Theory Highlights* of Quark Matter 2004

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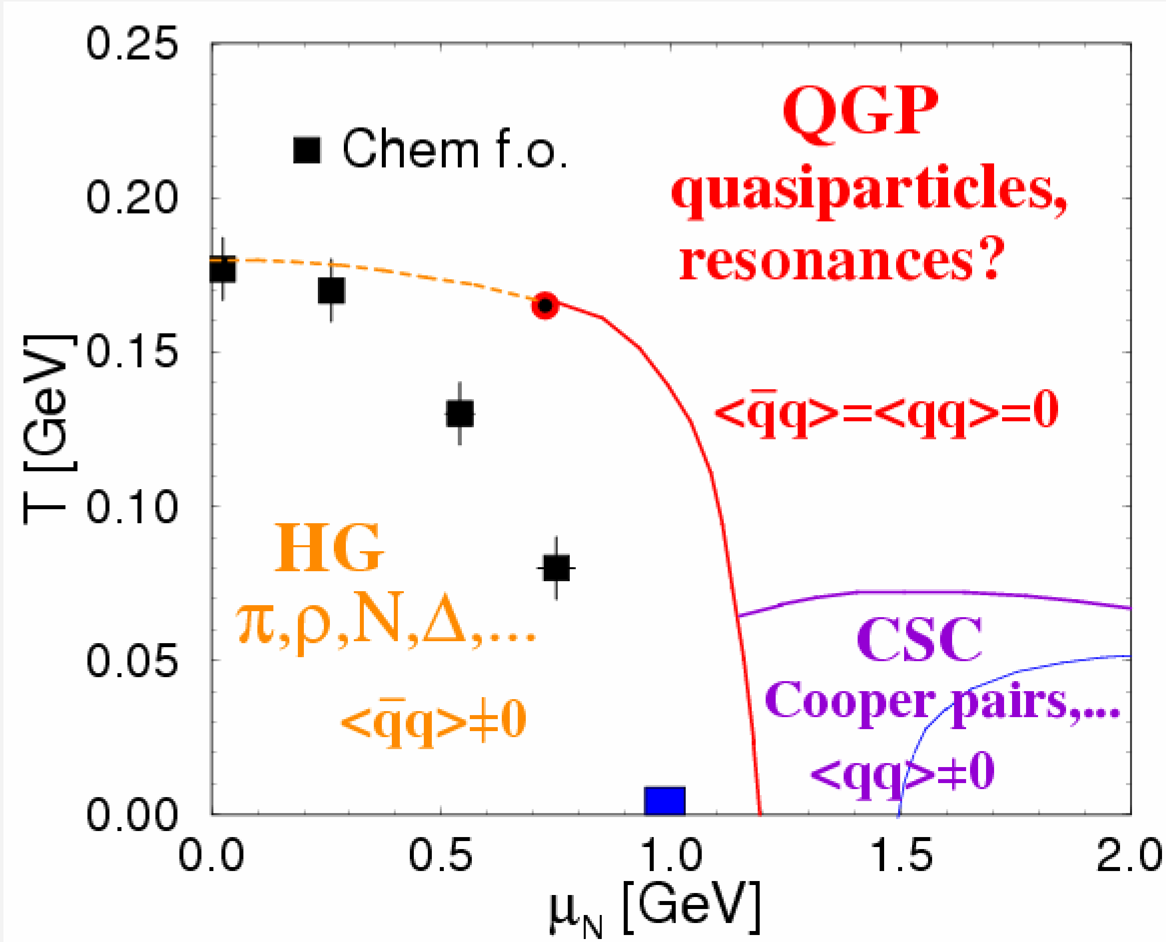
* biased and incomplete, apologies for omissions

1.Introduction: Exploring the Phase Diagram



- Bulk Properties: Equation of State
- Phase Transitions: (Pseudo-) Order Parameters
- Microscopic Properties: Spectral Functions

Outline

2.) QCD Theory

- Color-Super-Conductor ; Chiral vs. Deconfinement
- Lattice: Critical Point, Charmonium

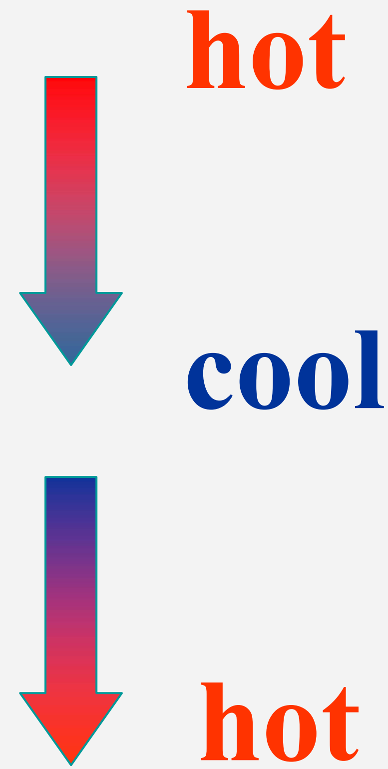
3.) QCD Bulk Properties at RHIC

- Color-Glass Condensate
- Opacity, Thermalization
- Quark Coalescence vs. Hydro
- HBT “Puzzle”

4.) Microscopic Probes of QCD Matter

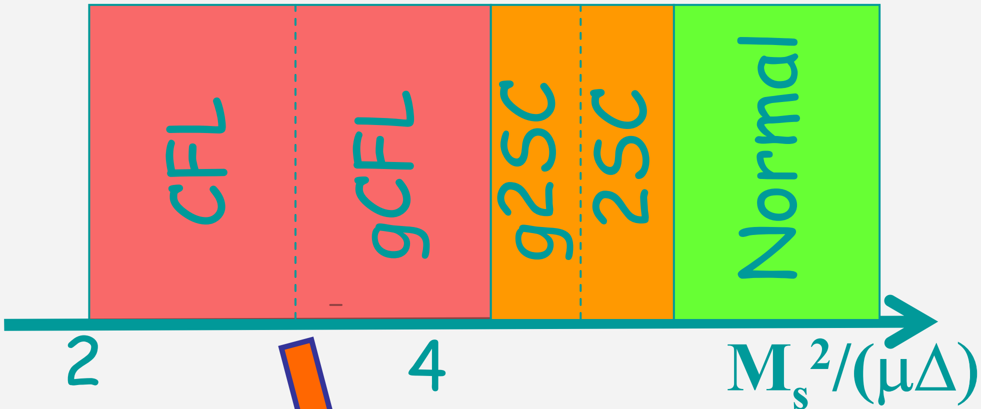
- Resonance Spectroscopy
- E.M. Emission (Photons)
- Charm/onium

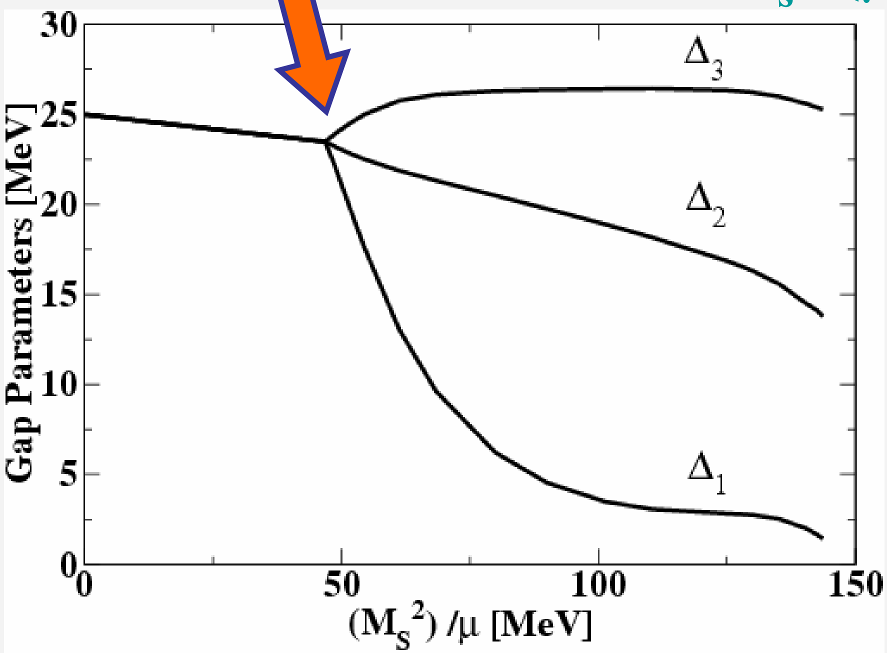
5.) Conclusions



2.1 Colorsuperconductivity and Compact Stars

color+charge neutral **u,d,s,e⁻** matter → M_s key parameter





[Rajagopal]

M_s-asym ⇒ 1 **d-s** pair gapless

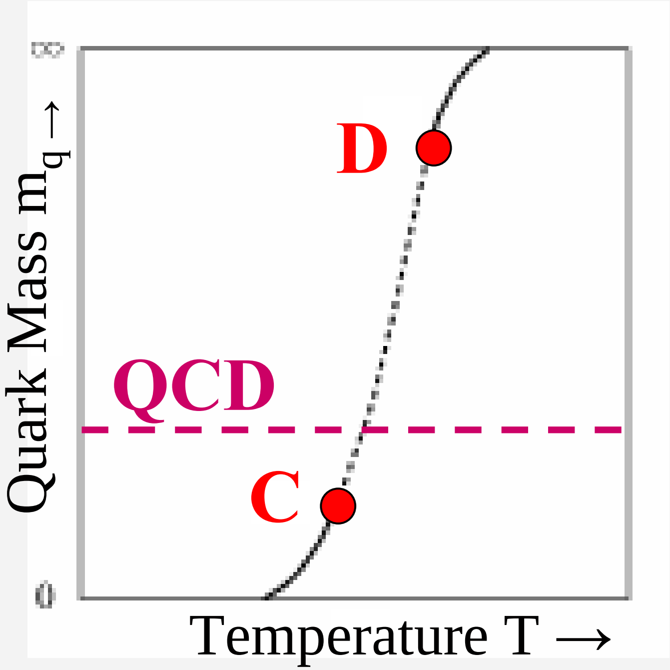
Star Observables [Reddy]

- bulk:
  R≤8km favors quark EoS
- probes:
  - in-medium **ν**-propagation
  - grav. wave signal from binary mergers **[Prakash]**

2.2 Confinement vs. Chiral Symmetry Breaking

Order Parameters:

- Chiral Symmetry ($m_q \to 0$): $\langle \bar{q}q \rangle$ (quark condensate)
- Deconfinement ($m_q \to \infty$): $\langle L \rangle$ (Polyakov loop)



at **C**: $m_\sigma \to 0$
at **D**: $m_G \to 0$

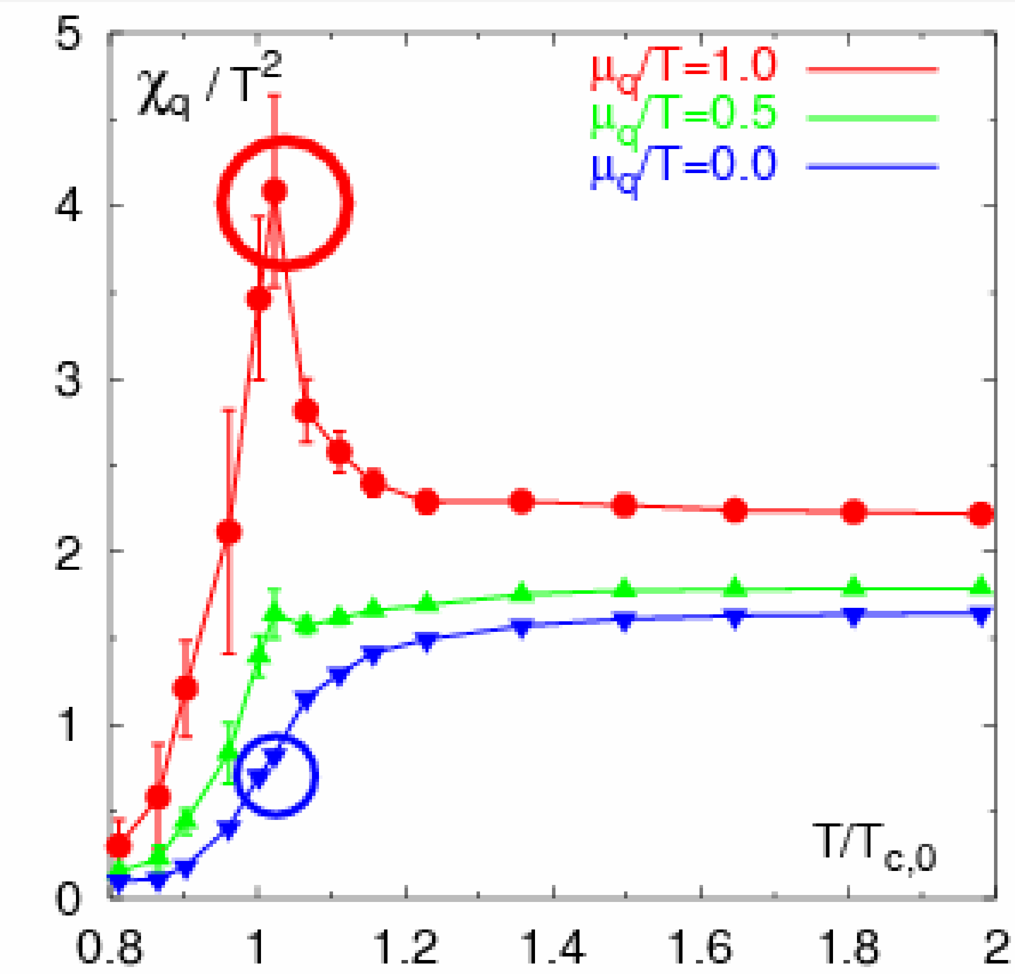
Mixing of σ-Meson and 0^{++} Glueball **connects** $\langle \bar{q}q \rangle$ and $\langle L \rangle$

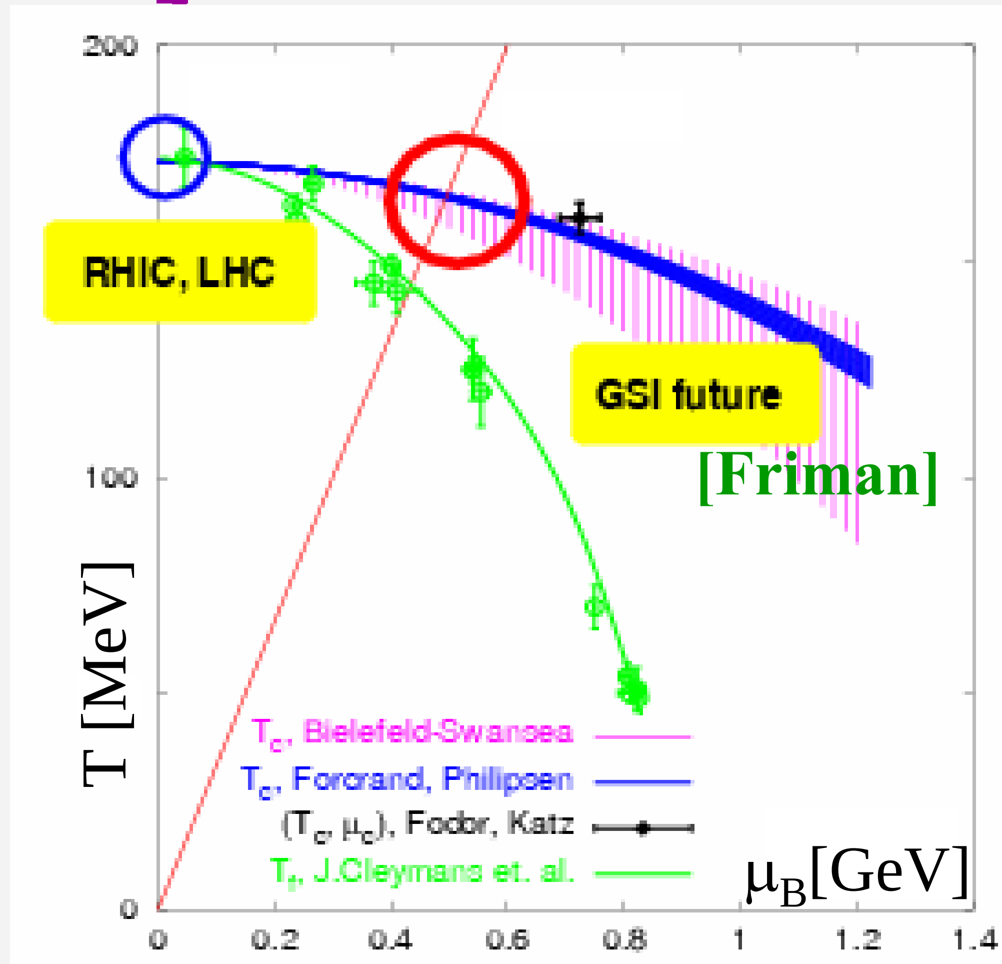
[Fukushima]

[Mocsy]: loop effects entangle $\langle L \rangle$ and $\langle \bar{q}q \rangle$

2.3 QCD Lattice for GSI: The Critical Point

Quark Number Susceptibility at μ_q>0 [Karsch,Redlich,Ejiri]





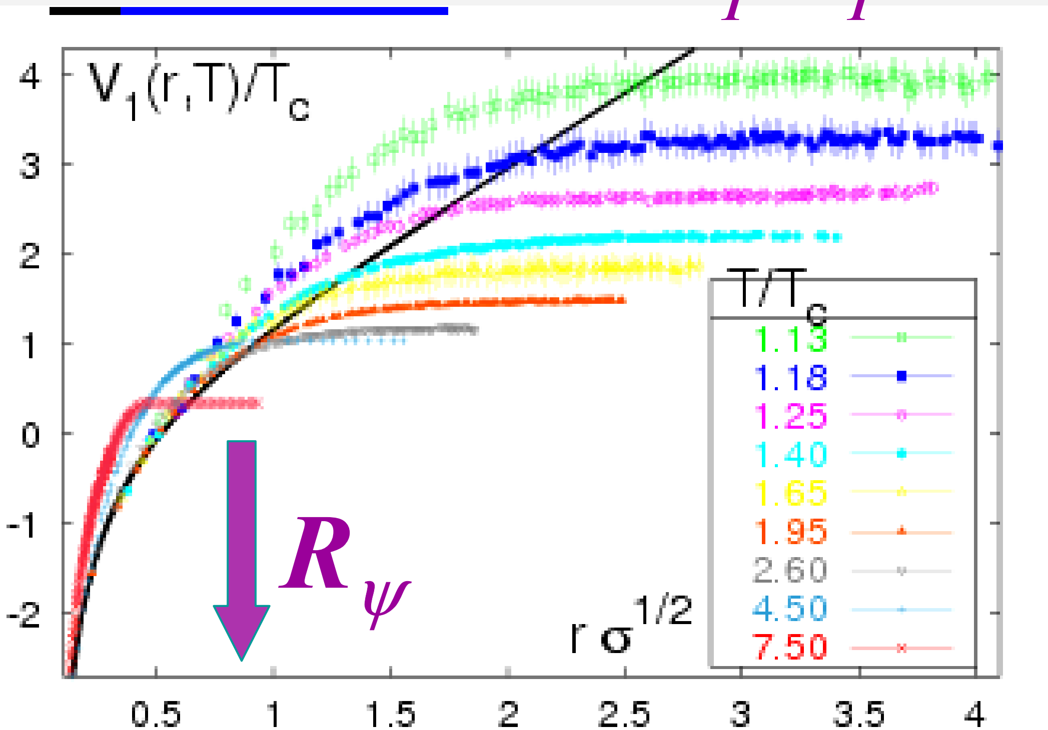
$\Rightarrow$ $\mu_{B,c} \geq$ *400 MeV* ([Fodor+Katz]: *~700MeV*)

2.4 QCD Lattice for RHIC: Charmonia [Karsch]

Singlet free energy:

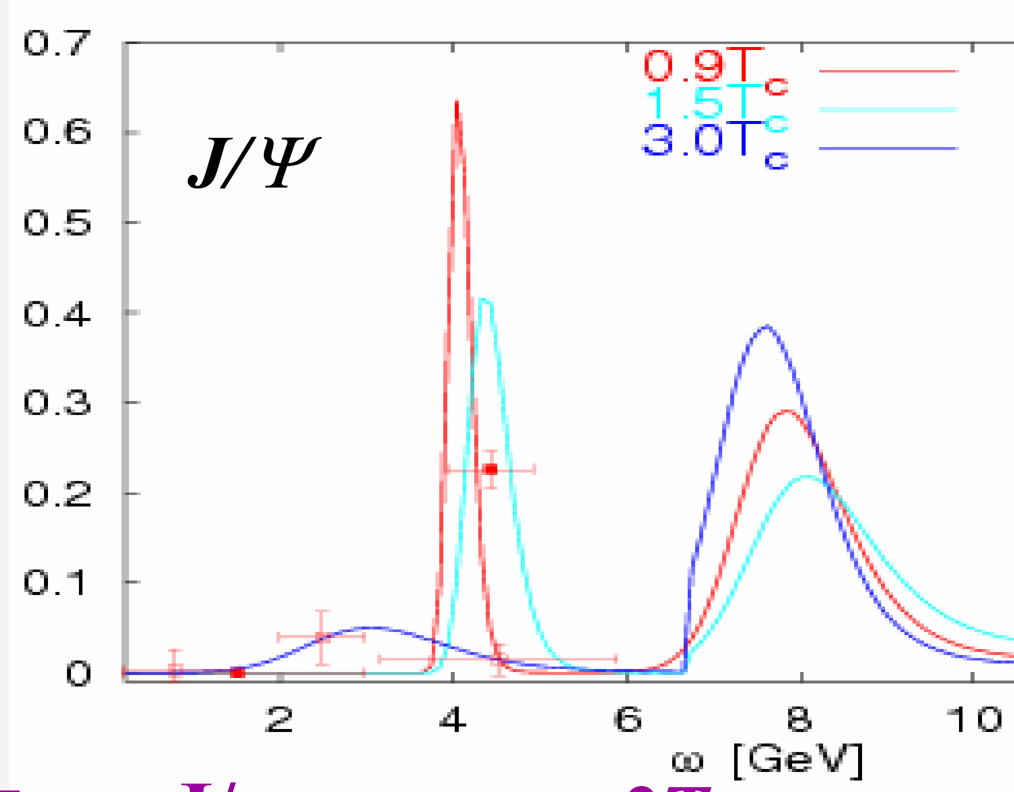
$exp(-F_1/T) = \langle \mathrm{Tr} L_r L_0^\dagger \rangle$

$c\bar{c}$ Potential from: $F_1 = V_1 - TS$



Spectral Functions

[Asakawa,Datta]



- suggests boundstates at $T \leq 1.5 T_c$
- reduced open-charm threshold?

- **J/ψ, η_c** up to $2T_c$
- **χ_c** dissolves close to T_c

3.) QCD Bulk Properties at RHIC

3.1 Initial: CGC

3.2 QGP : Opacity

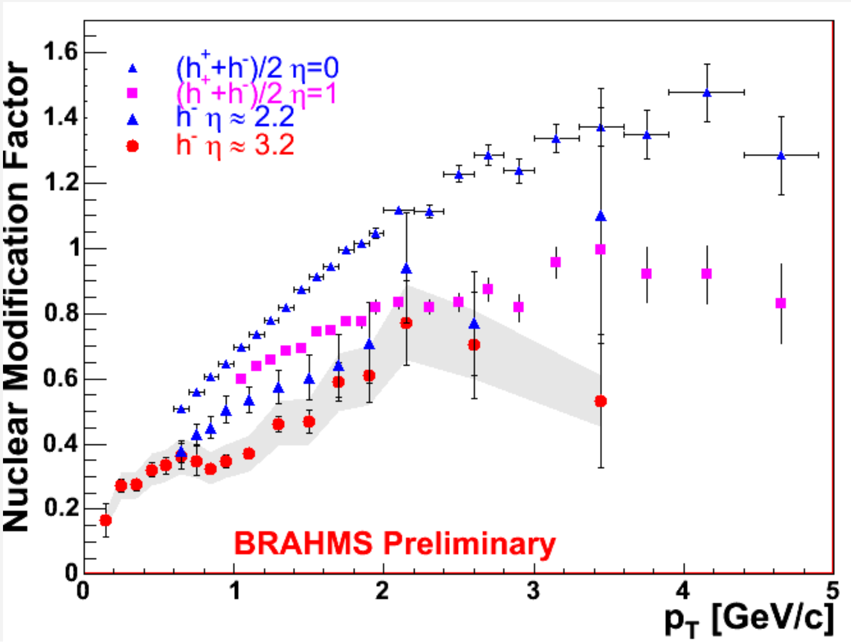
3.3 QGP : Thermalization (nonpert?)

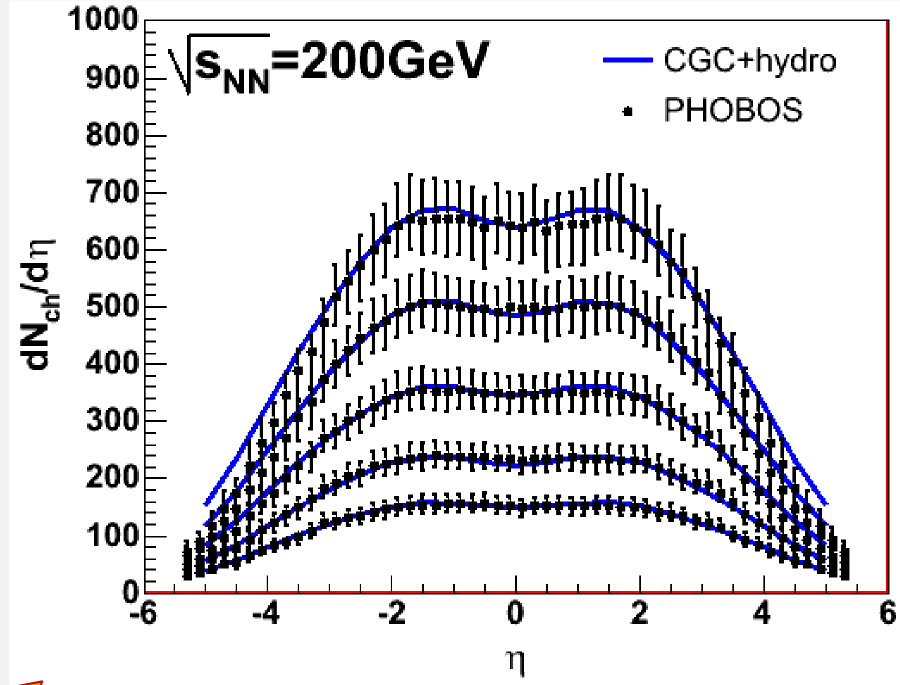
3.4 T_c : Quark Coalescence vs. Hydro

3.5 T_{fo} : HBT "Puzzle"

3.1 Pre-Equilibrium: Color Glass Condensate?

Look forward in d-Au

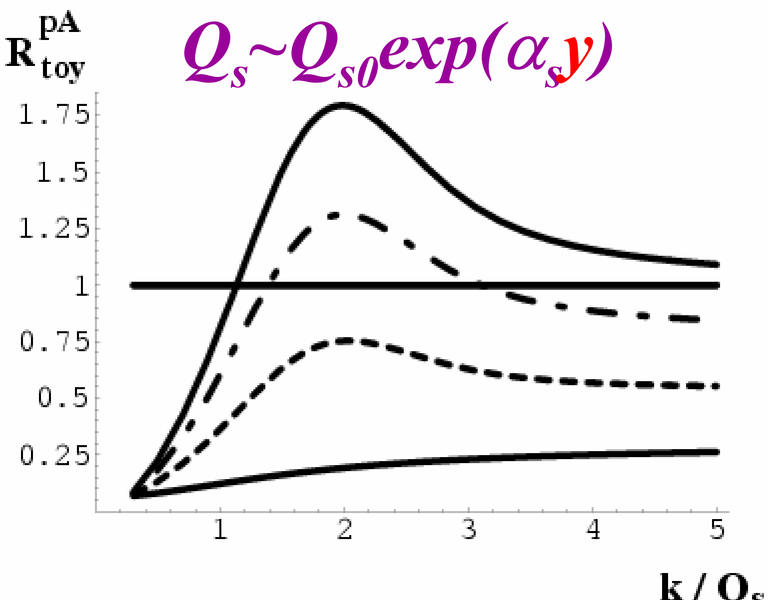




initial cond. in 3+1 hydro

[Hirano,Nara]

$Q_s \sim Q_{s0} exp(\alpha_s y)$



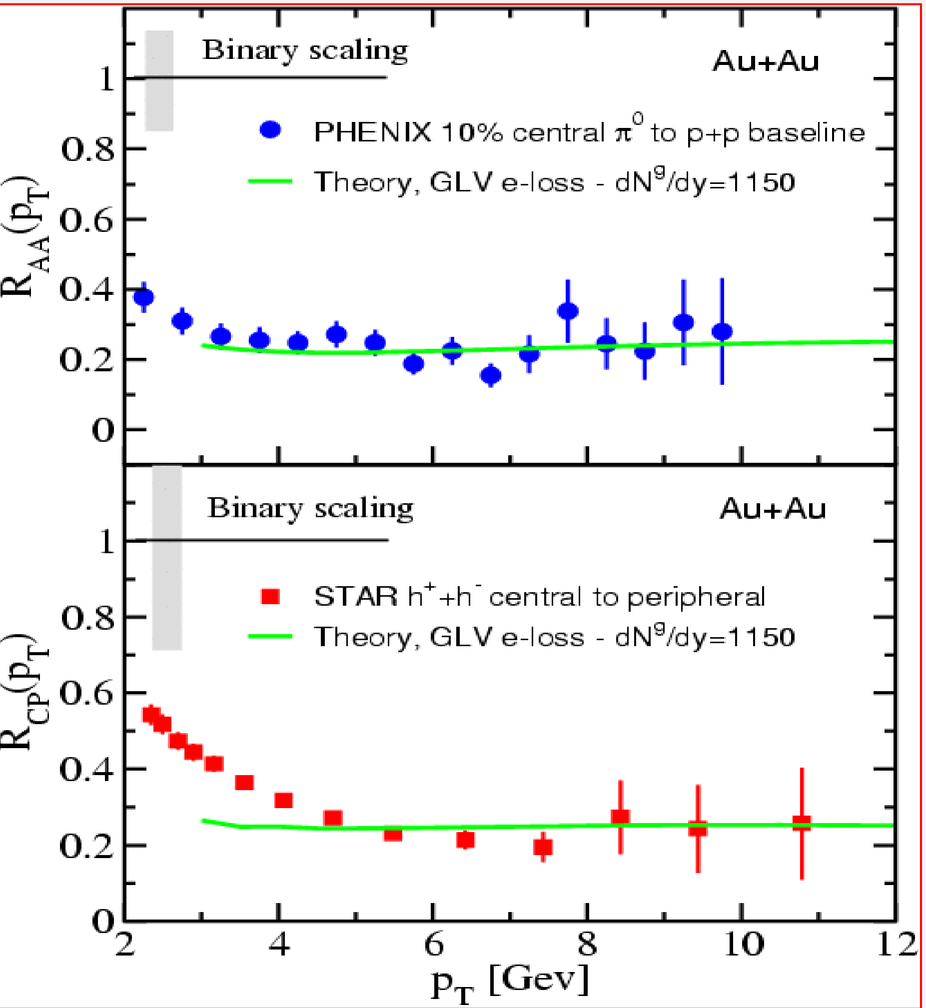
Qualitatively consistent with **CGC**

[Jalilian-Marian,Venugopalan,Kovchegov]

Note: valence-quark dominance (**$h^+/h^- > 1$**)

→ same suppression? rapidity energy loss?

3.2 Opacity of QCD Matter: High-p_t Frontier



- **GLV** works quantitatively, incl.
  - **d-Au** (+away-side broad.)
  - re-app. in-plane away-side jet
  - connection to DIS

  [Vitev,Majumder,Salgado, Accardi,Barnaföldi,Povh]

$\Rightarrow$ $\varepsilon_{ini} \approx 20$ **GeV/fm^3**

- **[Greiner]** : absorpt. of colorless "prehadrons" ; problems:
  - v_2 of supp.+bulk, - SPS ?!

Notes: - non-jet ***baryon/meson*** for **$p_T < 6$ GeV**

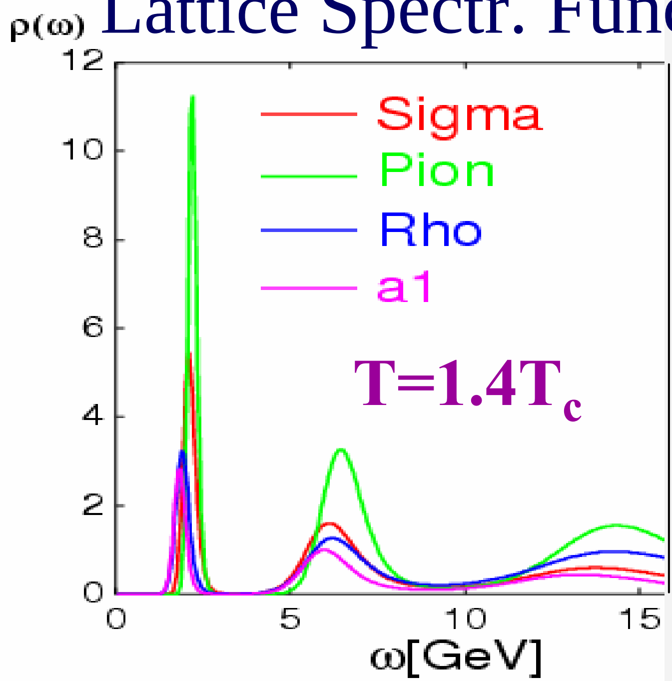
- where does R_{AA} rise again? LHC?!

3.3 Thermalization and Nonperturbative QGP

early thermalization ⟷ Hydro $v_{0,1,2,4}$ [Corrections: [Hirano,Heinz,Gavin]]

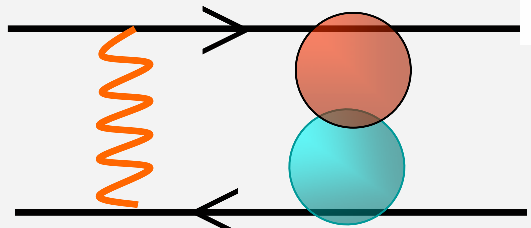
↳ Resonant $\bar{q}q$, qg , gg ↔ "meson" rescattering ?

Lattice Spectr. Functs.

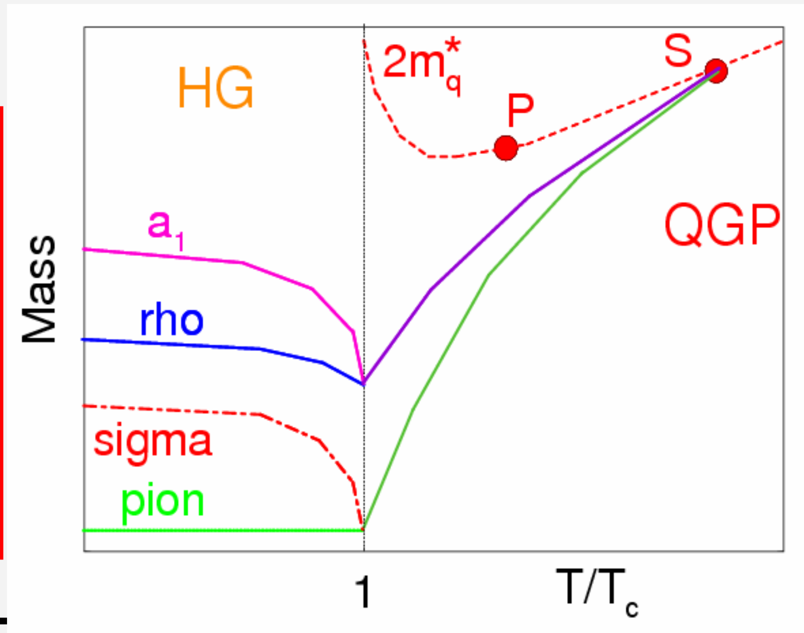


[Asakawa+Hatsuda]

above T_c:
Color-Coulomb
+Instanton-Mol.
$\alpha_s(m_D^2) \rightarrow 0.5$



Quasi-Quark "Boundstates"!



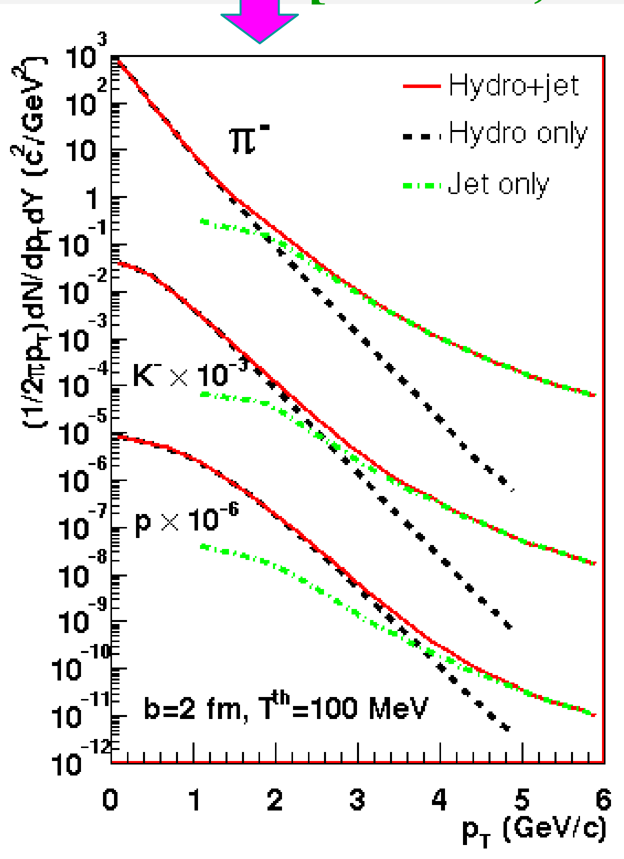
[Shuryak,Zahed,Brown, Polchinski]

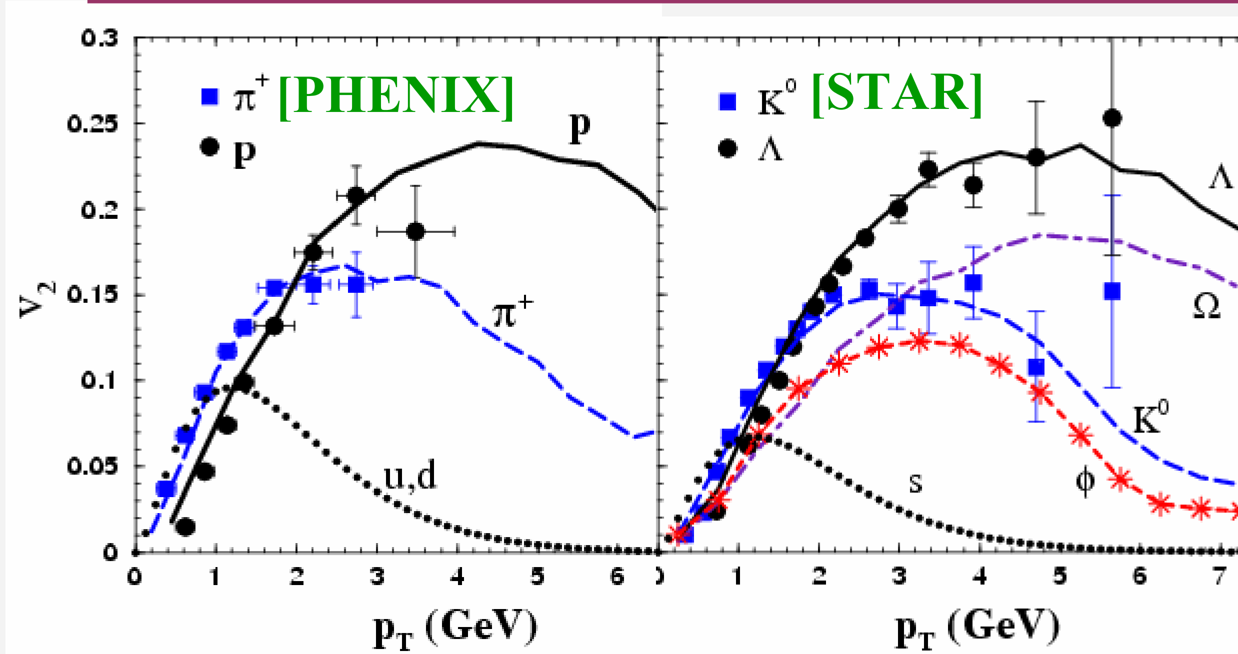
3.4 Hydro vs. Coalescence: The 2-6GeV Regime

[Hirano,Nara]

[Fries,Hwa,Molnar]

$$E\frac{dN_h}{d^3p} = g_h \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3q\, |\psi_h(\vec{q})|^2\, f_a(\vec{p}_a)\, f_b(\vec{p}_b)$$





[Greco et al.]

v_2: mass-dependent

But: p/π(4GeV)≈0.3

[PHENIX]: 1±0.15

⇒ universal partonic $v_2(p_T/n)$ / n

soft-soft ≈ thermal (p_T » m)

soft-hard: explicit thermal+jet (correlations!)

Challenges: **p/π=1 + jet correlation , φ elliptic flow**

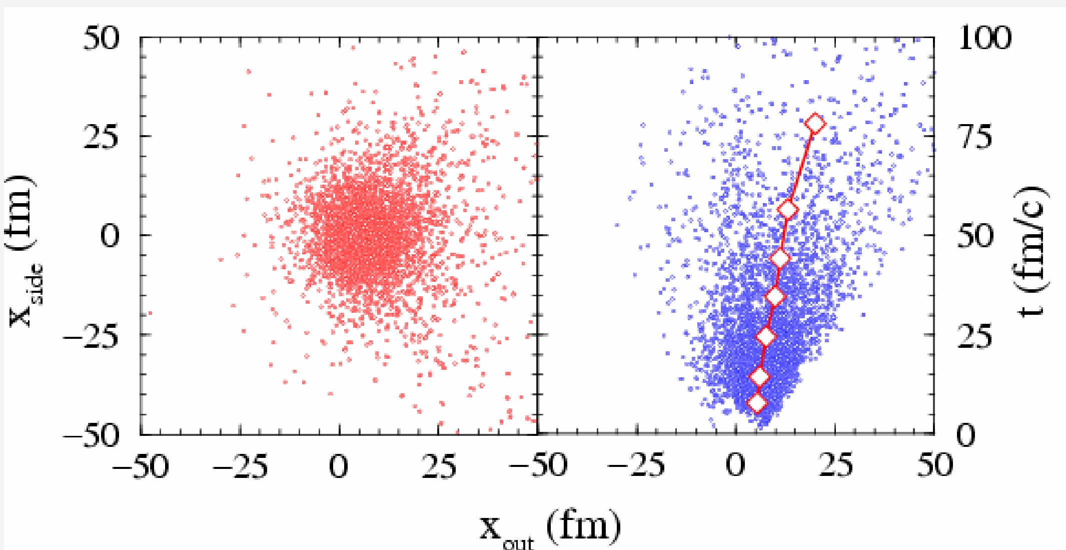
3.5 HBT "Puzzle"

Hydro/Transport models overpredict

$$(R_{out})^2 = D(x_{out}, x_{out}) - 2D(x_{out}, \beta_t t) + D(\beta_t t, \beta_t t)$$

Potential Remedies:

- **[Teaney]**: viscosity in hydro
- **[Kapusta,Wong]**: incl. quant. phases in rescatt. ↔ ***initial*** size?!
- Multiphase Transport Model **[Lin+Ko]**



positive $R_{out} - t$ correlation (not in Hydro, UrQMD …)

4.) Microscopic Probes of QCD Matter

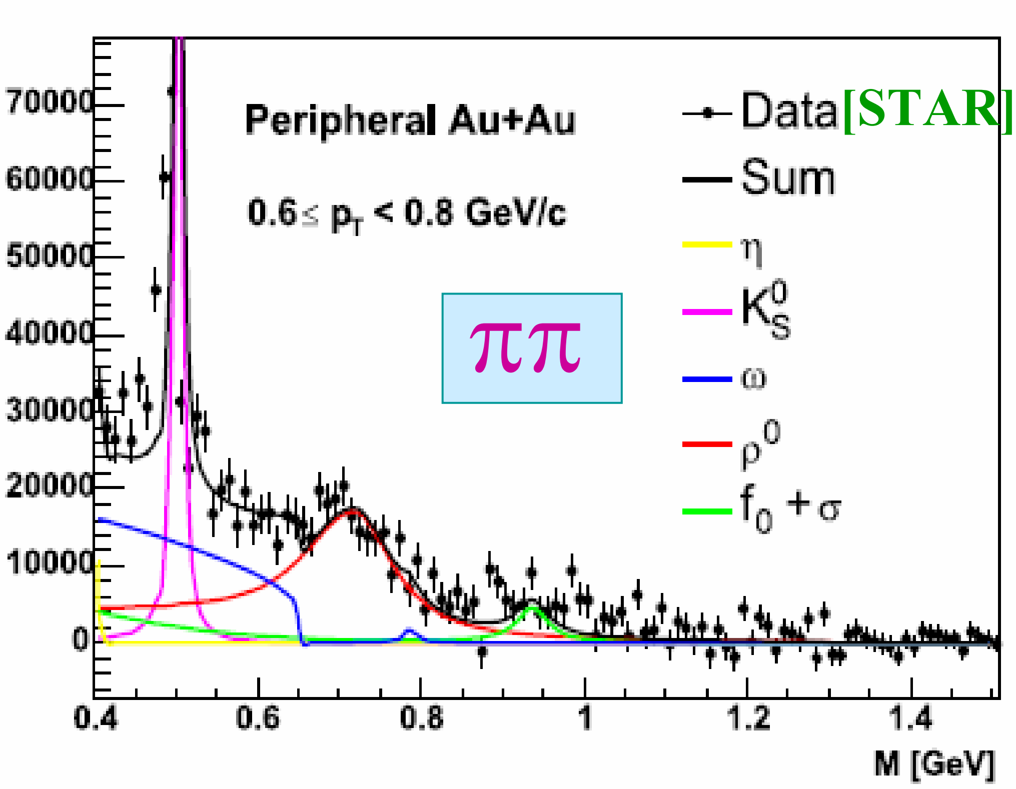
4.1 Hadronic In-Medium Effects:
Resonances and Chem. Freezeout

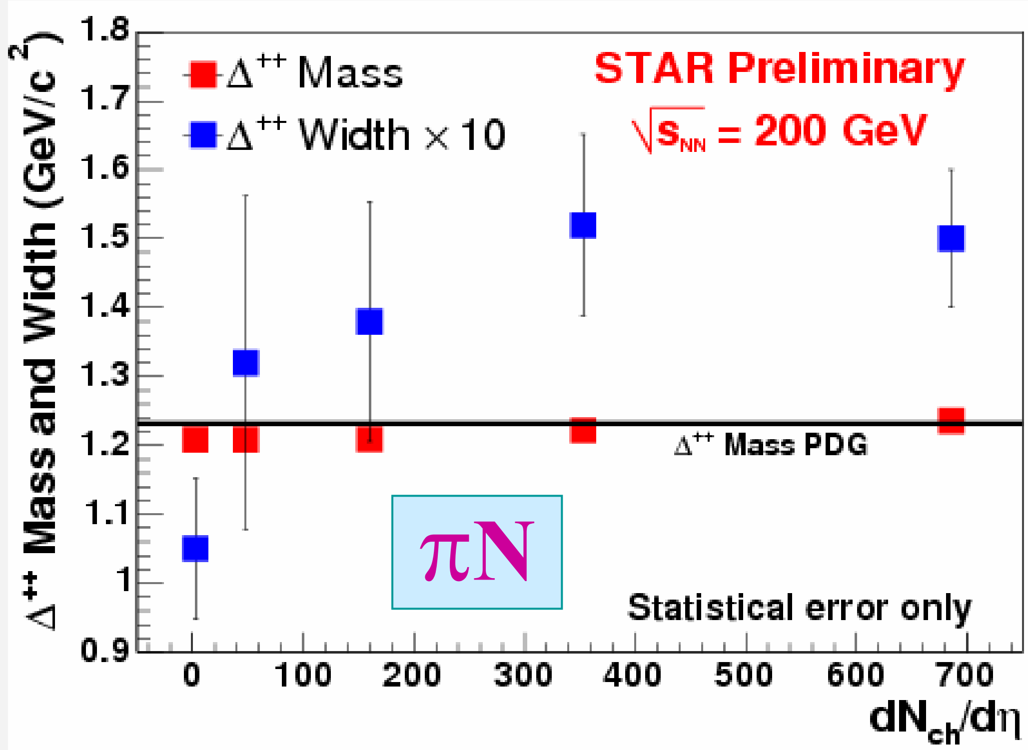
4.2 E.M. Emission

4.3 Charm/onium

4.1 Resonance Spectroscopy at RHIC

$\rho \rightarrow \pi\pi$, $\Delta \rightarrow \pi N$, $\tau_{\rho,\Delta} \approx 1.5 fm/c$, $T_{fo} \approx 110 MeV$, $n_\pi = \frac{2}{3} n_0$





Model fit: Δm_ρ=-50MeV [Florkowski]
But: Bose correlations, broadening,
nonres. "background", *p-p* ?
Also: ρ/π, f_0/π factor ~2 too small

Δ-mass $m_\Delta \approx const$
Δ-width Γ_Δ increases

From Thermal to Chemical Freezeout

at $T_c \approx 175 MeV$: **Chiral Restoration!**

⇒ chiral partners **must** degenerate (***m*** and Γ):

$\pi \equiv \sigma$, $\rho \equiv a_1$, $N \equiv N^*$ (or: $\pi \equiv \rho_L$ **[Harada]**)

⇒ Substantial medium modifications required

(supported by **CERES** dileptons, $\rho \rightarrow e^+e^-$)

Challenge: Reconcile with chem. f.o. systematics !?

(à la **[Braun-Munzinger+Stachel etal],…**)

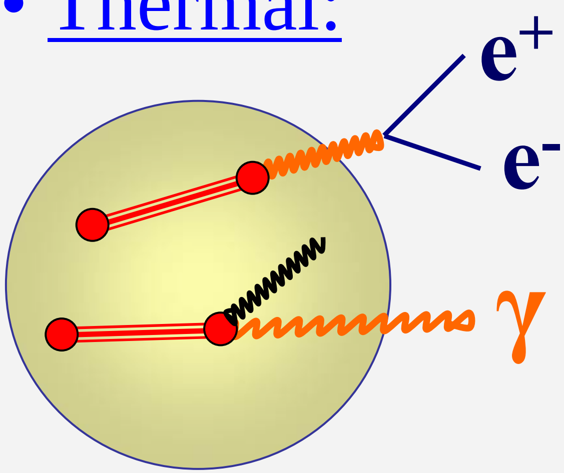
Optimistic: measure (and calculate!)

$a_1 \rightarrow \pi\gamma$, $N^*(1535) \rightarrow N\eta$

4.2 Direct Photons and Dileptons

Sources:

- Initial hard scatt.: Drell-Yan / Compton (tag jets! **[Gale]**)
- Pre-equilibrium: Radiation off jets **[Gale]** ,
  rescatt.+fragment. of secondaries (parton cascade **[Bass]**)
- Thermal:



$$\frac{dR_{ee}}{d^4q} = -\frac{\alpha^2}{\pi^3}\frac{1}{M^2} f^B(q_0,T) \;\; \mathbf{\mathit{Im}\, \Pi_{em}(M,q)}$$

$$q_0 \frac{dR_\gamma}{d^3q} = -\frac{\alpha}{\pi^2} f^B(q_0,T) \;\; \mathbf{\mathit{Im}\, \Pi_{em}(q_0=q)}$$

e.m. correlator

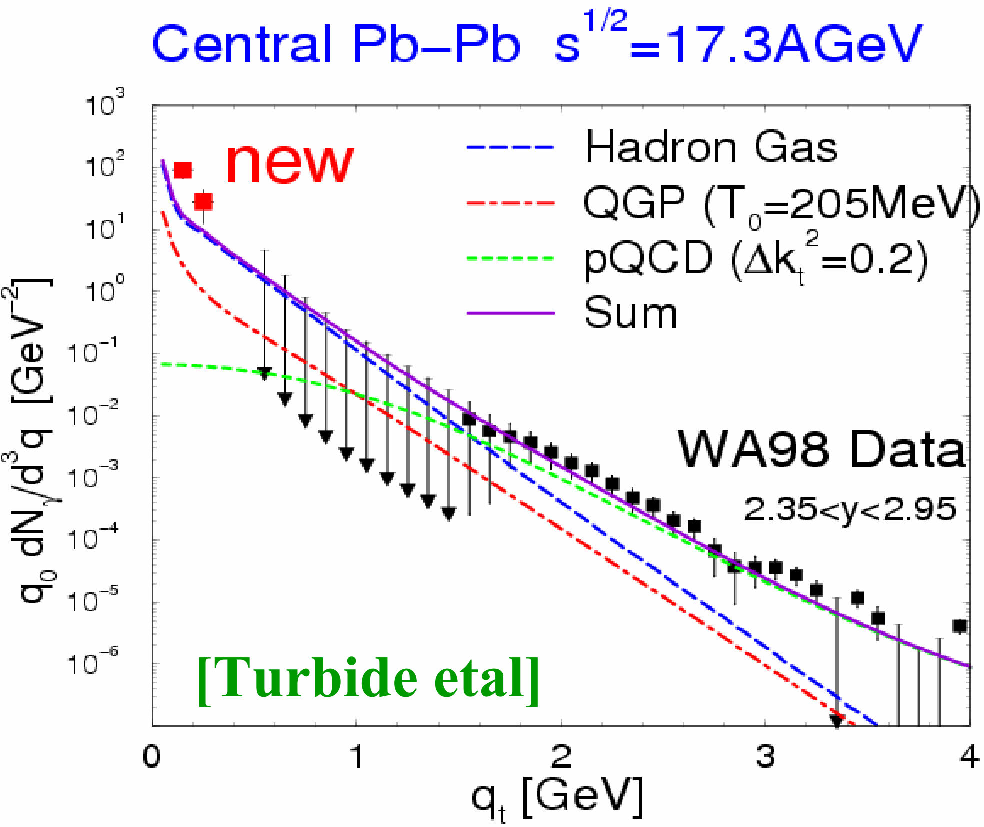
chemical off-equilibrium:

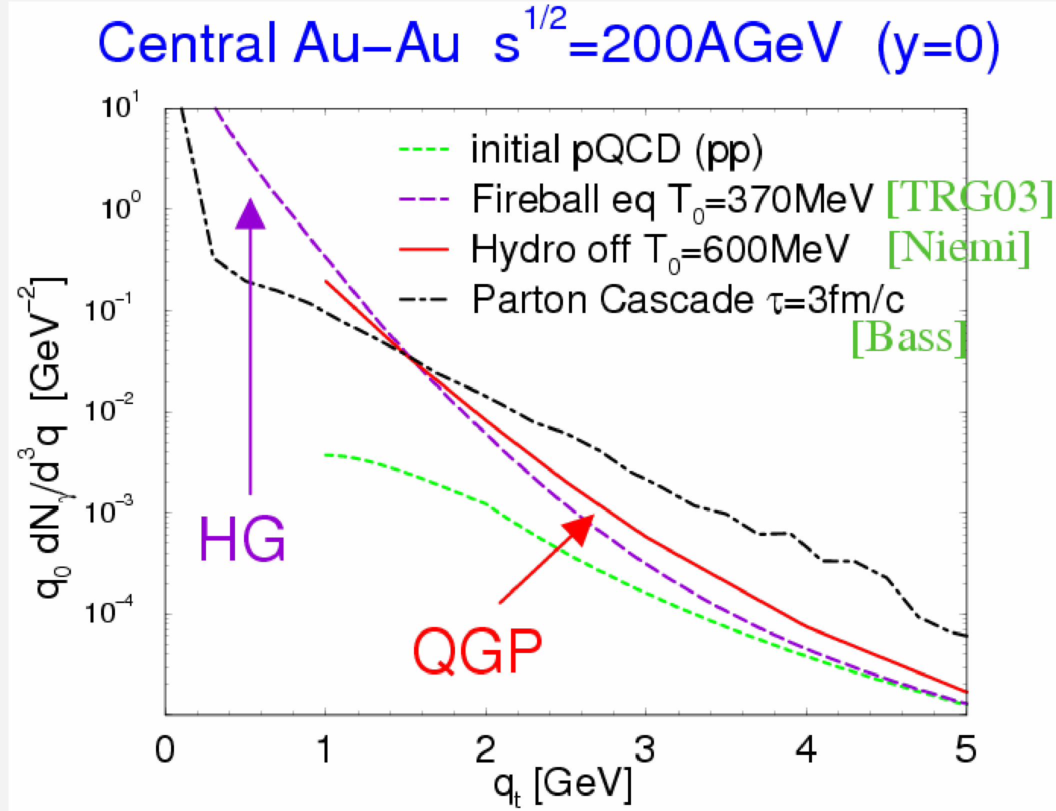
QGP: $\lambda_{q,g} \leq 1$

HG: $\mu_{\pi,K,..} > 0$

[Niemi,Moore]

Direct Photons at SPS and RHIC





- pQCD Cronin ~ π^0
  $\Rightarrow$ ***$T_0 \approx 205 MeV$*** sufficient
- new **WA98** points:
  ππ-Bremsstr. via soft σ ?
- large "pre-equilibrium" yield
  from parton cascade **(no LPM)**
- thermal yields ~ consistent
- QGP undersaturation small effect

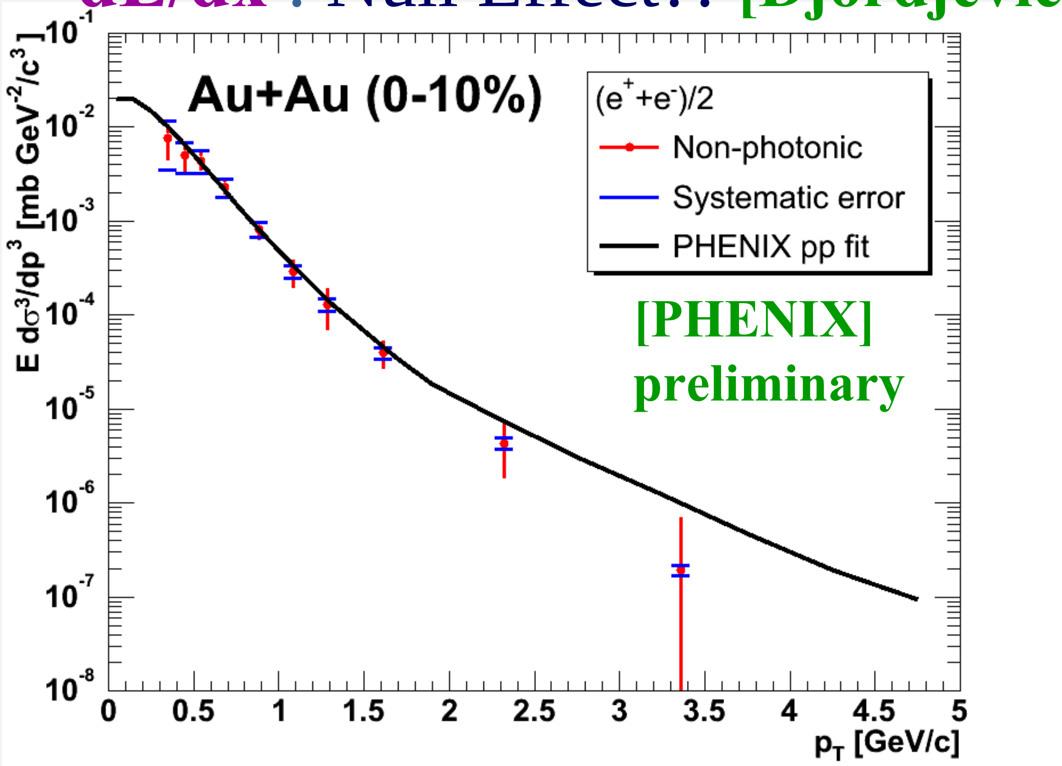
4.3 Charm I: Open Charm (Central A-A)

(i) Yields

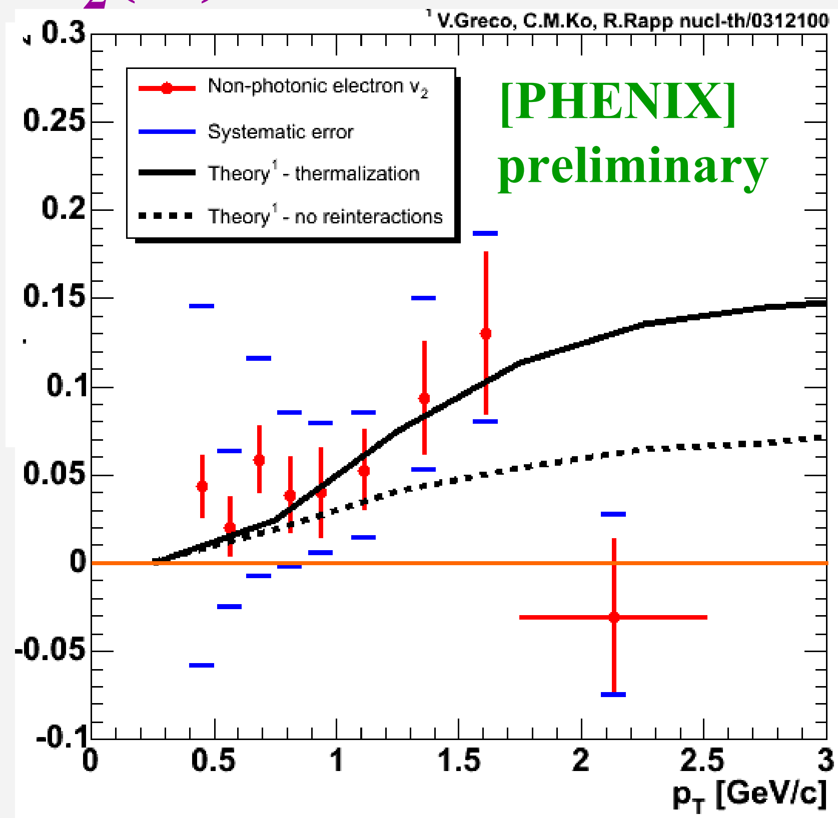
- RHIC: -30% for η=0→2: CGC [Tuchin], Color-Dipole [Raufeisen]
- LHC: CGC: N_{part} ; nonlin. DGLAP: enhanced! [Kolhinen]

(ii) p_T-Spectra

dE/dx : Null Effect?! [Djordjevic]



$v_2(e^{\pm})$: Thermalization?!



4.3 Charm II: Charmonium

- RHIC central: $N_{cc} \approx 10\text{-}20$,
- QCD lattice: J/ψ's to $\sim 2T_c$

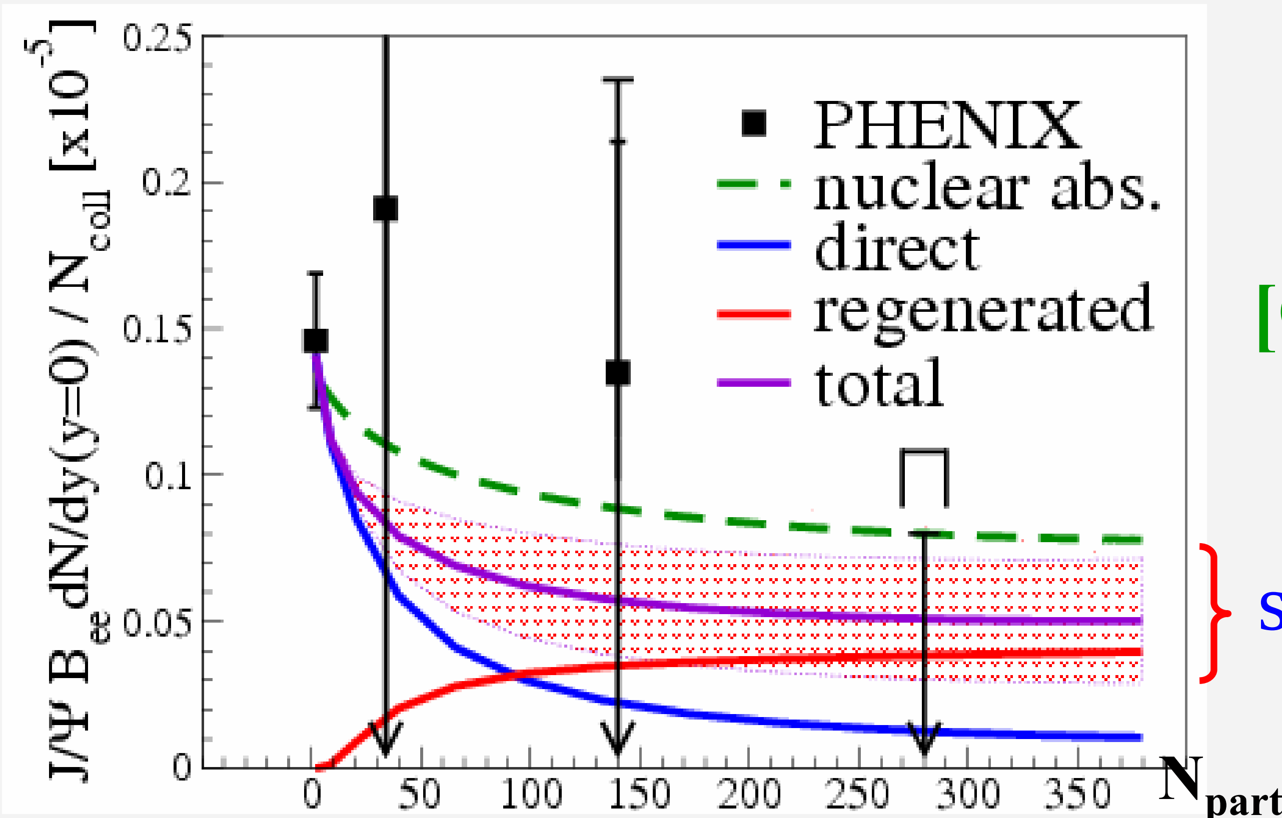
Regeneration in **QGP** / at T_c

$$J/\psi + g \rightleftarrows \bar{c} + c + X$$

[PBM etal, Thews etal]

If **c**-quarks thermalize:

$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi (N_\psi - N_\psi^{eq})$$



[Grandchamp]

sensitivity to m_c^*

5. Conclusions

Produced Matter at RHIC is

- **Dense (opacity)**
- **Thermalized (hydro)**
- **probably nonperturbative (resonances,…)**

Microscopic probes required to assess the phase transition

**Need to find broad consensus on signatures
to go beyond circumstantial evidence from the SPS**