Electromagnetic Probes at the LHC

in (real + virtual) light of SPS and RHIC Results

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

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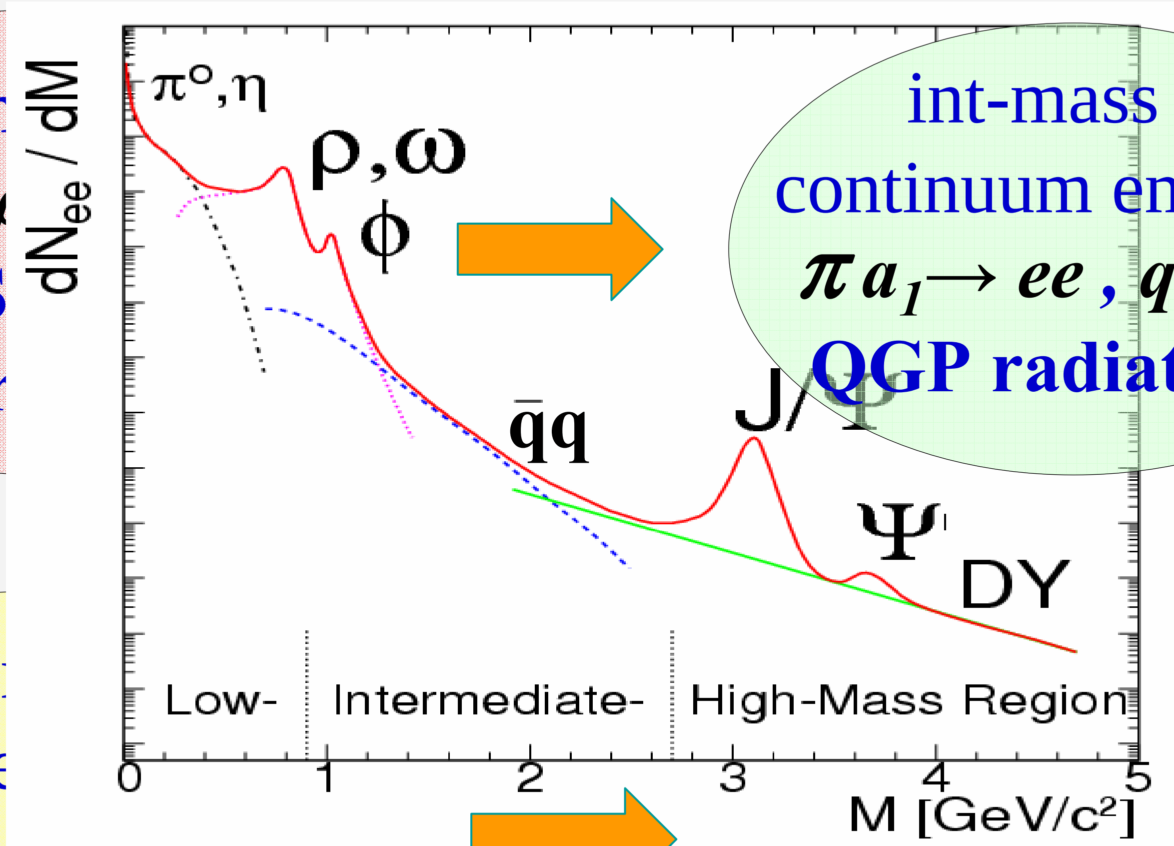
Outline

1. Four Pillars Electromagnetic Radiation
2. EM Correlator and Chiral Symmetry
3. Space-Time Evolution of A-A
4. Low-Mass Dileptons: Vector Mesons in-Medium
5. Photons
6. Perspectives for LHC
7. Conclusions

1.) Four Pillars of Thermal EM Radiation

low-m
in-med ρ
Chiral S
restor



int-mass ***ee***
continuum emission
$\pi\, a_1 \rightarrow ee$, $qq \rightarrow ee$
QGP radiation?

low-e
hadron de
$a_1 \rightarrow \pi\gamma$, $\pi\rho \rightarrow \pi\gamma$
Medium effects?

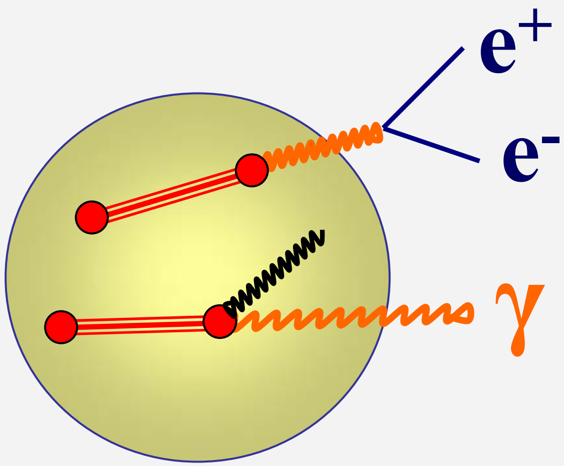
...gy γ
...mission
HG vs. QGP , $O(\alpha_s)$
QGP radiation?

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

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

2.) EM Emission Rates and Chiral Symmetry

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



$$\frac{dR_{ee}}{d^4q} \propto \alpha^2 f^B(T)\, Im\, \Pi_{em}(M,q) \quad = O(1)$$

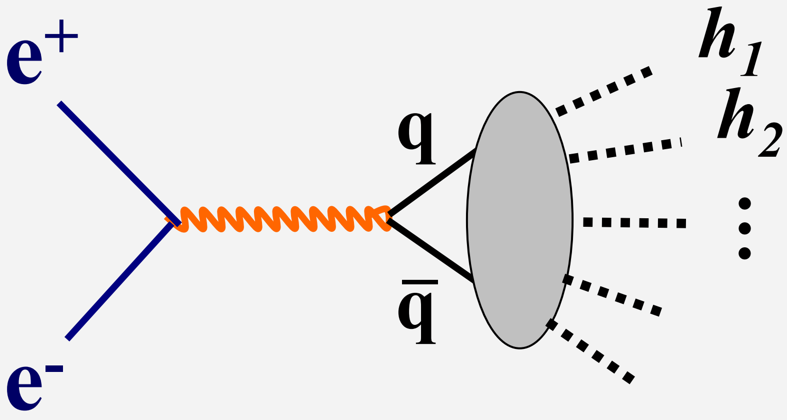
$$q_0 \frac{dR_\gamma}{d^3q} \propto \alpha\, f^B(T)\, Im\, \Pi_{em}(q_0=q) \quad = O(\alpha_s)$$

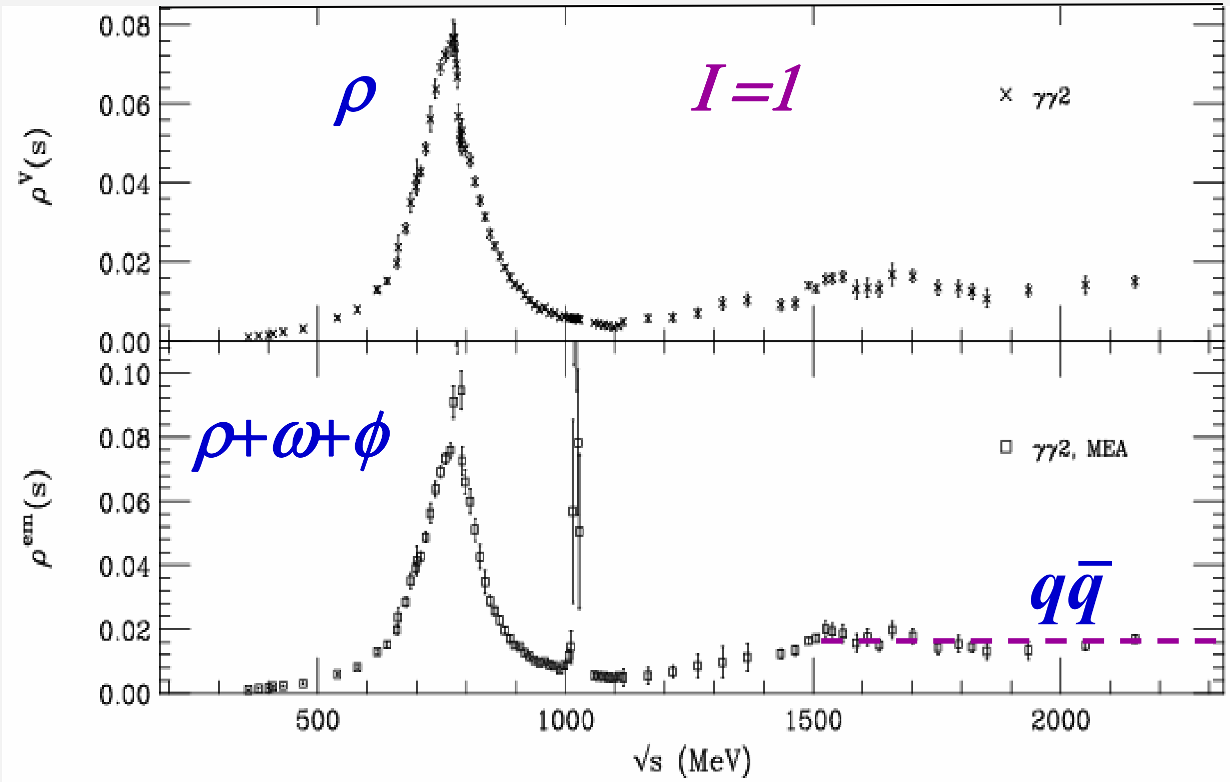
also: e.m susceptibility (charge fluct.): $\chi = \Pi_{em}(q_0=0, q\to 0)$

In URHICs:

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

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





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

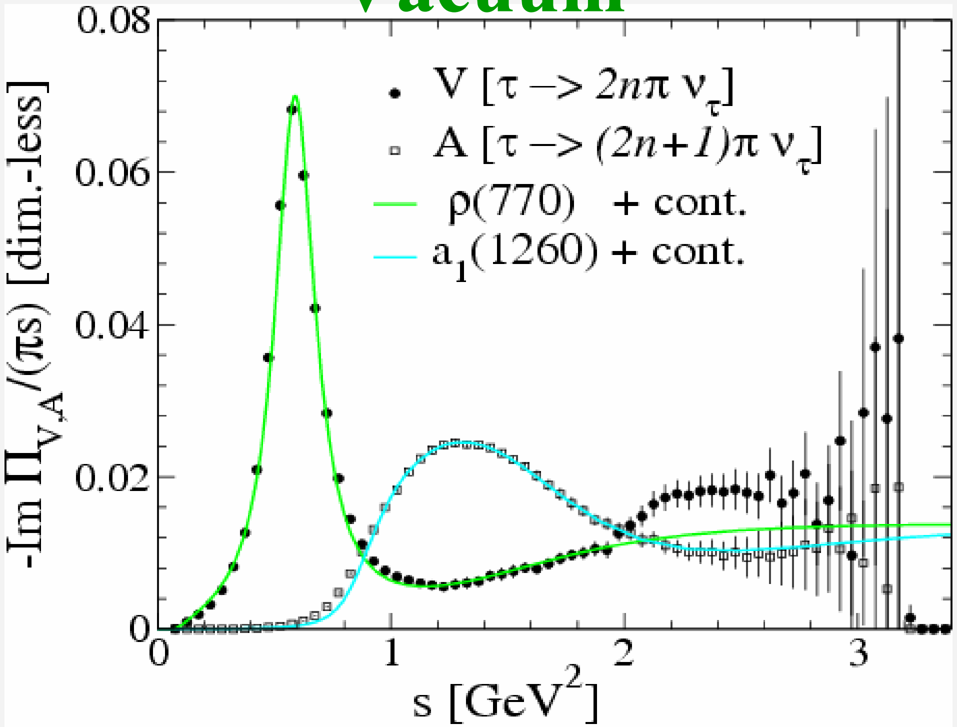
$s \geq (1.5GeV)^2$: **pQCD continuum**

$s < (1.5GeV)^2$: **V-meson spectral functs.**

2.2 Low-Mass Dileptons + Chiral Symmetry

Im Π_{em}(M) dominated by ρ-meson → chiral partner: a_1(1260)

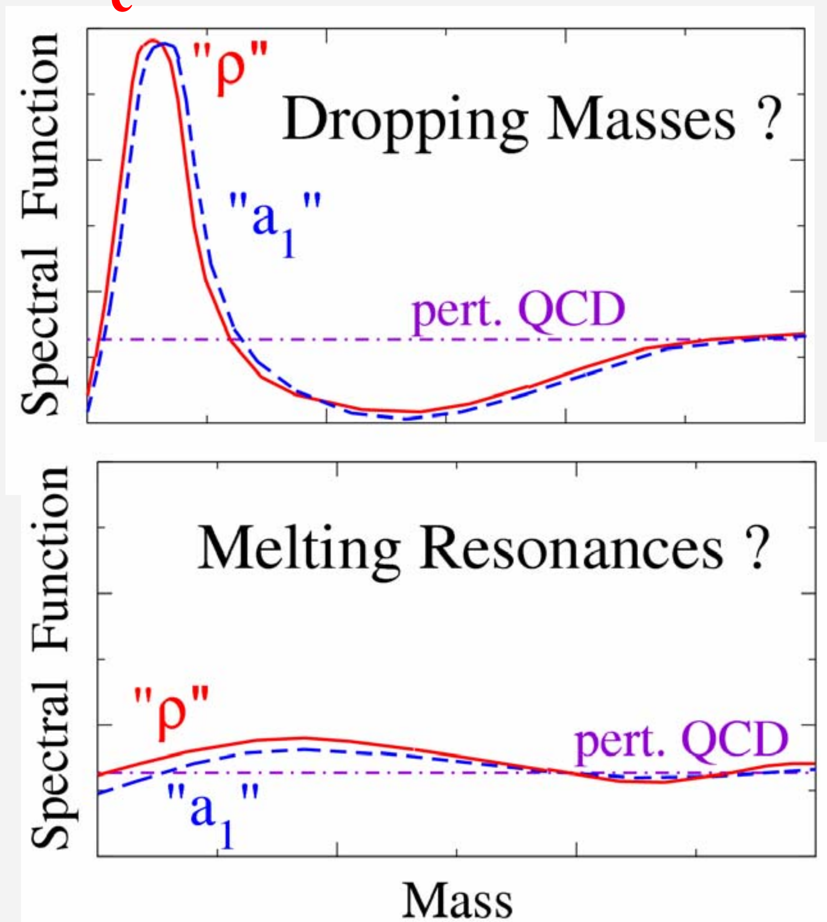
Vacuum



pQCD cont.

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

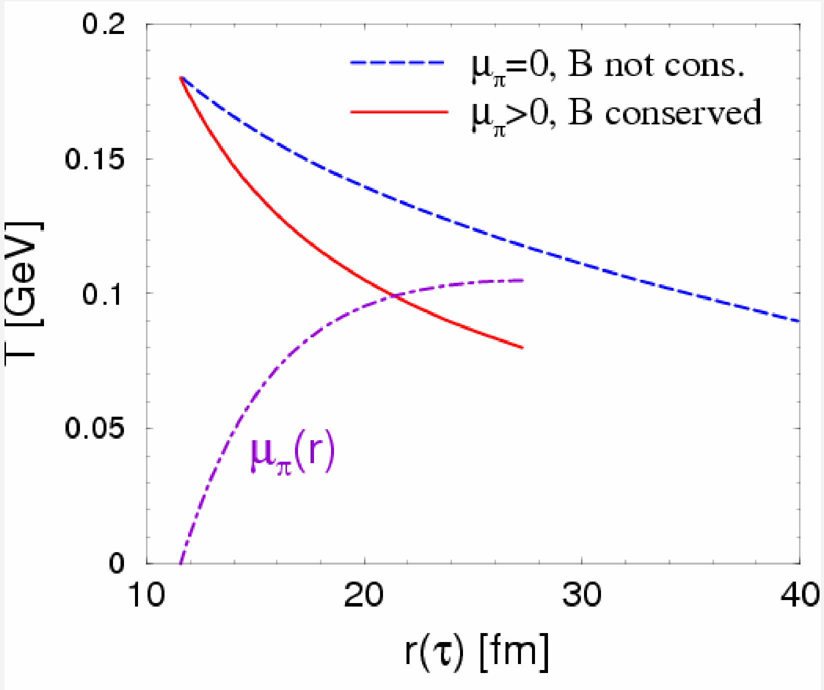
At T_c: Chiral Restoration

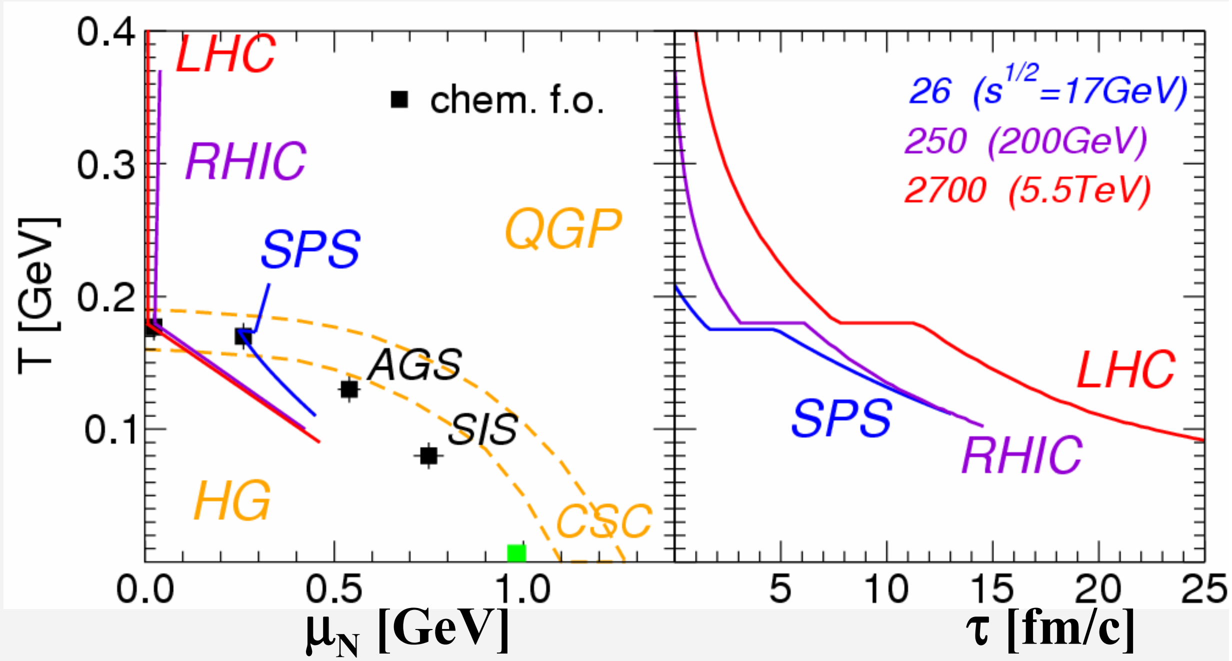


or: ρ_{long} chiral partner of π ≡ "Vector Manifestation" **[Harada+ Yamawaki '01]**

3.) Space-Time Evolution of A-A Collisions: Trajectories in the Phase Diagram

- Entropy+baryon conservation $\Rightarrow$ fixes $T(\mu_B)$ in the phase diagram
- Time scale: hydrodynamics, e.g. $V_{FB}(\tau)=(z_0+v_z\tau)\,\pi\,(R_0+0.5a_\perp\tau^2)^2$



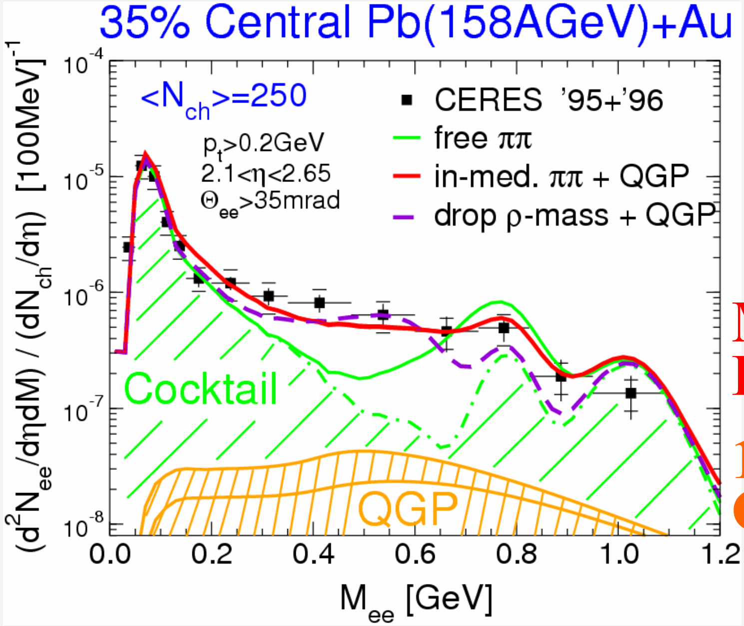


Thermal Dilepton Emission Spectrum

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

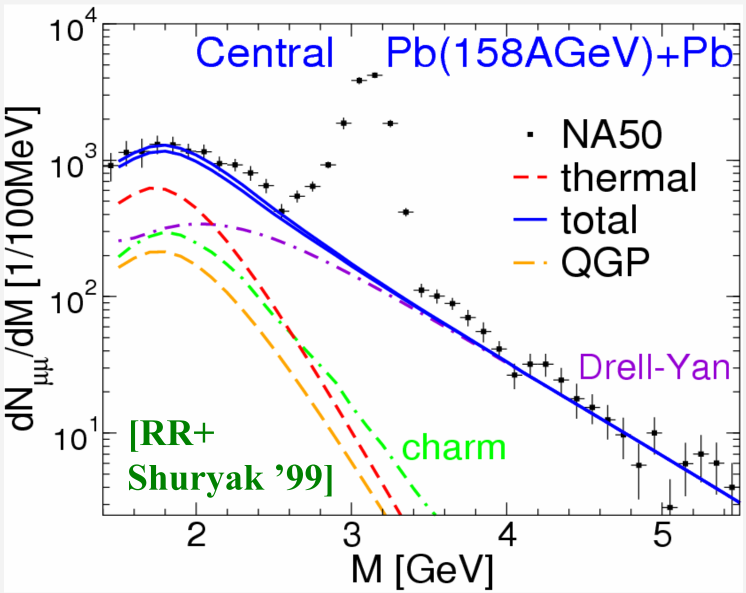
3.1 Electromagnetic Probes at SPS: Anno ~2004

Dileptons



Medium Effects!

10% QGP

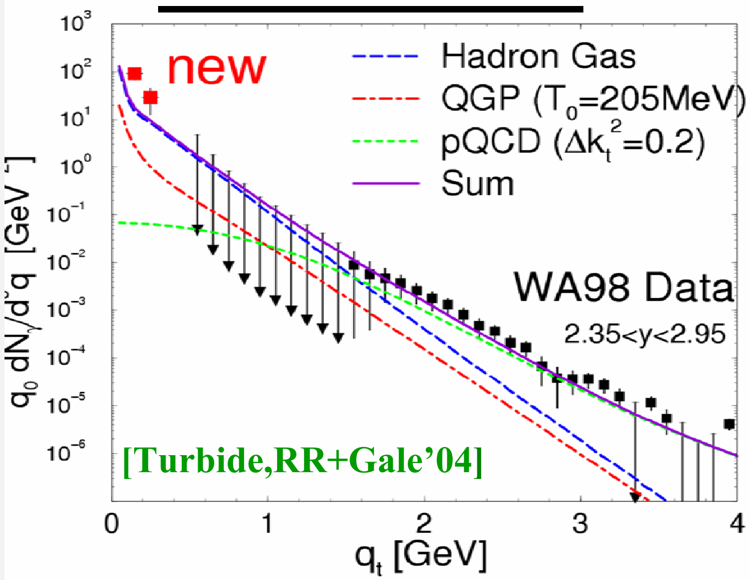


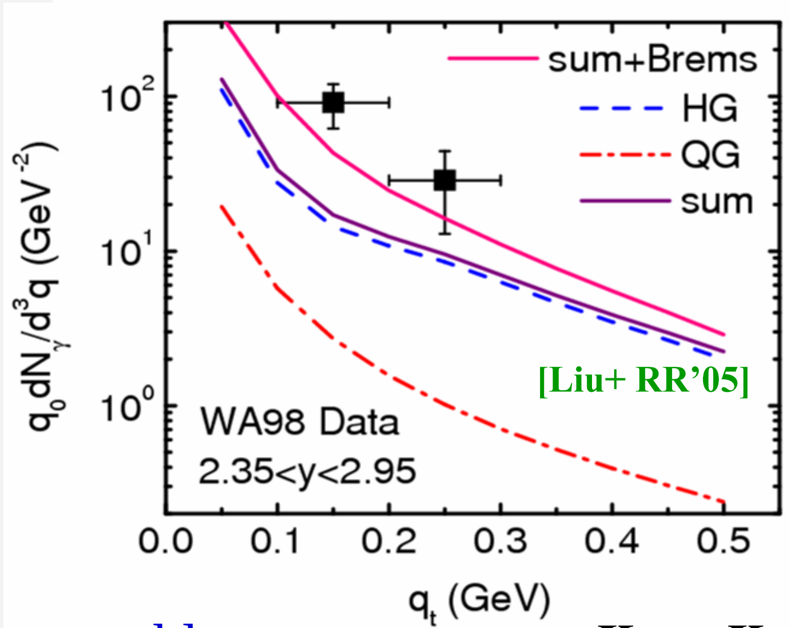
HG: $4\pi \rightarrow \mu^+\mu^-$

30% QGP

common thermal source!?

Direct Photons





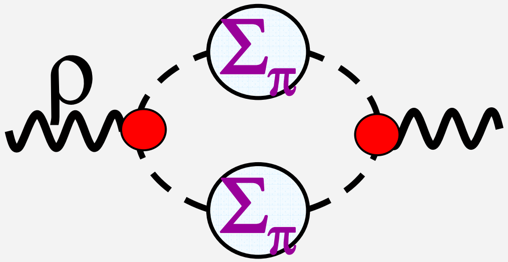
- Bremsstrahlung $\pi\pi \rightarrow \pi\pi\gamma$ $\pi K \rightarrow \pi K\gamma$

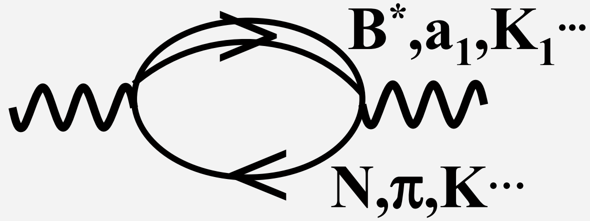
4.) Vector Mesons in Medium

(a) Hadronic Many-Body Theory

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

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





Constraints:
- B,M→ρN,ρπ
- γN, γA, πN→ρN
- QCDSRs, lattice

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

(b) Scale Invariance of $\mathcal{L}_{QCD}$

[Brown+Rho '91]

$$\langle\bar{q}q\rangle_T^{1/n}/\langle\bar{q}q\rangle_{vac}^{1/n}=f_\pi^*/f_\pi=m_N^*/m_N=m_\rho^*/m_\rho\,,\quad e.g.=\left[1-\left(\frac{T}{T_c}\right)^2\right]^{0.3}\left[1-C\frac{\rho_B}{\rho_0}\right]$$

(c) Vector Manifestation of Chiral Symmetry

[Harada, Yamawaki etal]

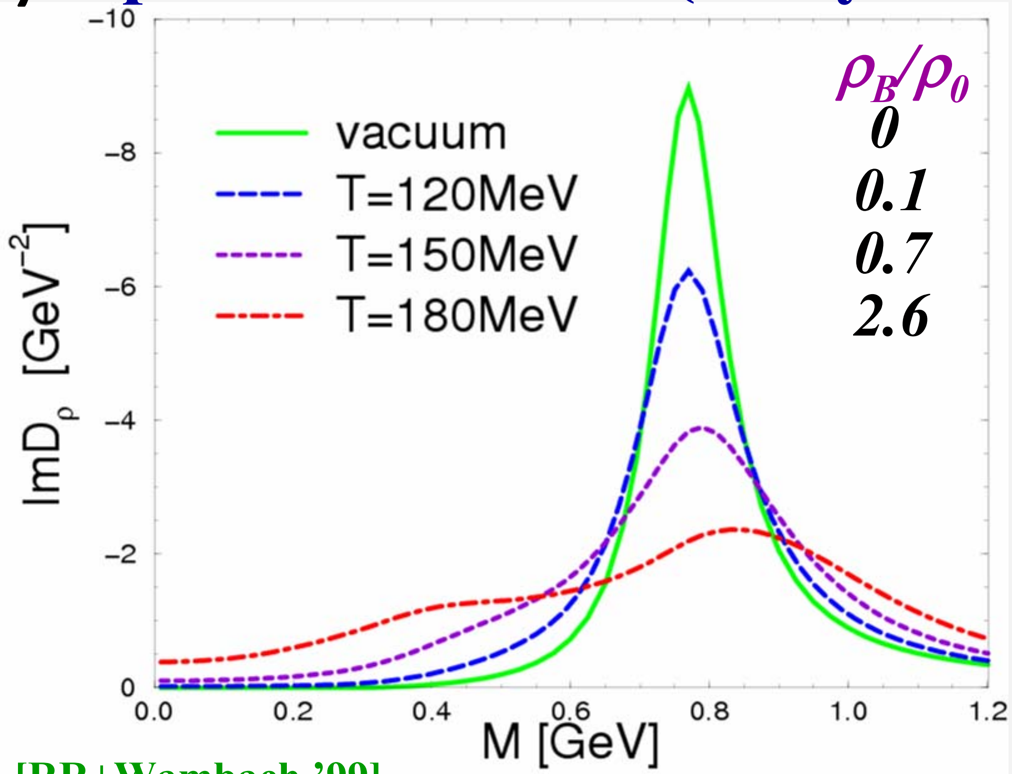
HLS with $\rho_L\equiv\pi$ ("VM"); **vacuum:** loop exp. $O(p/\Lambda_\chi, m_\rho/\Lambda_\chi, g)$

In-Med.: T-dep. $m_\rho^{(0)}$, g_ρ matched to OPE, $\Lambda_{match}<\Lambda_\chi$, RG → on-shell

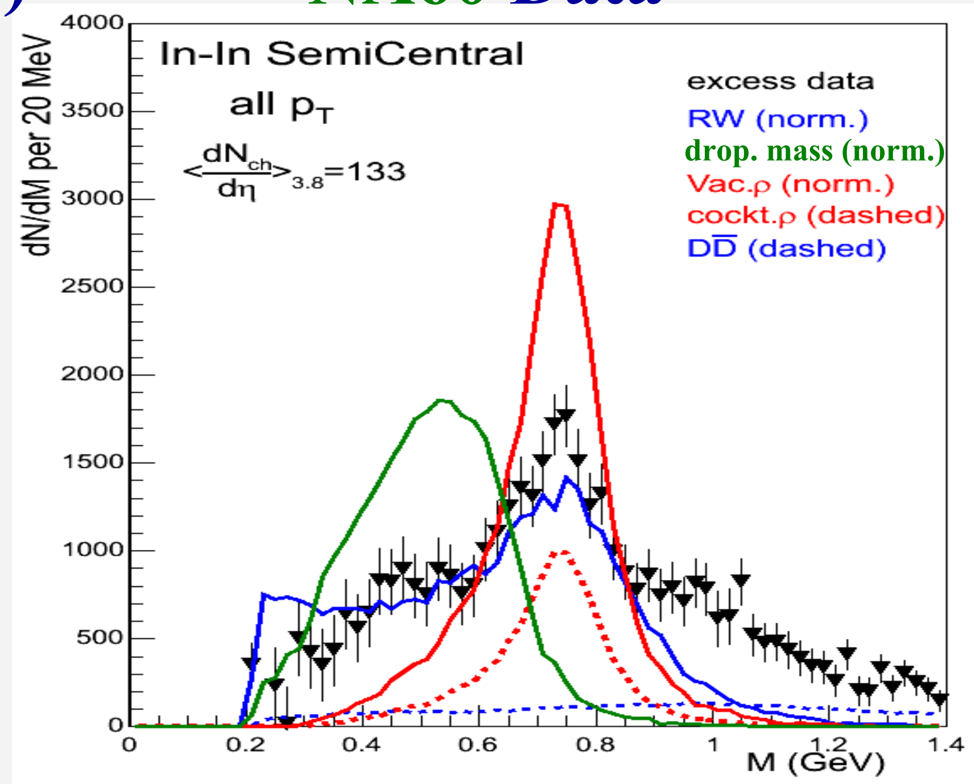
⇒ dropping ρ-mass, no vector dominance; spectral function?

4.2 Dileptons I: News from SPS

ρ Spectral Function (many-body) **NA60 Data**

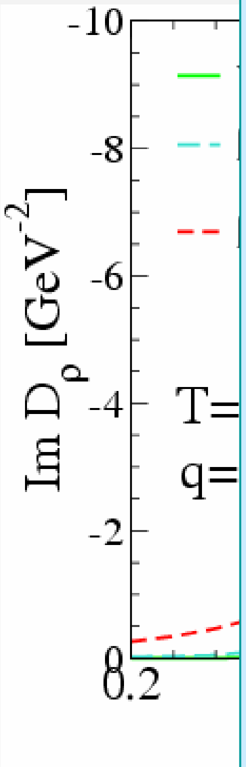


[RR+Wambach '99]

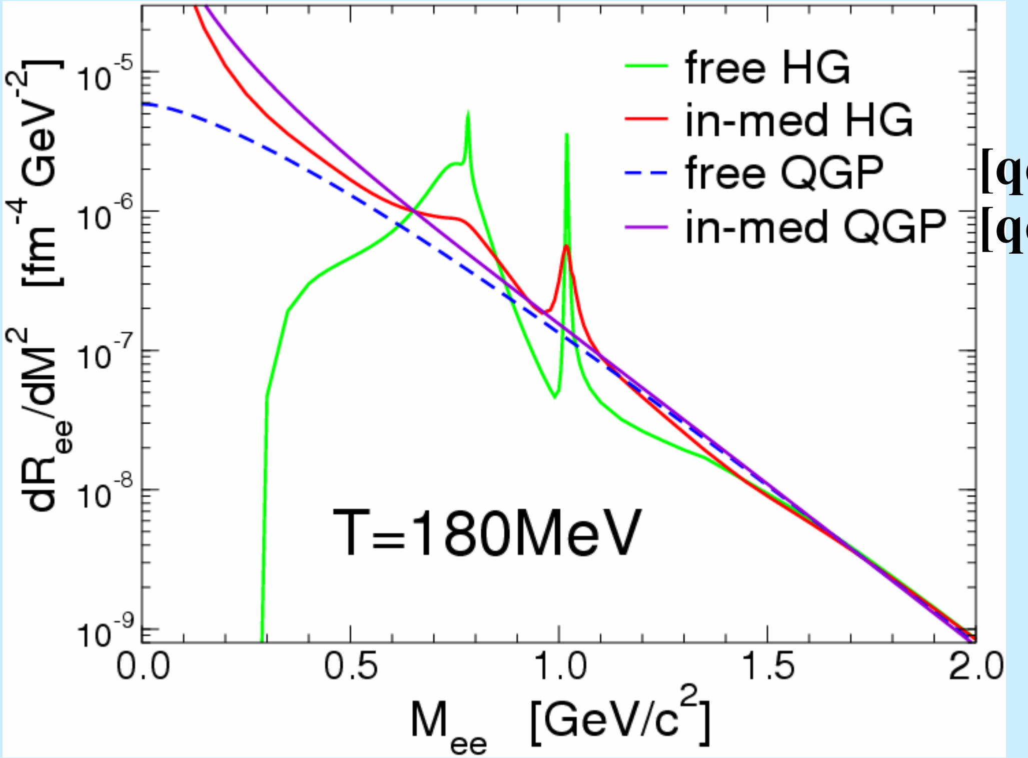


- **ρ-meson "melting" (+fireball) predictions ok, dropping mass not**
- **open issues: - absolute normalization + p_t-dependence**
  - **$M > 0.9GeV$? ($4\pi \rightarrow \mu^+\mu^-$!), in-medium $\omega + \phi$?**
  - **"cocktail-ρ" (+smooth signal)? vector dominance?**

4.3 Vector Mesons + Dilepton Rates at LHC

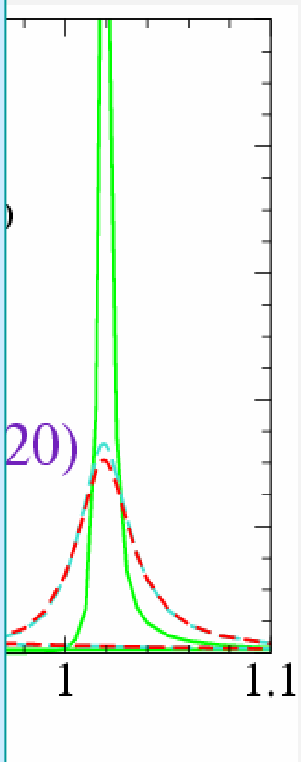


e^+e^- Emission Rates: $dR_{ee}/dM \sim f^B\, Im\Pi_{em}$



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

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



in-med HG ≈ in-med QGP !

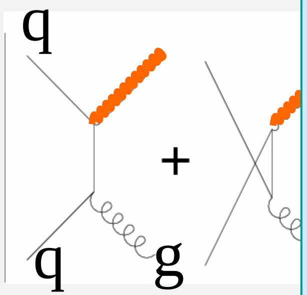
Quark-Hadron Duality ?!

5.) Direct Photons

Quark | **n Gas**

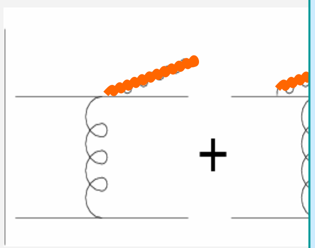
"Naïve" **LO** | ance

(q_0=q)



But: other c | hange

collinear en



Bremsstrahl

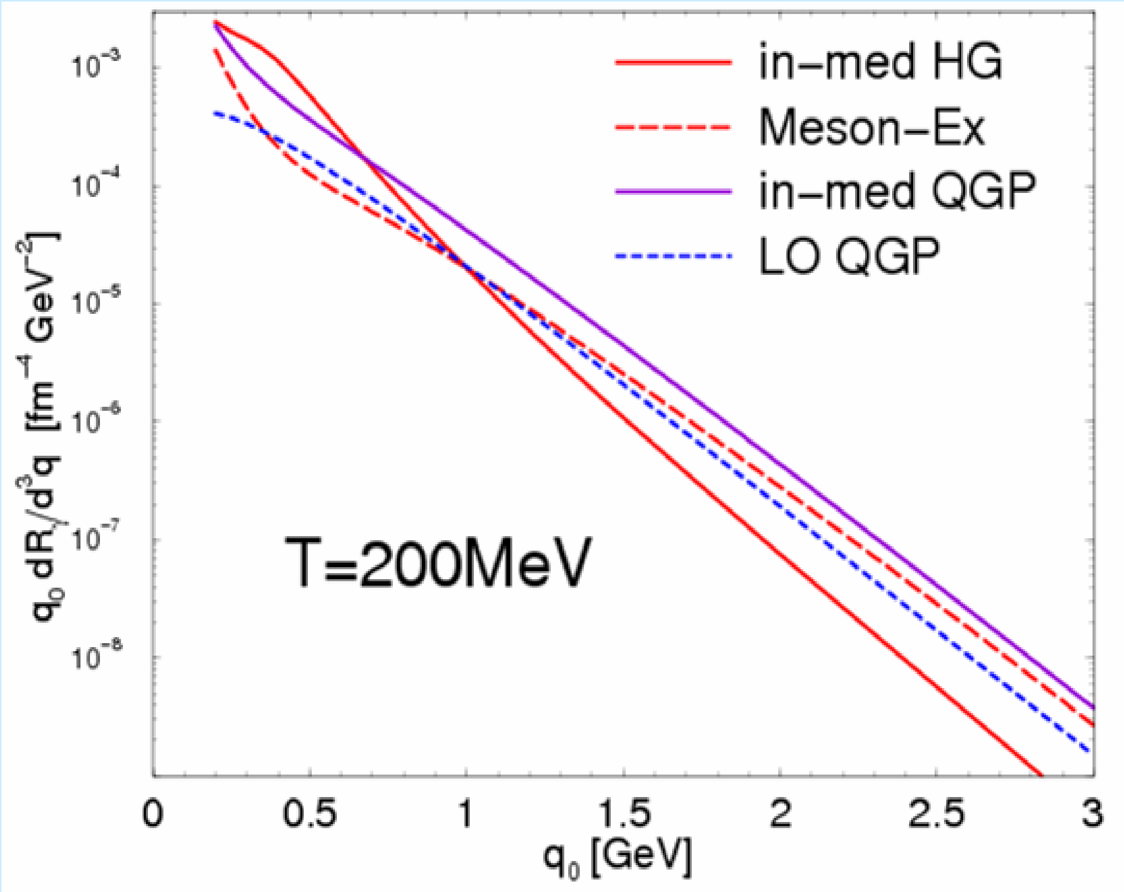
\+ ladde

'91, … ,

[Aurenche etal '00, Arnold,Moore+Yaffe '01]

Turbide,RR+Gale'04]

Emission Rates

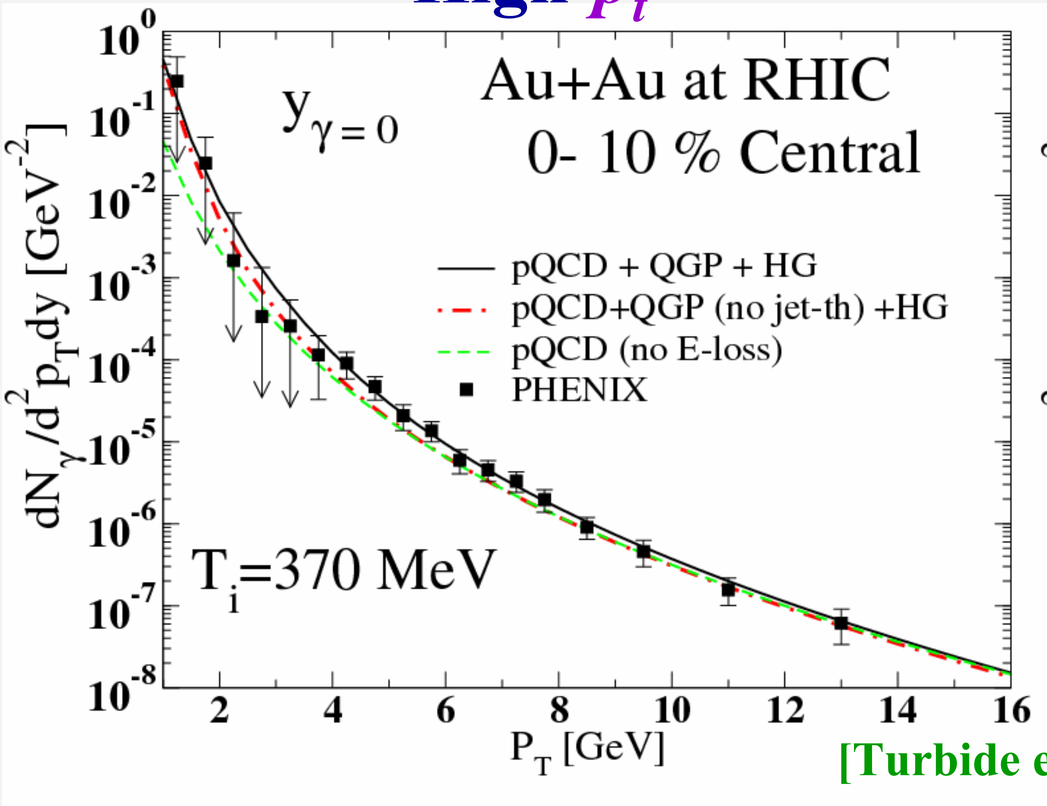


In-med QGP ≈ total HG ! to be understood…

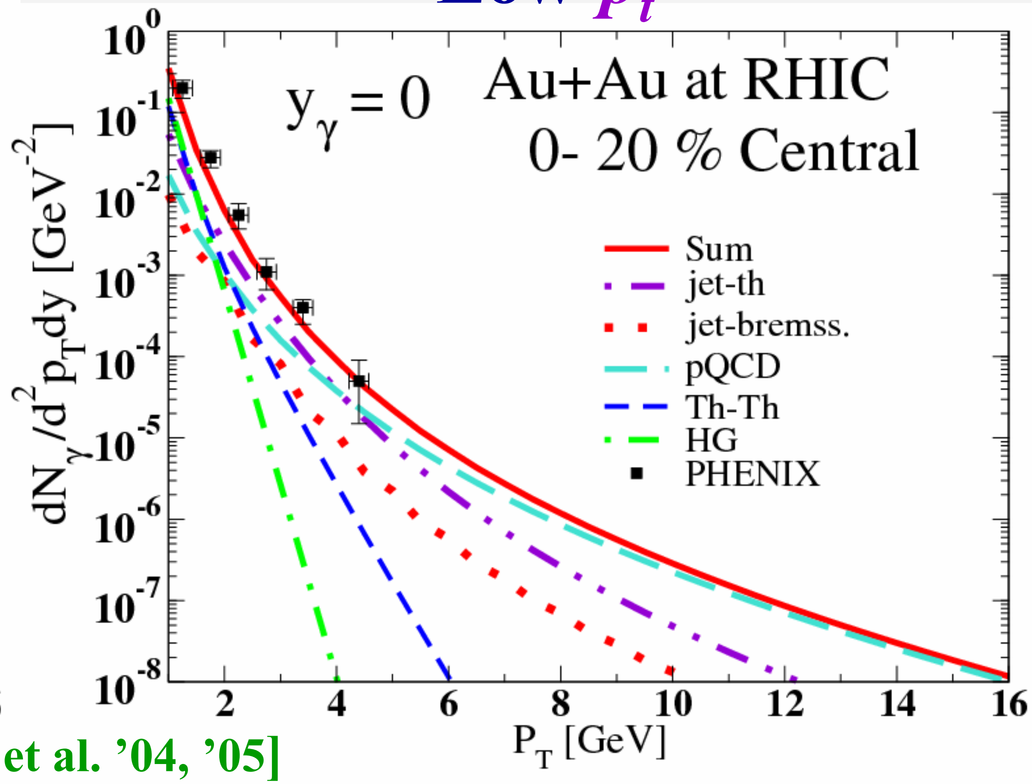
5.2 Direct Photon Spectra at RHIC: PHENIX

Model Predictions with initial + jet-induced + thermal

High-p_t



Low-p_t



[Turbide et al. '04, '05]

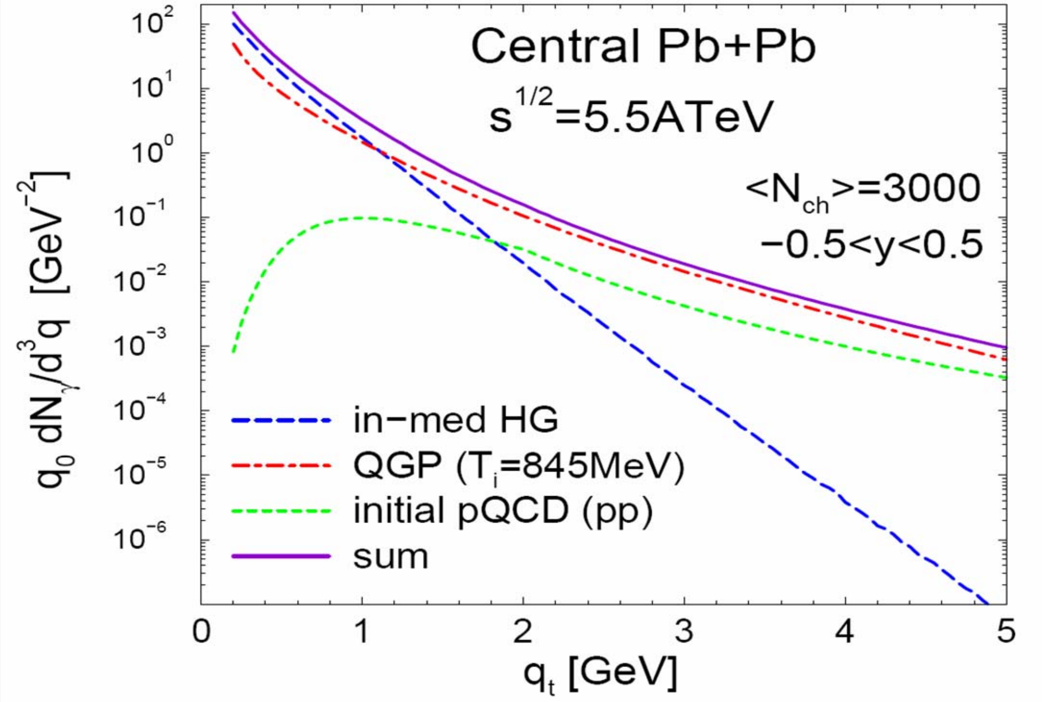
- quantitative agreement with new **PHENIX** data
- jet-plasma interactions outshine thermal radiation above 2GeV?!

6.1 Perspectives for LHC I: Direct Photon Spectra

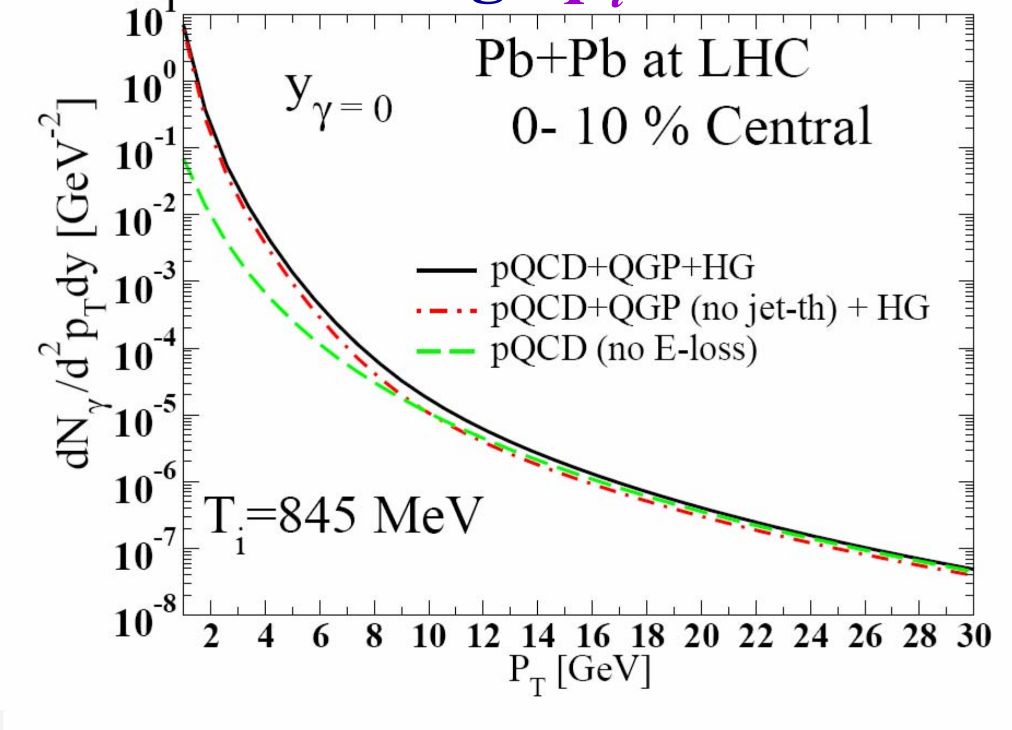
Same sources as at RHIC

[Turbide et al. ’04. ‘05]

Low-p_t



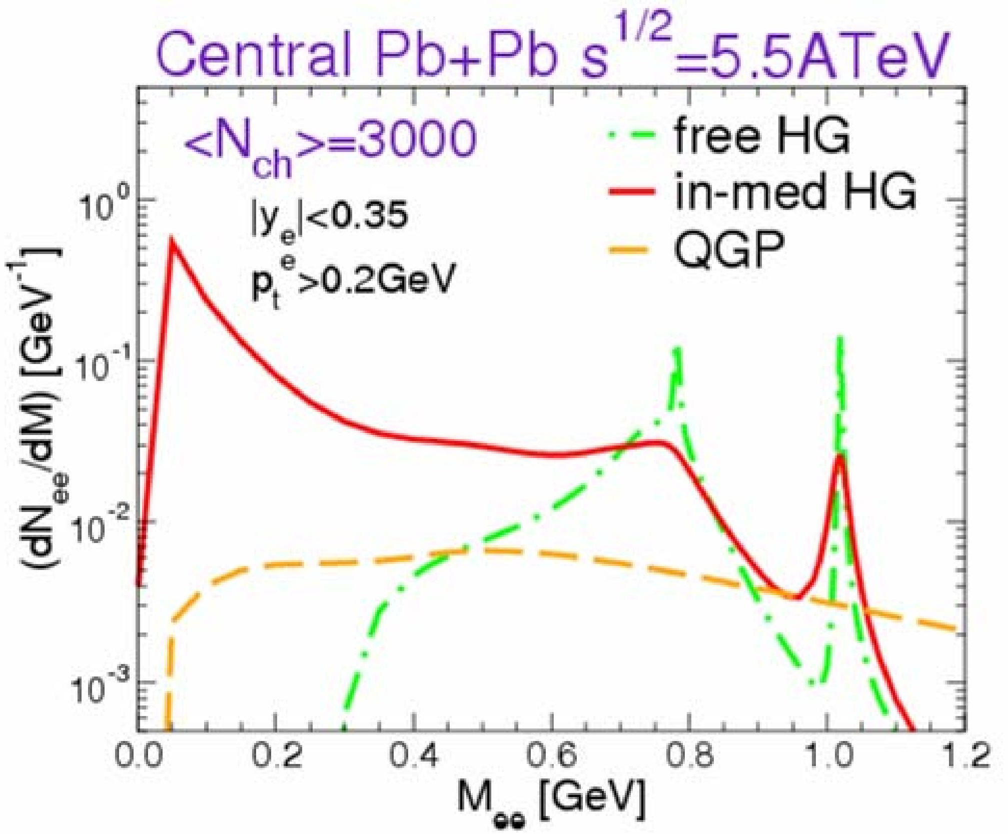
High-p_t



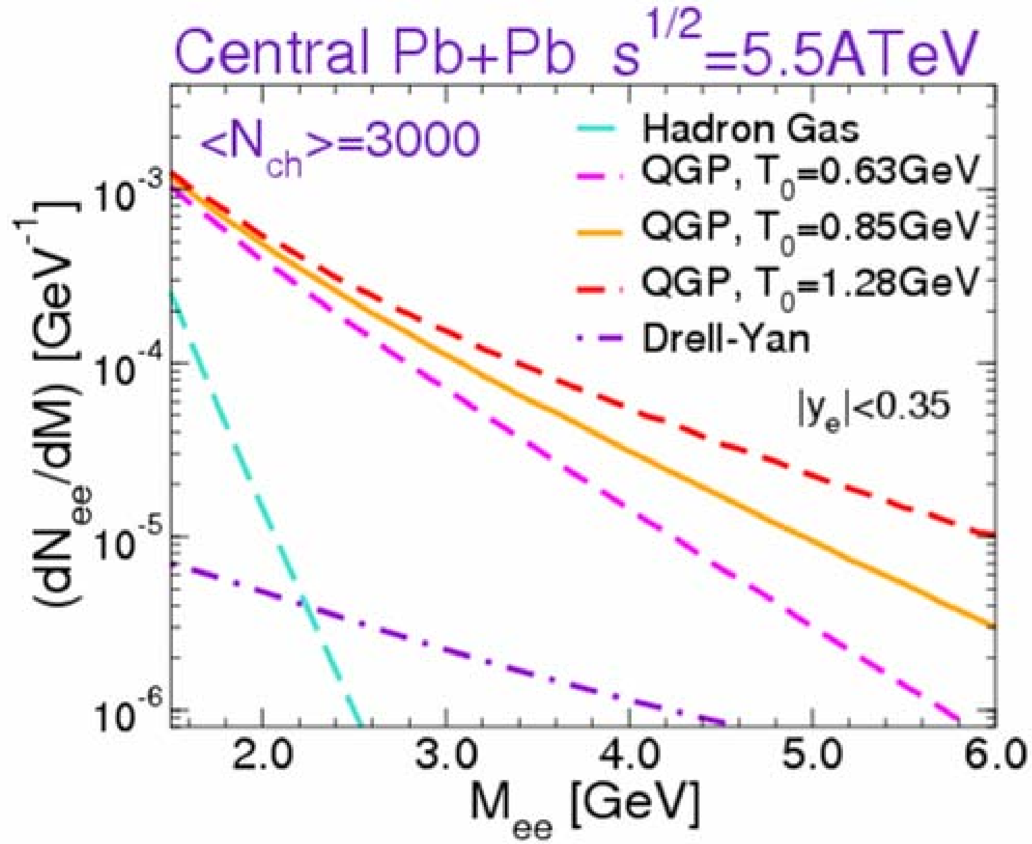
- thermal **QGP** prevails over pQCD up to 10GeV?!
- thermal yield ~ $N_{ch}^{1.4}$
- jet-plasma interactions relatively less important

6.2 Perspectives for LHC II: Thermal Dileptons

Low Mass



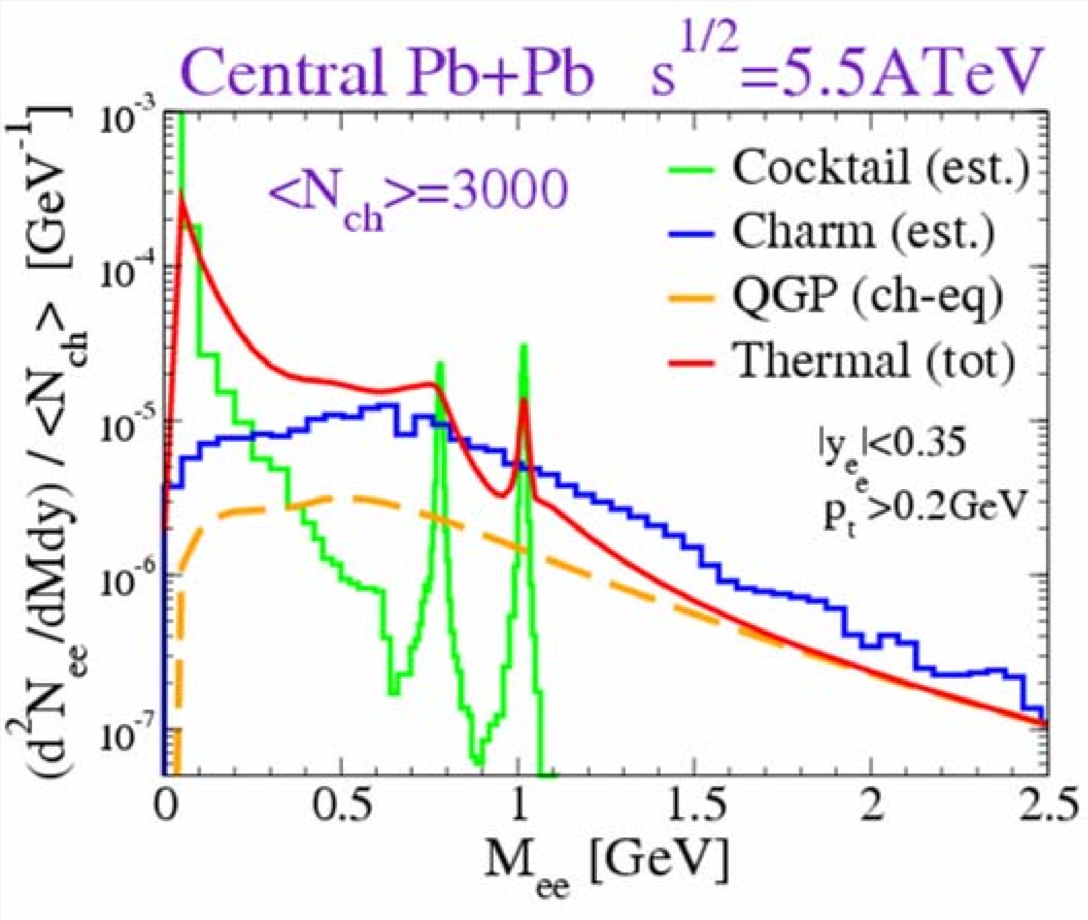
Intermediate Mass

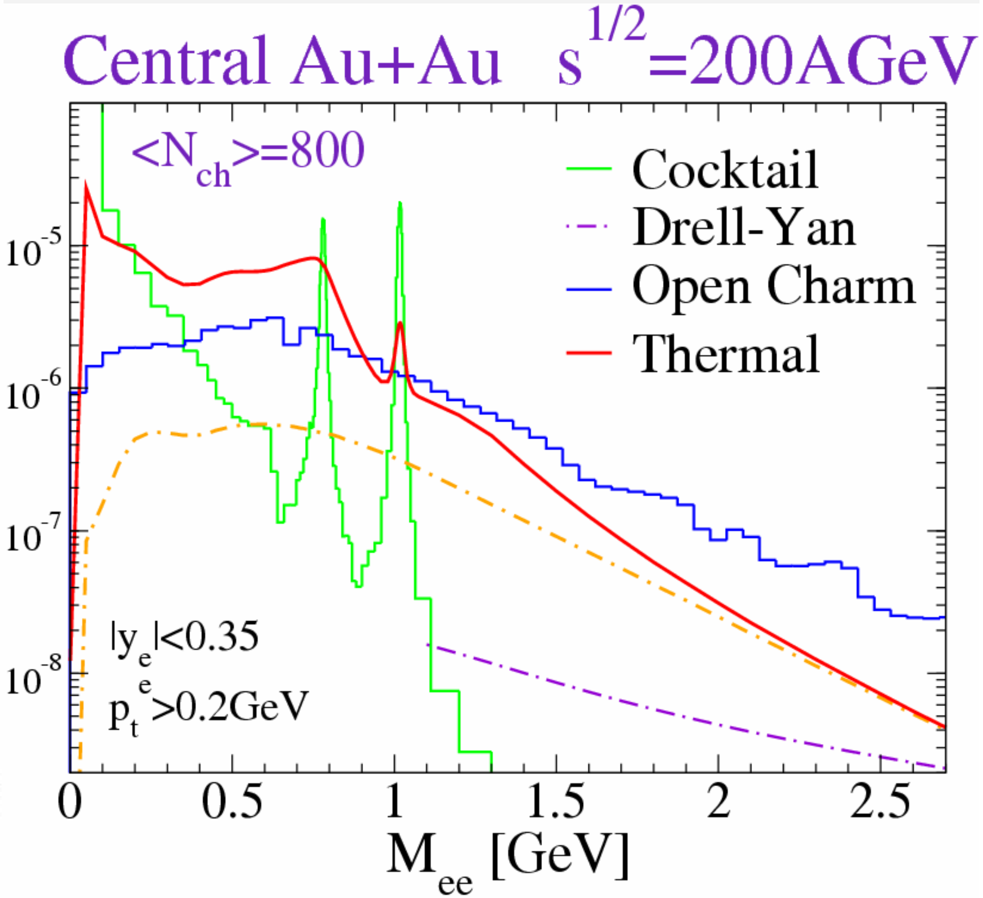


- hadron gas dominant, sensitive to τ_{FB}
- strong medium effects
- enrich QGP with $p_t^e > 1GeV$ (or so)

- moderate sensitivity to therm. time τ_0=0.28, 0.11, 0.03fm/c
- $\tau_0 >> R_{Pb} / \gamma \approx 10^{-3}$

6.3 Perspectives for LHC III: Dilepton Spectra





- open charm (bottom?) strong source at all M (energy loss?!), especially for ***N_{ch} < 3000***

- less open charm at low mass, but more relative to QGP (IM)

7.) Conclusions

- **Thermal EM Radiation** in **QCD**: $\Pi_{em}(q_0,q,\mu_B,T)$

  low mass: ρ,ω,φ, **(anti-/baryons) + IMR + thermal photons**

- **in-med HG - QGP shine equally bright? (resonances!?)**

- **NA60 precision data at SPS open the way for progress, explicit model predictions needed**

- **LHC: - QGP signal relatively more prevalent than at RHIC**
  - **reduced sensitivity to initial (thermalization) time,**
  - **hadronic signal (chiral restoration) compromised by charm**
  - **open-charm E-loss: background or signal?**

⇒ LHC can address the full set of EM-Probes Physics ?!