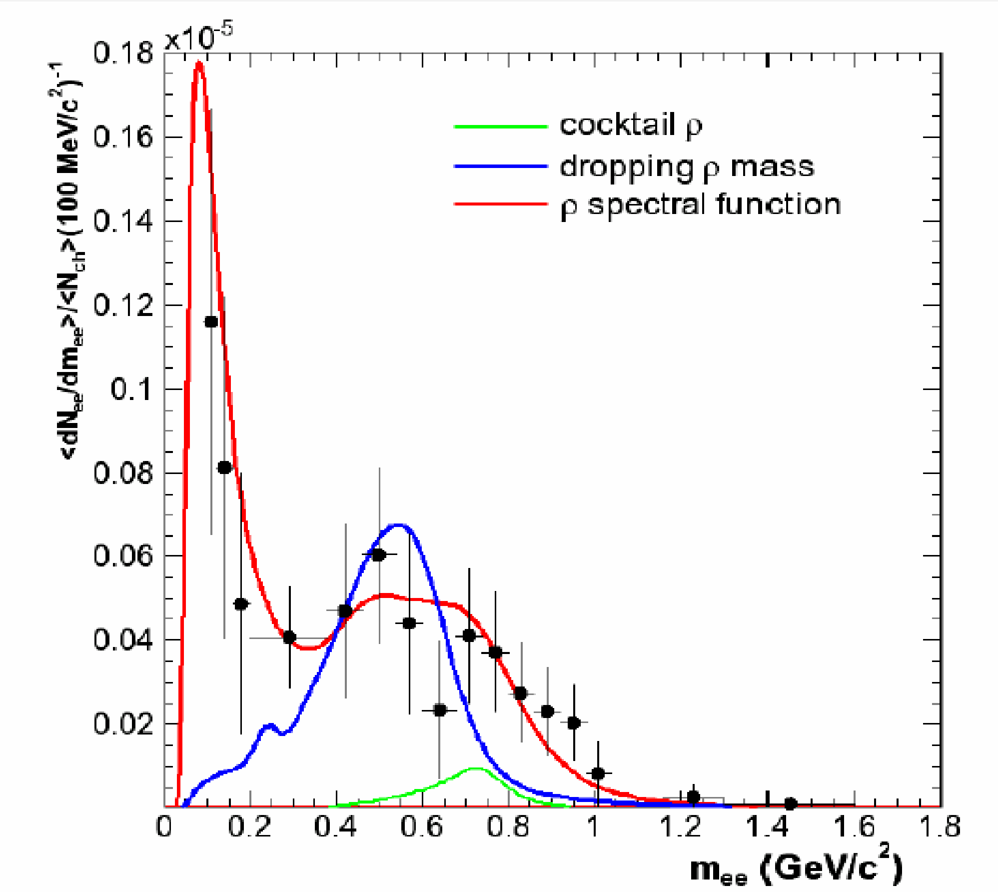




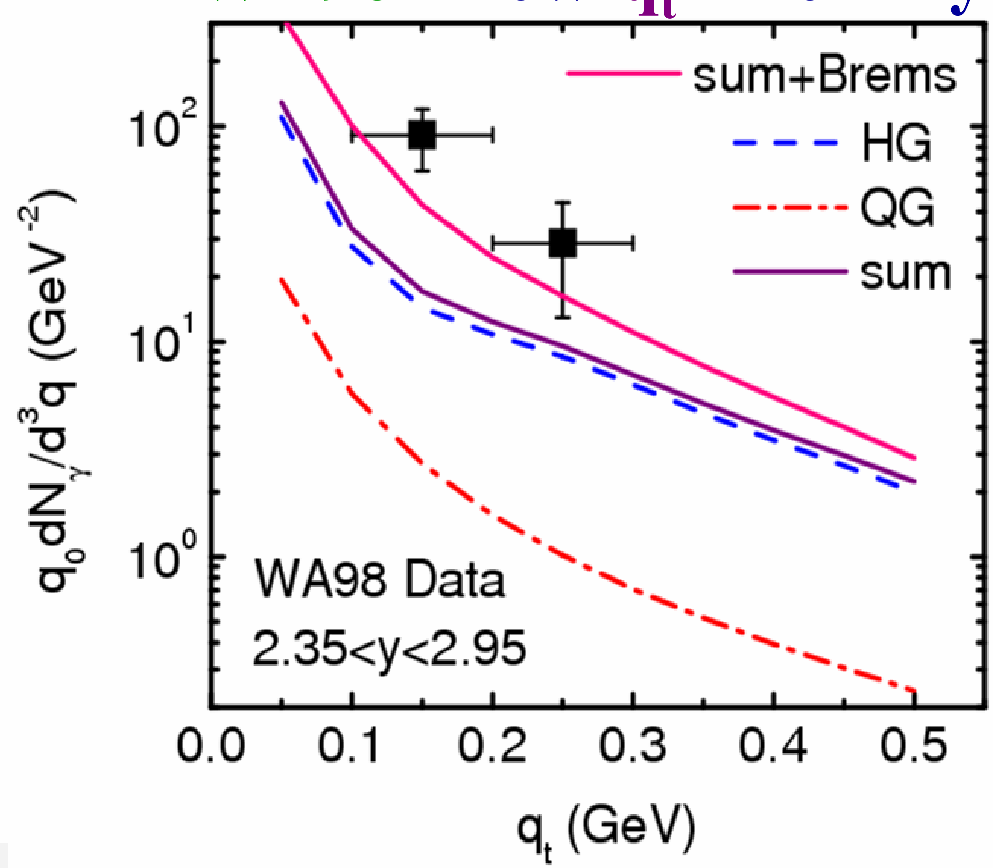
- free spectral function ruled out
- meson gas insufficient either

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

4.3 Pb-Au Excess Radiation: CERES/NA45



WA98 "Low-q_t Anomaly"



- very-low-mass enhancement, required for photon production
- addt'l meson-Bremsstrahlung $\pi\pi \rightarrow \pi\pi\gamma \quad \pi K \rightarrow \pi K\gamma$ [Liu+RR'06]

4.4 (Some) Open Issues

- **Heavy-Ion Collisions** **[NA60]**
  - centrality dependence, free ρ's (surface vs. volume)
  - sensitivity to dynamical evolution (hydro, transport)
  - 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

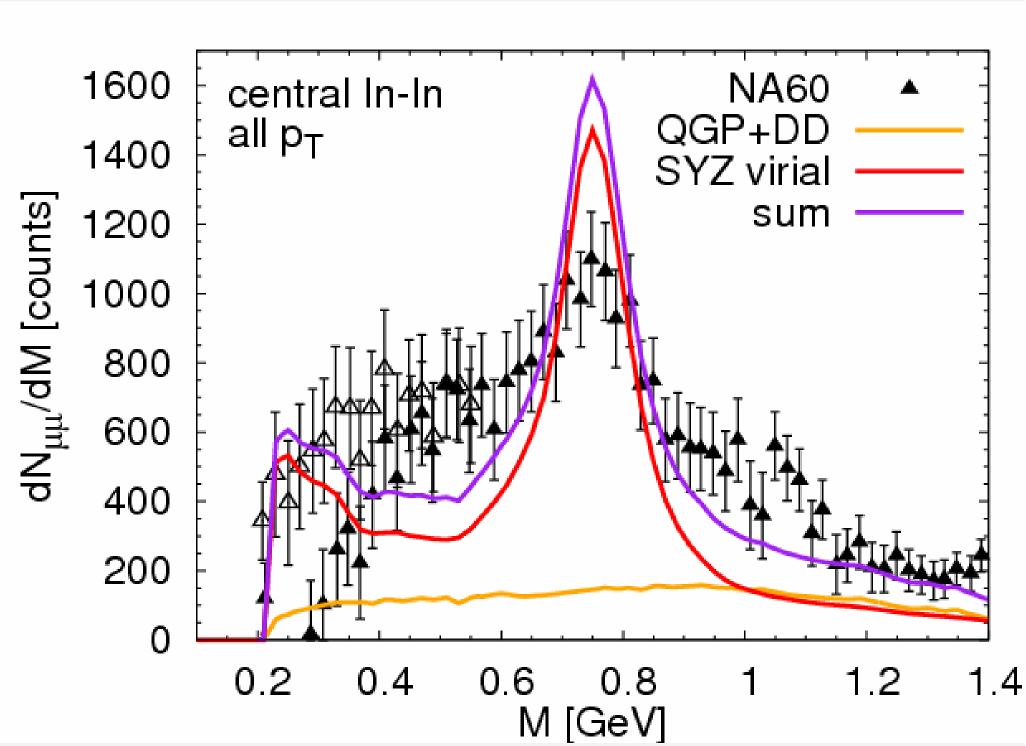
- **Strong medium effects in l^+l^- spectra**
- **new level of precision in NA60**
- **ρ-melting at T_c, no apparent mass shift**
- **alternative models? (quality control)**

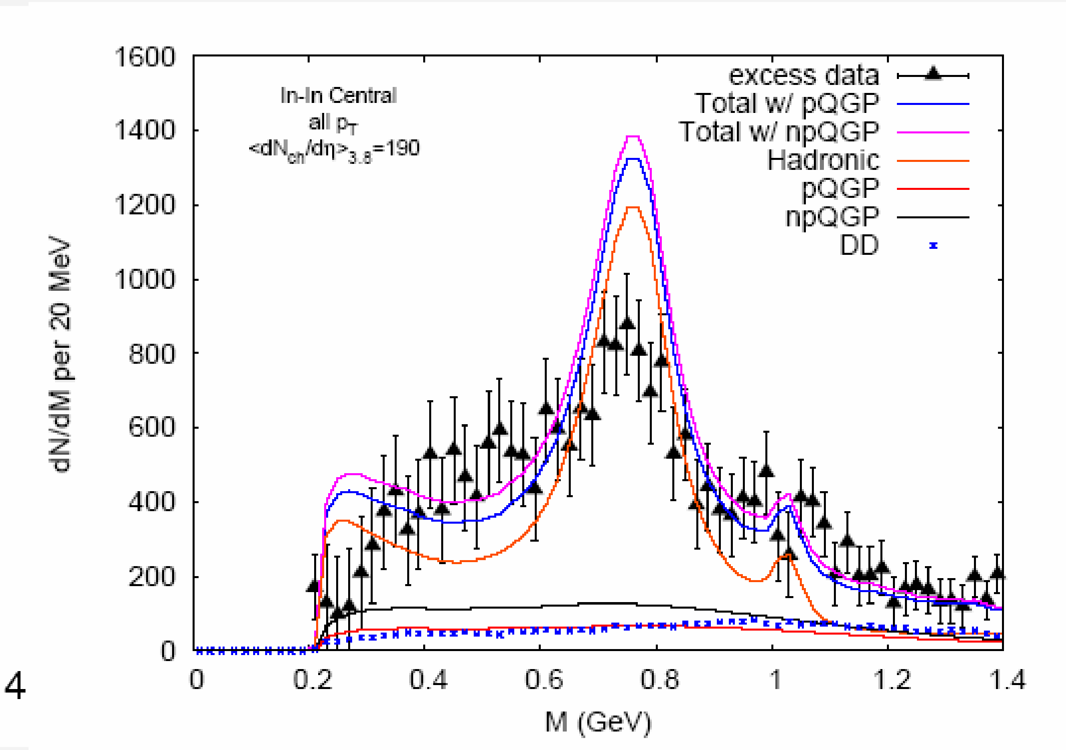
- **Chiral Restoration:**
  - **direct (exp.): measure axialvector**
  - **indirect (theo.): (1) effective model (constraints)**
    (2) chiral sum rules (V-A moments) vs. lQCD
    (3) compatibility with dilepton/photon data
- **HADES, RHIC, LHC, SPS-09, CBM, …, elementary reactions**

In-medium V-meson spectroscopy has begun …

4.2.4 NA60 Data: Chiral Virial Approach

- also compare fireball vs. hydrodynamics





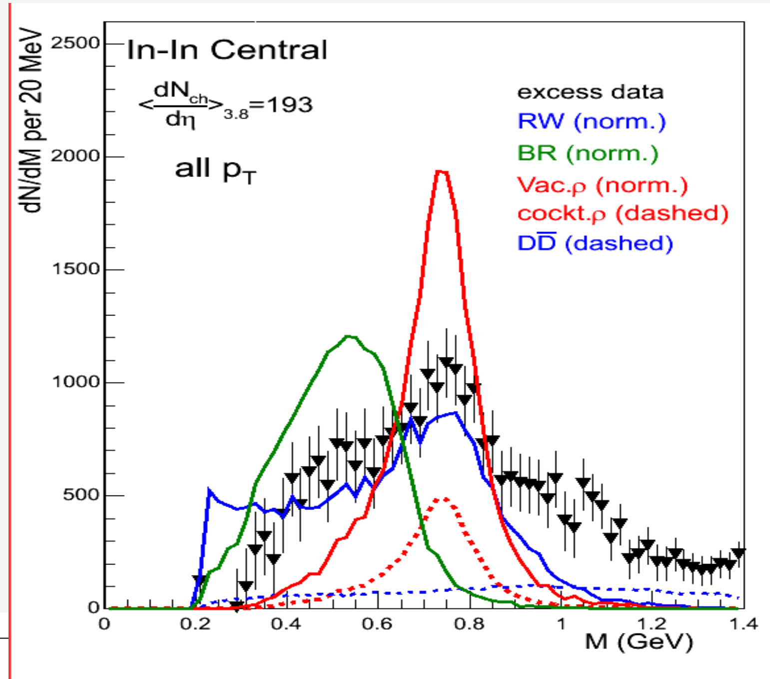
[van Hees+RR '06]

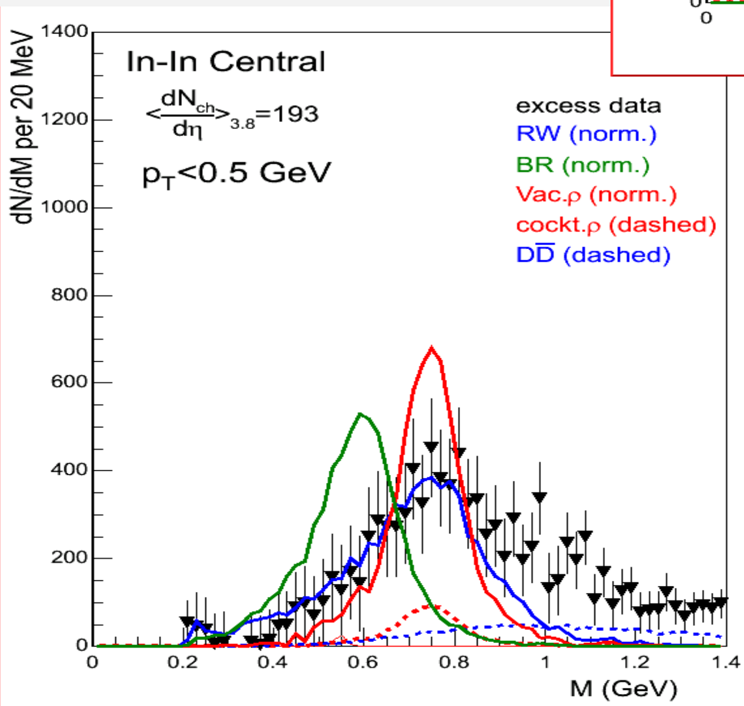
[Dusling,Teaney+Zahed '06]

- lack of broadening
- good agreement hydro - fireball

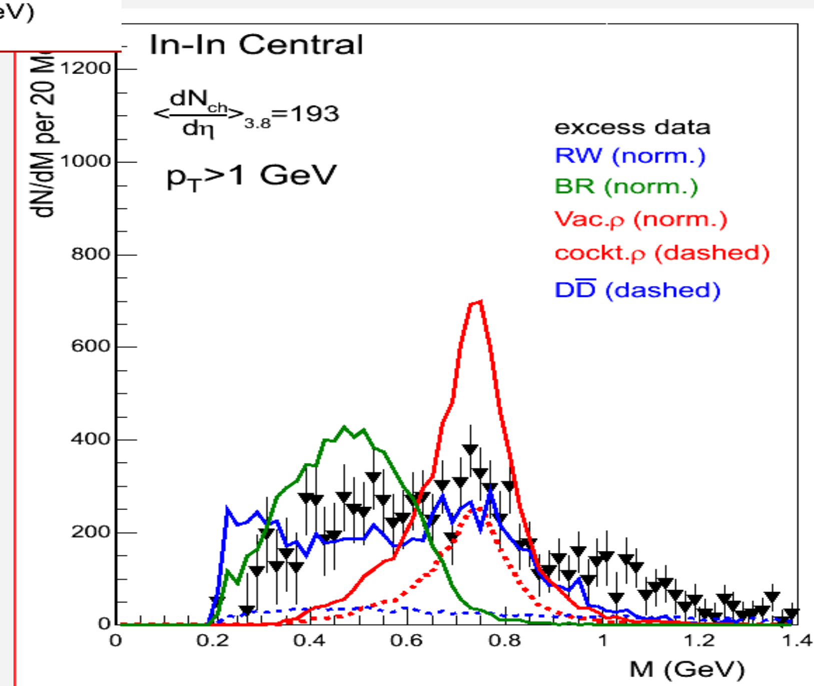
4.2.4 NA60 Data: Cocktail vs. in-Medium ρ

[Damjanovic '05]



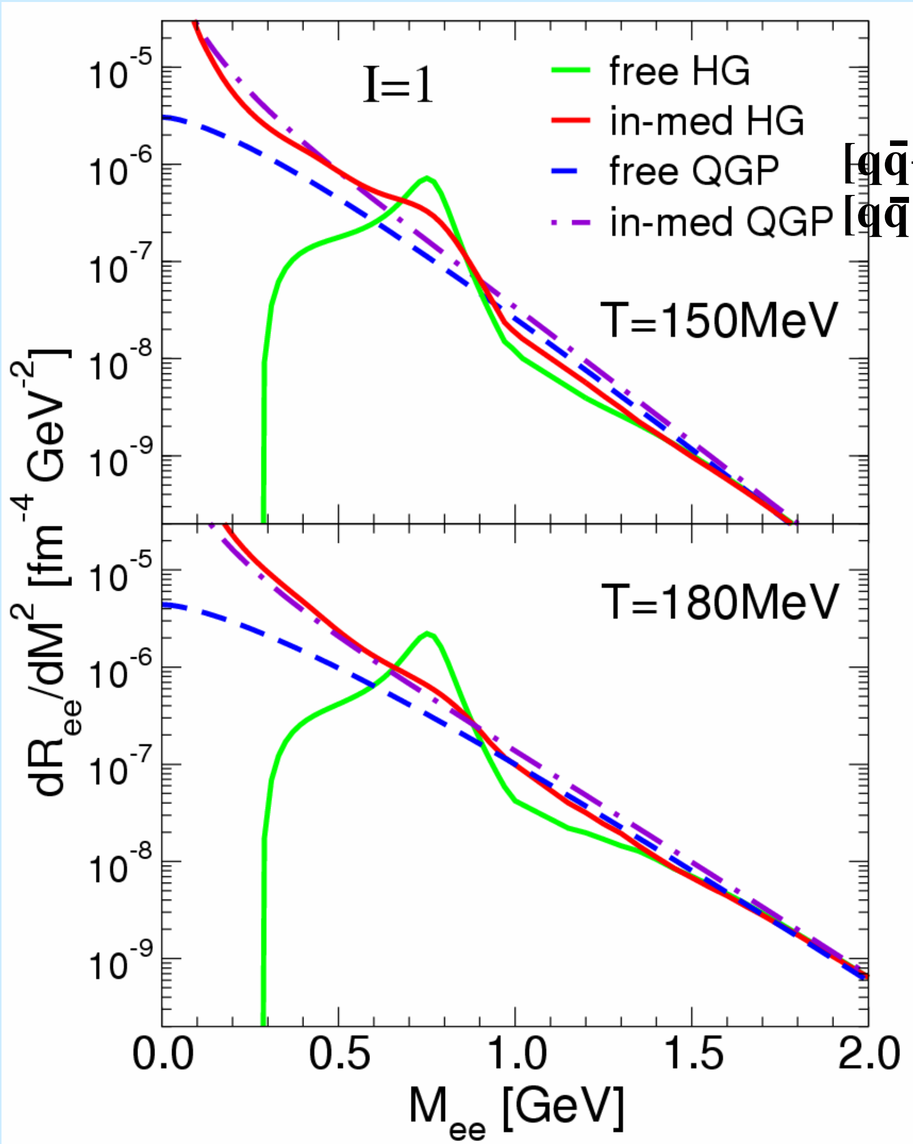


- cocktail concentrated at high p_t !



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" ?!**

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]

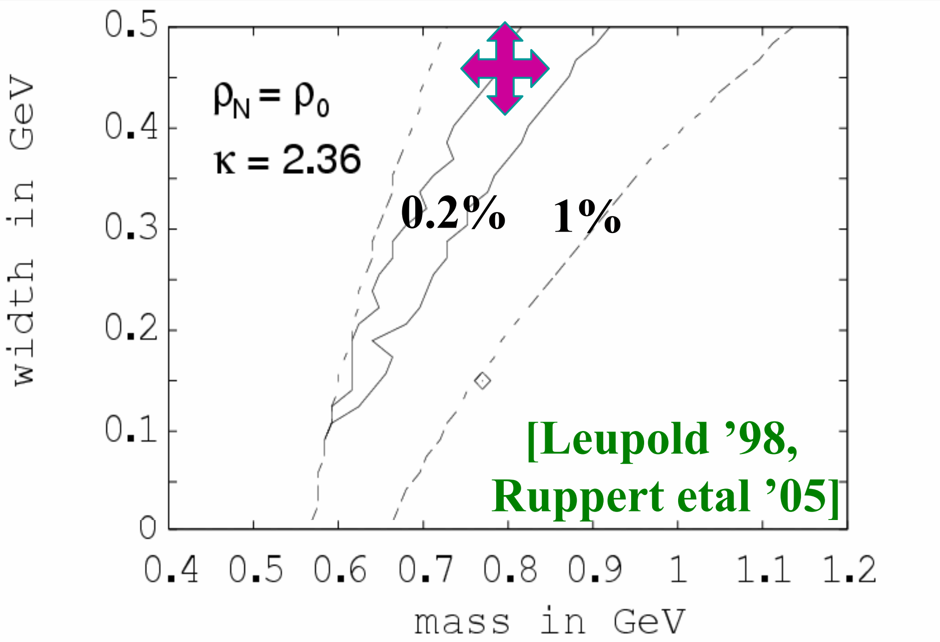
• ***lhs:*** OPE (spacelike Q^2):

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

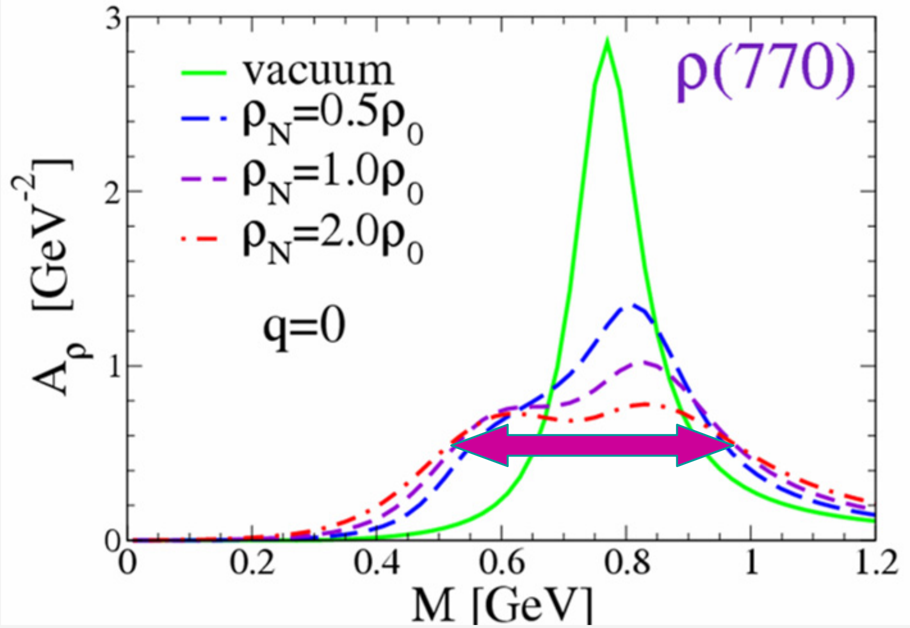
4-quark condensate!

• ***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]



3.3 Medium Effects II: Dropping Mass

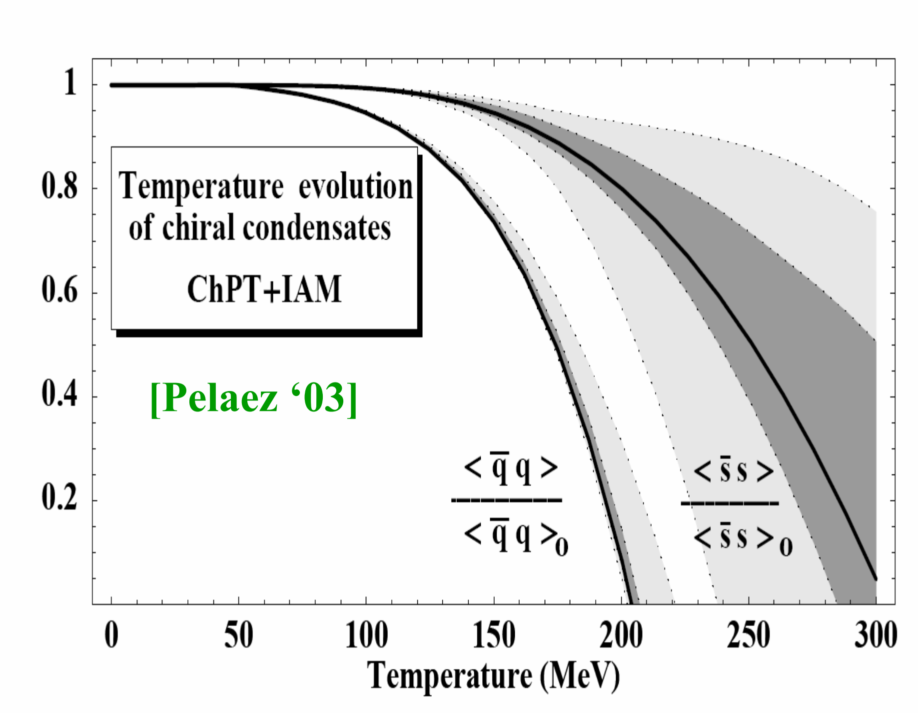
Scale Invariance of $\mathcal{L}_{QCD}$ → bare parameters change!?

[Brown+Rho '91, '02]

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

- 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:

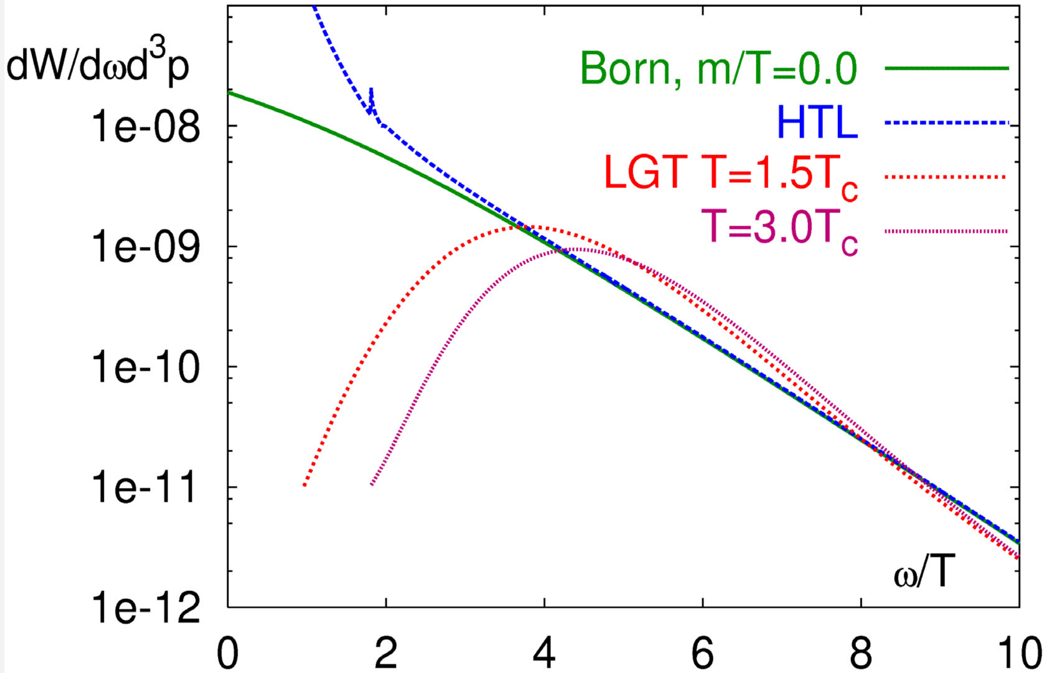
$$Im\,\Pi_\rho = \frac{(m_\rho^*)^4}{g_\rho^2} Im\,D_\rho(m_\rho^*)$$

(gauge invariance!)

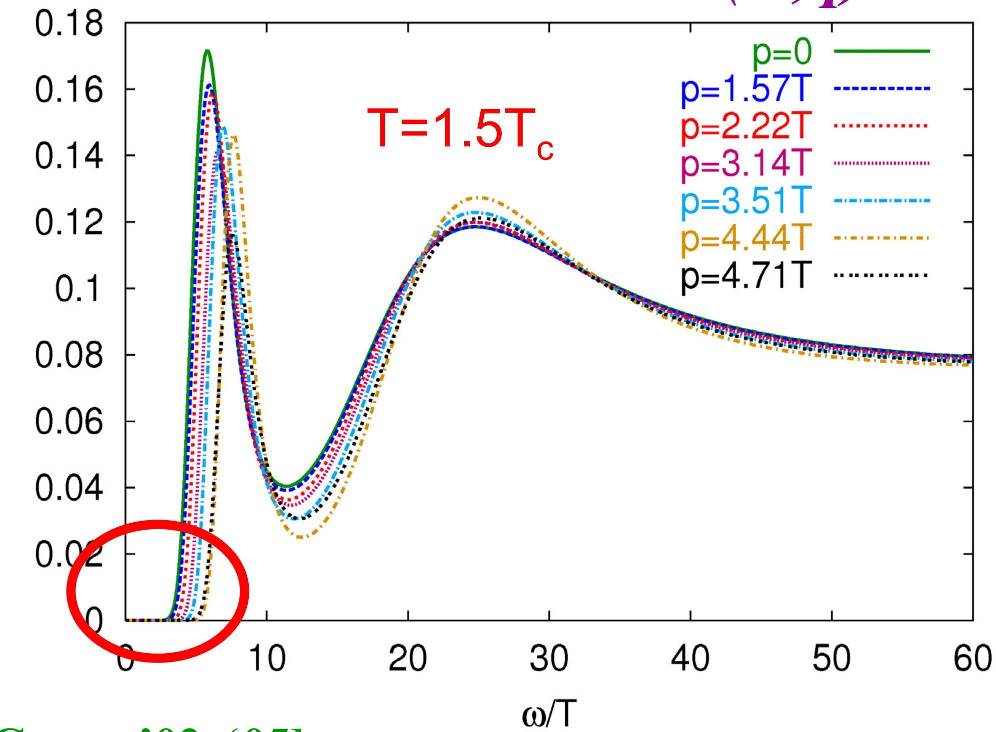
3.) Medium Effects and Thermal Dileptons

3.1 Lattice QCD (QGP)

Dilepton Rate ~ *ImΠ(ω,q=0)/ω²*



EM Correlator *ImΠ(ω,q)/ω²*



[Bielefeld Group '02, '05]

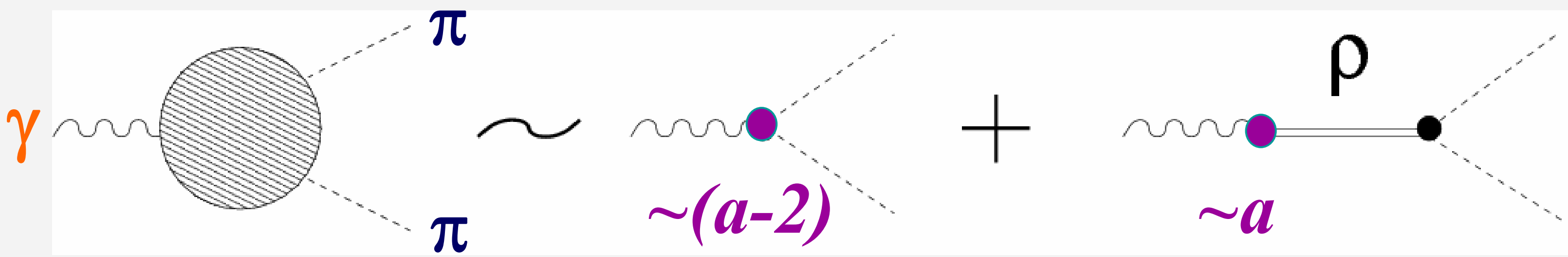
- **l**QCD << **p**QCD at low mass (finite volume?)
- currently no thermal photons from lQCD
- vanishing electric conductivity!? but: **[Gavai '04]**

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. $O(p/\Lambda_\chi, m_\rho/\Lambda_\chi, g)$)
- **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]

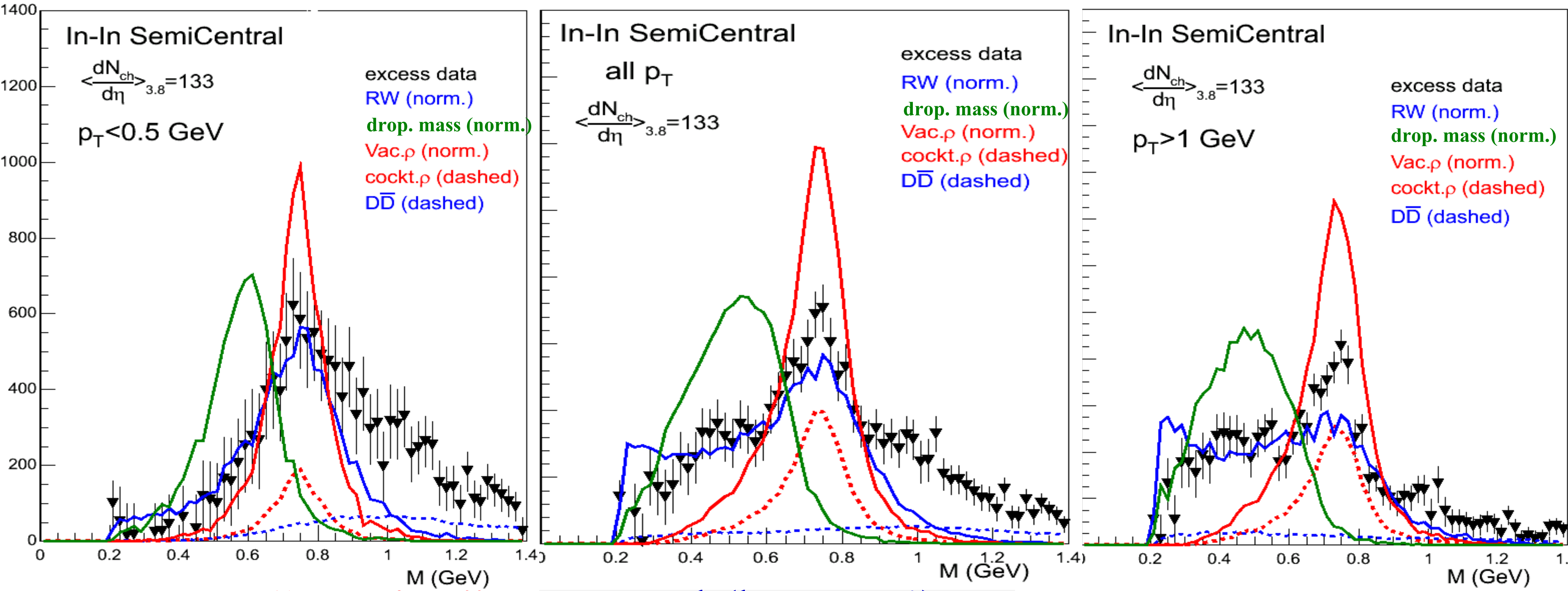
⇒ **- dropping ρ-mass → 0 (RG fixed point at T_c) ,**
- violation of vector dominance: $a = 2 \rightarrow 1$



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

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

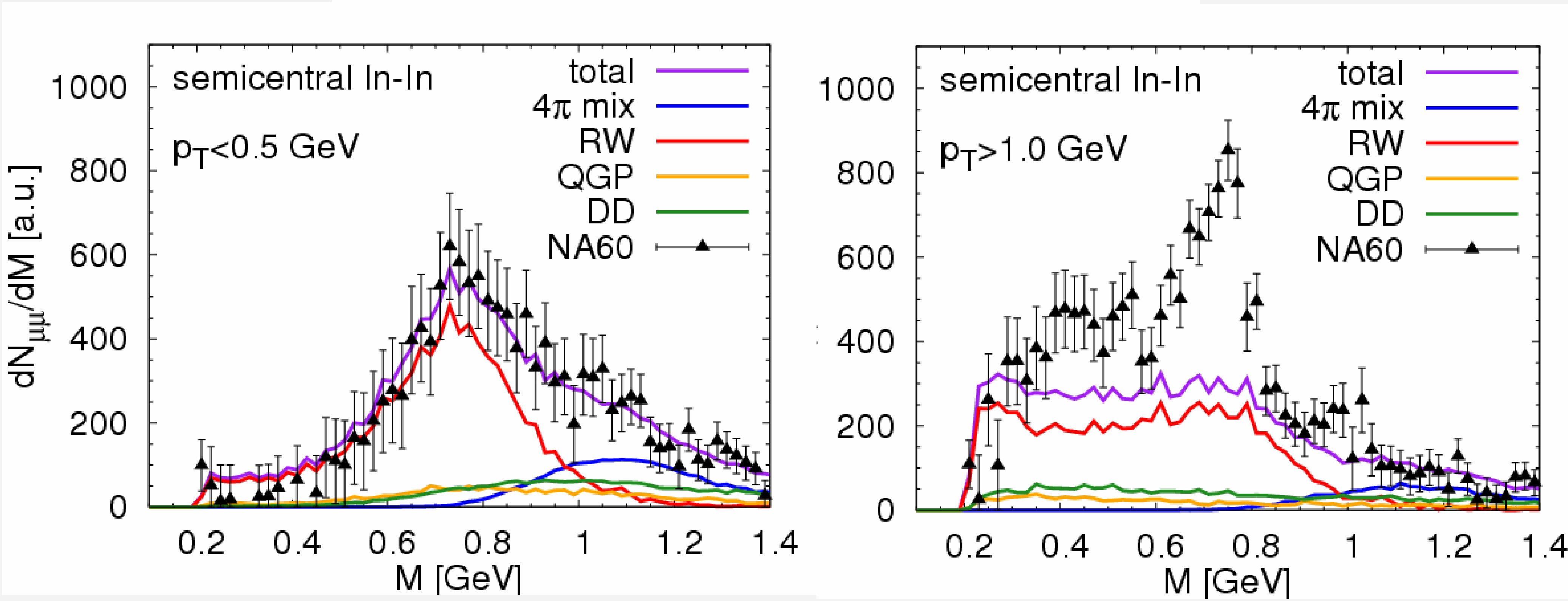
  (3) other models (vector manifestation, chiral virial approach, …)

4.2.2 Modified Fireball and Absolute Normalization

• ρ-spectral function unchanged since **[RR+Wambach '99]**

• expanding fireball, fixed ***S*** (↔N_{ch}): $V_{FB}(\tau)=(z_0+v_z\tau)\ \pi\,(R_{\perp 0}+0.5a_\perp\tau^2)^2$

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



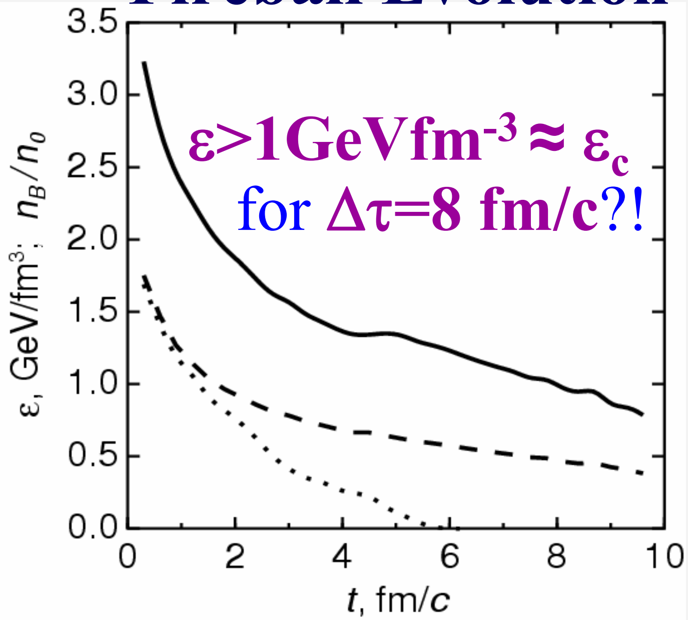
• reasonable agreement with absolute normalization, but …

• too little yield at high $\mathbf{p_t}$; "free ρ"? ω? check central …

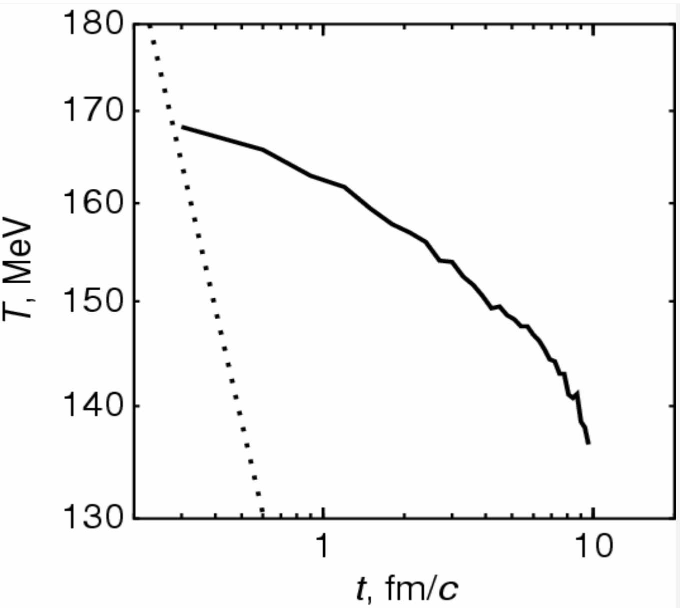
Revival Attempts for Dropping ρ-Mass

Fireball Evolution

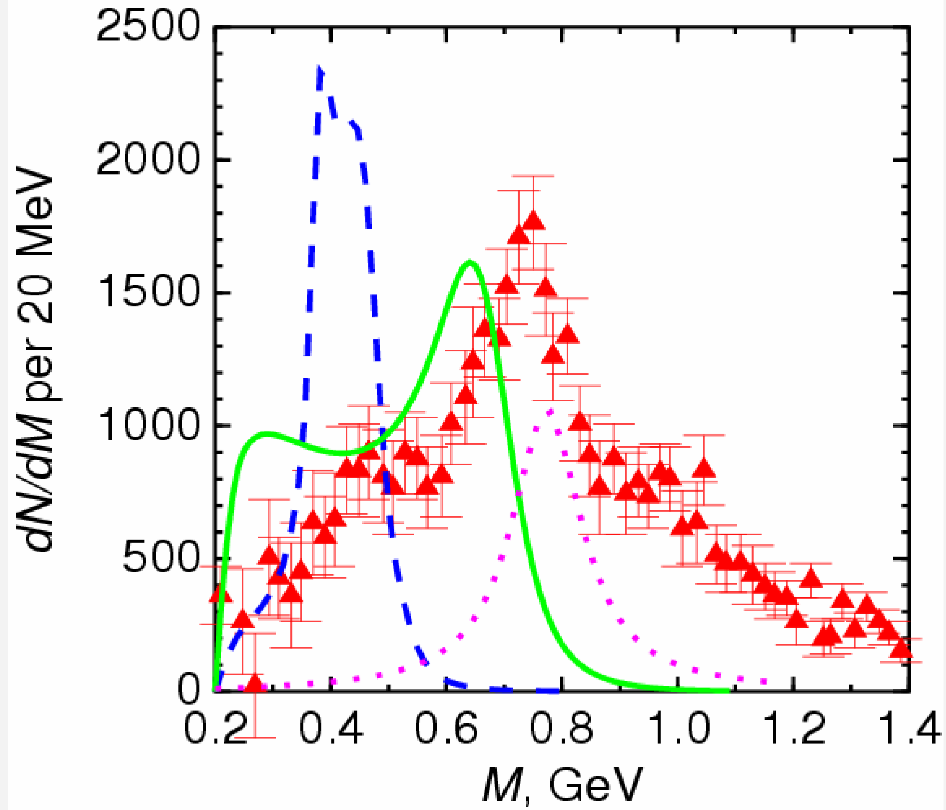
E.g., [Skokov+Toneev '05]



$\varepsilon > 1\,\mathrm{GeV fm^{-3}} \approx \varepsilon_c$
for $\Delta\tau = 8$ fm/c?!

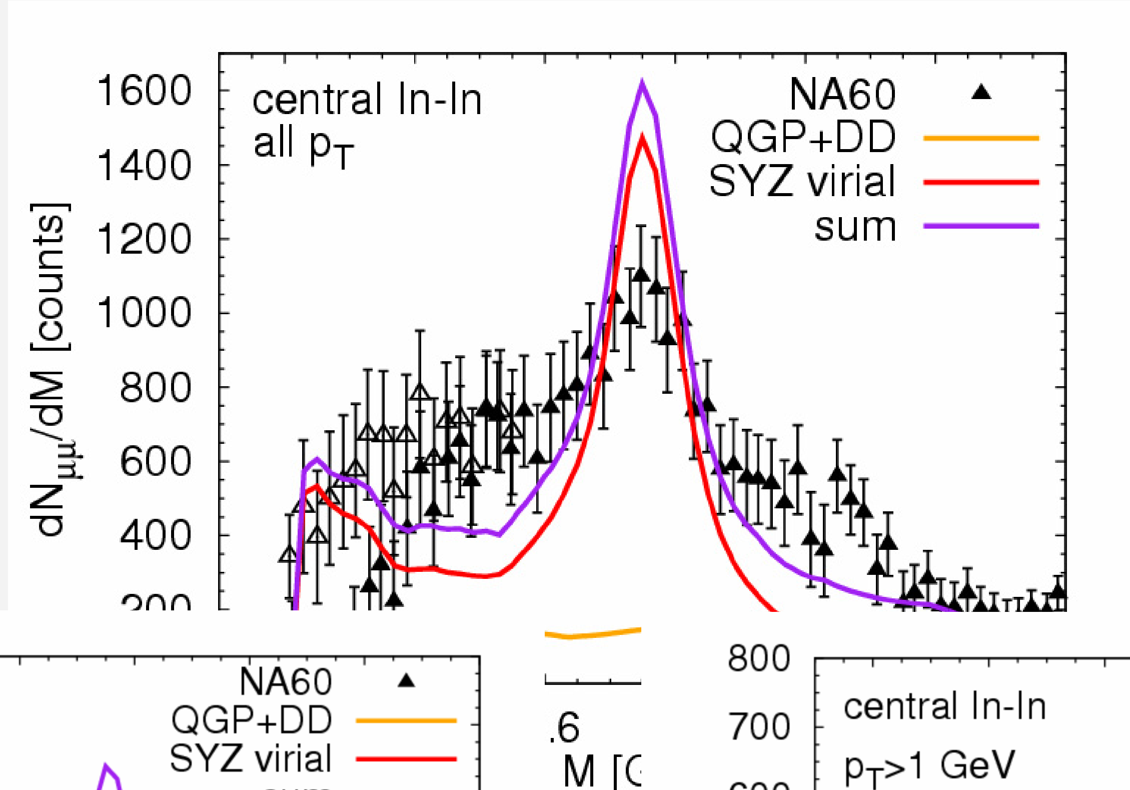


Bjorken regime:
$\tau_{FB} = 0.5$ fm/c?!



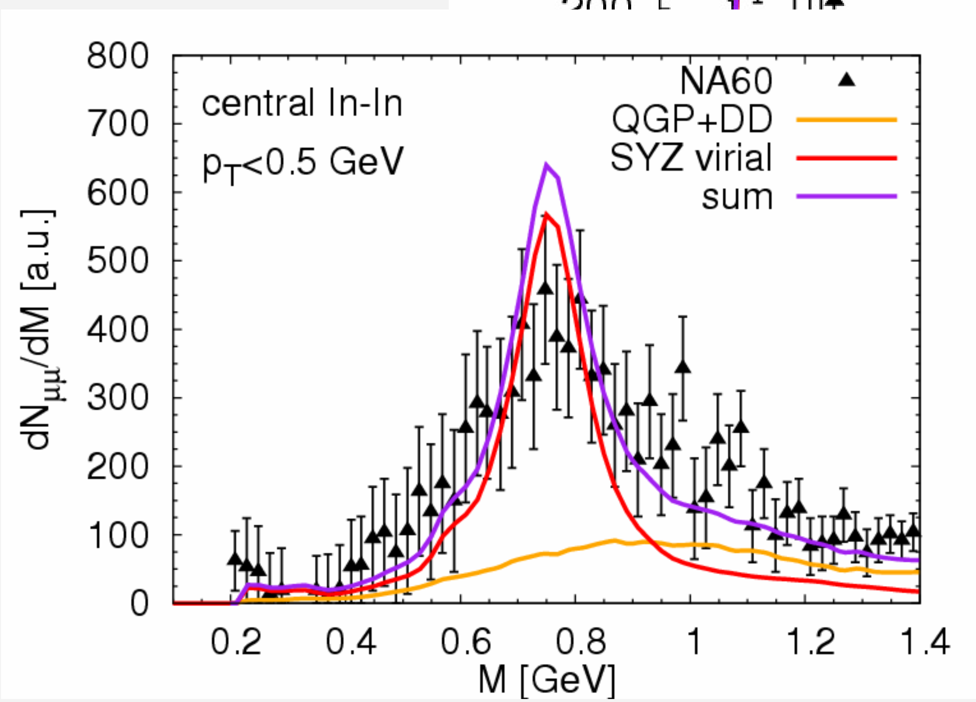
- Not compatible with gauge invariance (no $\mathbf{m}_\rho^*$ in VDM)
- acceptance?

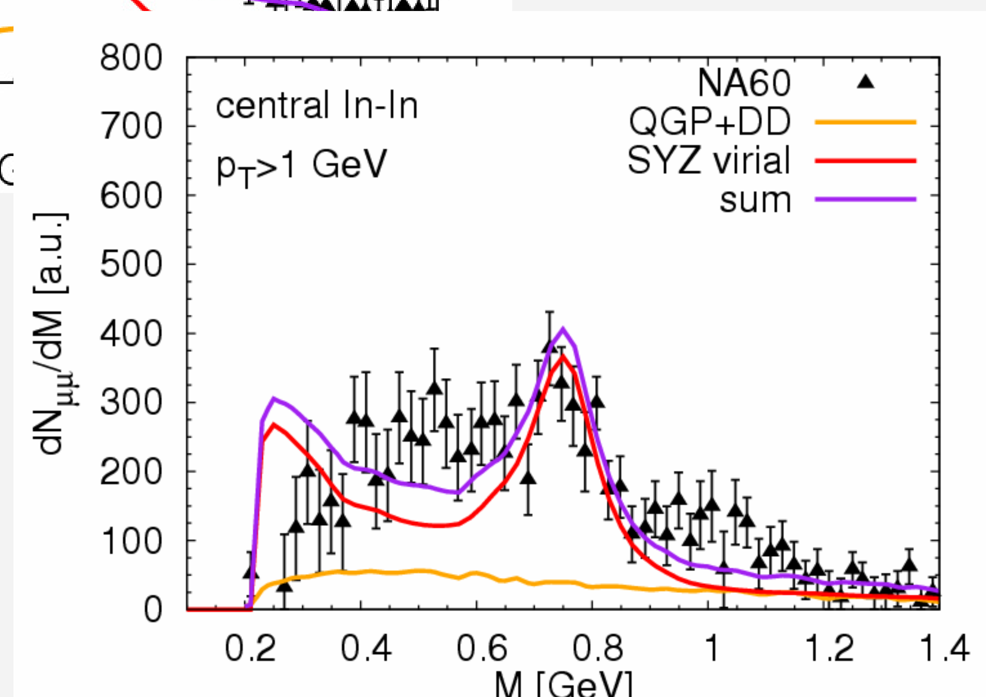
4.2.5 Chiral Virial Approach vs. NA60 (central)



[Steele,Yamagishi +Zahed '99]

[implementation van Hees+RR '05]

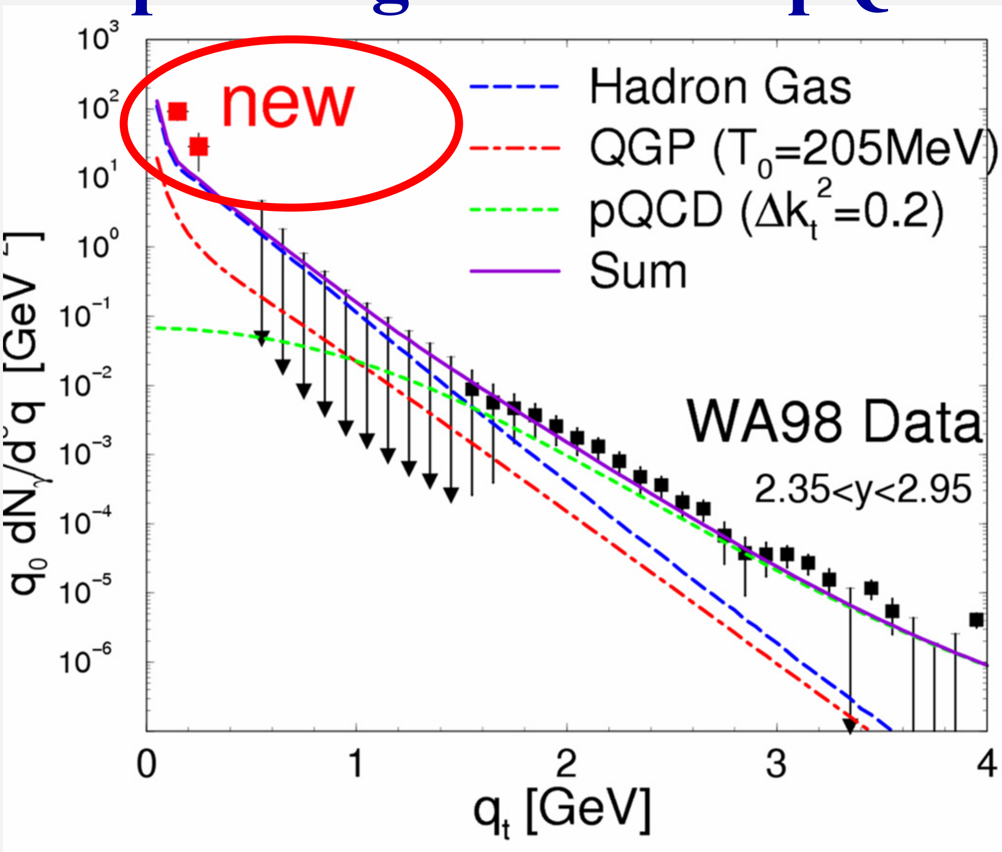




5.) Electromagnetic Probes

5.1.1 Thermal Photons I : SPS

Expanding Fireball + pQCD

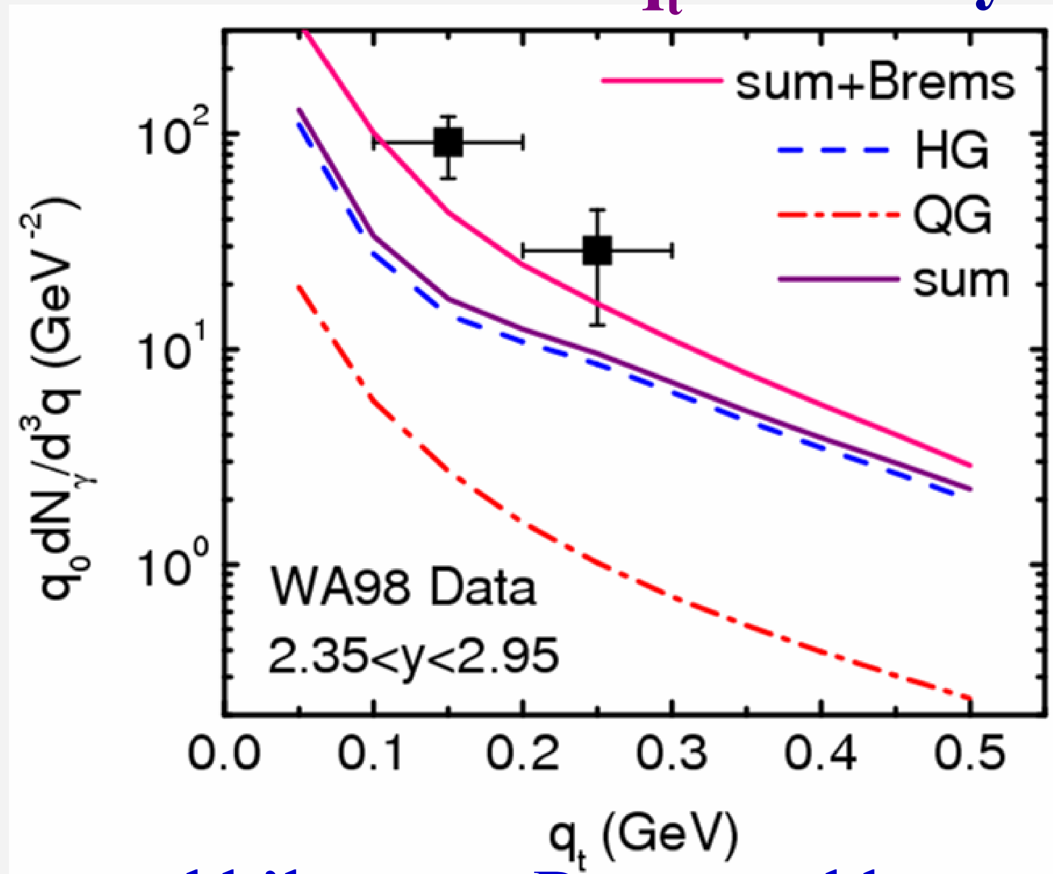


• pQCD+Cronin at q_t *>1.6GeV*

⇒ T_0*=205MeV* suff., HG dom.

[Turbide,RR+Gale'04]

WA98 "Low-q_t Anomaly"



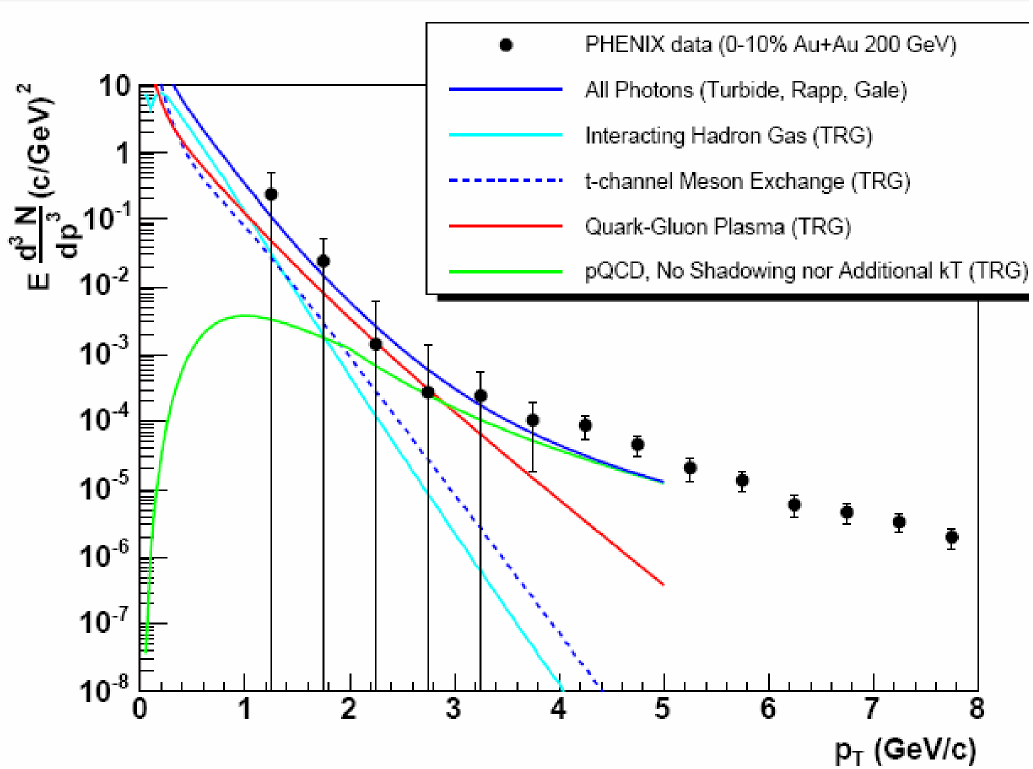
• addt'l meson-Bremsstrahlung

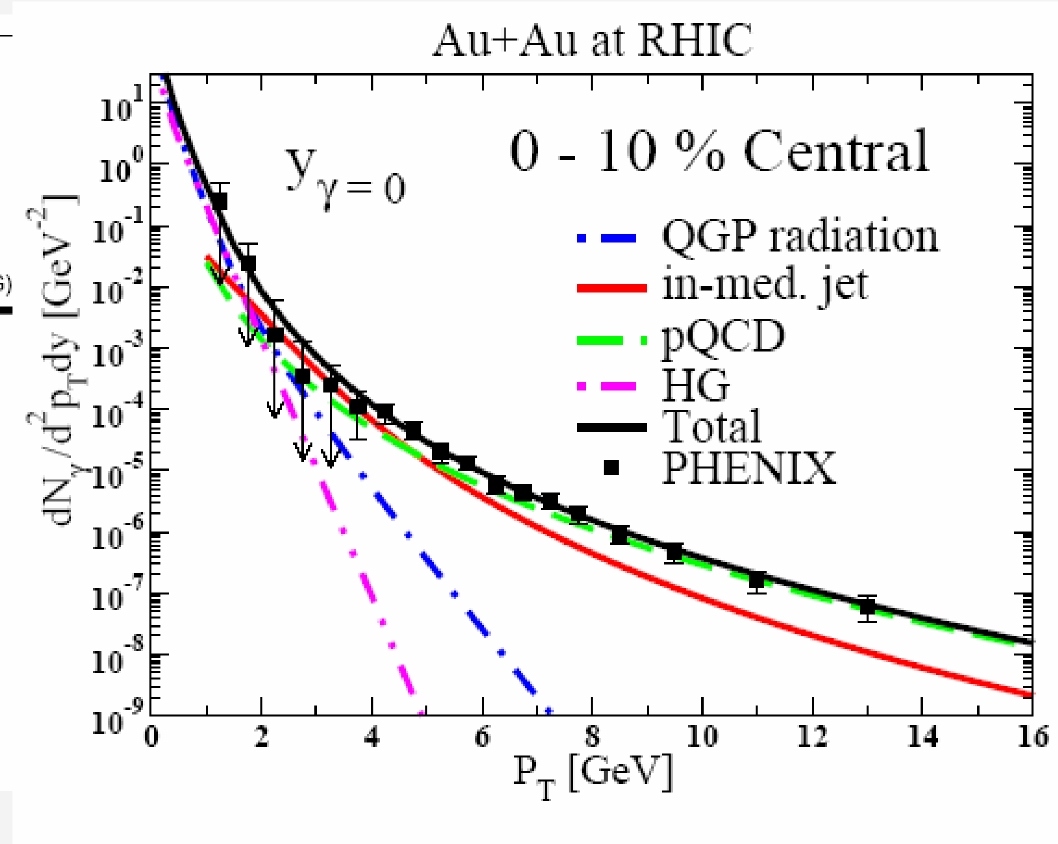
$\pi\pi \rightarrow \pi\pi\gamma \quad \pi K \rightarrow \pi K\gamma$

substantial at low q_t

[Liu+ RR'05]

5.1.2 Thermal Photons II: RHIC



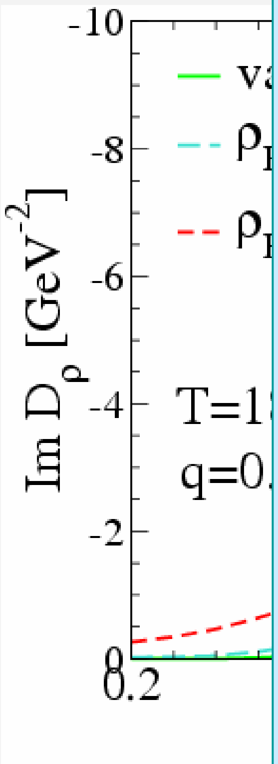


- thermal radiation q_t<3GeV ?!
- QGP window 1.5<q_t<3GeV ?!

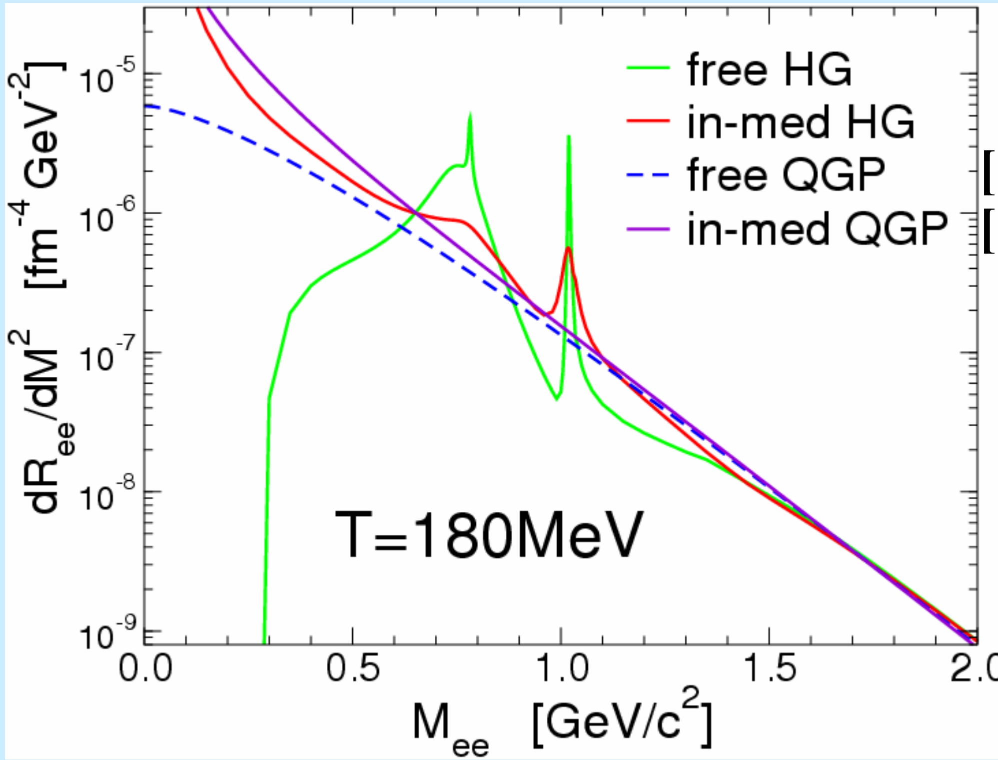
- also: γ-radiation off jets
- shrinks QGP window q_t<2GeV ?!

[Gale,Fries,Turbide,Srivastava '04]

5.3.1 RHIC: Vector Mesons in Medium

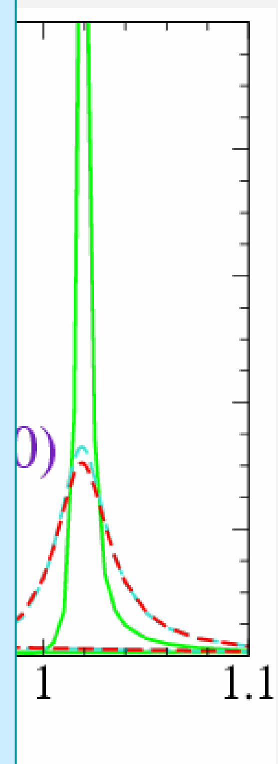


Dilepton Emission Rates



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

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

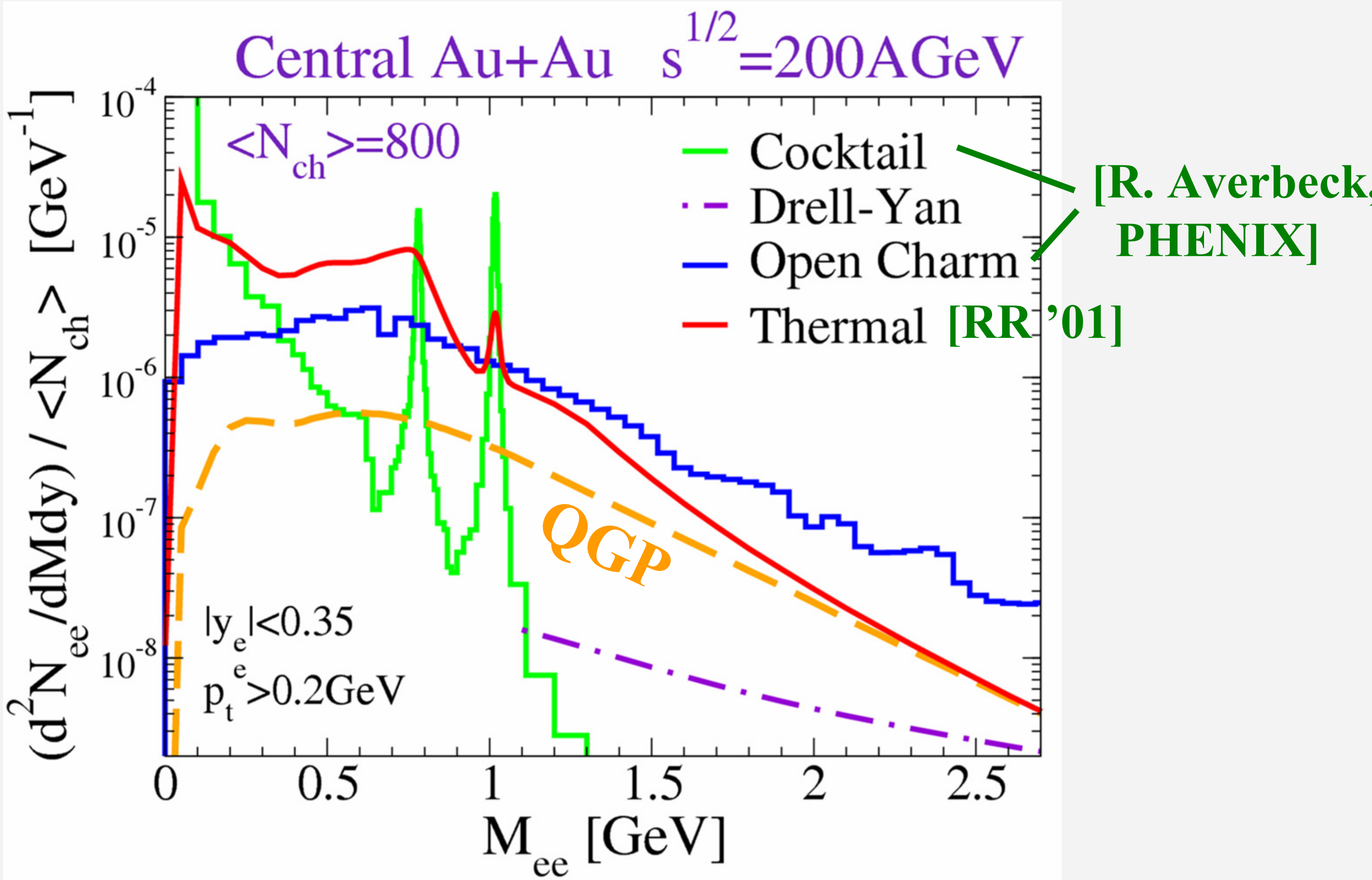


in-med HG ≈ in-med QGP !

Quark-Hadron Duality ?!

- bary
  sens
- φ m

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?)