

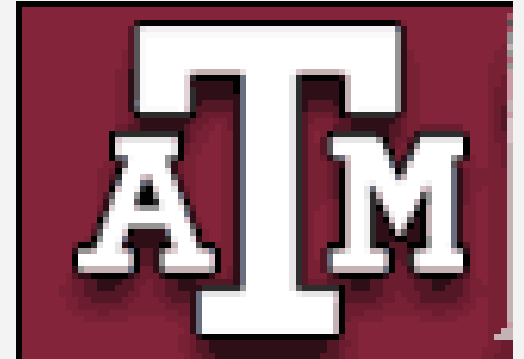
# Towards Chiral Restoration with Dileptons

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**College Station, USA**



**European Graduate School Workshop**

**“In-Medium Hadron Physics”**

**Giessen, 11.11.04**

# Outline

## 1. Introduction

## 2. Chiral Symmetry in QCD

## 3. E.M. Emission and in-Medium Vector Mesons

- E.M. Correlation Function + Chiral Symmetry
- Vector Mesons in Medium
- Low-Mass Dileptons in HICs

## 4. Further Theoretical Developments

- Chiral+Resonance Scheme
- In-Medium  $a_1(1260)$
- Lattice QCD

## 5. Perspectives for RHIC

## 6. Conclusions

# 1.) Introduction: QGP in Heavy-Ion Collisions

- To date: RHIC observables

↔ **bulk properties** of the produced matter:

- energy density  $\varepsilon \approx 20 \text{ GeV fm}^{-3}$  ↔ jet quenching (high  $p_t$ )
- thermalization + EoS ↔ hydrodynamics ( $v_0, v_2$ )
- partonic degrees of freedom ↔ coalescence ( $p/\pi, v_2$ -scal)

- Future: need to understand

**microscopic properties** (phase transition, “QGP” !?):

- Deconfinement ↔ quarkonia ( $J/\psi, Y, \dots$ )
- Chiral Symmetry Restoration ↔ dileptons
- ( - temperature ↔ photons )

## 2.) Chiral Symmetry in QCD: Vacuum

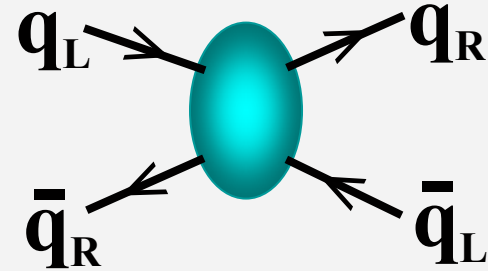
$$\mathcal{L}_{\text{QCD}} = \bar{q} (i\partial - gA - \hat{m}_q) q - \frac{1}{4} G_{a\mu\nu}^2$$

$SU(2)_L \times SU(2)_R$   
invariant ( $m_{u,d} \approx 0$ )

Spontaneous Breaking: strong  $q\bar{q}$  attraction

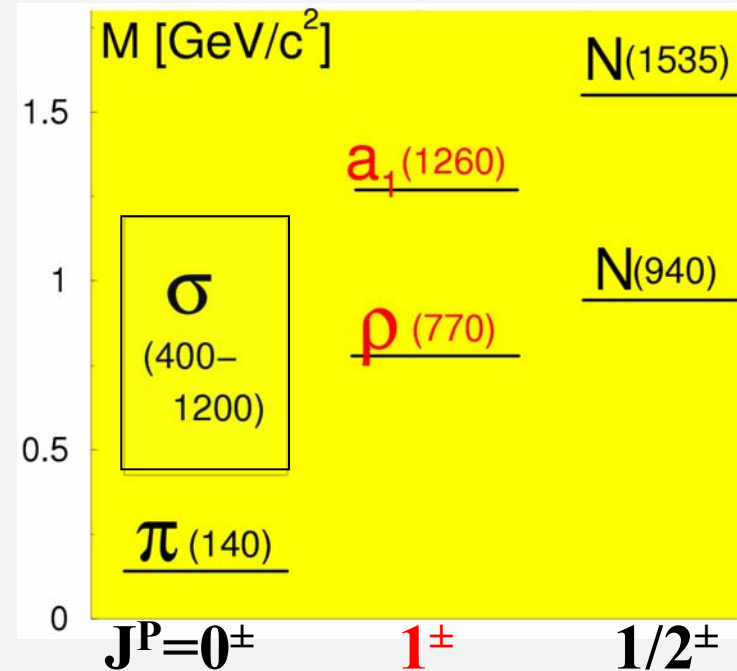
$\Rightarrow$  Bose Condensate  $\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \neq 0$

fills QCD vacuum! [cf. Superconductor:  $\langle ee \rangle \neq 0$   
Magnet  $\langle \mathcal{M} \rangle \neq 0$ , ...]



Profound Consequences:

- energy gap:  $\Delta_{\bar{q}q} \approx 2m_q^* \propto \langle \bar{q}q \rangle$   
 $\leftrightarrow$  mass generation!
- massless Goldstone bosons  $\pi^{0,\pm}$
- “chiral partners” split,  $\Delta M \approx 0.5 \text{ GeV}$ :

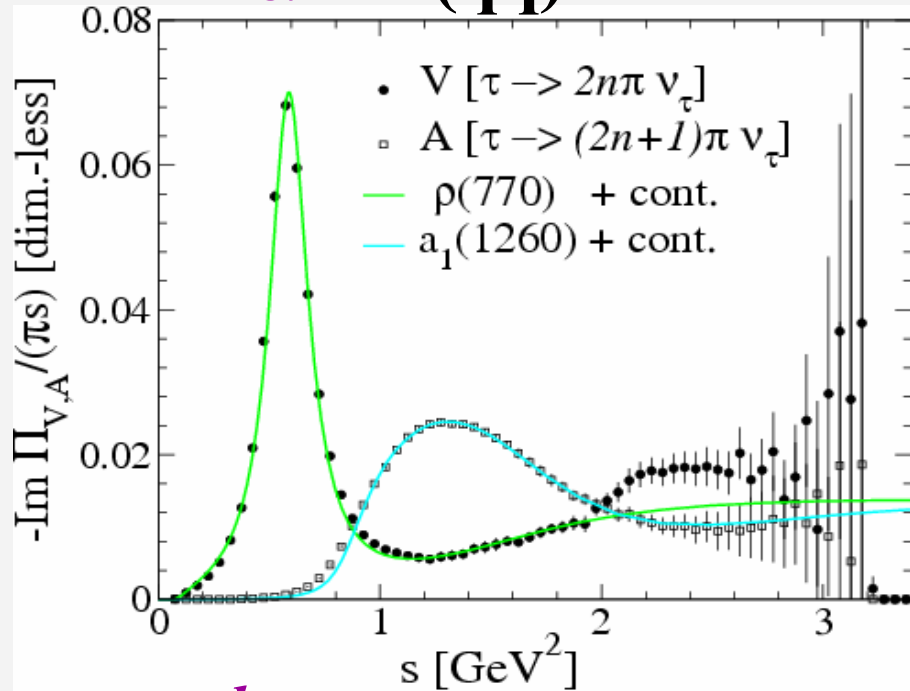


# 2.1 Light Hadrons: Vacuum

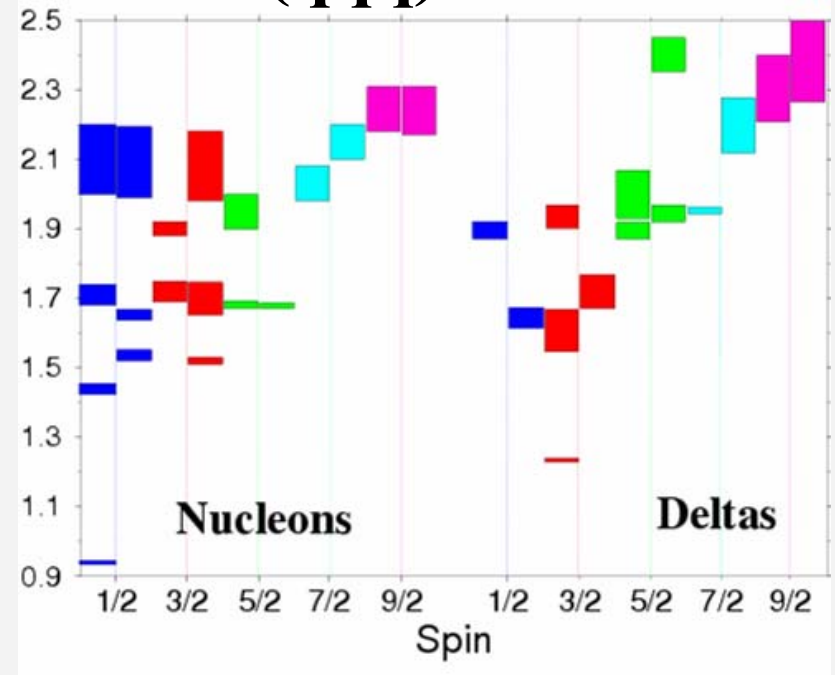
Correlation Function:  $\Pi_\alpha(q) = -i \int d^4x e^{iqx} \langle j_\alpha(x) j_\alpha(0) \rangle_T$

Timelike ( $q^2 > 0$ ):  $\text{Im} \Pi_\alpha(q_0, q) \rightarrow$  physical excitations

$\alpha=1^\pm (q\bar{q})$



$(qqq)$



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

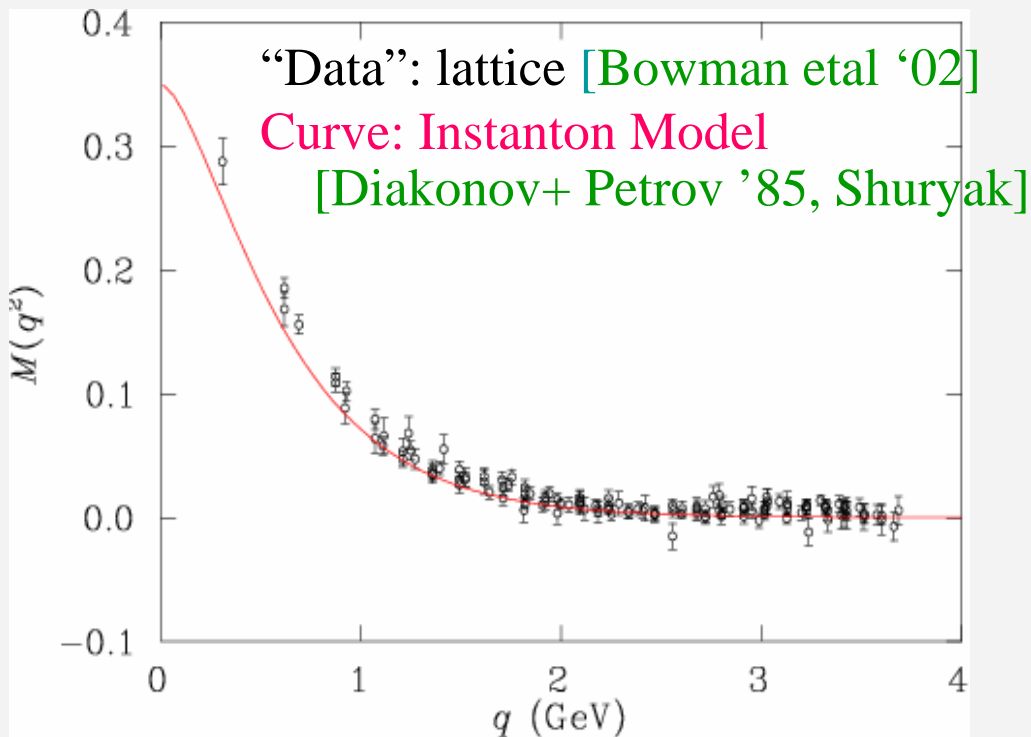
$$\text{Im} \Pi_\alpha(s) = \left( \frac{m_\alpha^2}{g_\alpha} \right)^2 \text{Im} D_\alpha(s)$$

**Chiral breaking:**

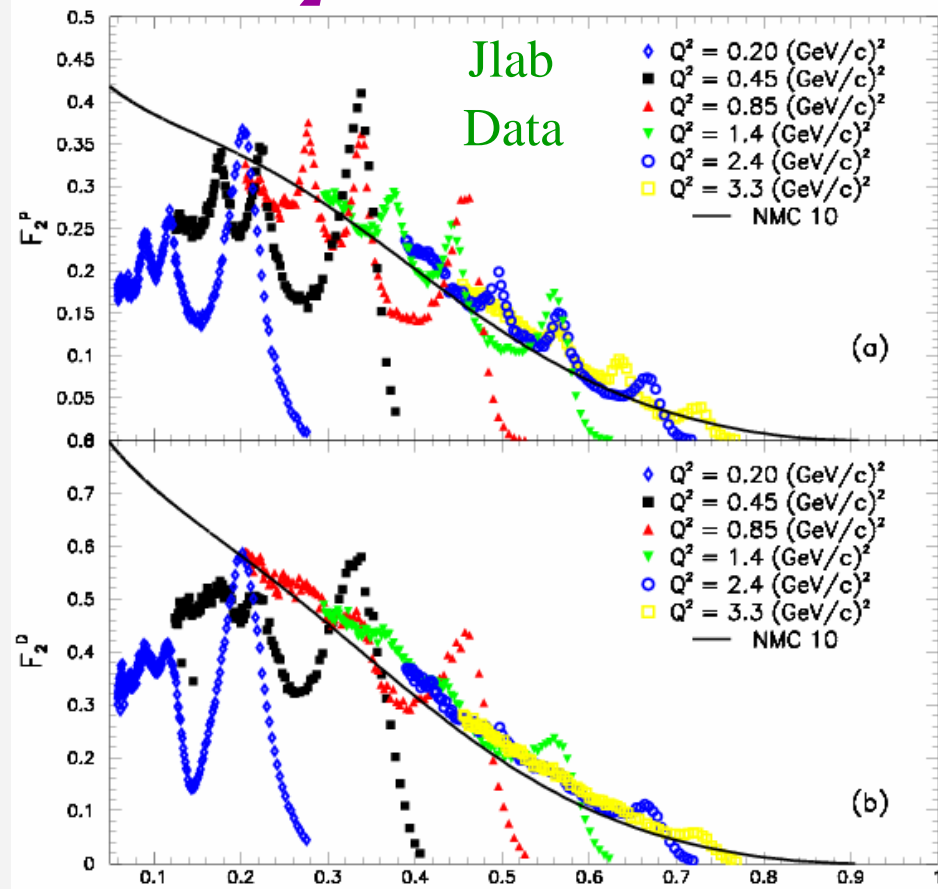
$Q^2 < (1.5-2 \text{ GeV})^2$  ,  $J^\pm < 5/2$  (!?)

# 2.1.2 Light Sector in Vacuum II: Spacelike

## Constituent Quark Mass



## $p$ and $d$ $F_2$ Structure Functions



$\xi = 2x / (1 + \sqrt{1 + 4M^2x^2/Q^2})$  (Nachtmann Variable)

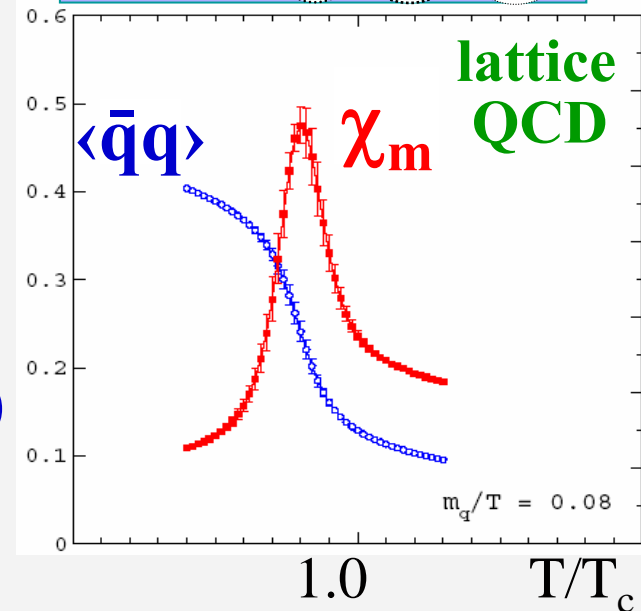
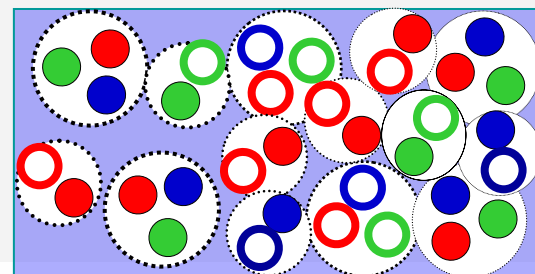
average  $\rightarrow$  “Quark-Hadron Duality”  
[Niculescu etal. '00]

# 2.2 “Melting” the Chiral Condensate

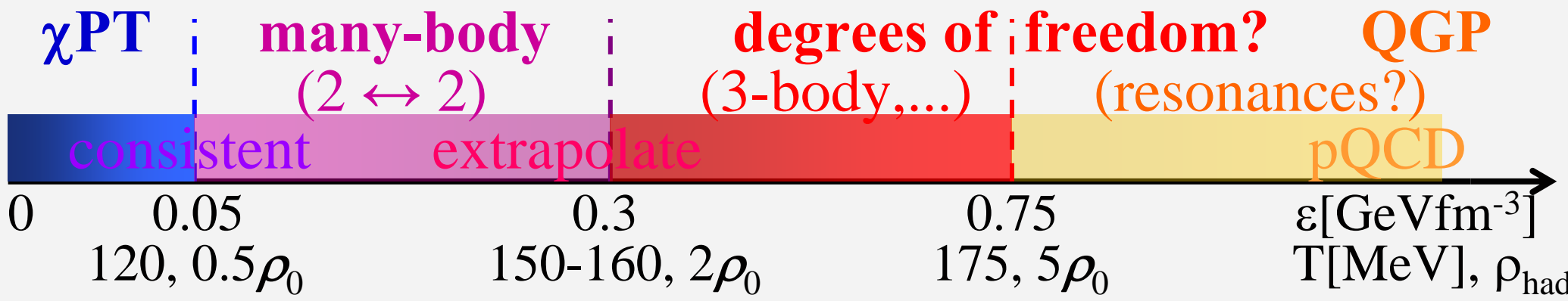
Excite vacuum (hot+dense matter)



- quarks “percolate” / liberated  
 ⇒ **Deconfinement**
- $\langle \bar{q}q \rangle$  condensate “melts”,  
 chiral partners degenerate } **Chiral Symm. Restoration**
- ( $\pi$ - $\sigma$ ,  $\rho$ - $a_1$ , ... medium effects → precursor!)



**How?**

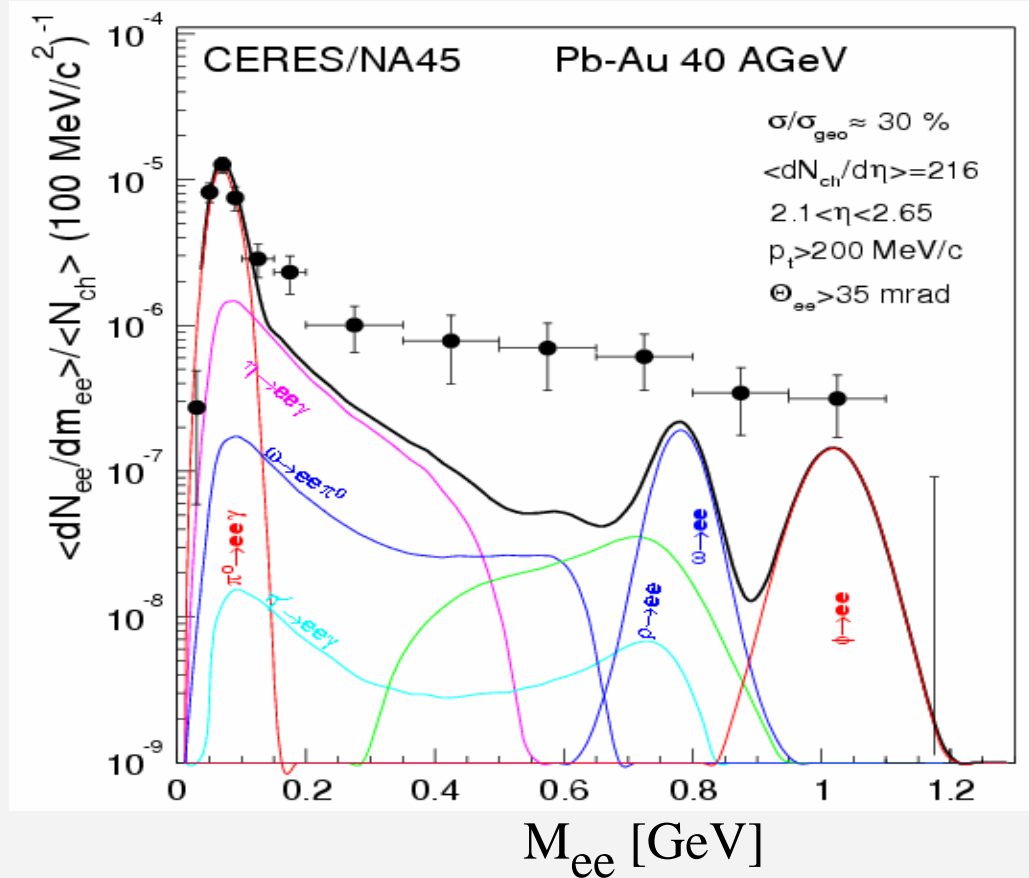
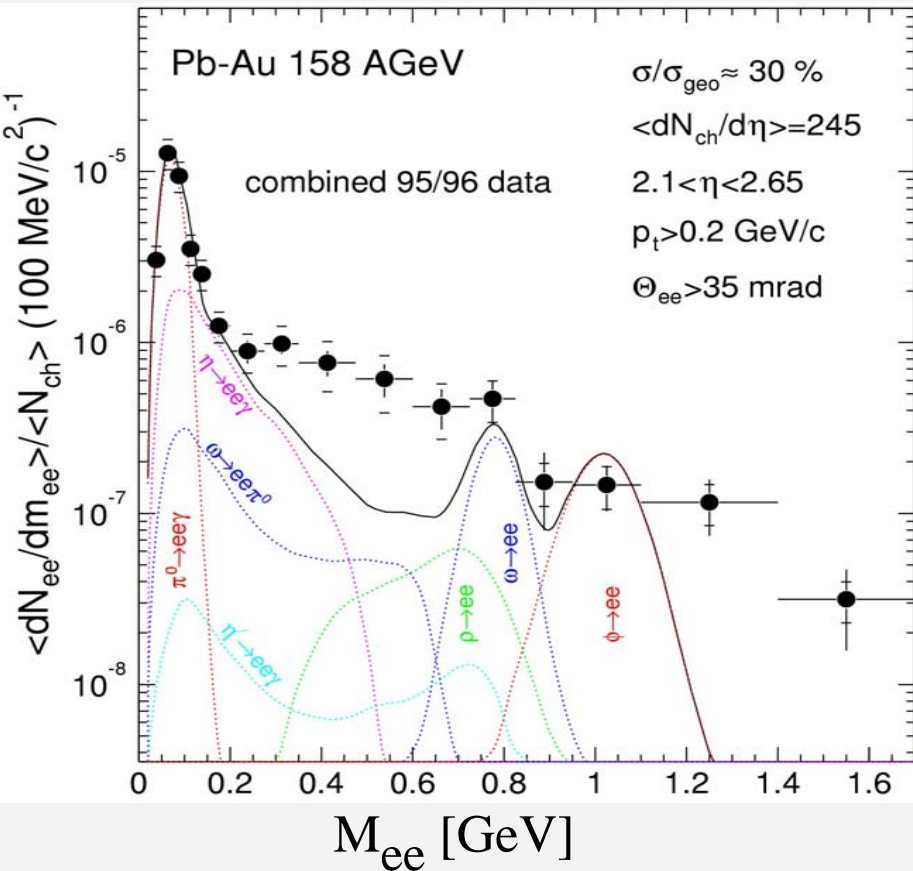


# 2.3 Low-Mass Dilepton Data at CERN-SPS

Full SPS Energy

[CERES/NA45]

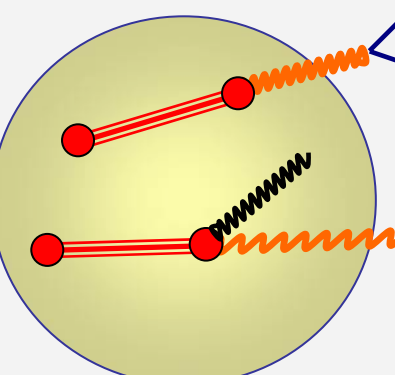
Lower SPS Energy



- excess above  $M \approx 0.2 \text{ GeV}$ :  $2.4 \pm 0.9$  [160]     $5.9 \pm 2.6$  [40]
- little excess in  $\rho, \omega, \phi$  region

# 3.) Electromagnetic Emission Rates

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



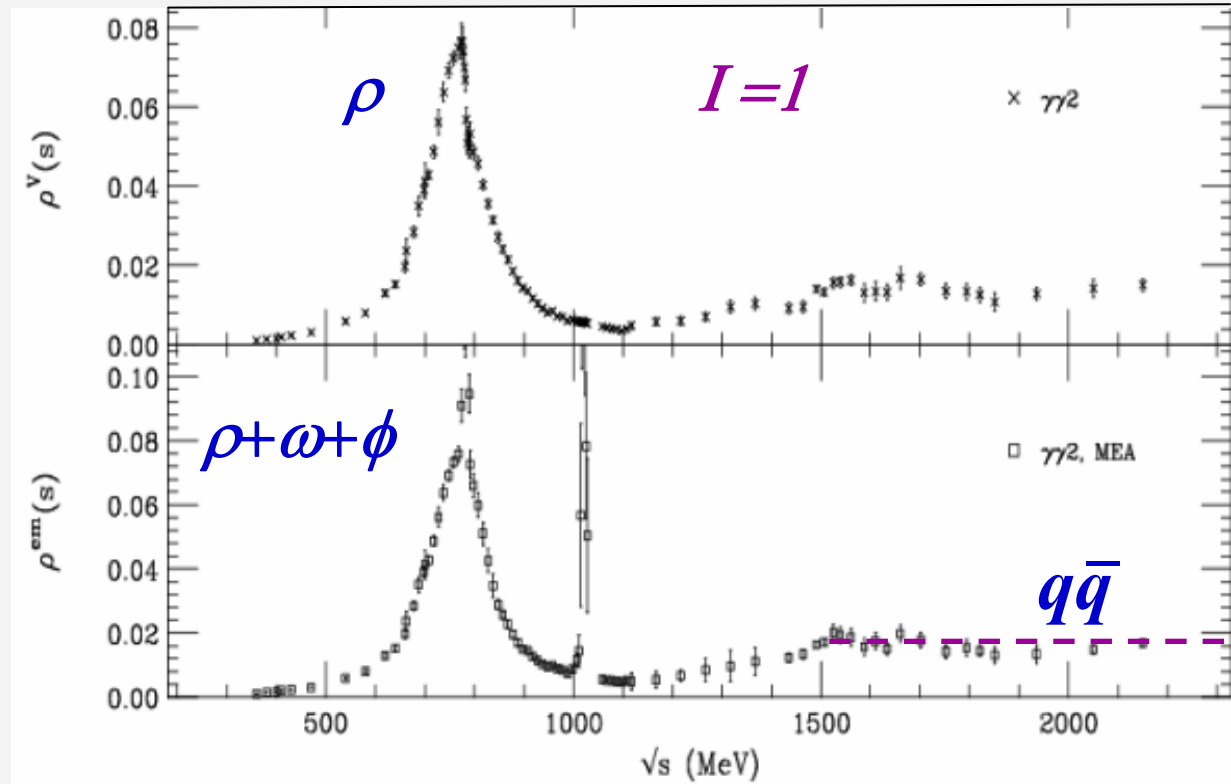
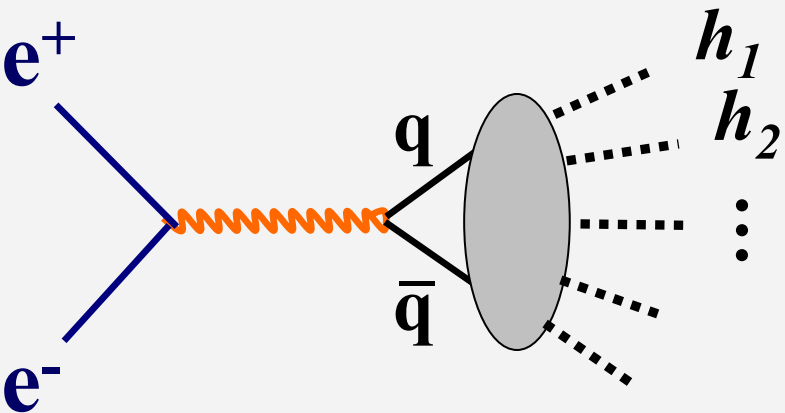
$e^+ \frac{dR_{ee}}{d^4q} \propto \alpha^2 f^B(T) \text{Im} \Pi_{\text{em}}(M, q) = \mathcal{O}(1)$   
 $e^- \frac{dR_{ee}}{d^4q} \propto \alpha^2 f^B(T) \text{Im} \Pi_{\text{em}}(M, q) = \mathcal{O}(1)$   
 $\gamma \frac{dR_{\gamma}}{d^3q} \propto \alpha f^B(T) \text{Im} \Pi_{\text{em}}(q_0=q) = \mathcal{O}(\alpha_s)$

also: e.m susceptibility (charge fluct):  $\chi = \Pi_{\text{em}}(q_0=0, q \rightarrow 0)$

## In URHICs:

- **source strength:** dependence on  $T, \mu_B, \mu_\pi$ , medium effects, ...
- **system evolution:**  $V(\tau), T(\tau), \mu_B(\tau)$ , transverse expansion, ...
- **nonthermal sources:** Drell-Yan, open-charm, hadron decays, ...
- **consistency!**

# 3.2 E.M. Correlator in Vacuum: $\sigma(e^+e^- \rightarrow hadrons)$

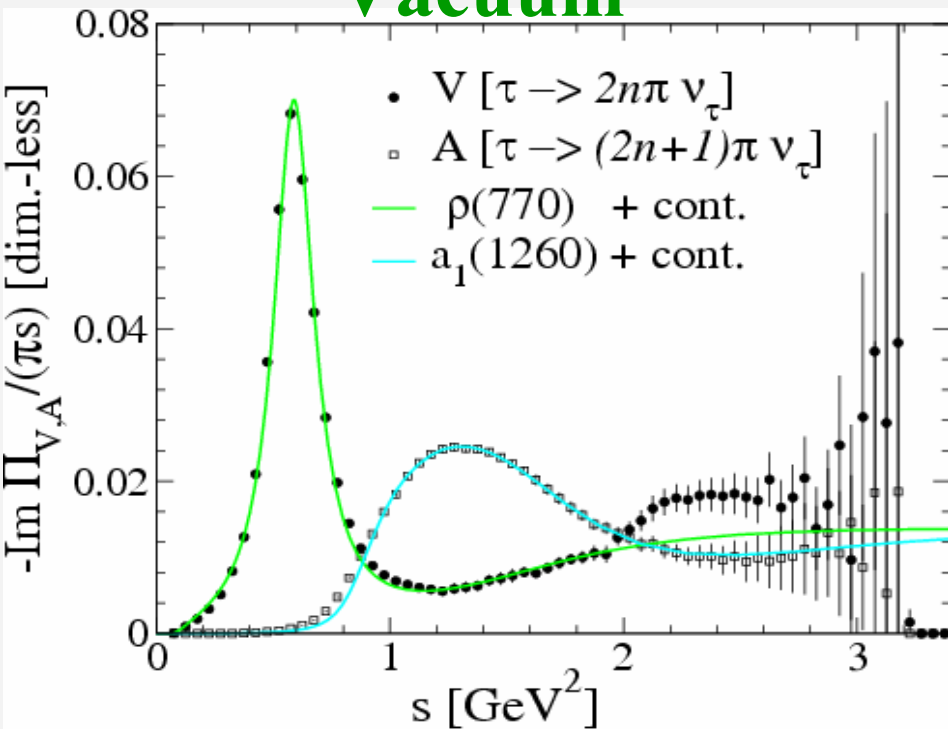


$$\text{Im } \Pi_{em}(s) = \begin{cases} \frac{-s}{12\pi} N_c \sum_{u,d,s} (e_q)^2 \left[ 1 + \frac{\alpha_S(s)}{\pi} + \dots \right] & s \geq (1.5 \text{ GeV})^2 : \\ & \text{pQCD continuum} \\ \sum_{\rho, \omega, \phi} \left[ \frac{m_V^2}{g_V} \right]^2 \text{Im } D_V(s) & s < (1.5 \text{ GeV})^2 : \\ & \text{V-meson spectral functs.} \end{cases}$$

# 3.3 Low-Mass Dileptons + Chiral Symmetry

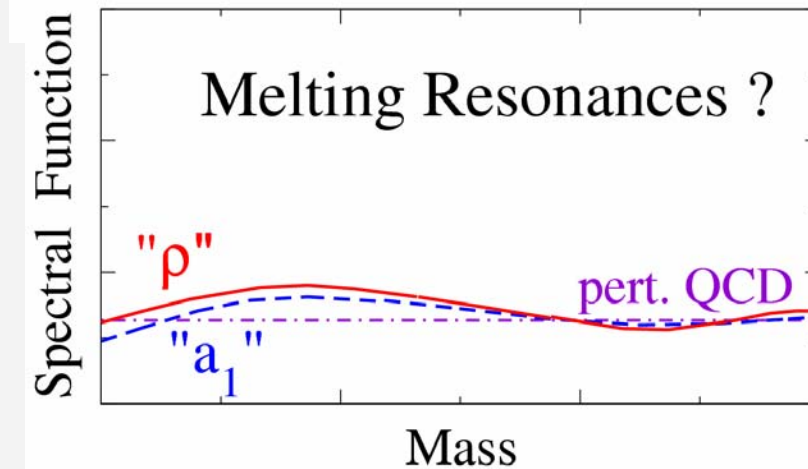
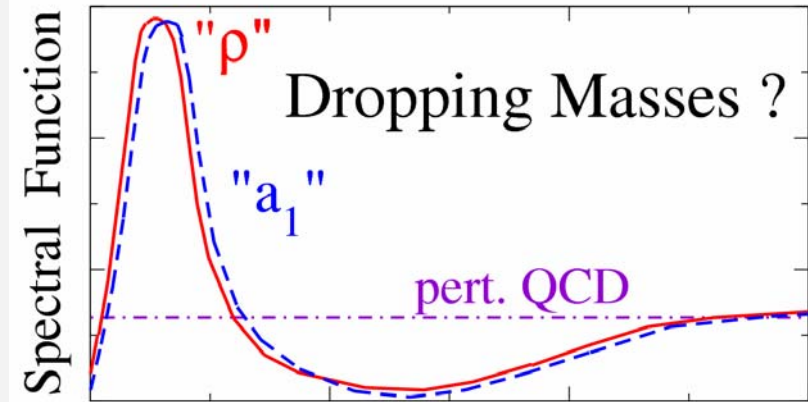
$\text{Im } \Pi_{em}(M)$  dominated by  $\rho$ -meson  $\rightarrow$  chiral partner:  $a_1(1260)$

**Vacuum**



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

**At  $T_c$ : Chiral Restoration**



**or:**  $\rho_{\text{long}}$  chiral partner of  $\pi \equiv$  "Vector Manifestation" [Harada+ Yamawaki '01]

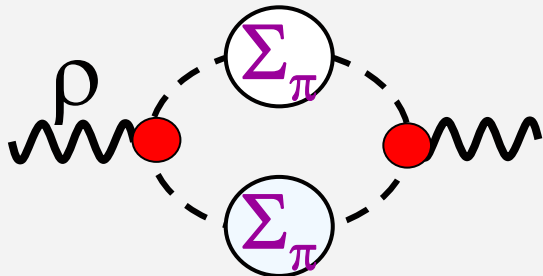
# 3.4. Vector Mesons in Medium

## (a) Hadronic Many-Body Theory

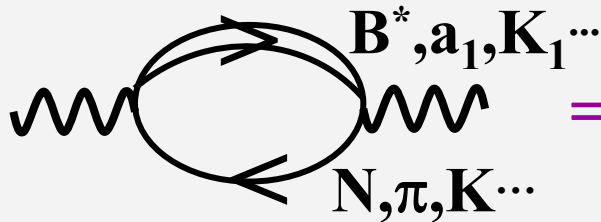
[Chanfray etal, Herrmann etal, RR etal, Koch etal, Weise etal, Post etal, Eletsky etal, Oset etal, ...]

Propagator:

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



$$= \Sigma_{\rho\pi\pi} = \int D_\pi^{med} v_{\rho\pi\pi}^2 D_\pi^{med}$$



$$= \Sigma_{\rho B, M} = \int D_M v_{\rho\pi M}^2 [f^\pi - f^M]$$

Constraints:

- B, M  $\rightarrow$   $\rho$ N,  $\rho\pi$
- $\gamma$ N,  $\gamma$ A,  $\pi$ N  $\rightarrow$   $\rho$ N
- QCDSRs, lattice

## (b) Effective Field Theory

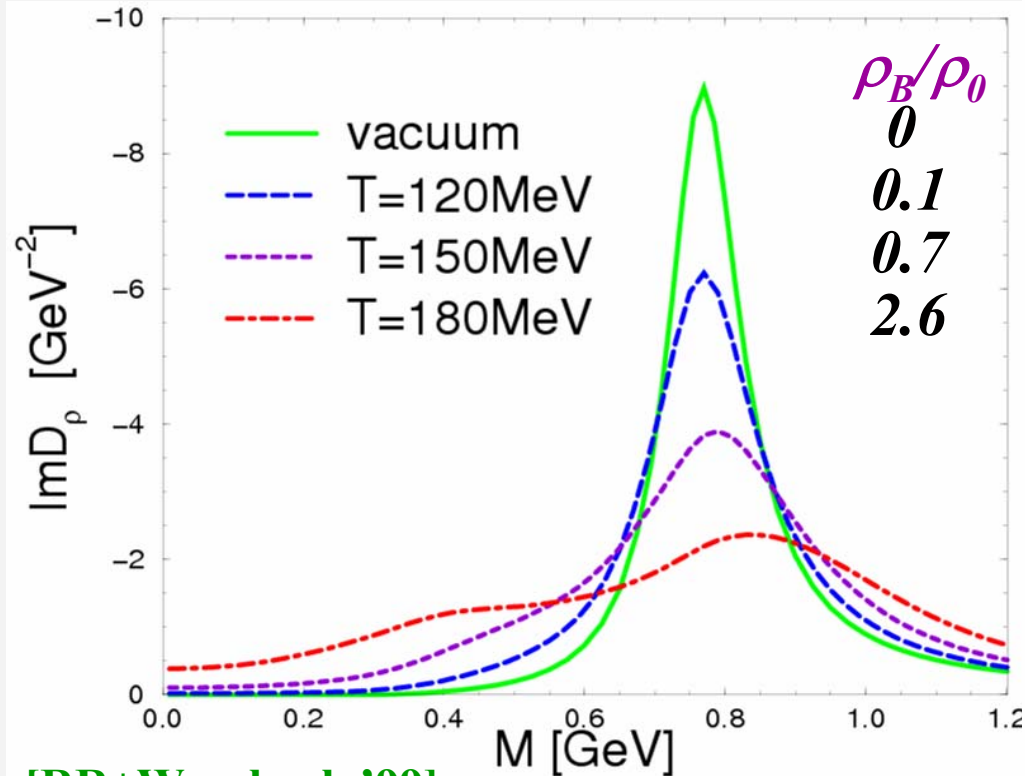
[Harada, Yamawaki, Sasaki etal]

HLS with  $\rho_L \equiv \pi$  ("VM"); vacuum: loop exp.  $\mathcal{O}(p/\Lambda_\chi, m_\rho/\Lambda_\chi, g)$

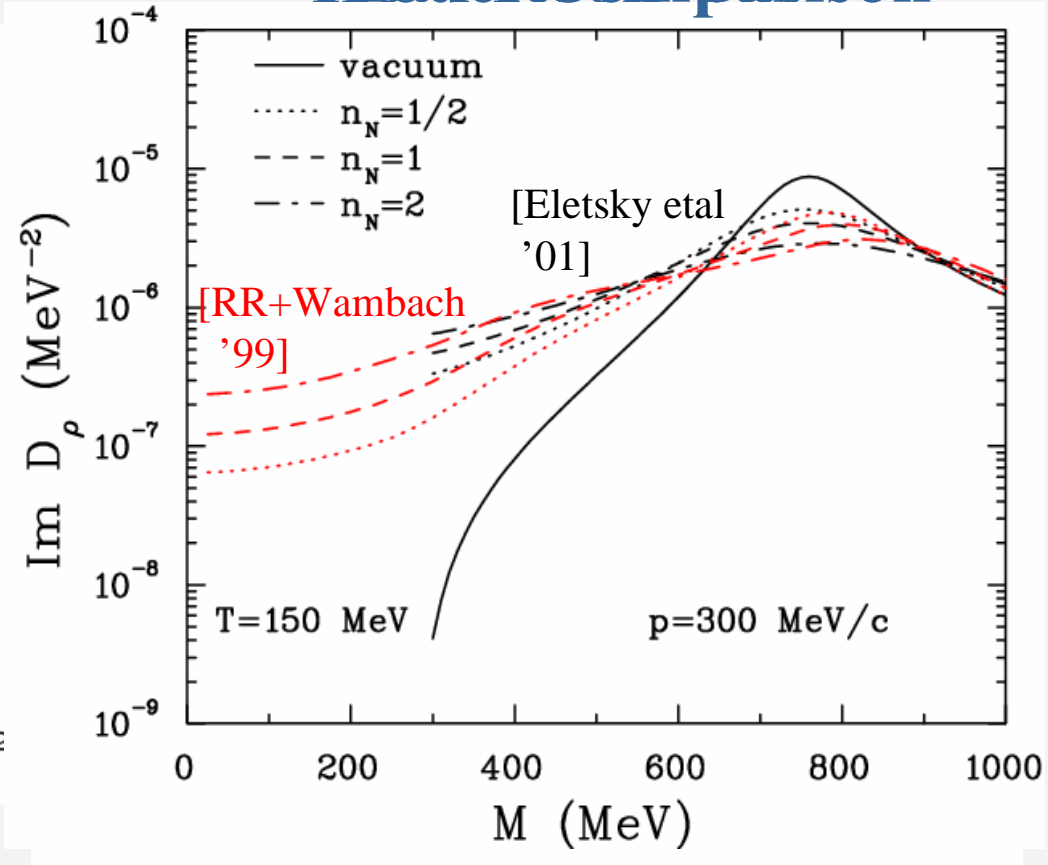
In-Med.:  $T$ -dep. of bare  $m_\rho^{(0)}, g_\rho$  via matching to OPE,  $\Lambda_{match} < \Lambda_\chi$   
 + RG-running to on-shell  $\Rightarrow$  dropping  $\rho$ -mass

# (i) $\rho$ -Mesons at SPS

## Hot+Dense Matter



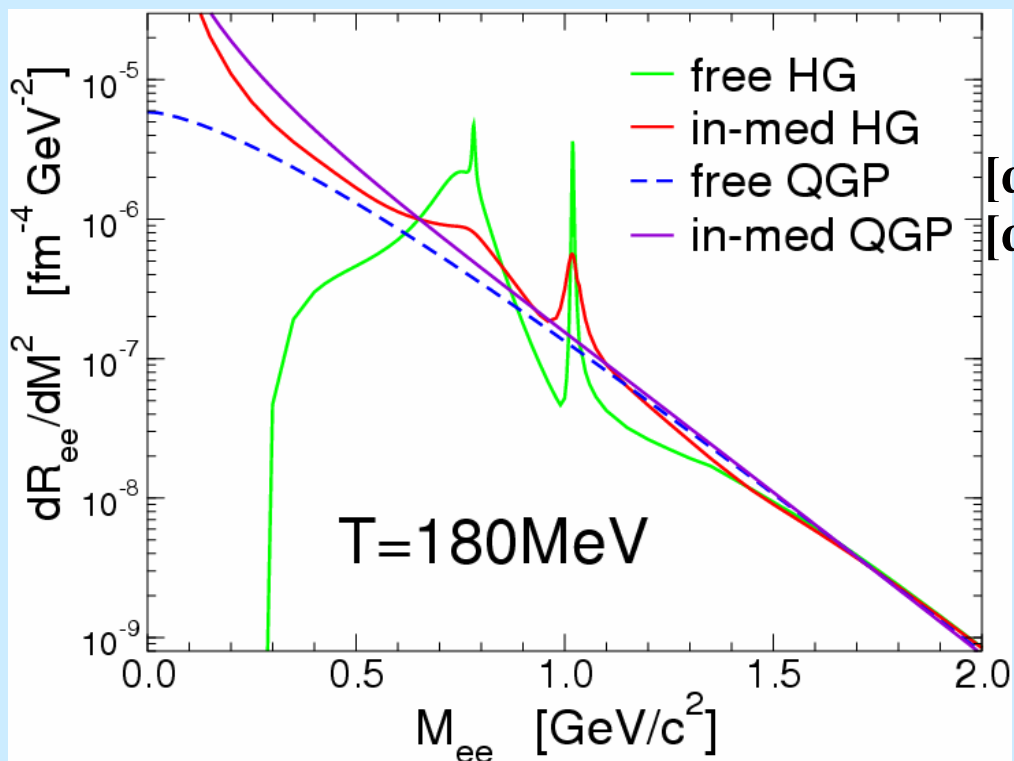
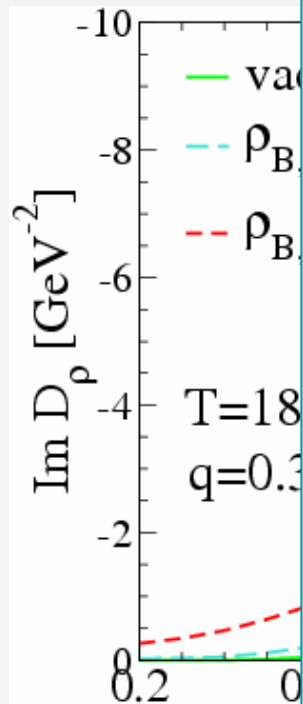
## Model Comparison



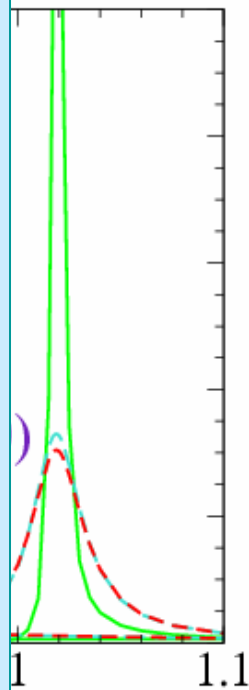
- $\rho$ -meson “melts” in hot and dense matter
- baryon density  $\rho_B$  more important than temperature

# (ii) Vector Mesons at RHIC

## Dilepton Emission Rates



$[\text{q}\bar{\text{q}} \rightarrow \text{ee}]$   
 $[\text{q}\bar{\text{q}} + \mathcal{O}(\alpha_s)]$



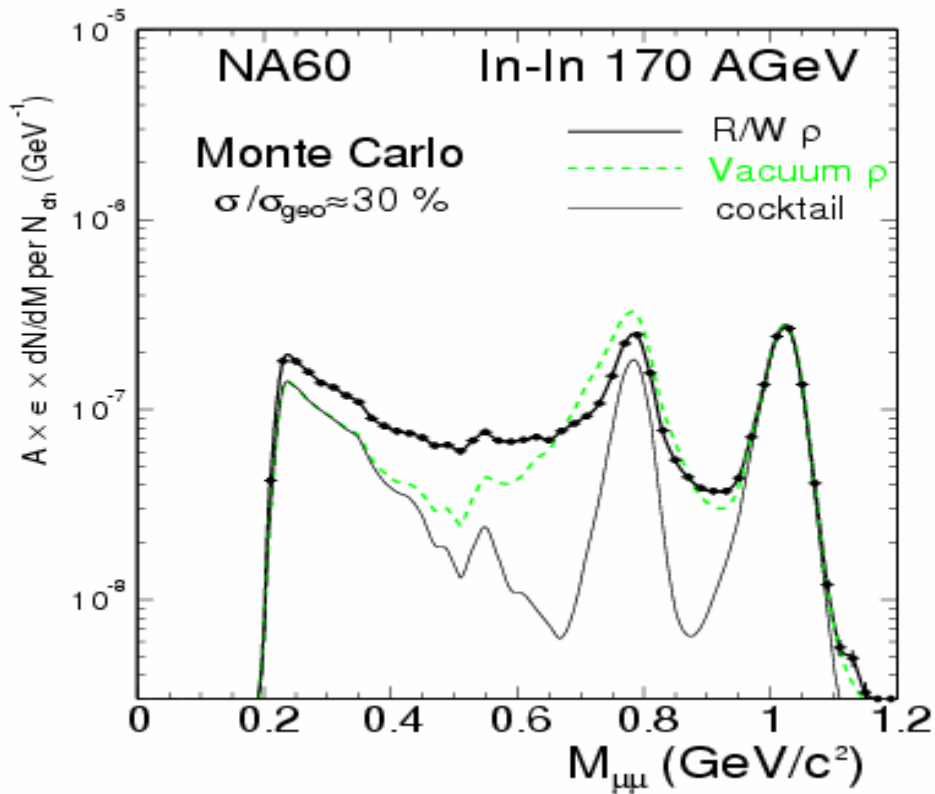
baryo  
 sensit

**in-med HG  $\approx$  in-med QGP !**

**Quark-Hadron Duality ?!**

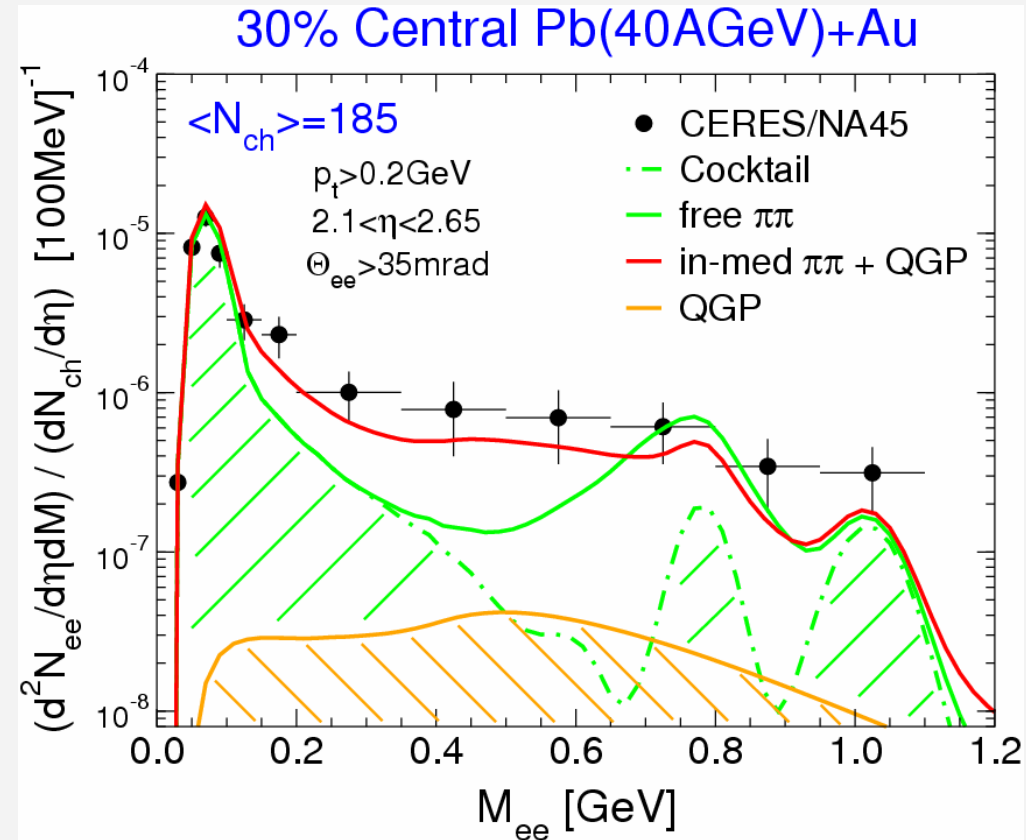
# 3.5 Low-Mass Dileptons I: SPS

## Top SPS Energy



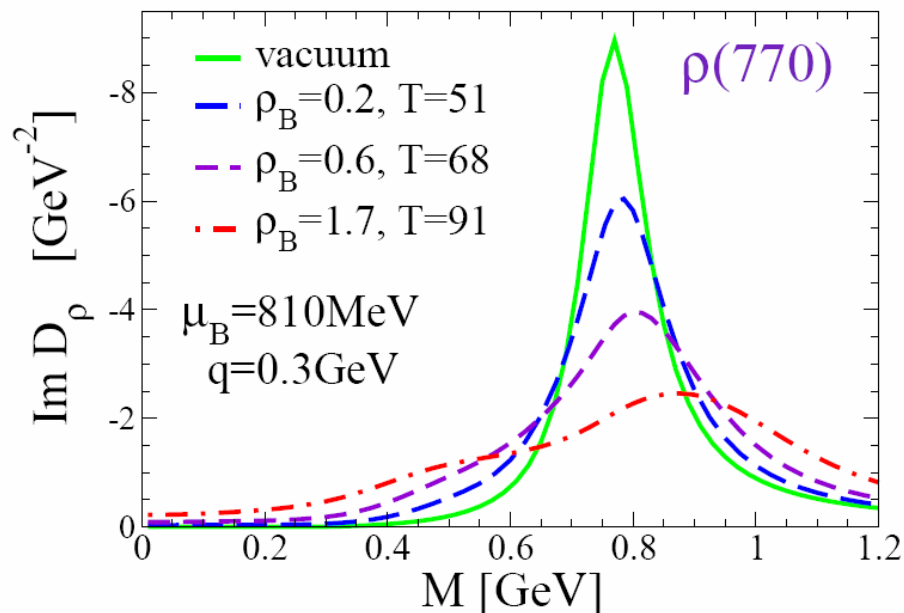
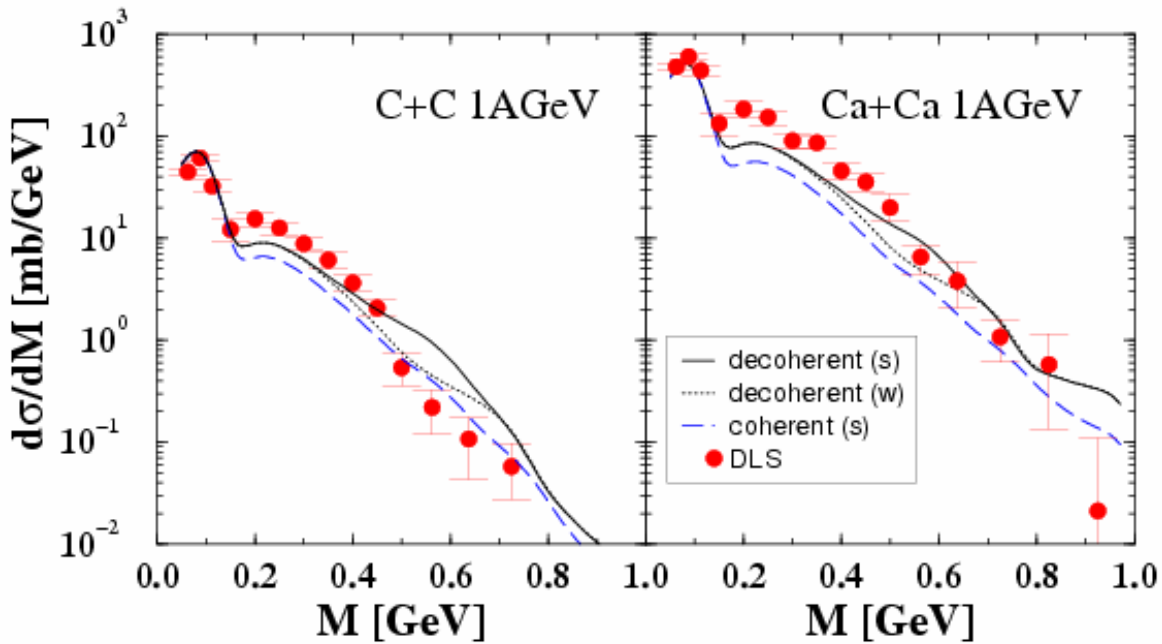
- baryon effects important!
- precision test by **NA60**!?

## Lower SPS Energy



- enhancement increases!

# (ii) Low-Mass Dileptons II: SIS / BEVALAC



## Transport Calculation

[Shekhter, Fuchs etal '03]

- Extended VDM  $pp \rightarrow pp \omega$
- “standard” calculation factor 2-3 below data
- improvement due to decoherence in-medium
- “optimal” values for in-med. coll. broadening

$$\Gamma_\rho^{coll} \approx \Gamma_\omega^{coll} \approx 200\text{MeV}$$

consistent with [Bratkovskaya etal '98]

# **4.) Further Theoretical Developments**

**4.1 Chiral + Resonance Scheme with Baryons**

**4.2  $a_1(1260)$  Spectral Function**

**4.3 Comparison to Lattice QCD**

# 4.1 Towards a Chiral + Resonance Scheme

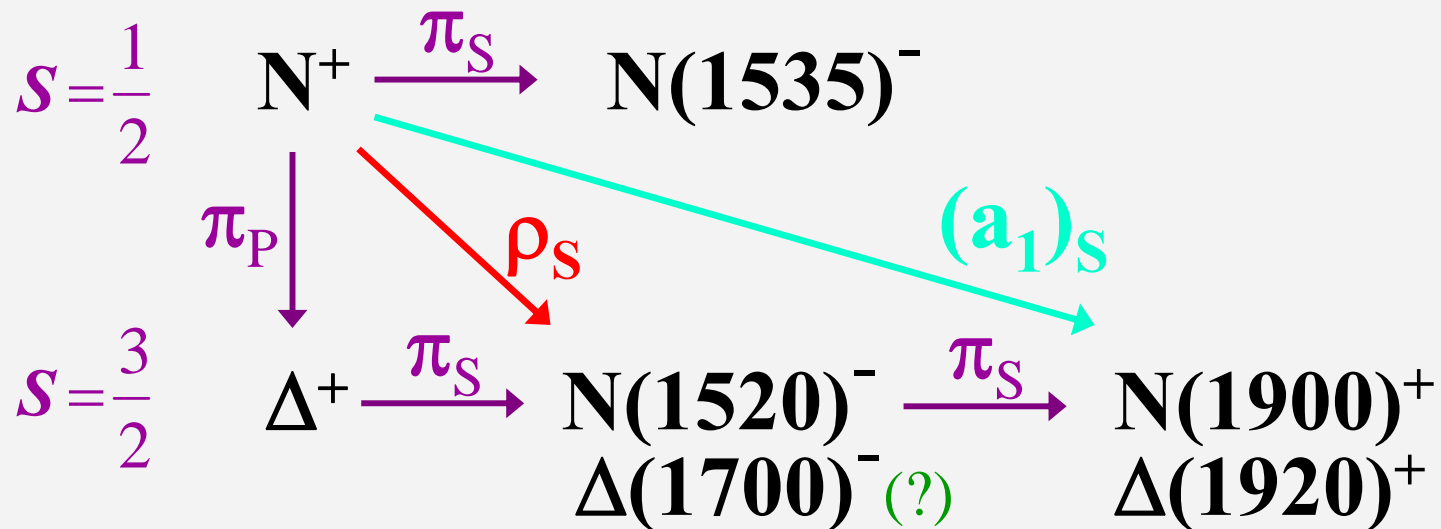
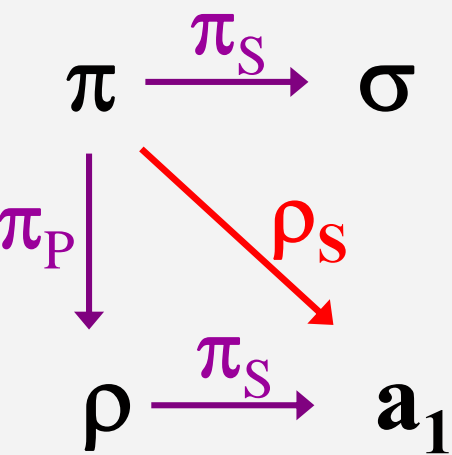
Options for resonance implementation:

(i) generate dynamically from pion cloud [Lutz et al '03, ...]

(ii) genuine resonances on quark level

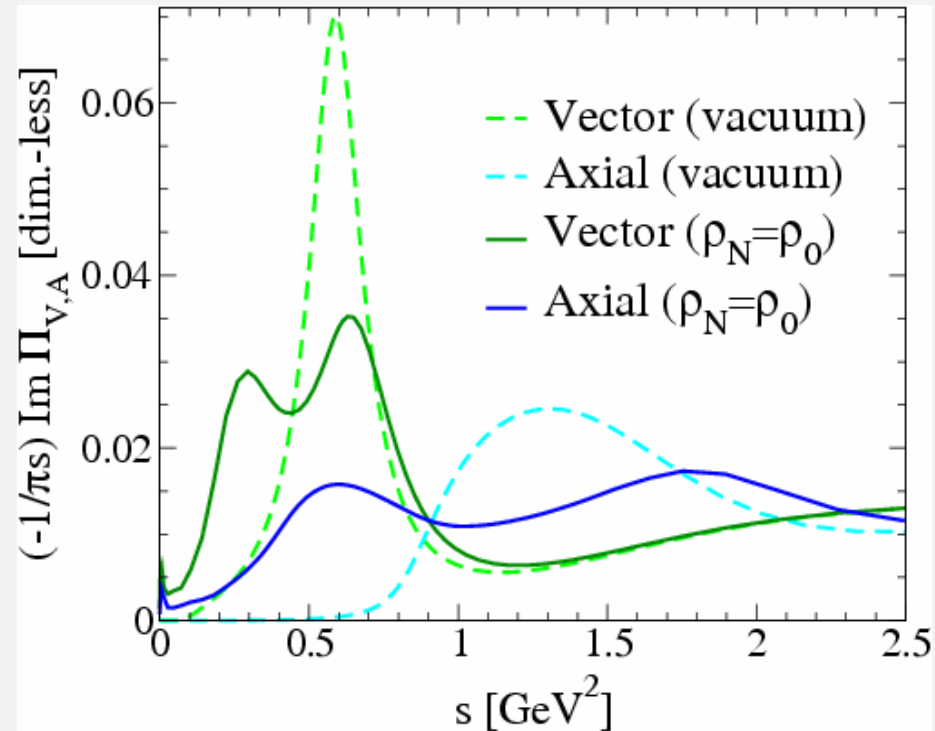
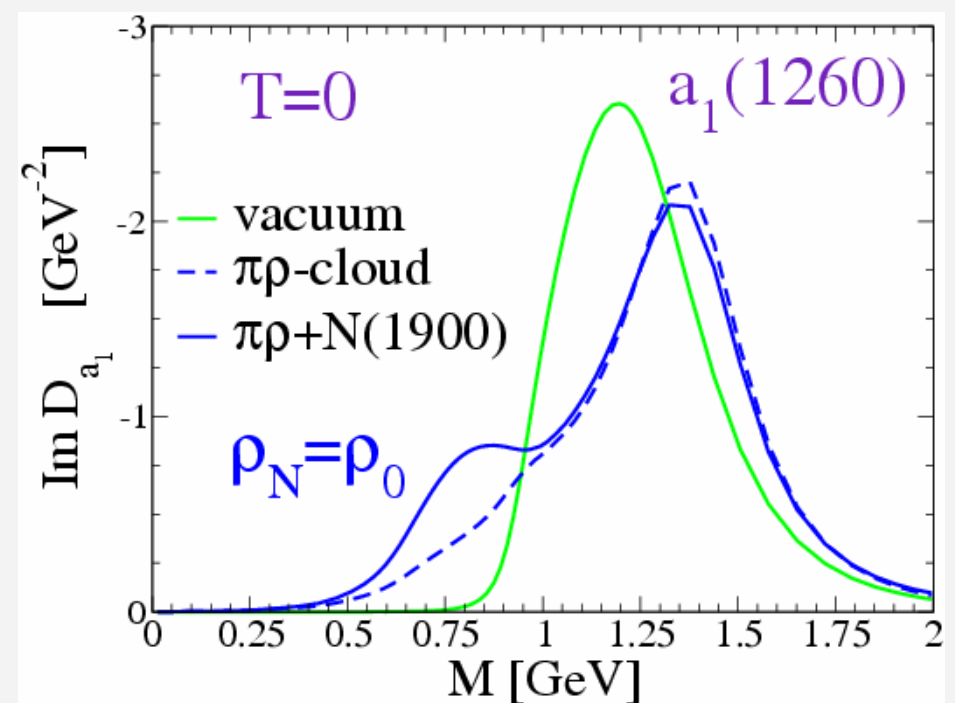
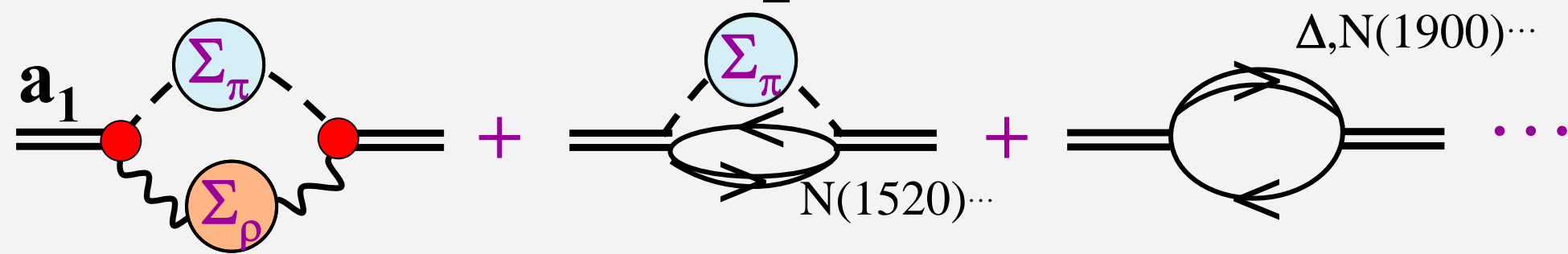
→ representations of chiral group [DeTar+Kunihiro '89, Jido et al '00, ...]

e.g.



Importance of baryon spectroscopy  
to identify relevant decay modes!

# 4.2 Current Status of $a_1(1260)$



Exp: - **HADES** ( $\pi A$ ):  $a_1 \rightarrow (\pi^+ \pi^-) \pi$   
 - **URHICs** ( $AA$ ):  $a_1 \rightarrow \pi \gamma$

$$f_\pi^2 = - \int \frac{ds}{\pi s} \left( \frac{m_\rho^4}{g_\rho^2} \text{Im} D_\rho - \frac{m_{a_1}^4}{g_{a_1}^2} \text{Im} D_{a_1} \right)$$

# 4.3 Lattice Studies of Medium Effects

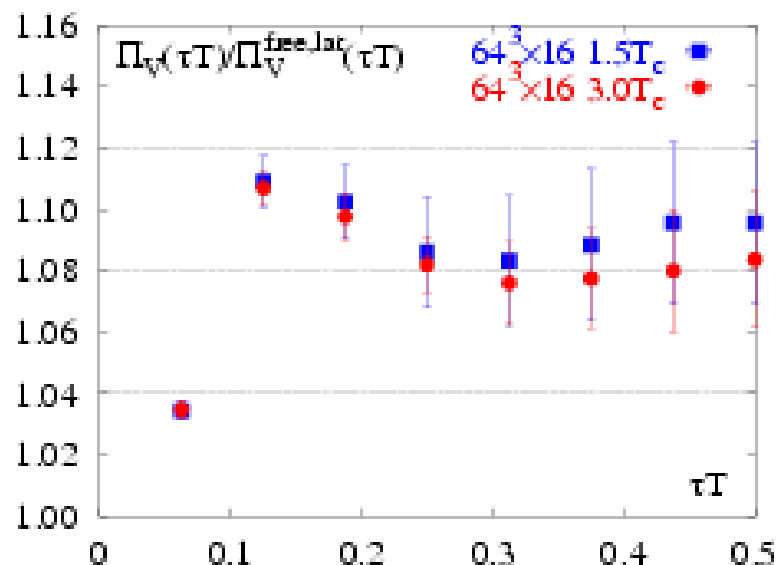
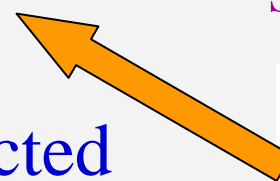
[Laermann, Karsch '04]

$$\Pi_\alpha(\tau, T) = \int_0^\infty dq_0 \operatorname{Im} \Pi_\alpha(q_0, T) \frac{\cosh(q_0(\tau - 1/2T))}{\sinh(q_0/2T)}$$

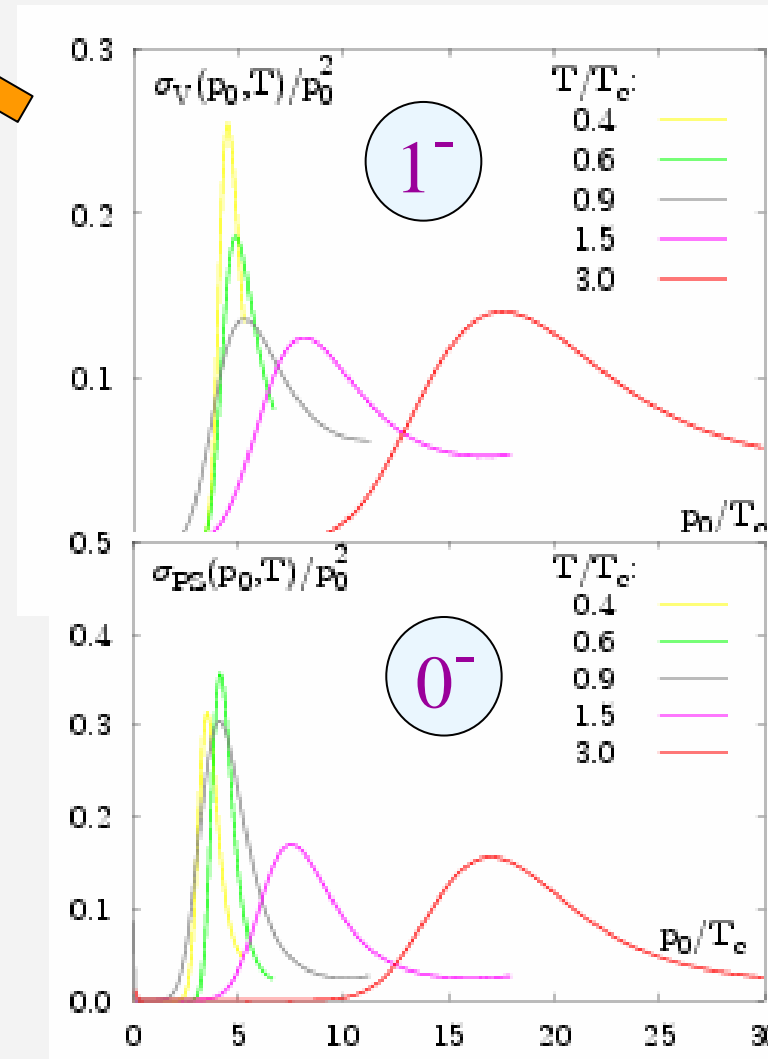
calculated  
on lattice



extracted



MEM

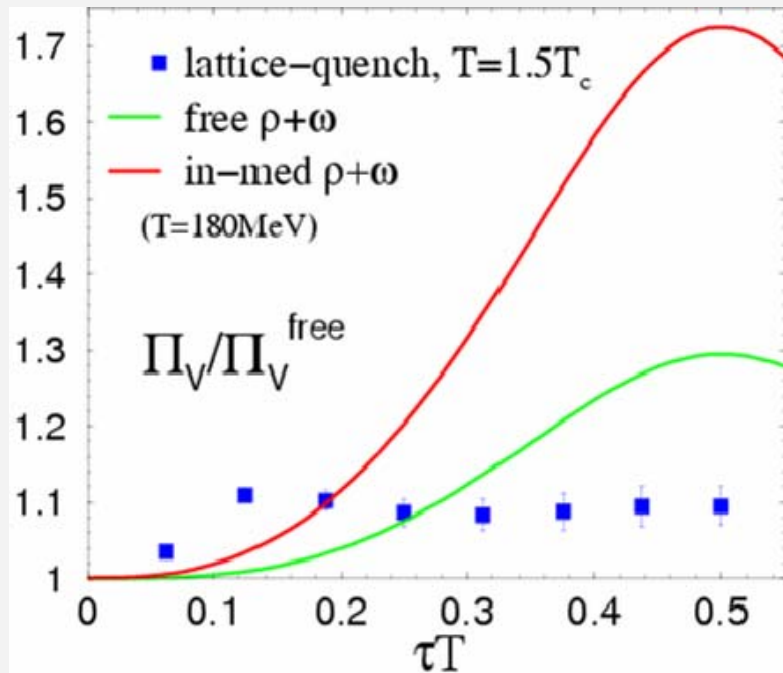


$\pi$  more stable than  $\rho$  below  $T_c$ ?!  
(but: quenched)

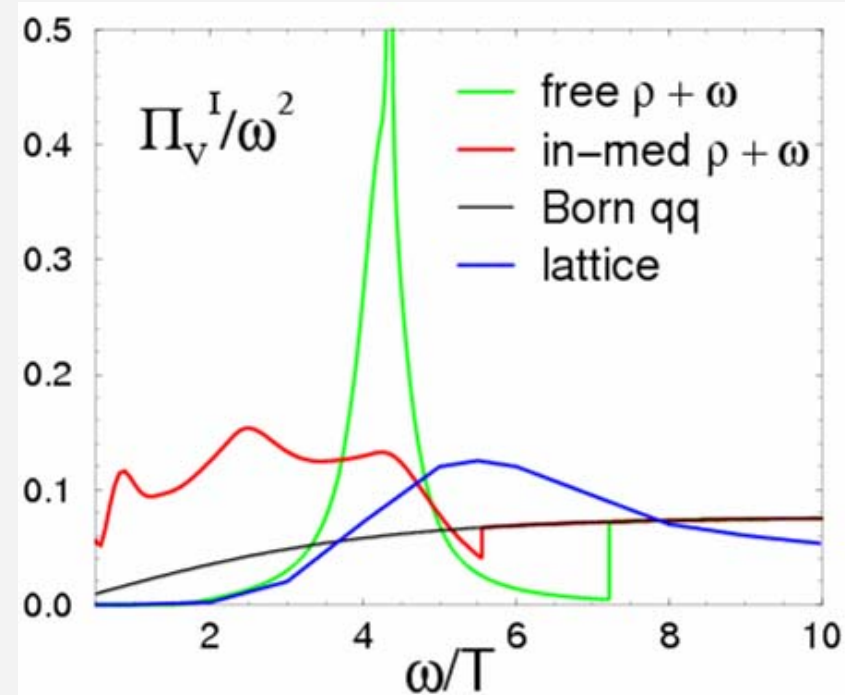
# 4.3.2 Comparison of Hadronic Models to LGT

$$\Pi_{\alpha}(\tau, T) = \int_0^{\infty} dq_0 \operatorname{Im} \Pi_{\alpha}(q_0, T) \frac{\cosh(q_0(\tau - 1/2T))}{\sinh(q_0/2T)}$$

calculate



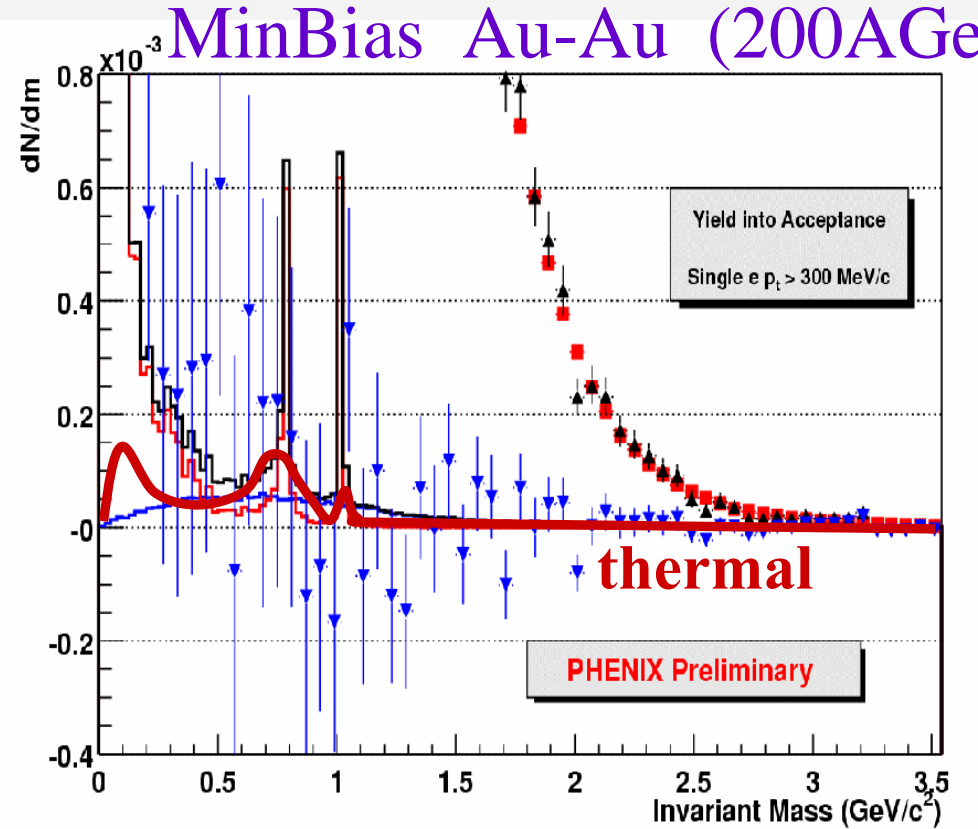
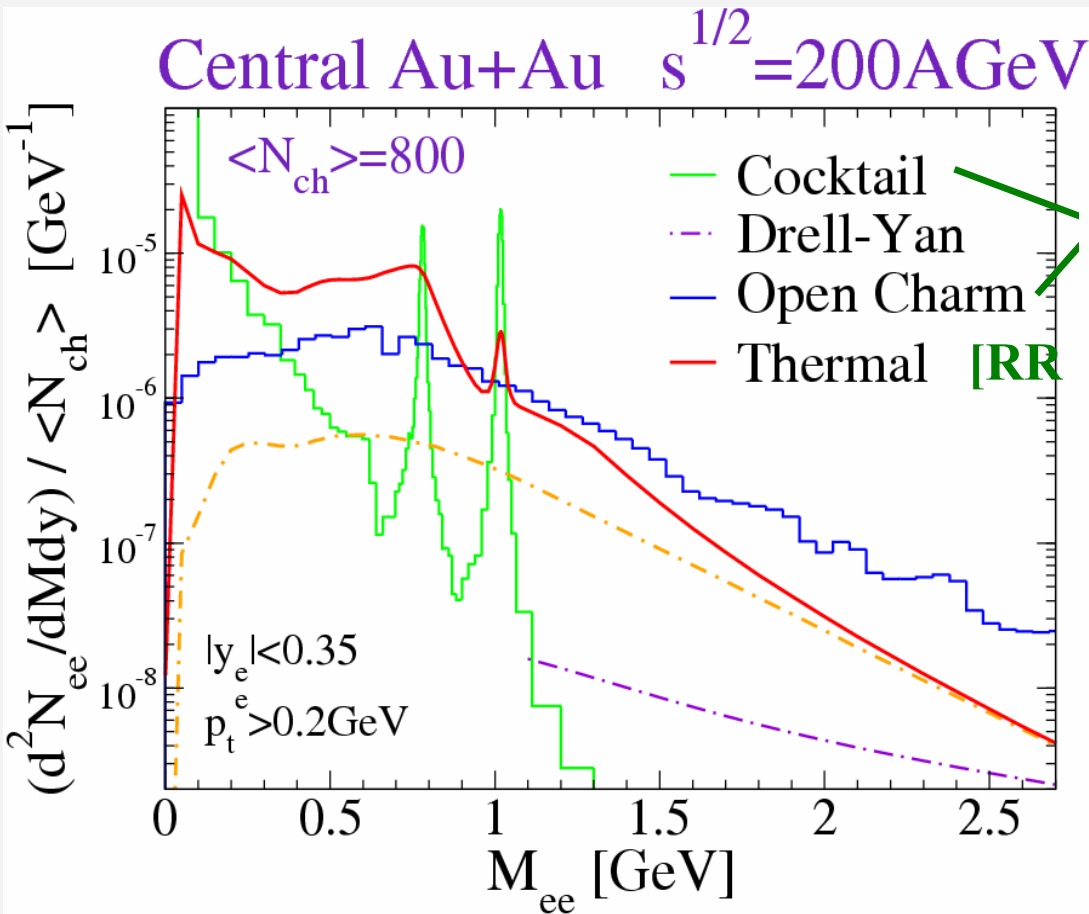
integrate



More direct!

Proof of principle, not yet meaningful (need unquenched)

# 5.) Perspectives for RHIC I: Dileptons



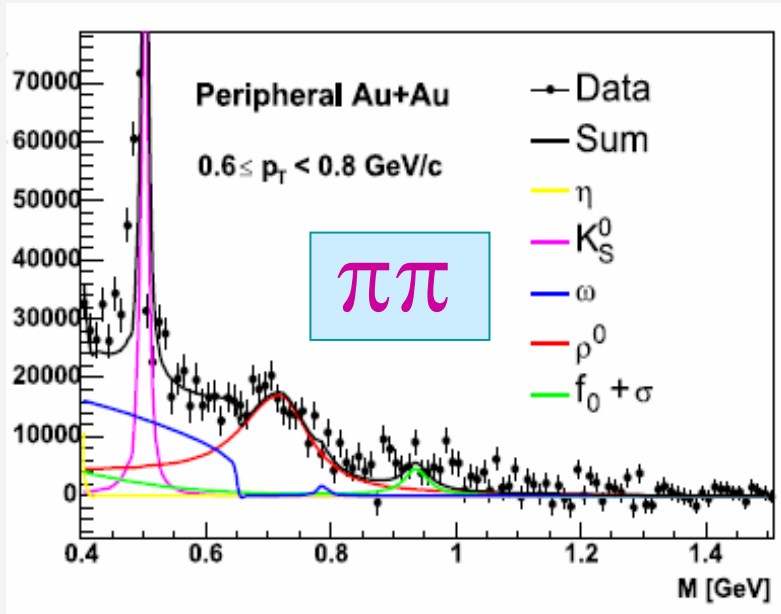
- low mass: thermal dominant
- int. mass:  $\bar{c}c \rightarrow e^+X, e^-X$ , rescatt.?

run-4 results  
eagerly awaited ...

# (ii) Resonance Spectroscopy: $\pi^+\pi^-$ Spectra

## Sudden Breakup

$$\frac{dN_{\pi\pi}}{d^3x dM} = \frac{d_R}{\pi} \int \frac{d^3q}{(2\pi)^3} f^R(q_0, T) \frac{\partial \delta_{\pi\pi}^{vac}}{\partial M}$$

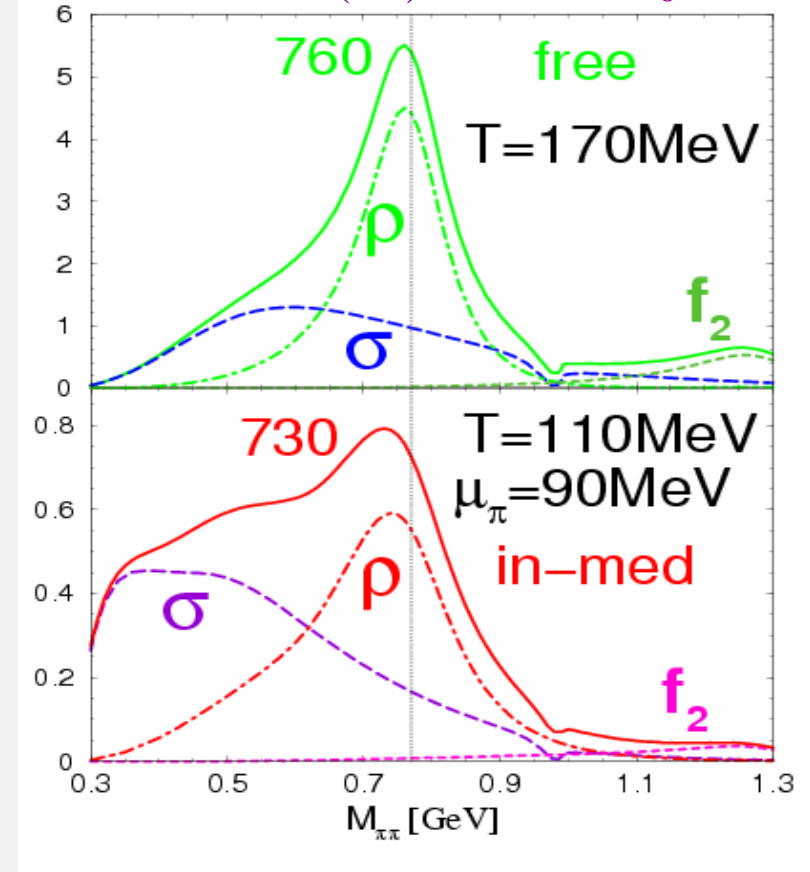


[Broniowski+Florkowski '03]

- $\rho$ -mass shift  $\sim -50\text{MeV}$  [Shuryak+Brown '03]
- small “ $\sigma$ ” contribution
- underestimates  $\rho/\pi$

## Emission Rate

$$\frac{dN_{\pi\pi}}{d^4x dM} = \frac{d_R}{\pi} \text{Im}\Sigma_{\pi\pi} \int \frac{d^3q}{(2\pi)^3} f^R(q_0) \frac{2M}{q_0} \text{Im}D_R(M, q)$$



Broadening+“ $\sigma$ ”+BE not enough?!

## 6.) Conclusions

- **Thermal Dileptons in QCD:**  $\Pi_{em}(q_0, q, \mu_B, T)$ 
  - low mass:  $\rho, \omega, \phi$  , **chiral restoration**  $\leftrightarrow$   **$\rho$ - $a_1$  degeneracy**
  - importance of baryon effects (even more in experiment?!)  
( - **thermal photons** )
- extrapolations into phase transition region  
 $\Rightarrow$  **in-med HG and QGP shine equally bright**  
lattice calculations? deeper reason?
- phenomenology for **URHIC**'s promising;  
precision data+theory needed for definite conclusions
- much excitement ahead: **CERES, NA60, HADES, PHENIX,**  
**ALICE,...** **and theory!**

Trento Program on  
Electromagnetic Probes in  
Heavy-Ion Collisions

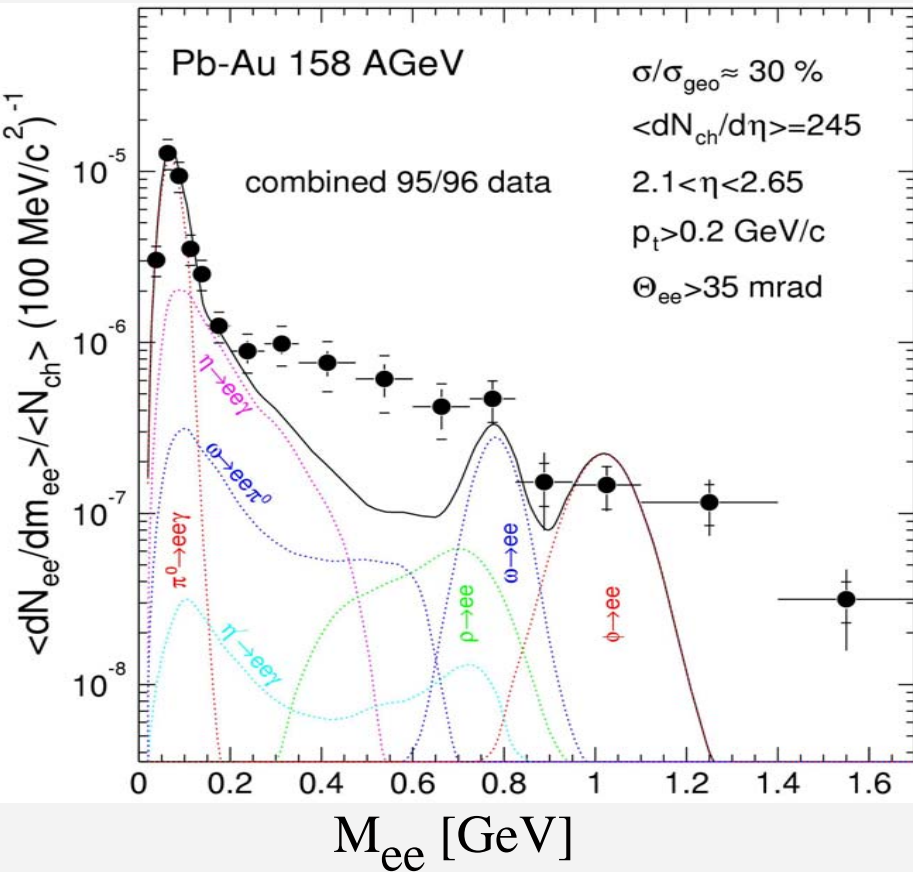
June 2-12, 2005

P. Braun-Munzinger, C. Gale, R. Rapp

# Additional Slides

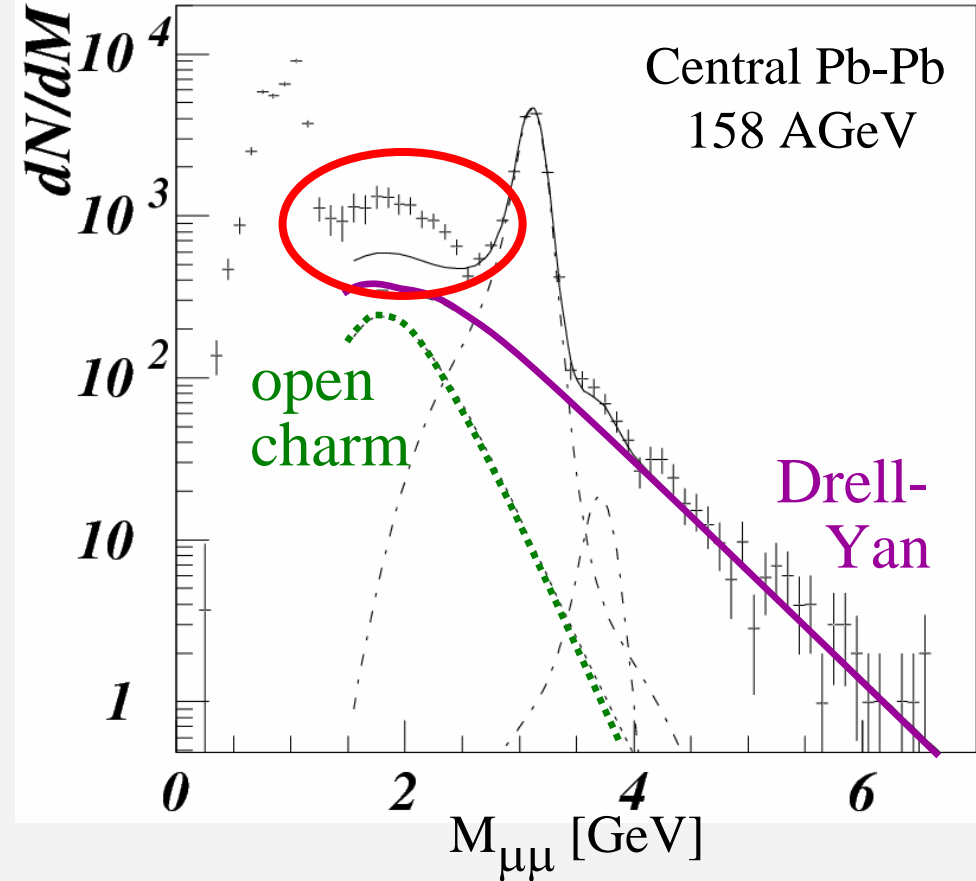
# 2.3 Dilepton Data at CERN-SPS

## Low Mass: CERES/NA45



- strong excess around  $M \approx 0.5 \text{ GeV}$
- little excess in  $\rho, \omega, \phi$  region

## Intermediate Mass: NA50



- factor  $\sim 2$  excess
- open charm? thermal? ...

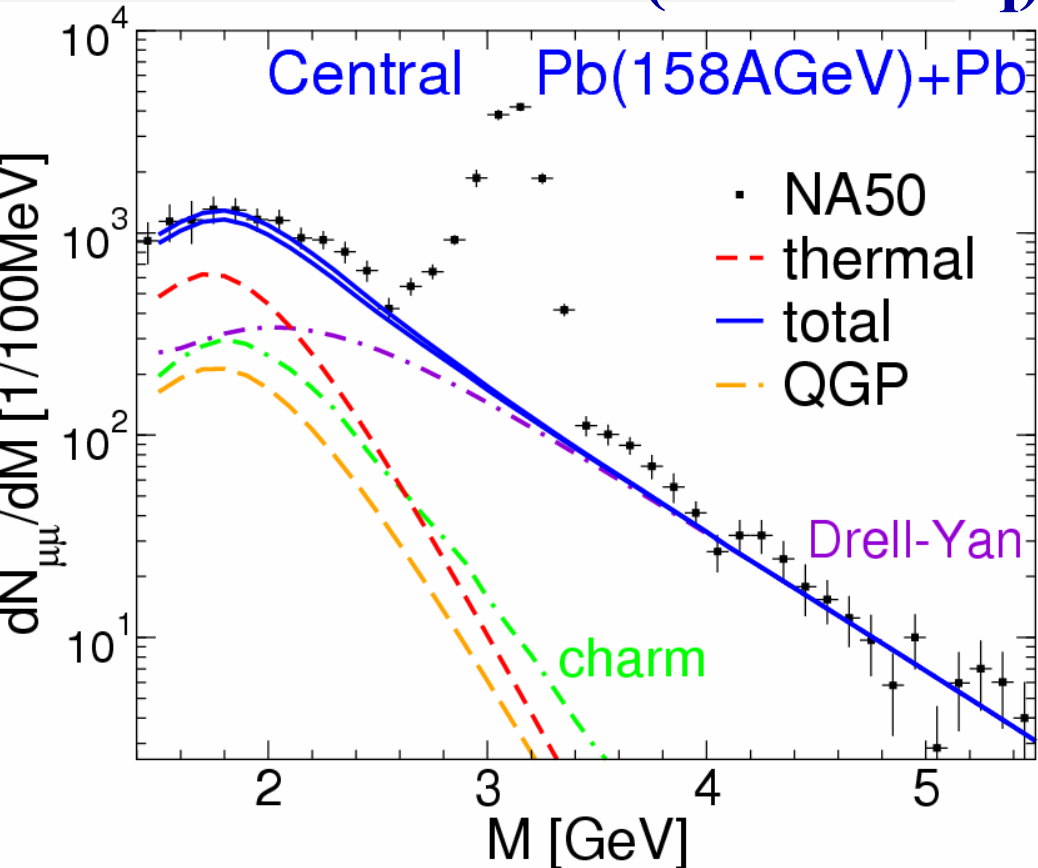
# 5.) Intermediate-Mass Dileptons: NA50 (SPS)

e.m. corr. continuum-like:

$$Im \Pi_{em} \sim M^2 (1 + \alpha_s/\pi + \dots)$$

QGP + HG!

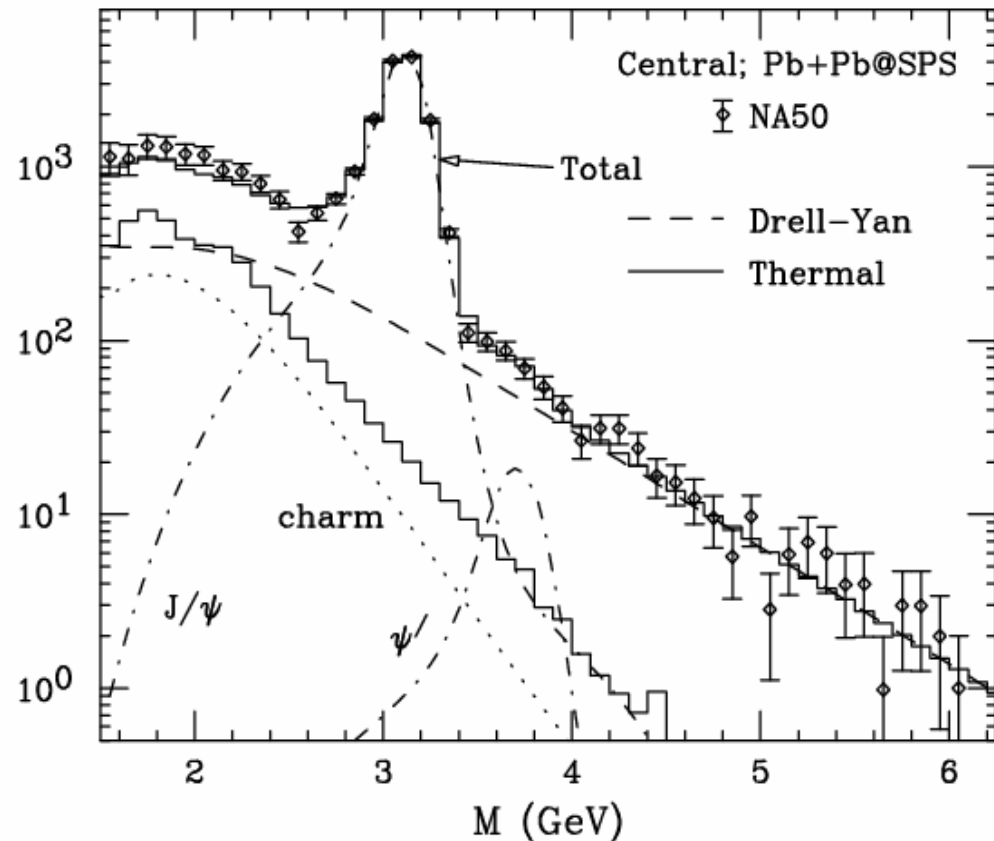
## Thermal Fireball (chem-off-eq)



$T_i \approx 210 \text{ MeV}$ , HG-dominated

[RR+Shuryak '99]

## Hydrodynamics (chem-eq)

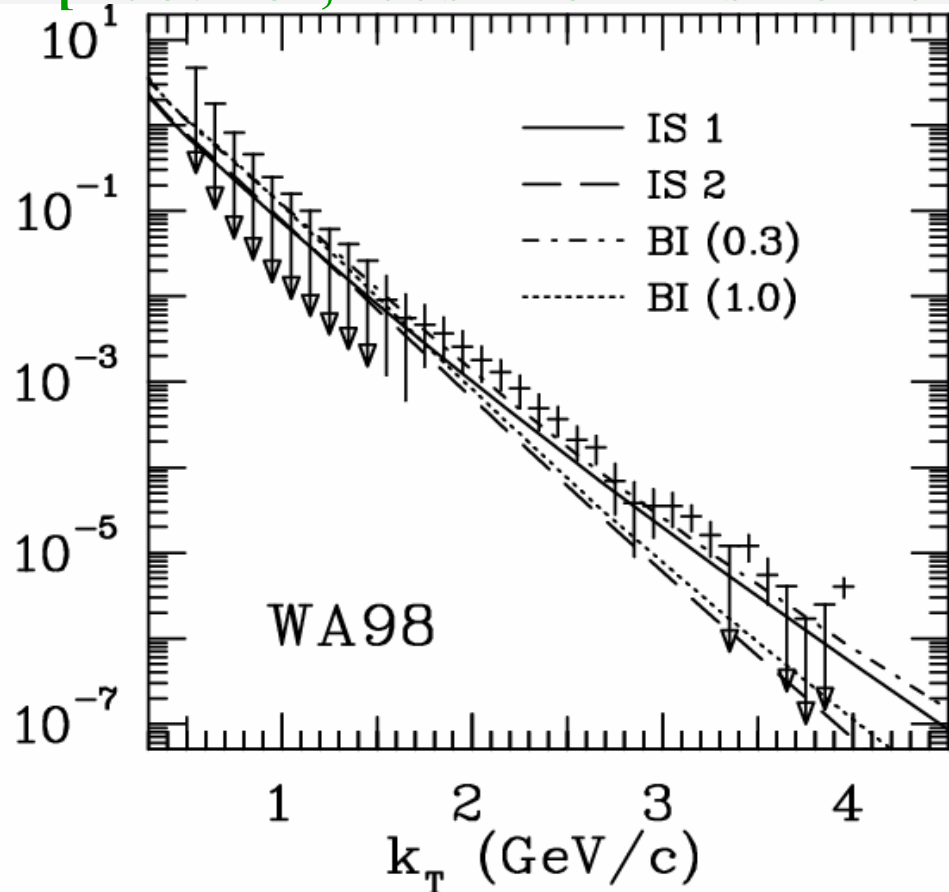


$T_i \approx 300 \text{ MeV}$ , QGP-dominated

[Kvasnikowa, Gale+Srivastava '02]

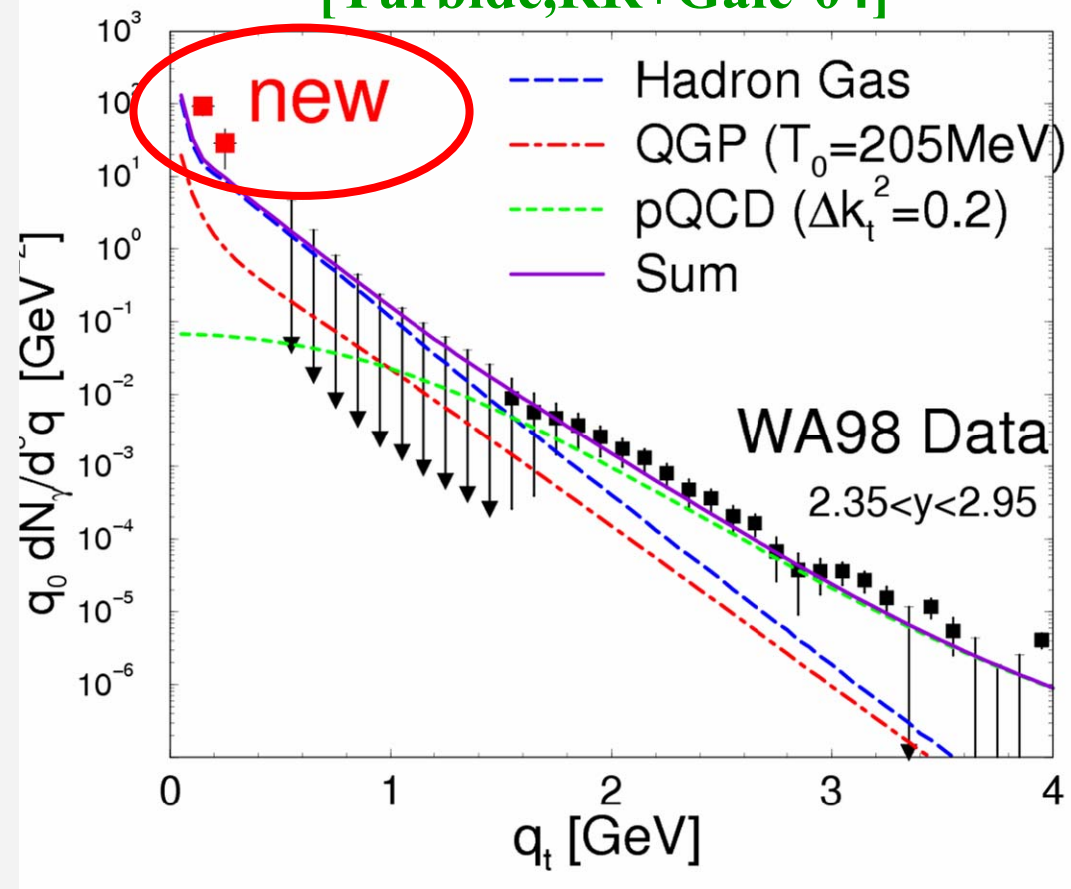
# 4.2 Comparison to Data I: **WA98** at SPS

## Hydrodynamics: QGP + HG [Huovinen,Ruuskanen+Räsänen '02]



- $T_0 \approx 260 \text{ MeV}$ , QGP-dominated
- still true if  $pp \rightarrow \gamma X$  included

## Expanding Fireball + pQCD [Turbide,RR+Gale'04]

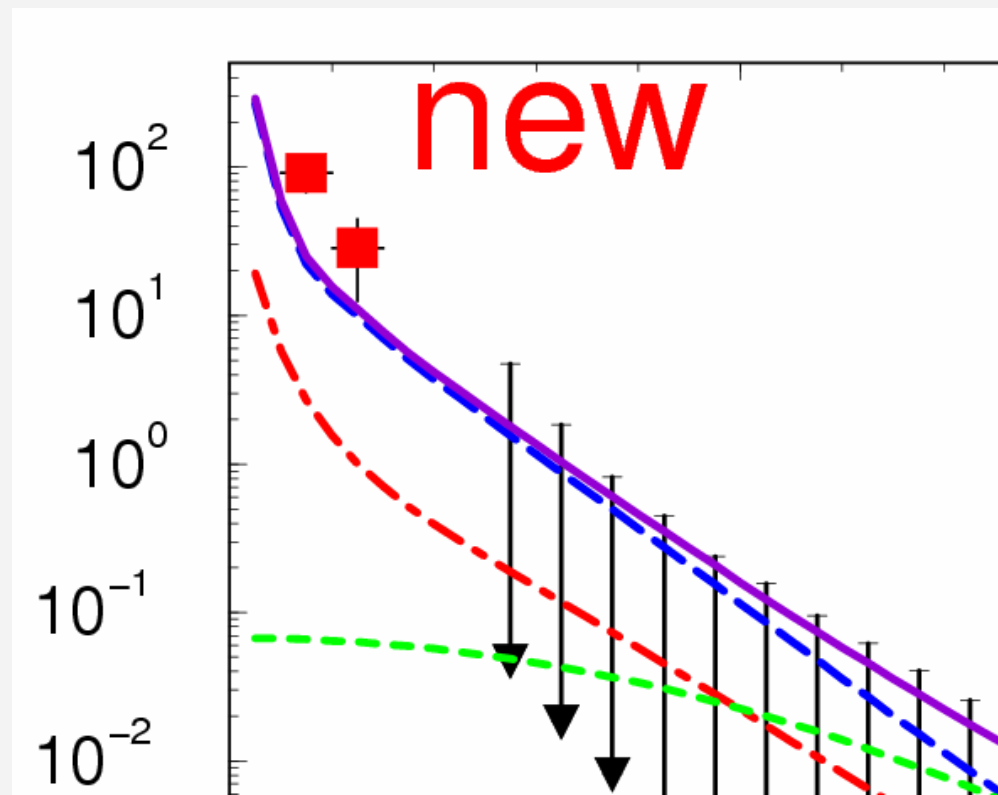
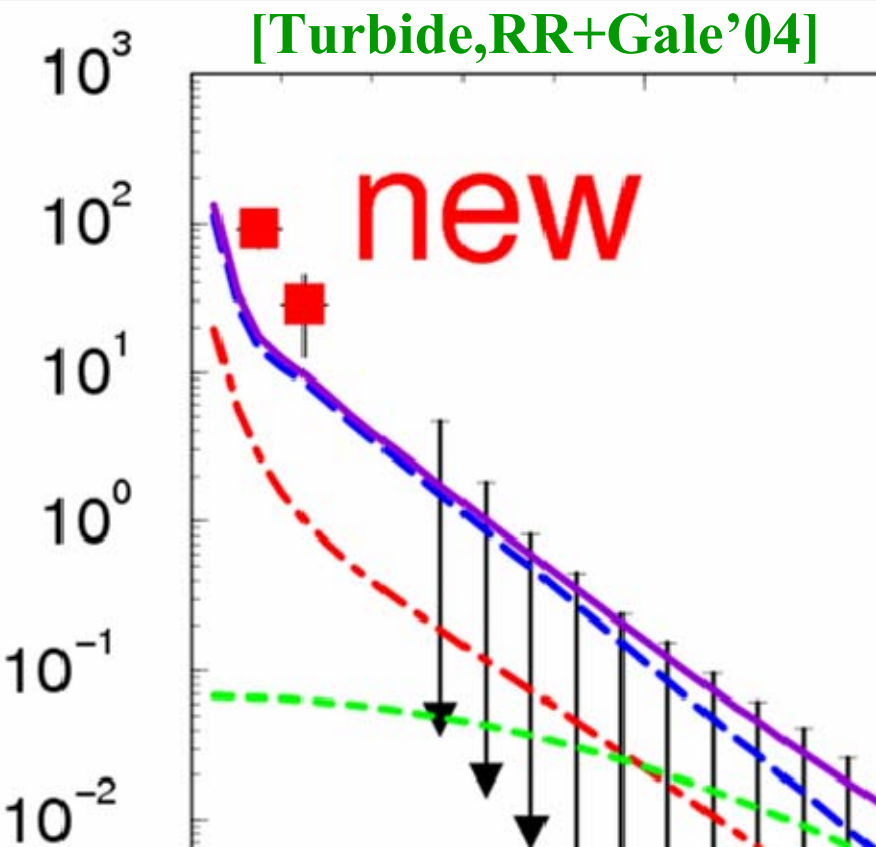


- pQCD+Cronin at  $q_t > 1.5 \text{ GeV}$   
 $\Rightarrow T_0 = 205 \text{ MeV}$  suff., HG dom.

# 4.2 Comp. to Data II: **WA98** “Low- $q_t$ Anomaly”

## Expanding Fireball Model

Include  $\pi\pi \rightarrow \pi\pi\gamma$  S-wave



- current HG rate much below
- 30% longer  $\tau_{FB} \Rightarrow$  30% increase

- slight improvement
- in-medium “ $\sigma$ ” or  $\Delta$  ?!

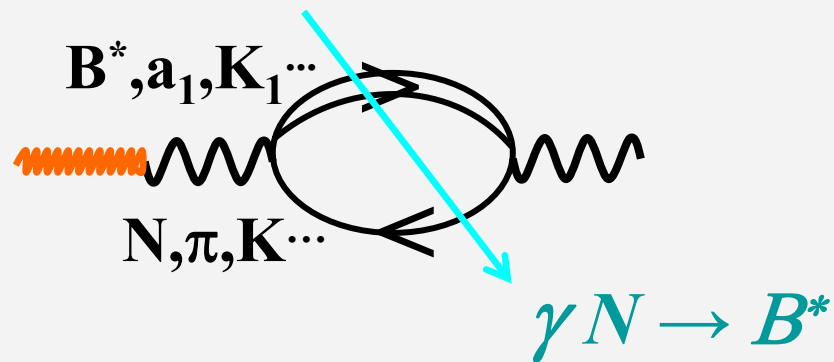
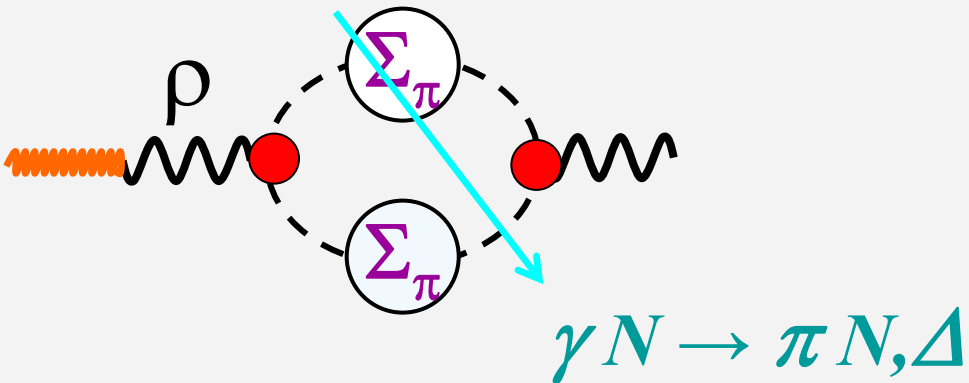
## 2.3.3 Baryonic Contributions

• use in-medium  $\rho$ -spectral funct:

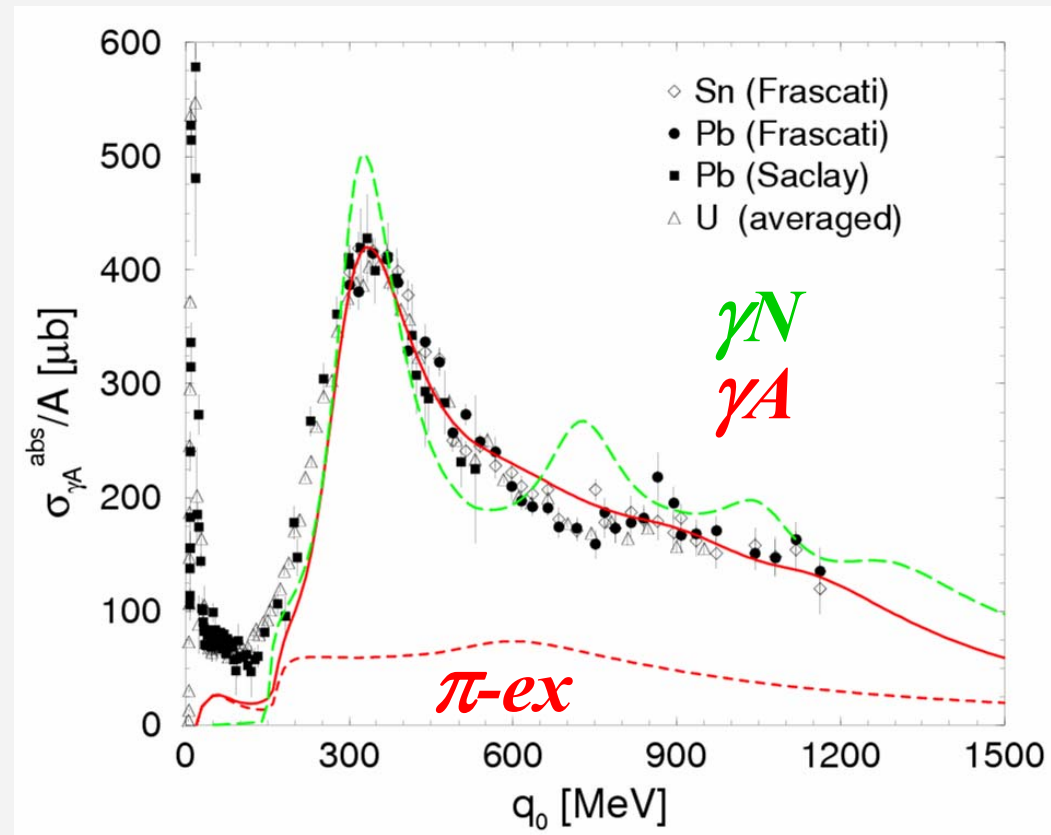
$$\text{Im } \Pi_{\text{em}} = \frac{m_{\rho}^4}{g_{\rho}^2} \text{Im } D_{\rho}^{\text{med}}(q_0 = q)$$

• constrained by nucl.  $\gamma$ -absorption:

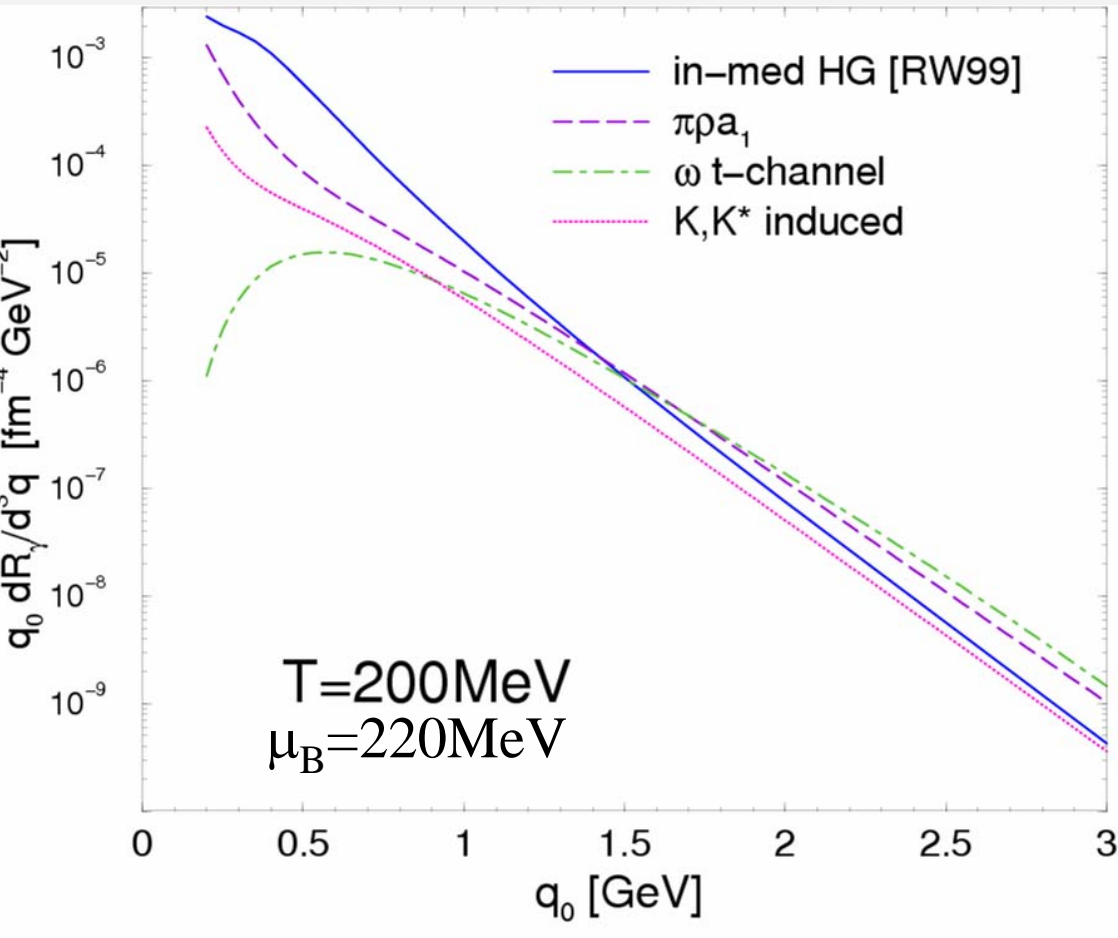
$$\frac{\sigma_{\gamma A}^{\text{abs}}(q_0)}{A} = \frac{4\pi\alpha}{q_0 \rho_N} \text{Im } \Pi_{\text{em}}(q_0 = q)$$



[Urban, Buballa, RR+Wambach '98]



## 2.3.4 HG Emission Rates: Summary

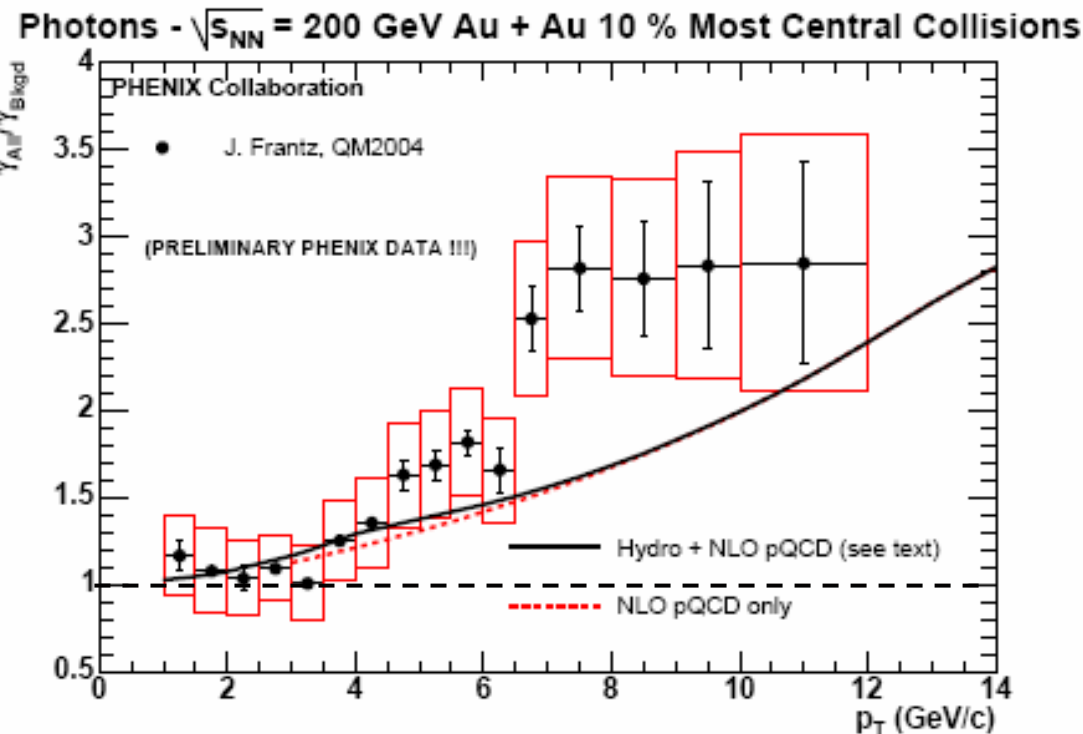
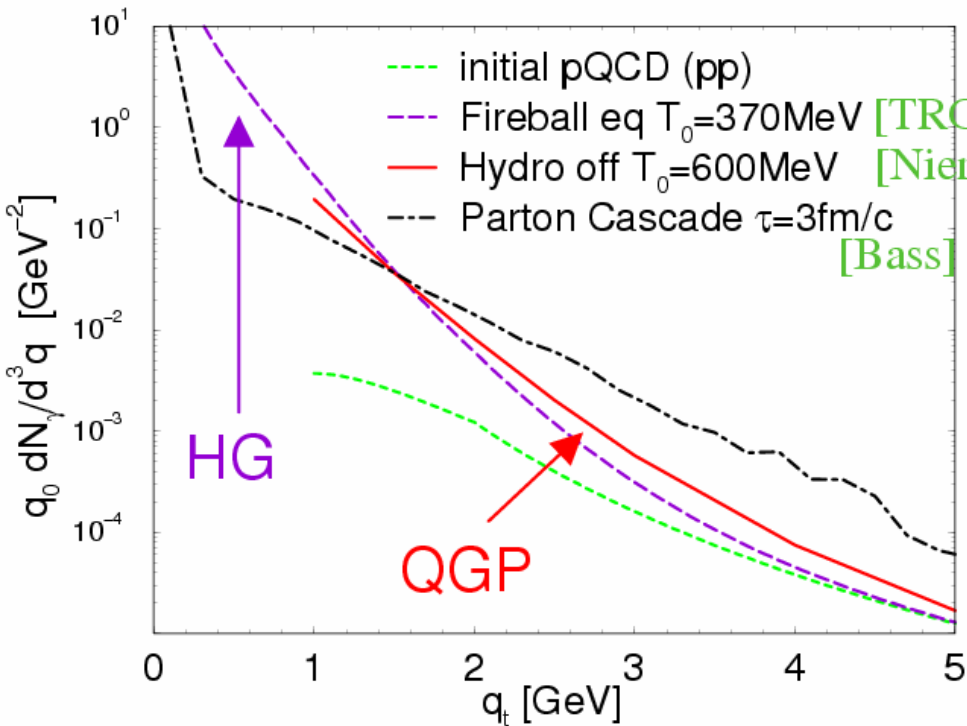


- $\omega$  t-channel (very) important at high energy
- formfactor suppression (2-4)
- strangeness significant
- baryons at low energy

# 7.2 Perspectives on Photon Data at RHIC

## Predictions for Central Au-Au

## PHENIX Data



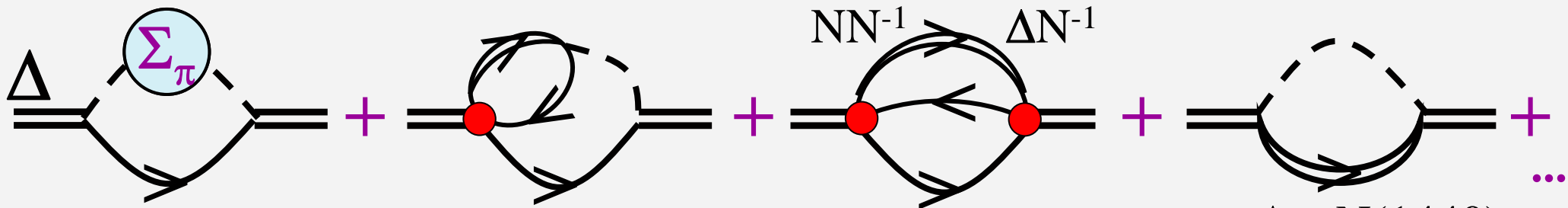
- large “pre-equilibrium” yield from parton cascade (**no LPM**)
- thermal yields ~ consistent
- QGP undersat. small effect

- consistent with **pQCD** only
- disfavors parton cascade
- not sensitive to thermal yet

## 2.2.4 In-Medium Baryons: $\Delta(1232)$

- long history in nuclear physics ! (  $\pi A$  ,  $\gamma A$  )  
e.g. nuclear photoabsorption:  $M_\Delta, \Gamma_\Delta$  up by **20MeV**
- little attention at finite temperature

$\Rightarrow$   $\Delta$ -Propagator at finite  $\rho_B$  and  $T$  [van Hees + RR '04]



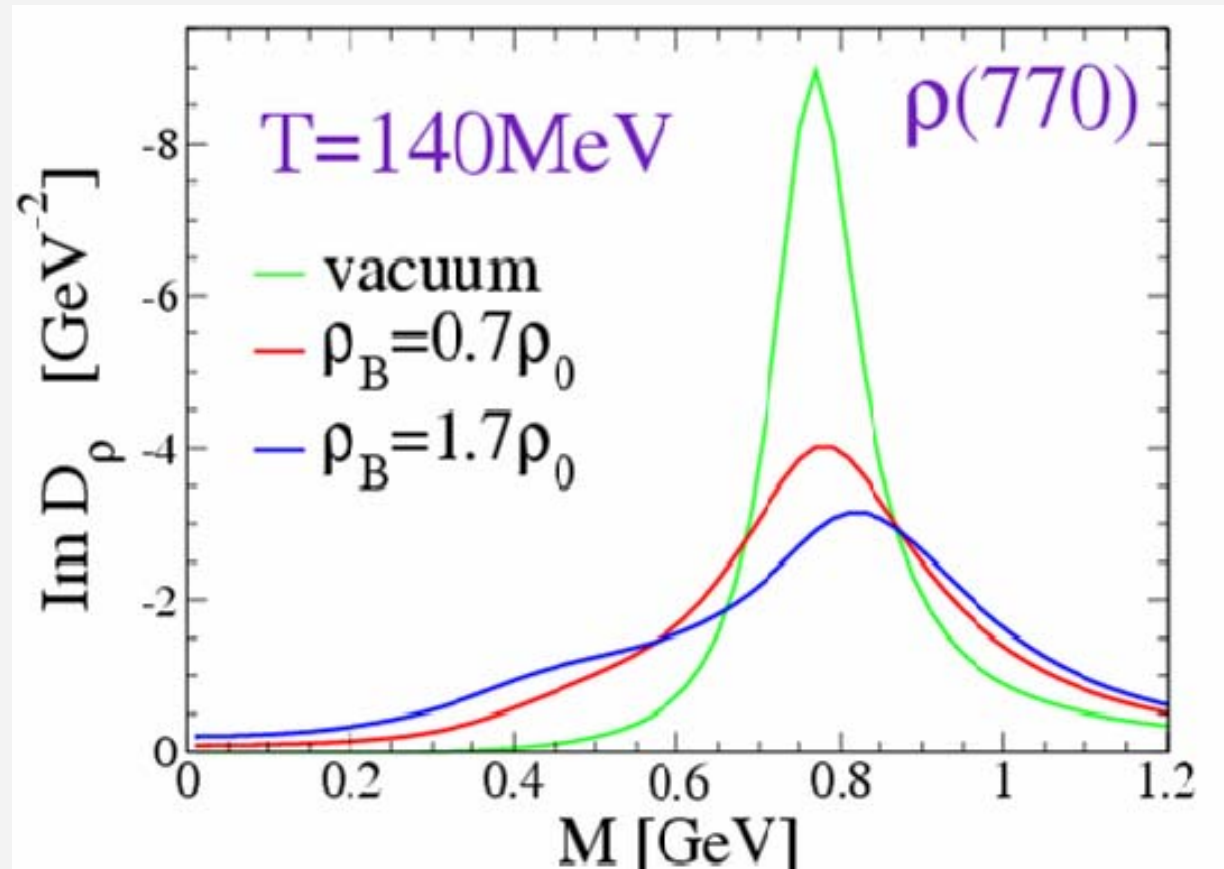
in-medium  
 $\pi$ -cloud,  
 $(1 + f^\pi - f^N)$

vertex corrections incl.  $g'$   
("induced interaction")

$\pi\Delta \rightarrow N(1440),$   
 $N(1520),$   
 $\Delta(1600)$

thermal  $\pi$ -gas

# Rho Spectral Function at Future GSI

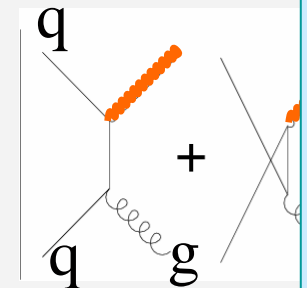


- high-density effects most prominent at low mass

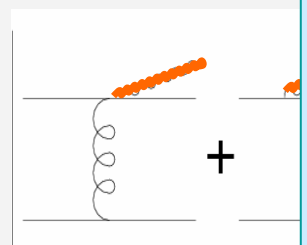
# 7.) Thermal Photons

Quark-Gluon

“Naive” LO

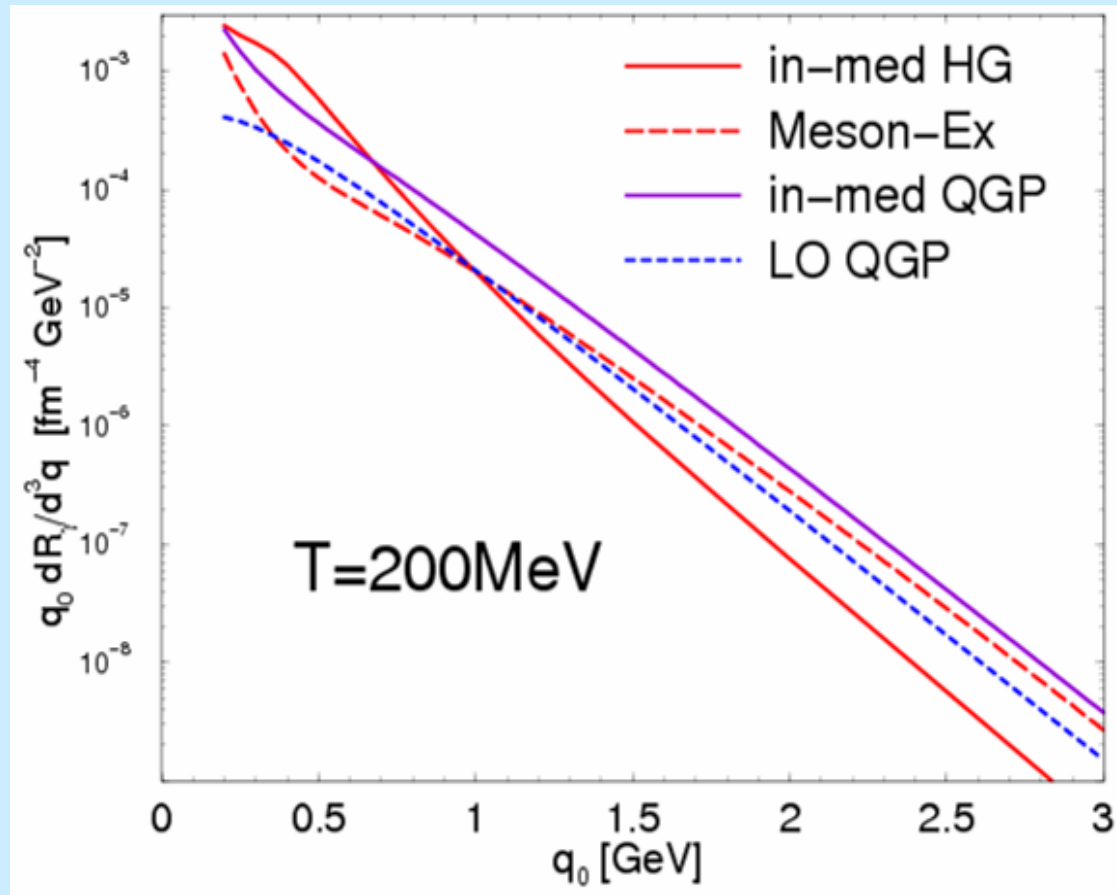


But: other collinear emissions



Bremsstrahlung + ladder

## Emission Rates



**Total HG  $\approx$  in-med QGP ! to be understood...**

Photon Gas

independence

$$f_{ec}(q_0=q)$$



exchange

$\omega$

et '91, ... ,