Dilepton Spectroscopy in (Ultra-) Relativistic Heavy-Ion Collisions

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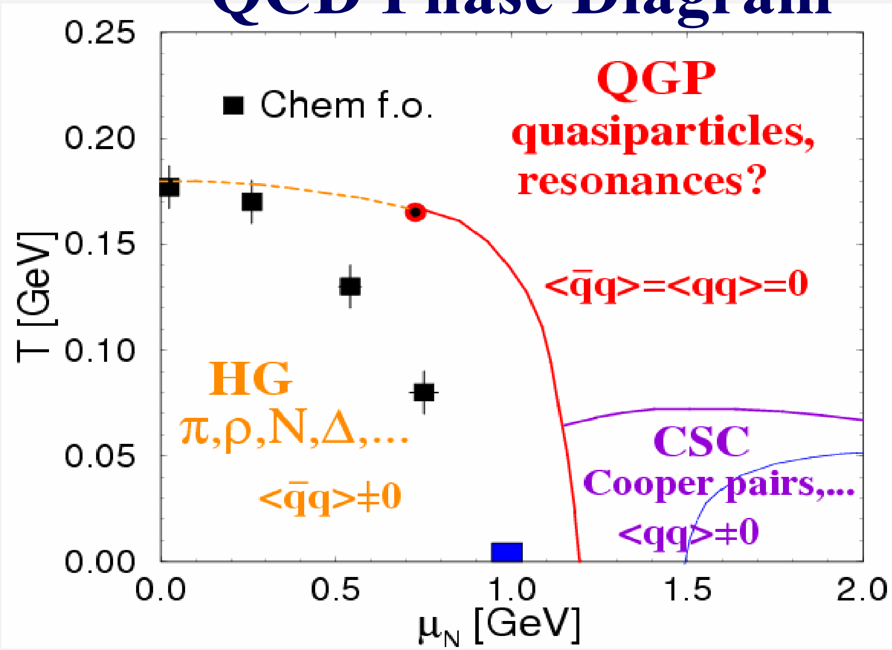
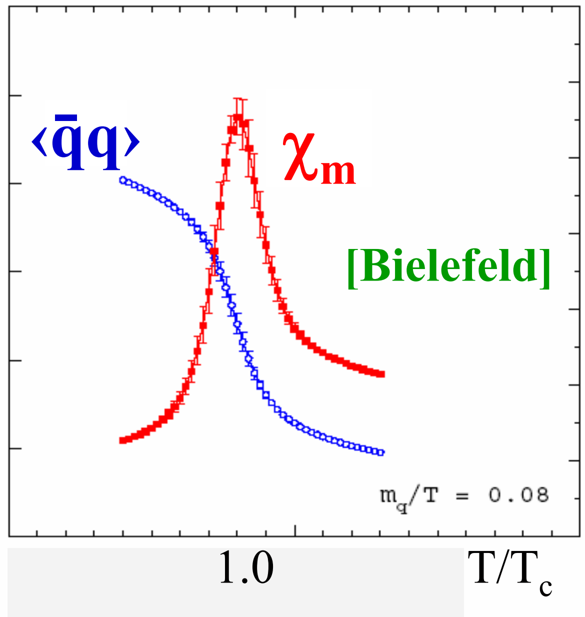
Introduction: EM-Probes -- Basic Questions

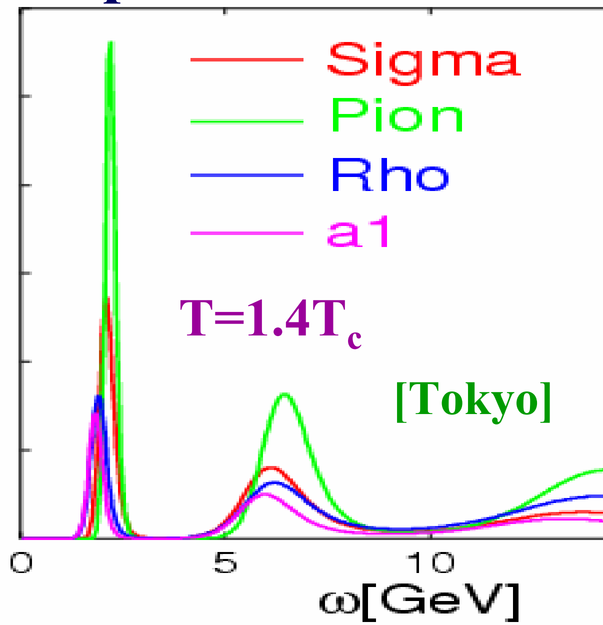
QCD Phase Diagram



Chiral Condensate



Spectral Functions



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.) EM Emission Rates and Chiral Symmetry

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

3.) Medium Effects and Thermal Dileptons

- Lattice QCD
- Hadronic Many-Body Calculations
- Dropping Mass and Vector Manifestation

4.) Dileptons at SPS

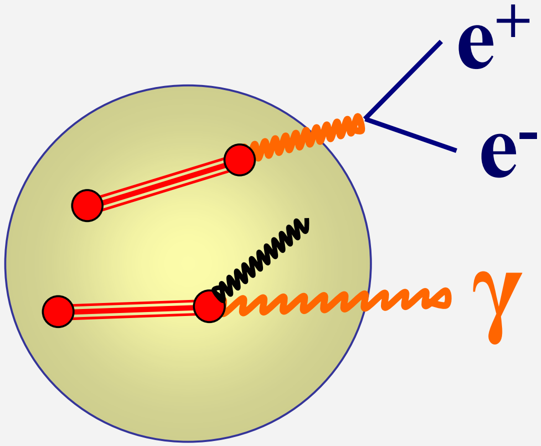
- Recent CERES Data
- NA60 Data: Critical Appraisal

5.) Conclusions

2.) EM Emission Rates and Chiral Symmetry

E.M. Correlation Function:

$$\Pi_{em}(q) = -i \int d^4x \, e^{iqx} \langle j_{em}(x) j_{em}(0) \rangle_T$$



$$\frac{dR_{ee}}{d^4q} = \frac{\text{const}}{M^2} \alpha^2 f^B(q_0,T) \, Im\, \Pi_{em}(M,q;\mu_B,T)$$

$$q_0 \frac{dR_\gamma}{d^3q} = \text{const}\, \alpha\, f^B(q_0,T) \, Im\, \Pi_{em}(q_0=q;\, \mu_B,T)$$

Medium Modifications:

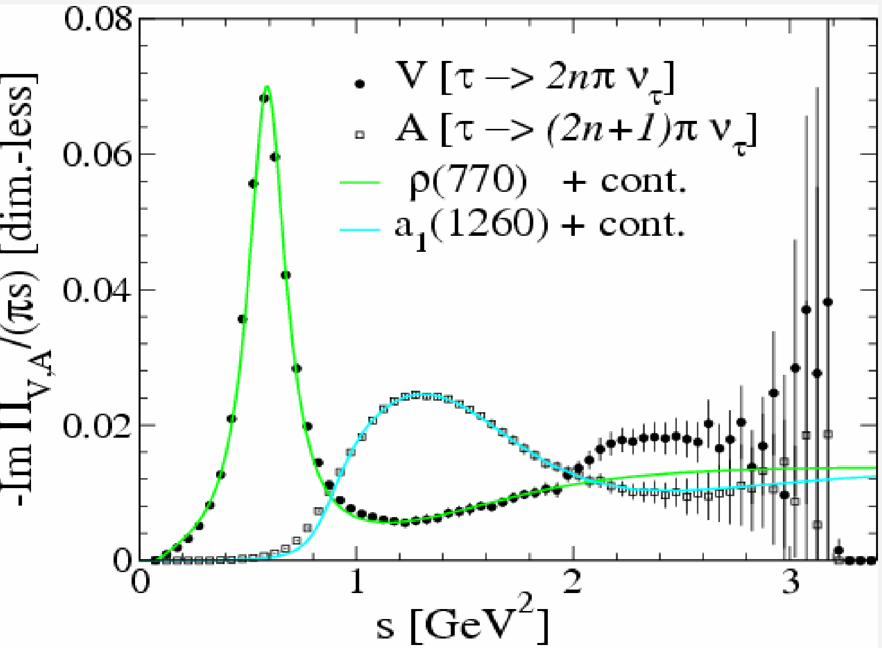
π-gas χPT	hadron gas many-body(2↔2)	hadron liquid deg. of freedom?	QGP liquid resonances?	QGP
consistent	extrapolate	⇒ phase transition ⇐		pQCD
0	0.05	0.3	0.75	ε[GeVfm^{-3}]
	120, 0.5ρ_0	150-160, 2ρ_0	175, 5ρ_0	T[MeV], ρ_{had}

To date: realistic descriptions extrapolated bottom-up (hadronic) or top-down (pQCD)

2.2 Chiral Symmetry Breaking and Restoration

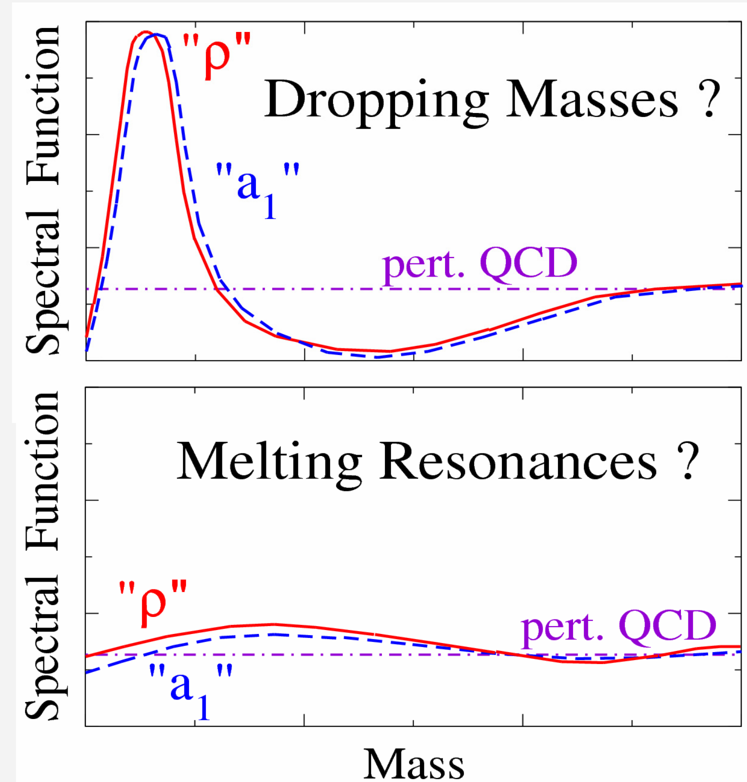
Splitting of "chiral partners" ρ - $a_1(1260)$ $\Rightarrow$ Chiral Symmetry Breaking

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

or: ρ_{long} chiral partner of π ≡ "Vector Manifestation" [Harada+Yamawaki '01]

2.3 Chiral Sum Rules and the $a_1(1260)$

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

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

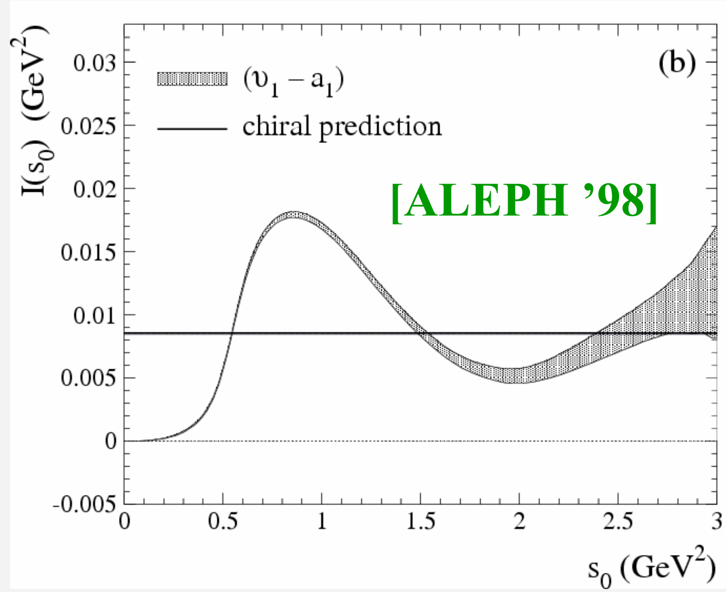
[Das etal '67]

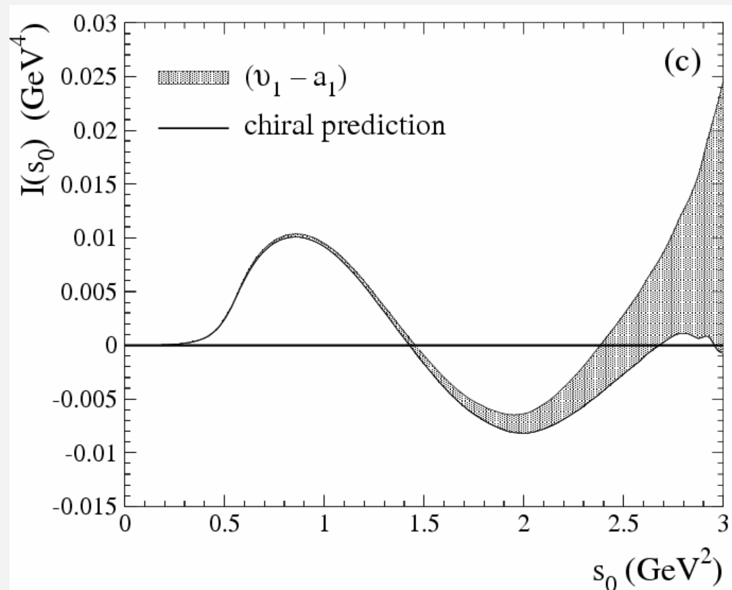
$$I_1(s_0) = -\int_0^{s_0} \frac{ds}{\pi s}(Im\Pi_V - Im\Pi_A) = f_\pi^2$$

[Weinberg '67]

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

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



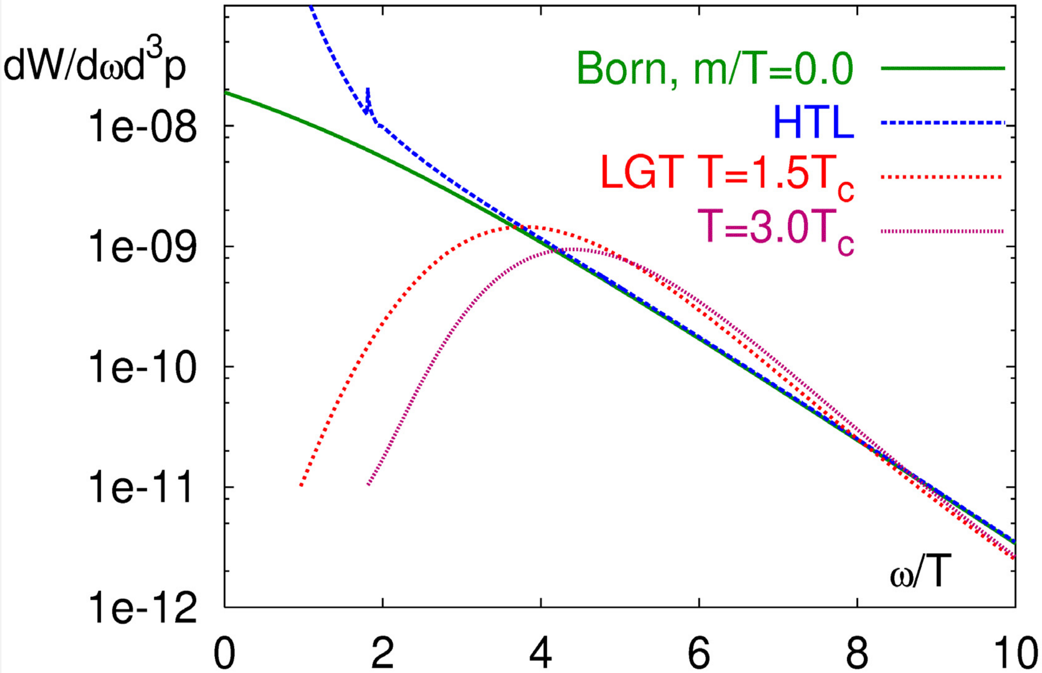


- require **a_1(1260)** contributions
- extended to finite temperature [Kapusta+ Shuryak '93]

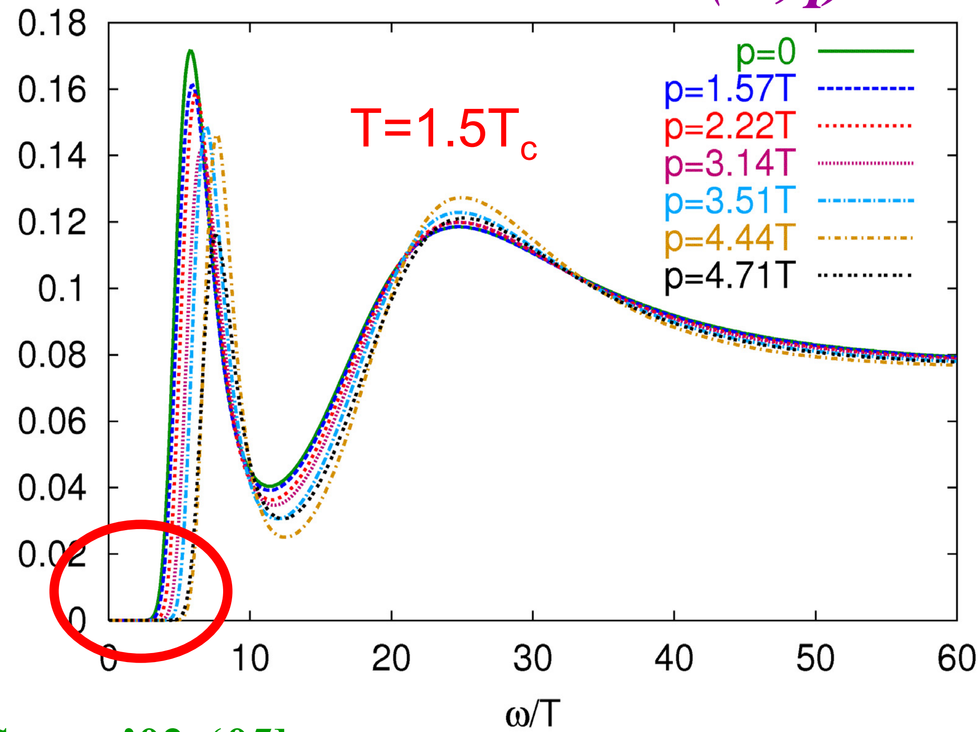
3.) Medium Effects and Thermal Dileptons

3.1 Lattice QCD (QGP)

Dilepton Rate ~ $Im\Pi(\omega,q=0)/\omega^2$



EM Correlator $Im\Pi(\omega,q)/\omega^2$



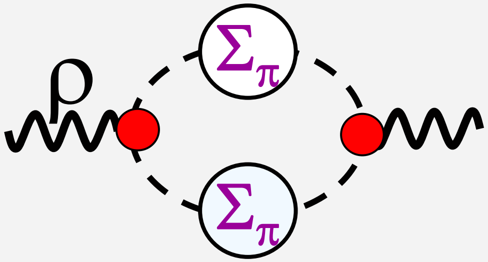
[Bielefeld Group ’02, ‘05]

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

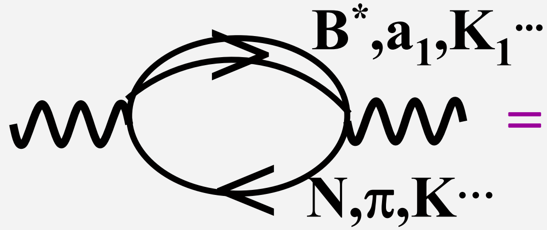
3.2 In-Medium II: Hadronic Many-Body Theory

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

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



$= \int D_\pi v^2_{\rho\pi\pi} D_\pi$,

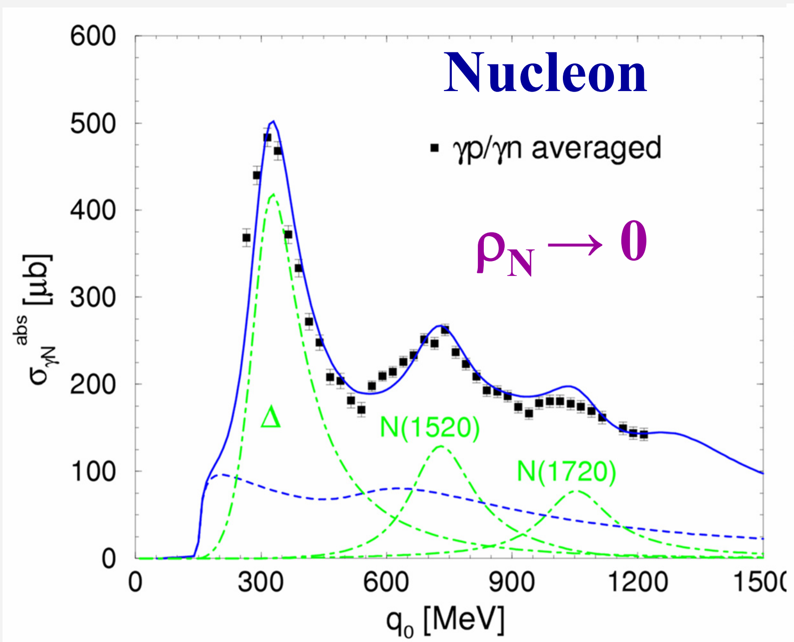


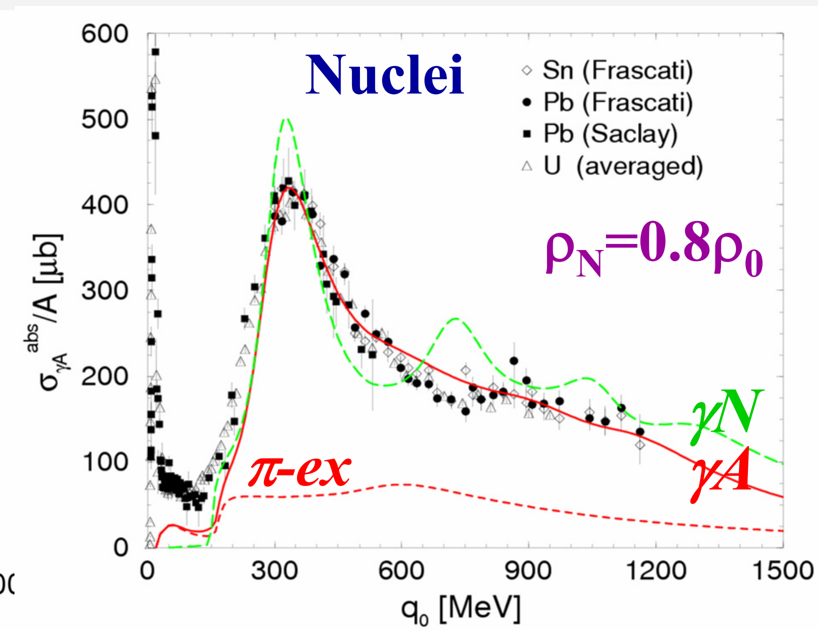
$= \int D_M v^2_{\rho\pi M} [f^\pi - f^M]$

Constraints:

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

[Urban et al. '98]

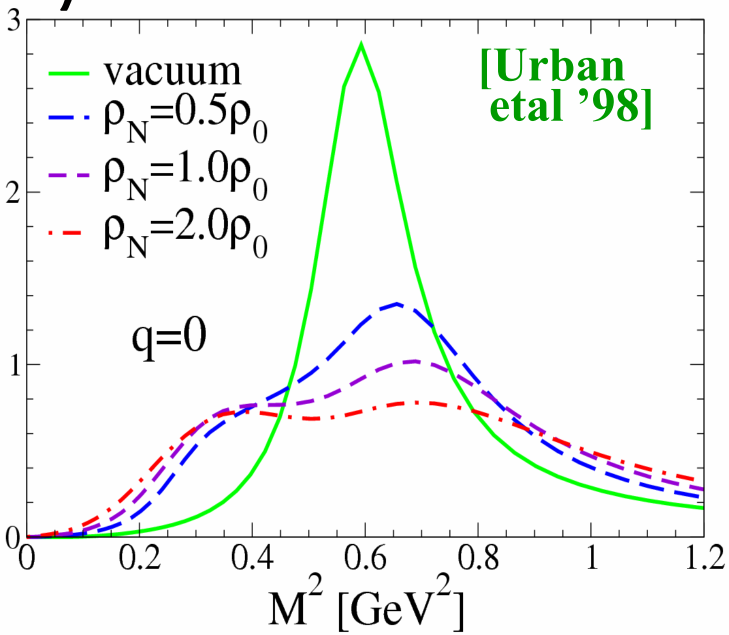




$\sigma^{abs}_{\gamma A}(q_0)/A = -\frac{4\pi\alpha}{q_0\rho_N} Im\Pi_{em}(q_0=q)$ ~ light-like ρ-spectral funct. $Im\, D_\rho(q_0=q)$

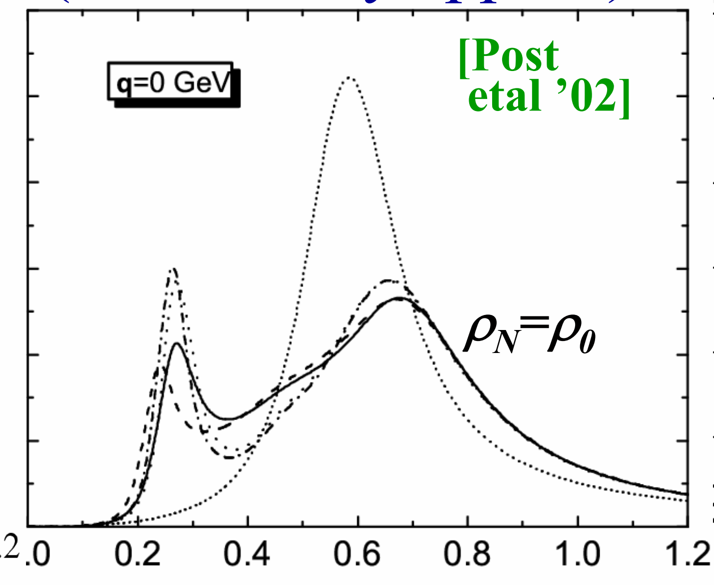
3.2.2 $\rho(770)$ Spectral Function in Nuclear Matter

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



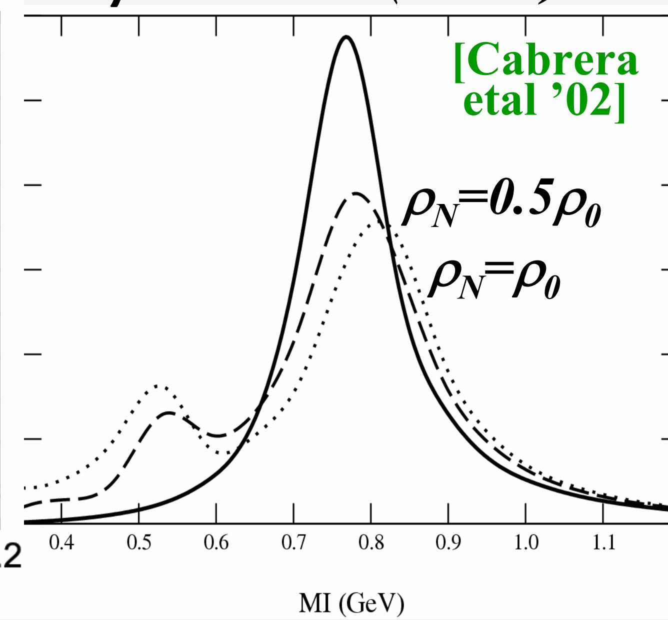
Constraints: γN, γA

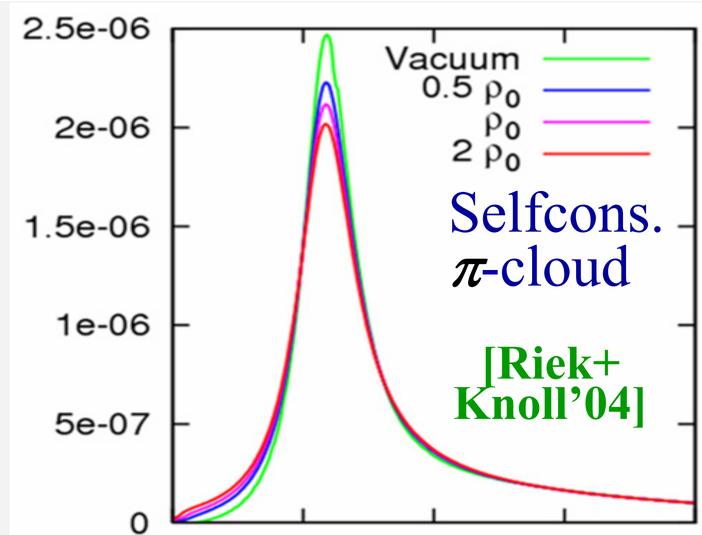
Relativist. ρ-$N \to B^*$ (low-density approx)



$\pi N \to \rho N$ PWA

In-med π-cloud + ρ-$N \to N(1520)$





- Consensus: broadening + mass-shift up
- Constraints from (vacuum) data important quantitatively

3.2.3 QCD Sum Rules + $\rho(770)$ in Nuclear Matter

dispersion relation for correlator:

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

[Shifman,Vainshtein +Zakharov '79]

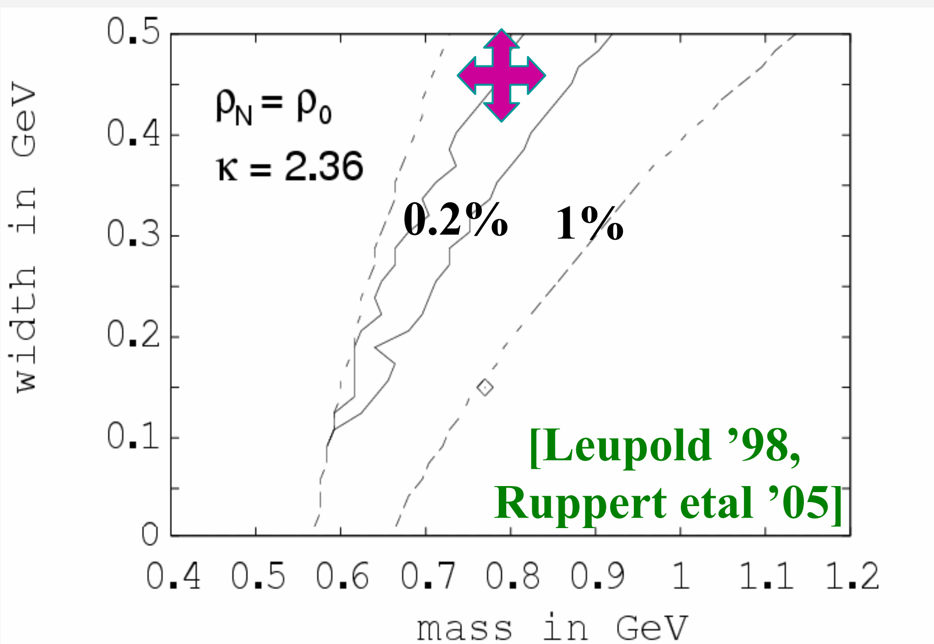
- ***lhs:*** OPE (spacelike Q^2):

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

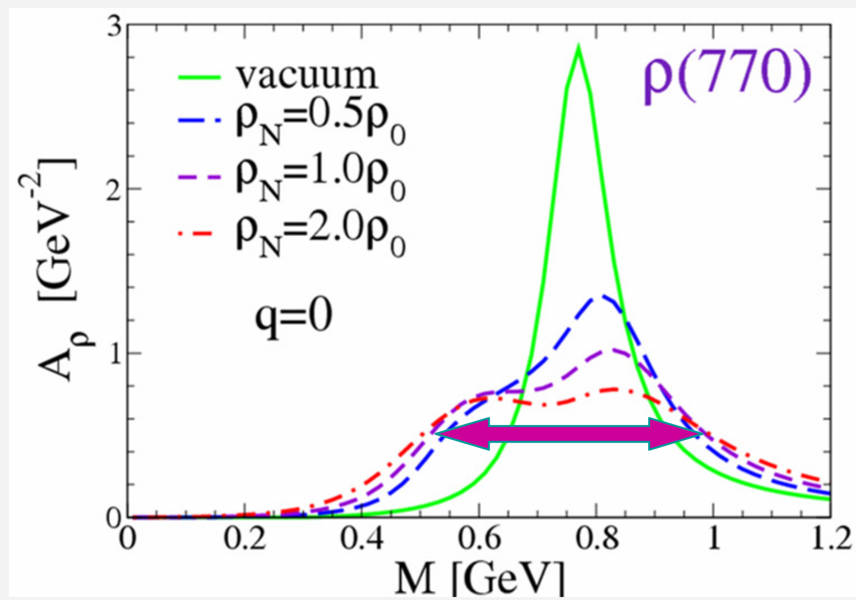
4-quark condensate!

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

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



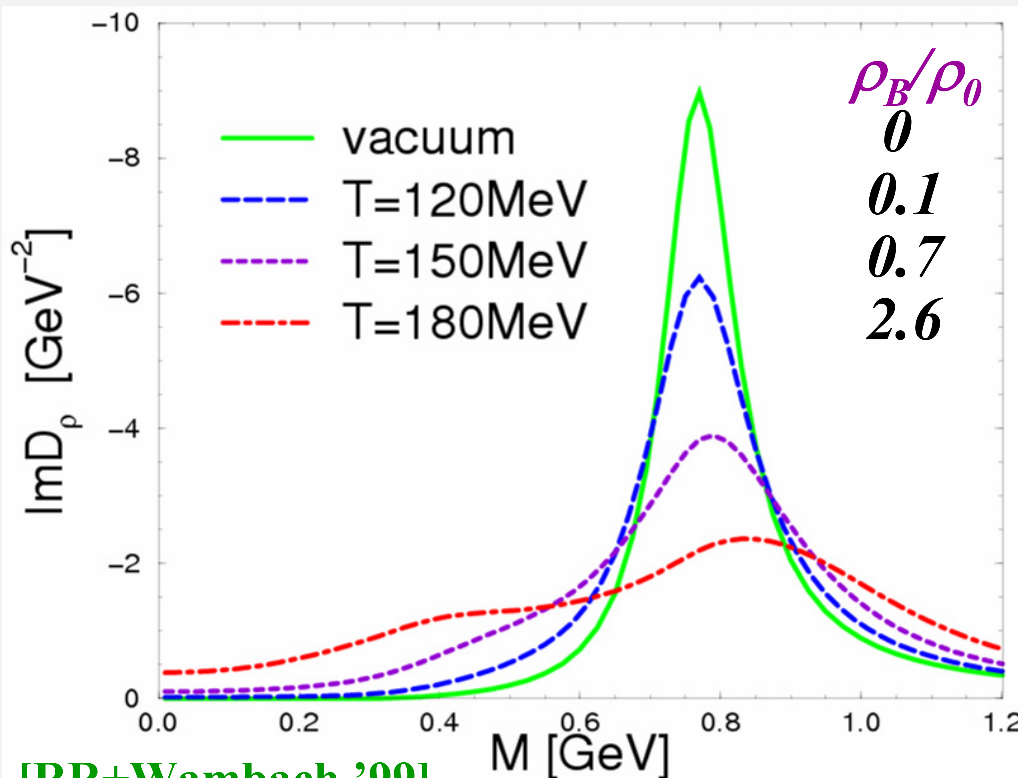
[Leupold '98, Ruppert etal '05]



also: [Asakawa+Ko '92, Klingl,Kaiser+Weise '97]

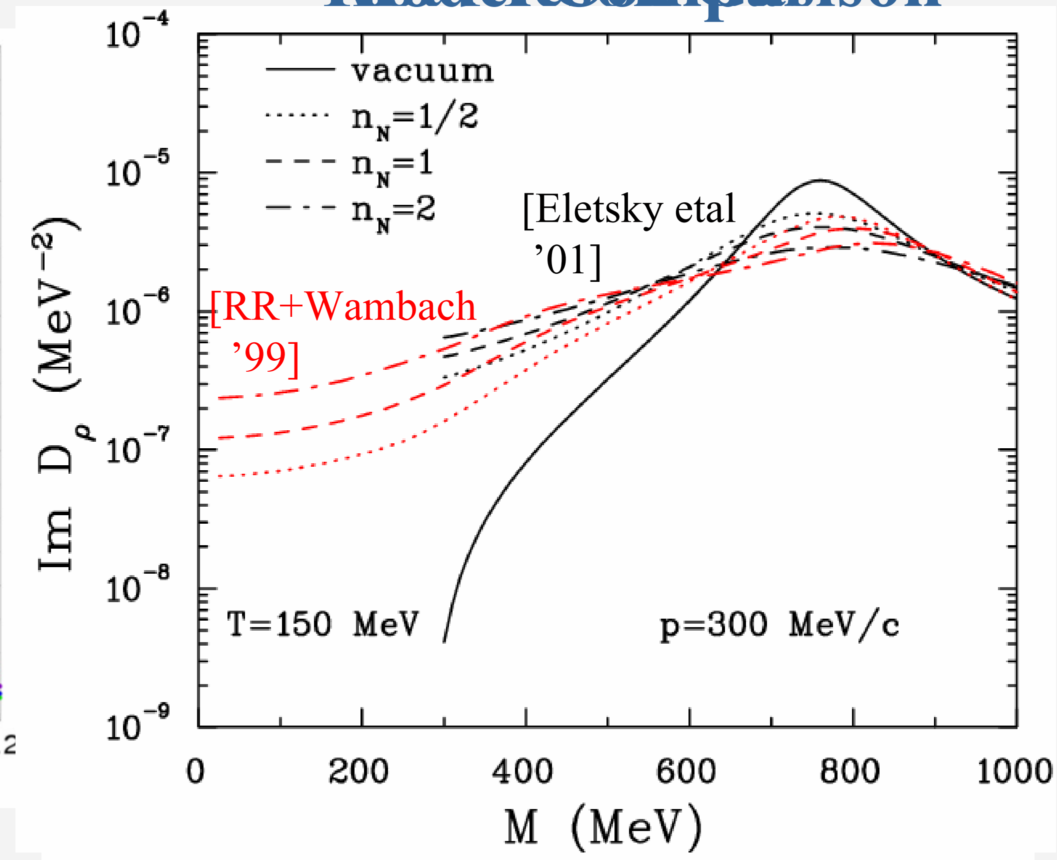
3.2.4 ρ-Meson Spectral Functions at SPS

Hot+Dense Matter



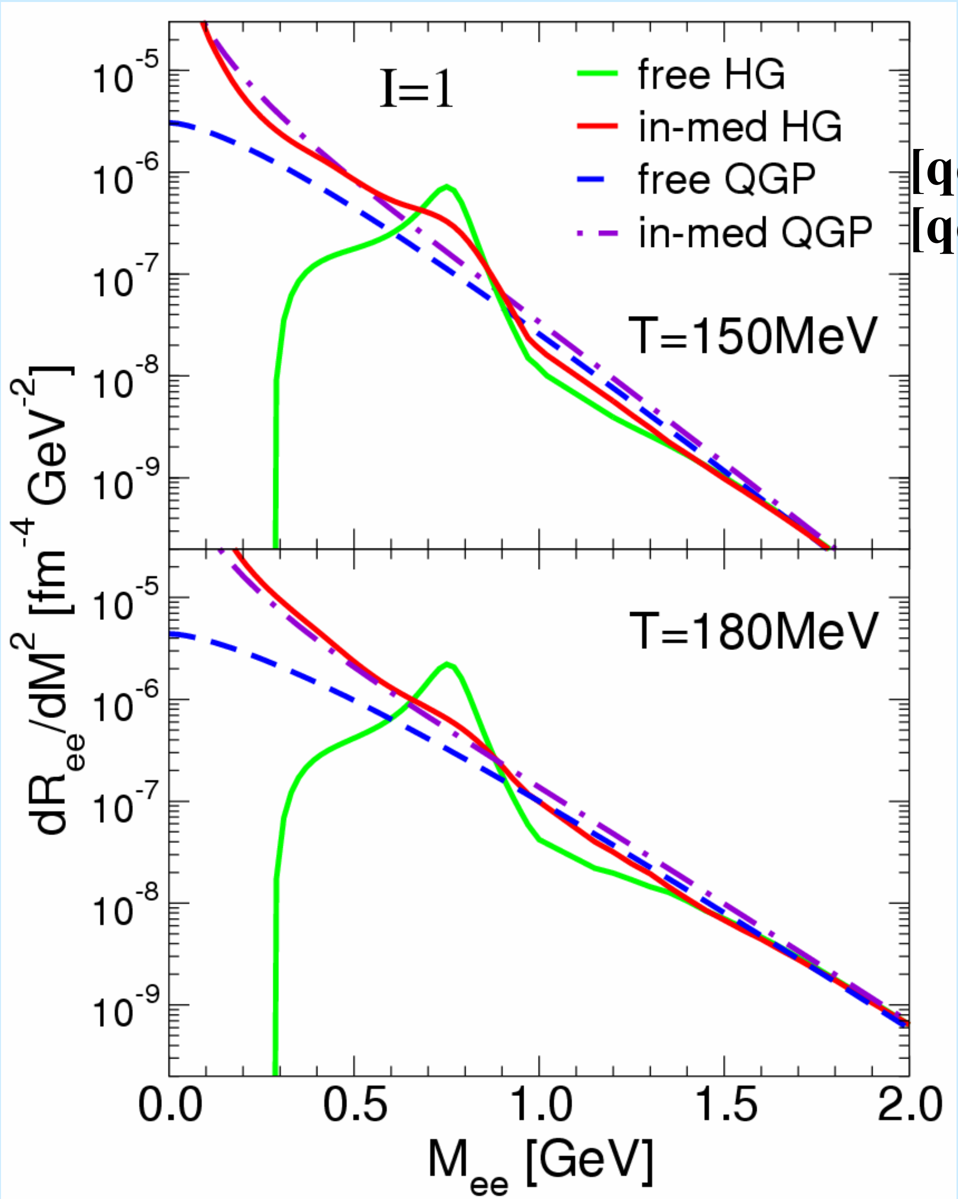
[RR+Wambach '99]

Hot Meson Gas
Model Comparison



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

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



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

[$q\bar{q}+O(\alpha_s)$-HTL] [Braaten,Pisarski +Yuan '90]

- HTL much enhanced over Born rate
- **"matching" of HG and QGP automatic!**
- **Quark-Hadron Duality ?!**

3.3 In-Medium III: Dropping Mass

Scale Invariance of $\mathcal{L}_{QCD}$

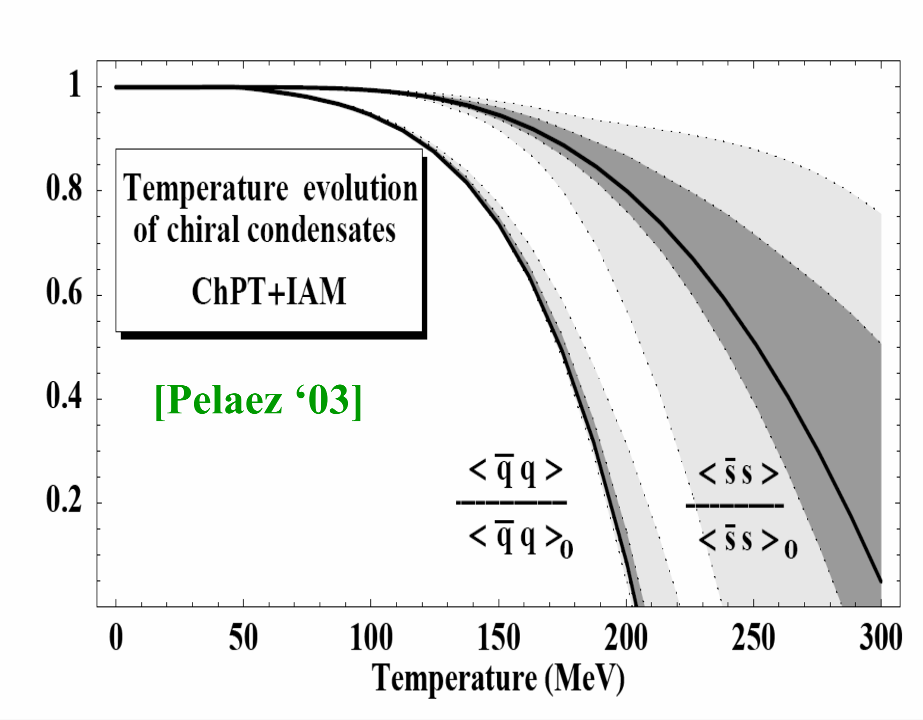
[Brown+Rho '91, '02]

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

- density dependence:
  QCD sum rules: ***C=0.15***

[Hatsuda+ Lee '92]

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



- vector dominance coupling:

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

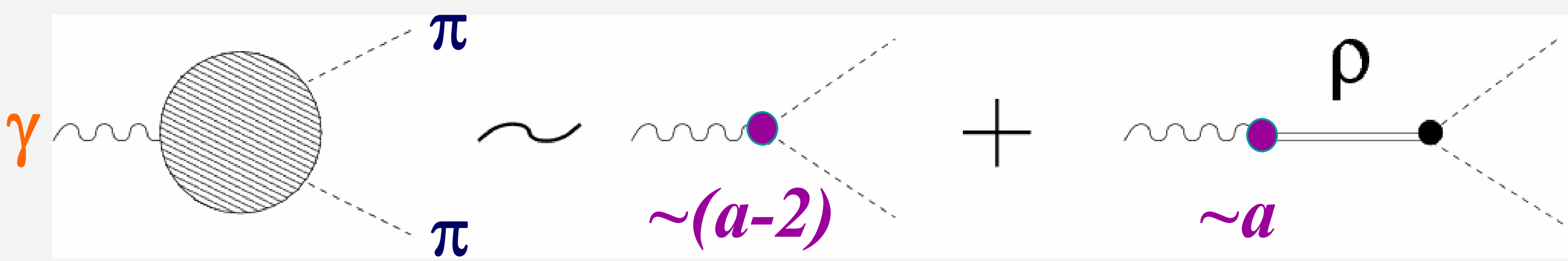
(gauge invariance!)

3.4 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

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

[Harada, Yamawaki etal, '01]

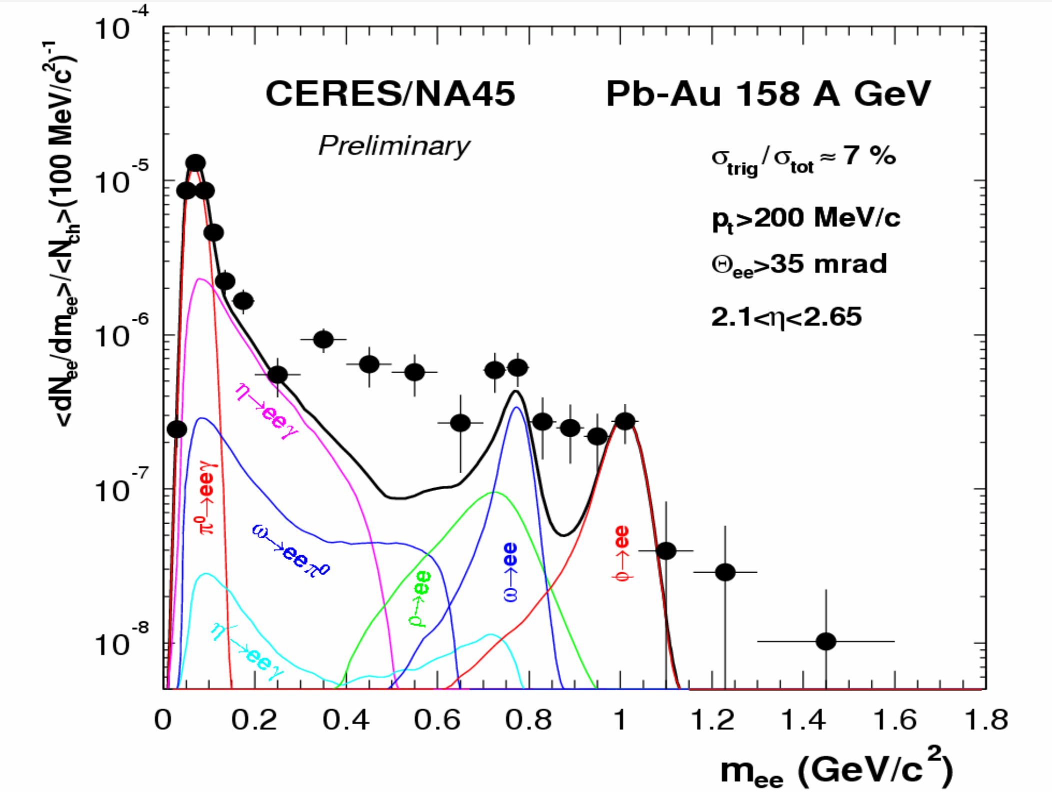


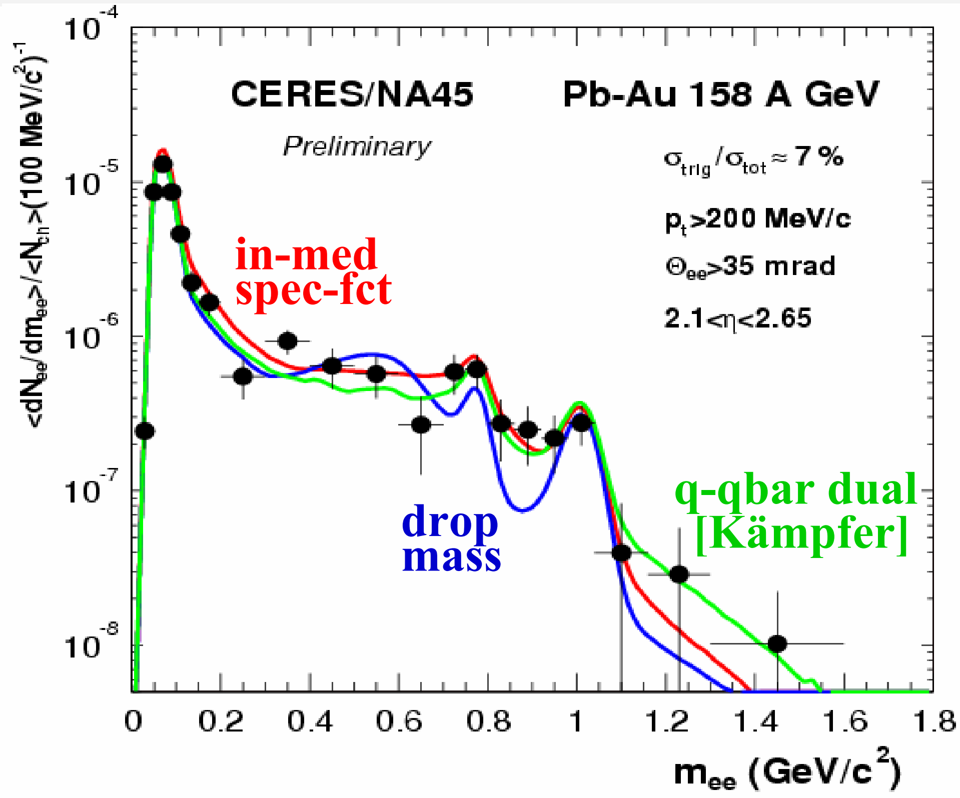
e.m. spectral function? matching HG-QGP: massless mesons?

4.) Dilepton Spectra in URHIC I: CERES/NA45

→ Evolve dilepton rates over thermal fireball QGP+Mix+HG:

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

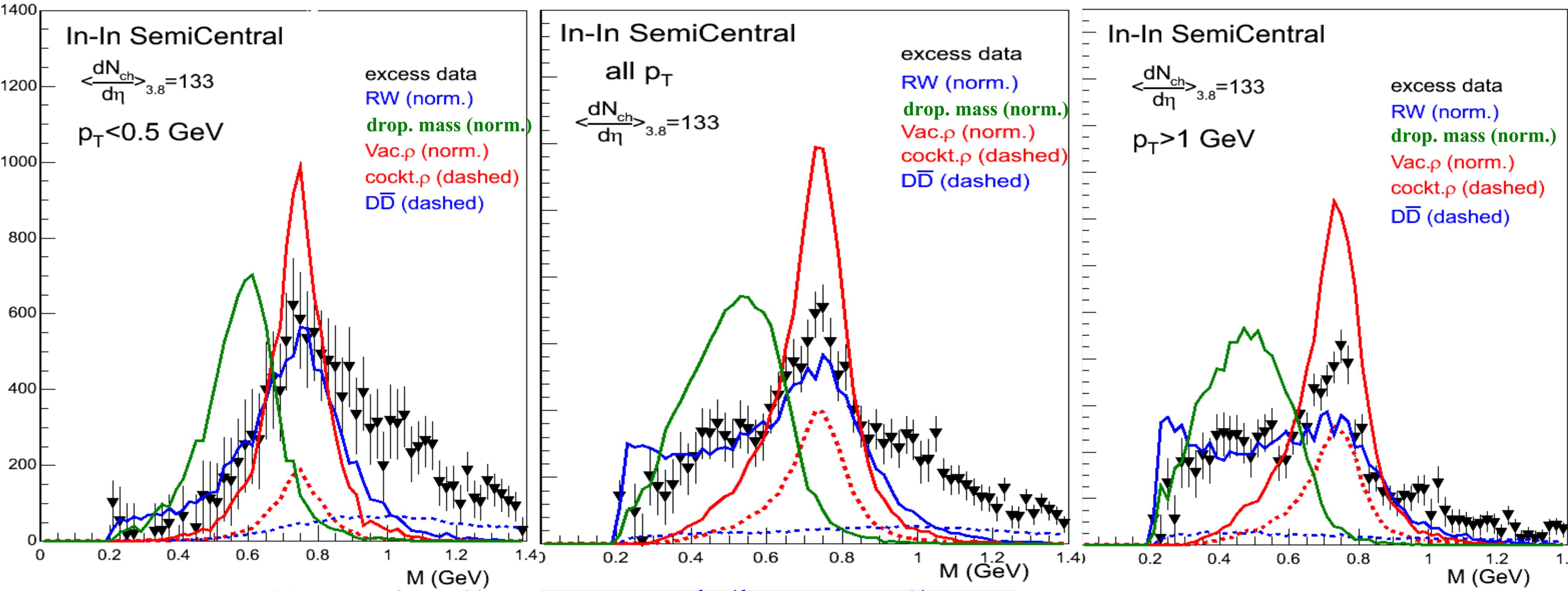




- central Pb-Au confirm strong medium effects
- **dropping mass** disfavored above ρ-mass?!

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

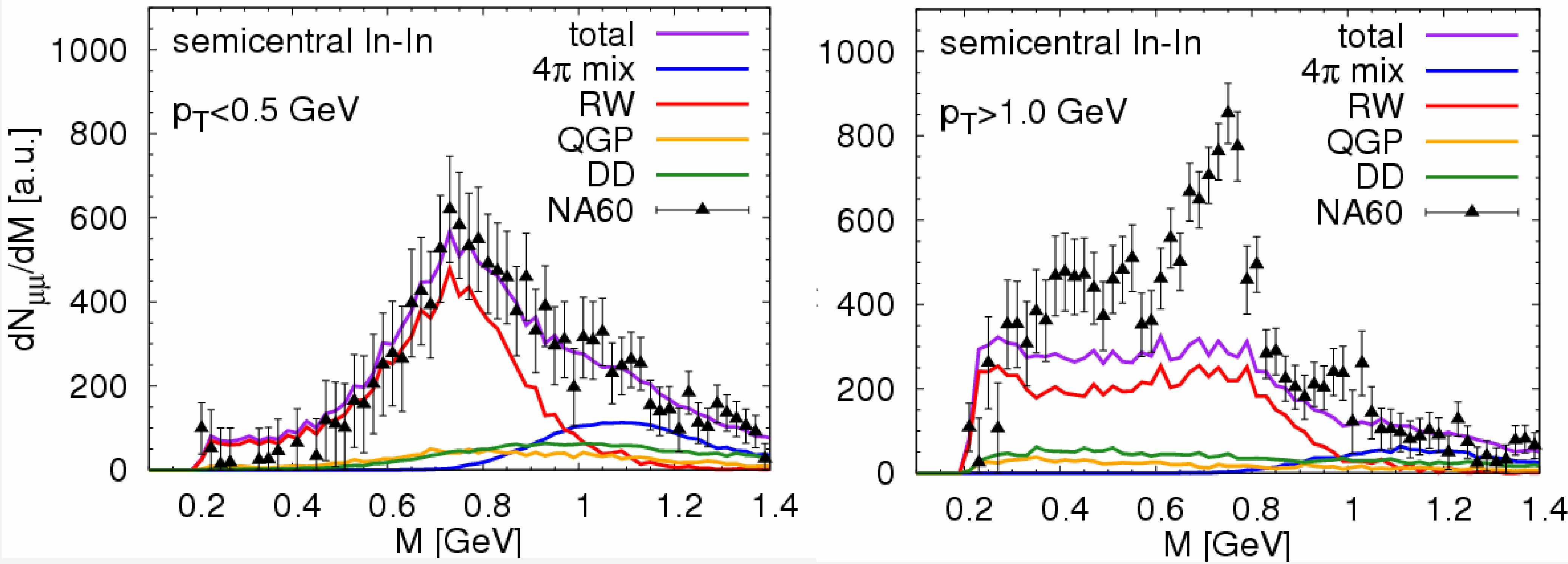
  (2) normalization: **0.6** (***p_t <0.5GeV***), **0.8** (all ***p_t***), **~2** (***p_t >1GeV***)

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

4.2.2 Modified Fireball and Absolute Normalization

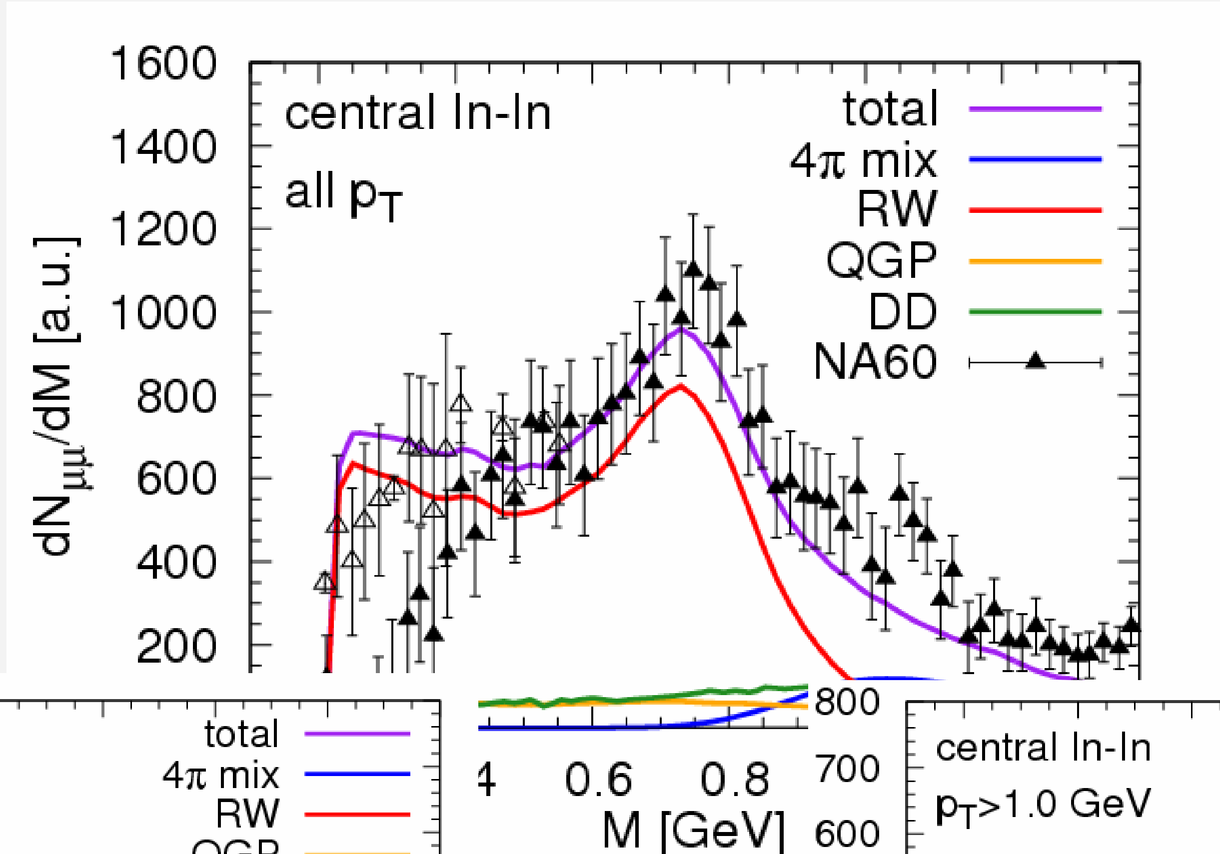
- ρ-spectral function unchanged since **[RR+Wambach '99]**
- expanding fireball, fixed S ($\leftrightarrow N_{ch}$): $V_{FB}(\tau)=(z_0+v_z\tau)\ \pi\,(R_{\perp 0}+0.5a_\perp\tau^2)^2$

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

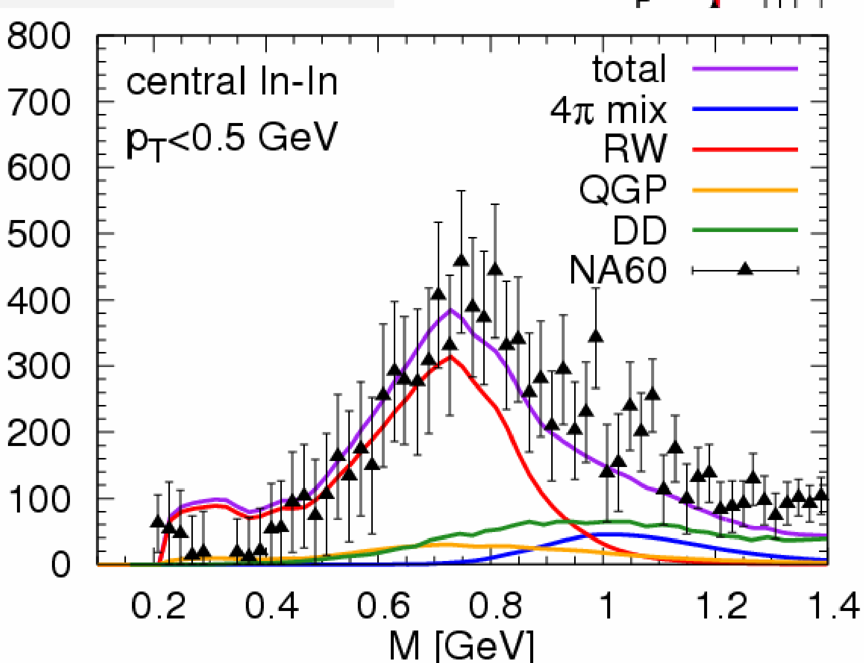


- reasonable agreement with absolute normalization, but …
- too little yield at high p_t; "free ρ"? ω? check central …

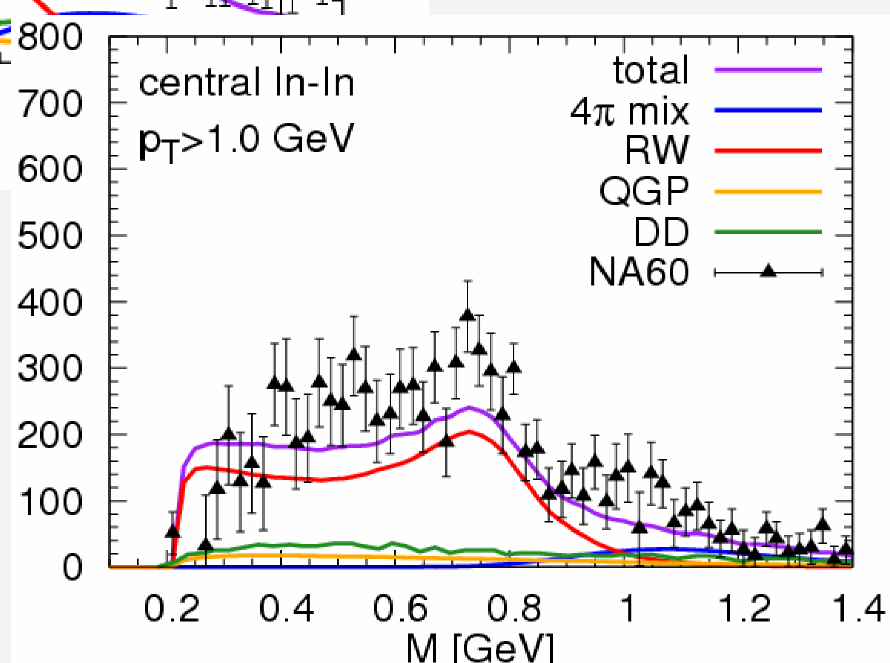
4.2.3 In-Medium Hadronic vs. NA60: Central Collisions



[van Hees+ RR in prep]



Quite ok!



4.2.4 Intermediate-Mass Region

- Previous calculation only included "2π" states via ρ(770)
- "4π" states dominate in the vacuum correlator above *~1.1GeV*
- medium effect: "chiral mixing":

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

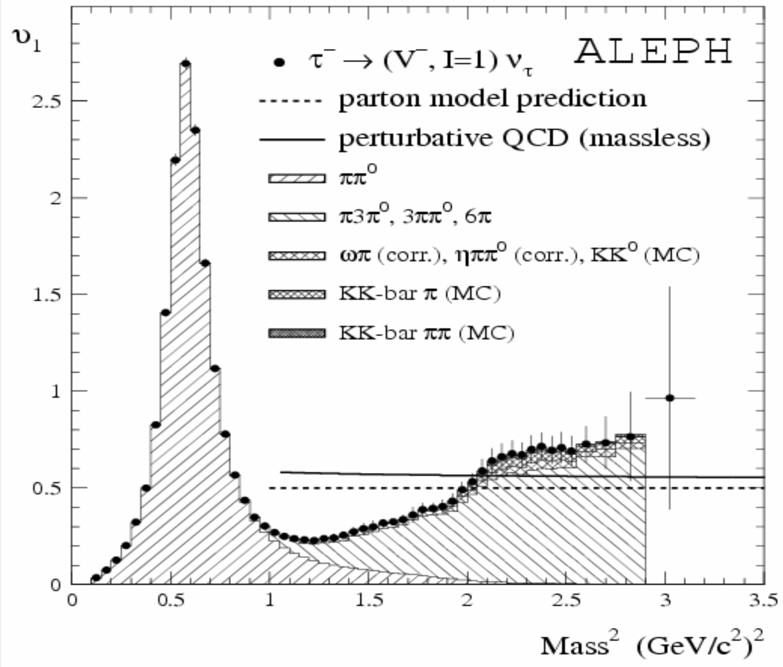
[Eletsky+Ioffe '90]

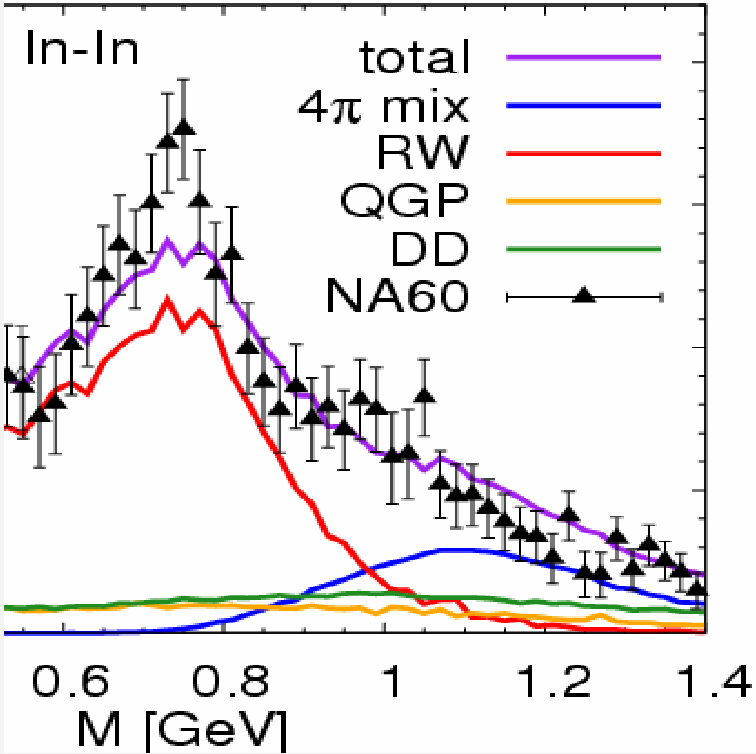
- upper estimate:

$$\varepsilon = \frac{1}{2}\frac{n_\pi(T,\mu_\pi)}{n_\pi(T_c)}$$

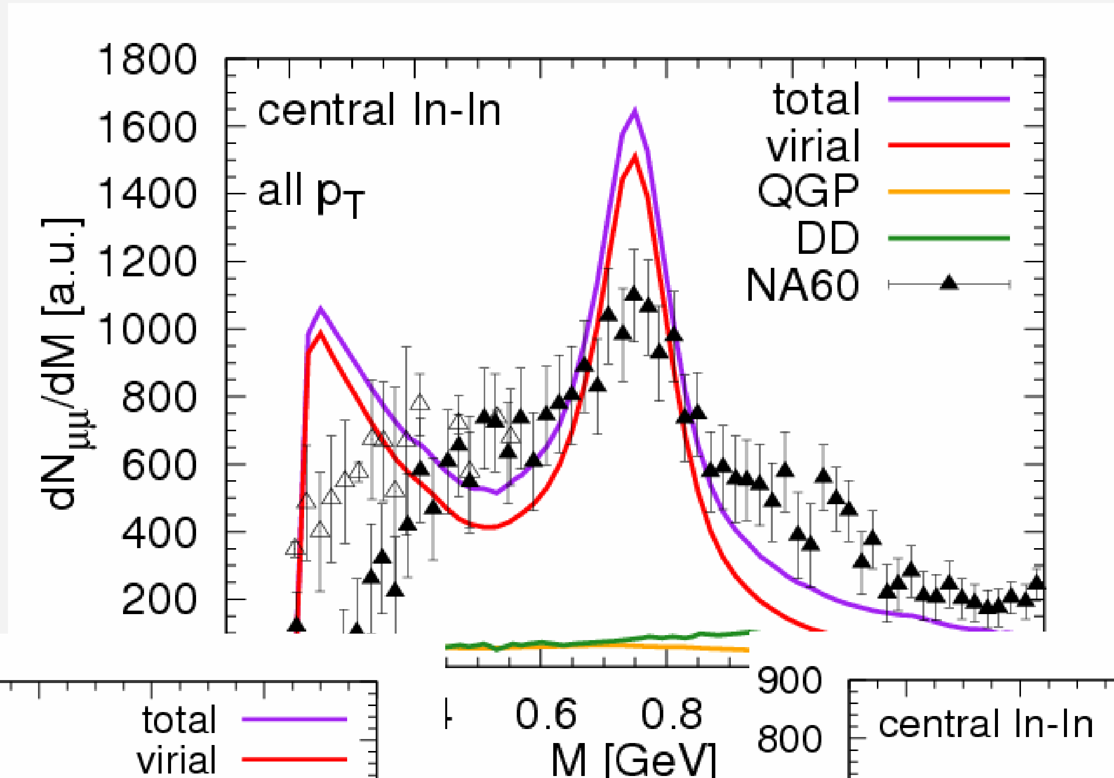
[van Hees +RR in prep]

⇒ excess above ρ-mass in principle accounted for; details forthcoming



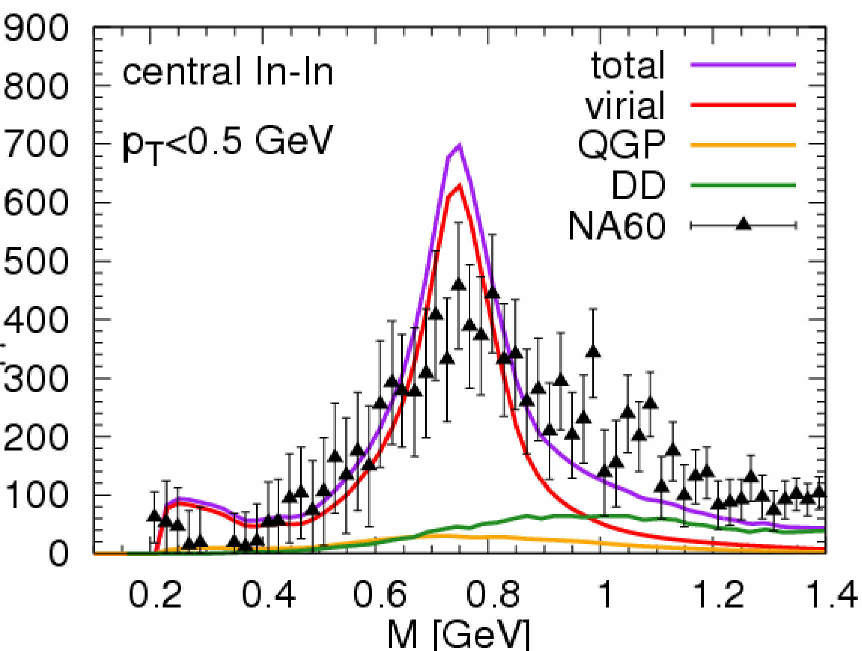


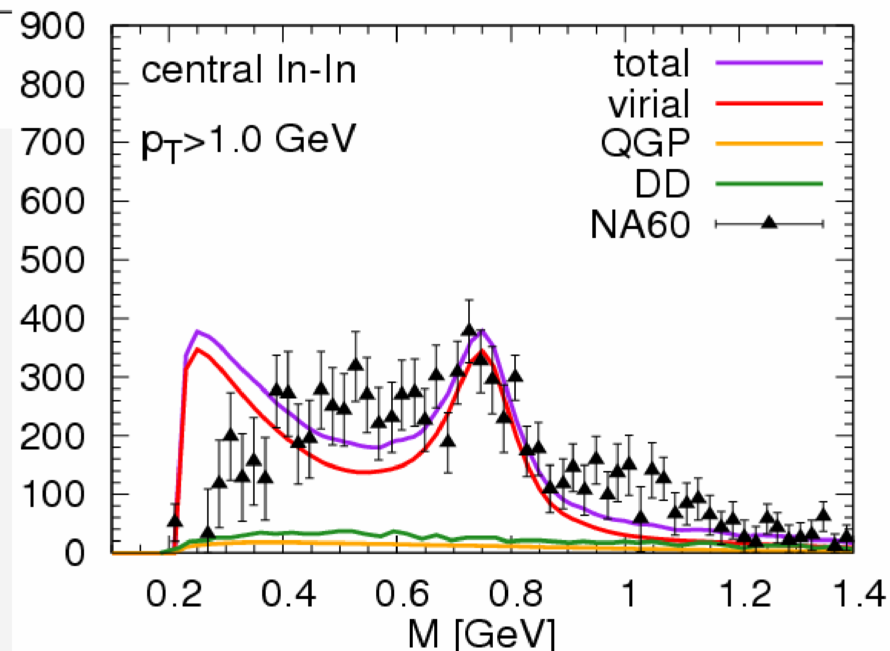
4.2.5 Chiral Virial Approach vs. NA60 (central)



[Steele,Yamagishi +Zahed '99]

[implementation van Hees+RR '05]





4.2.6 Preliminary Lessons from NA60

- hadronic many-body predictions supported data (“ρ-melting” at ~T_c)
- dropping mass as used for **CERES** in ’90’s ruled out
  revised versions?? (vector manifestation / VDM violations)
- quality control mandatory (model constraints, QCDSRs, ...)
- absolute yields important (fireball evolution)
- chiral virial approach: lack of broadening
- ***M=1-1.5 GeV***: indications for chiral mixing

To do:

- centrality dependence, free ρ’s (surface vs. volume)
- sensitivity to evolution: T_{chem}, T_c, lifetime
- chiral restoration: - “duality” viable (hadron liquid → sQGP)
  - evaluate chiral sum rules
- ω and ϕ , intermediate-mass region (***M=1-3 GeV***)

5.) Summary and Conclusions

- Strong medium effects in l^+l^- spectra
- New level of precision in NA60 enables model discrimination
- suggestive for 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? …

the future of dilepton spectroscopy has begun …