

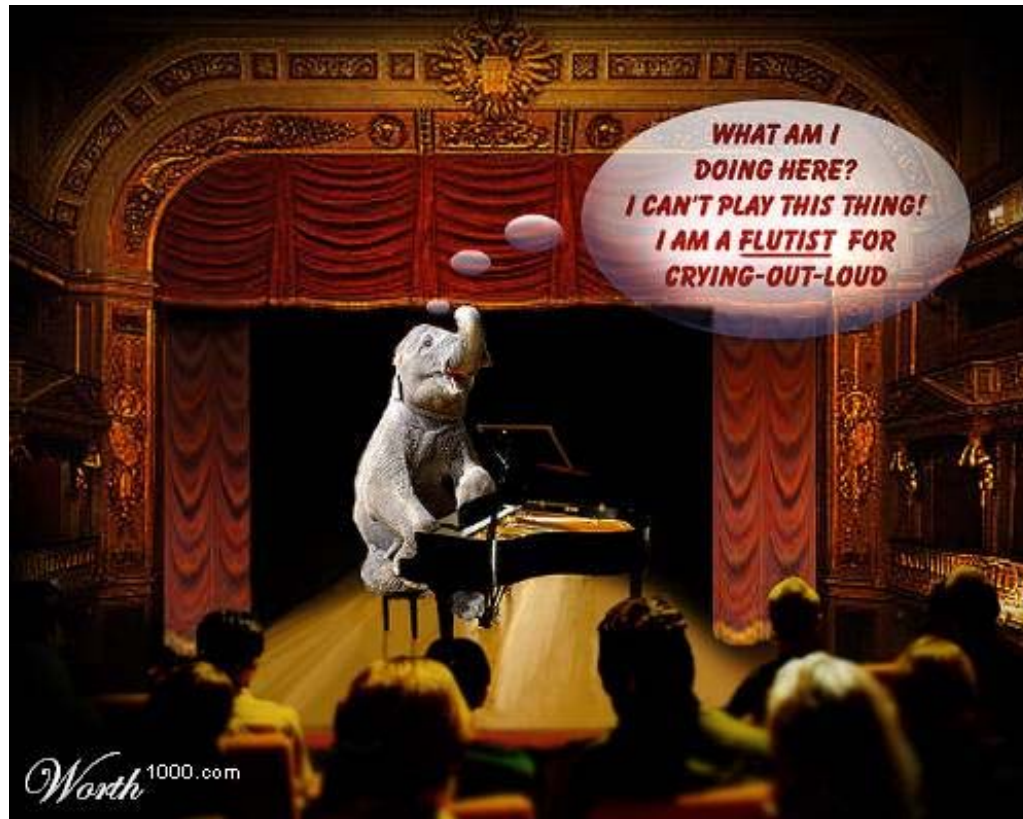


Quark Matter 2005

Theoretical Summary

Budapest: 4 - 9 August 2005

In case you wonder...



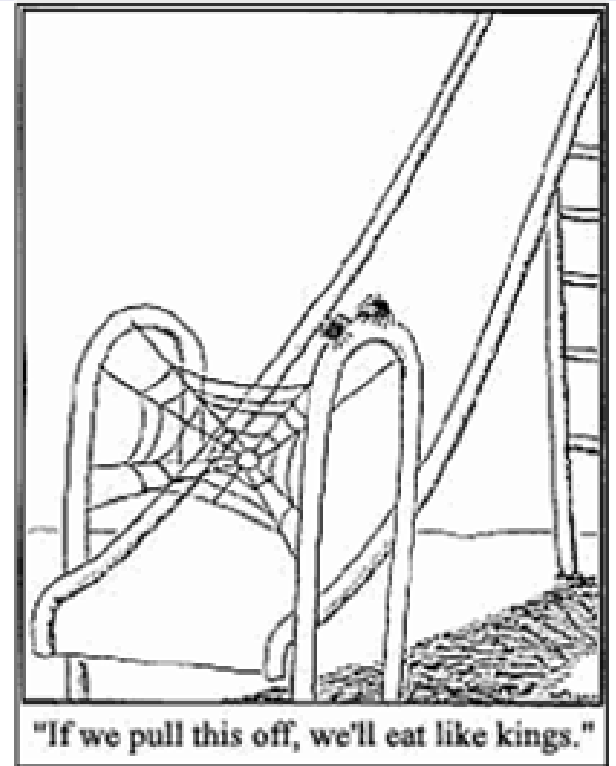
What we need from theory...

- **New** ideas – good and bad.
- Diligent work on good **old** ideas.
- Safe disposal of bad **old** ideas.

- Make sense of data.
- Suggest new experimental tests and analyses.

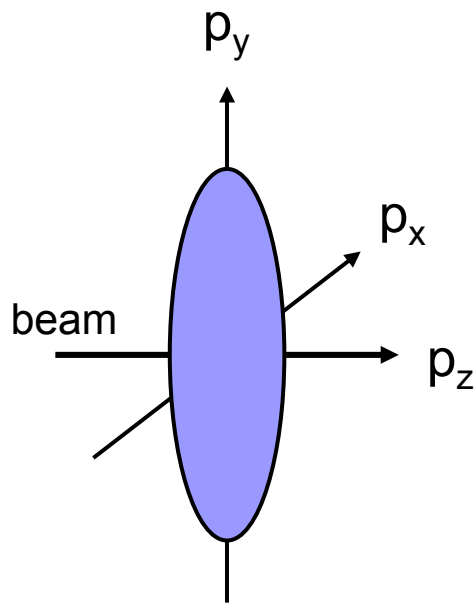
(GOOD & BAD)

NEW
IDEAS



Color instabilities

Unstable modes occur generally due to the anisotropy of the momentum distribution:



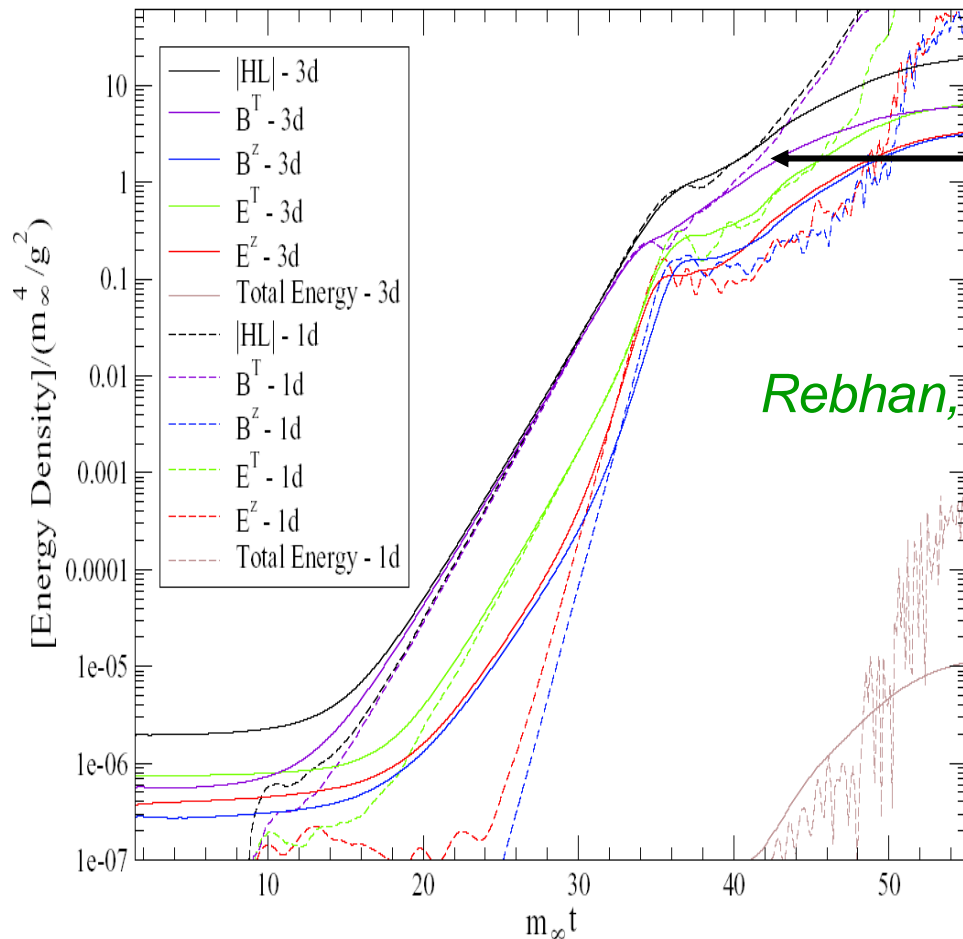
$$\langle (\Delta p_x)^2 \rangle = \langle (\Delta p_y)^2 \rangle = Q_s^2 \gg \langle (\Delta p_z)^2 \rangle \quad \text{for } \tau \gg \frac{1}{Q_s}$$

Wavelength and growth rate of unstable modes can be calculated perturbatively:

$$k_z \sim gQ_s, \quad \gamma \sim gQ_s < k_z$$

Mrowczynski, Strickland, Nara

Color instabilities (2)



Exponential growth
moderates when

$$B^2 > g^2 Q_s^4, g^2 T^4.$$

Rebhan, Romatschke, Strickland (Nara)

$$\text{Force} = g \mathbf{v} \times \mathbf{B} = dp/dt$$

$$\Delta p \sim p \quad \text{for} \quad t = t_{\text{iso}}$$

$$t_{\text{iso}} \sim \frac{gB}{p} \sim g^2 Q_s, g^2 T$$

Note: $t_{\text{iso}} \sim S/(dS/dt) = \lambda^{-1}$

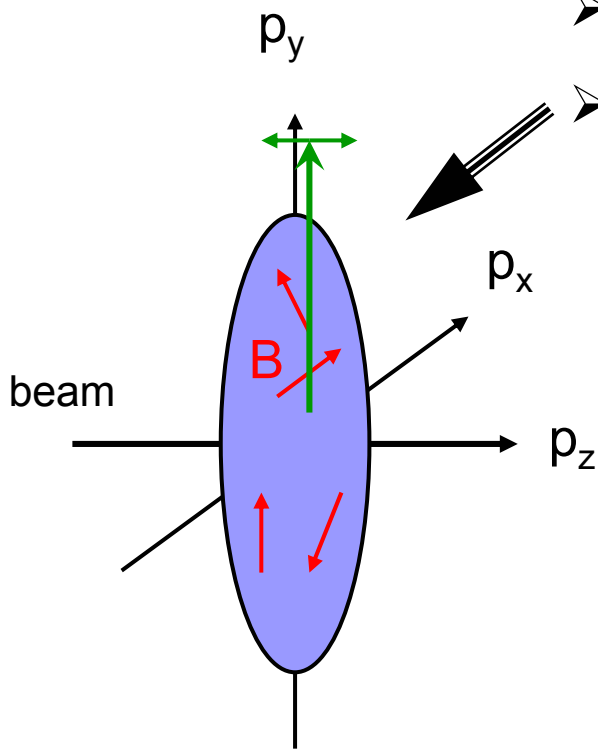
in classical gauge fields

Color instabilities (3)

1. Are the classical fields observable?

➤ v_2 fluctuations? (Mrowczynski)

➤ $r_\eta > r_\phi$ for jets cones?



2. Fields will persist at late times and counteract viscosity effects ($P_{zz} \neq P_{\perp\perp}$):

Effective *chromomagneto*hydrodynamics (CMHD) description may be possible (?)

Thermalization by “black magic”

Quantum fields in accelerated frames appear thermal with $T = a/2\pi$.

Application to AA collisions suggests “thermalization” time $t \sim \pi/Q_s$ (Kharzeev).

Interesting, but
not entirely new
concept

Interpretation of external fields as temperature

B. Müller, W. Greiner, J. Rafelski [*Phys. Lett. A* 63 (1977) 181]

“We show that average excitation of the vacuum state in the presence of an external electric field can be described by an effective temperature $kT = eE/(2\pi m)$.”

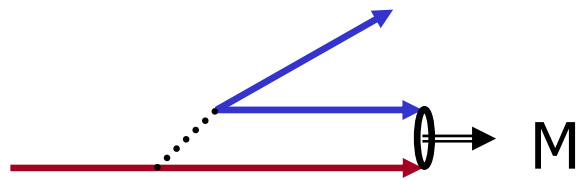
Not quite clear how far it carries:

Problems even in QED, because $a = F/m$, and forces (except gravity) distinguish particles by their charge. Temperature does not.

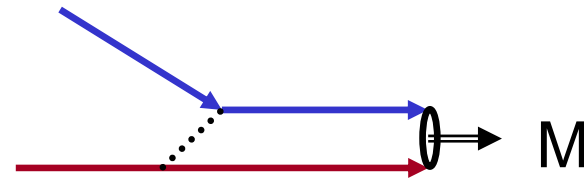
Moreover, QCD radiation can be generated by “rotation” rather than acceleration of color charges.

Other new ideas

- Jet-induced Mach cones (\rightarrow Ruppert's talk)
- DWBA treatment of FSI in HBT (**Cramer**) includes last inelastic interaction of emitted particles (not kinetics!) Correct V_{opt} ? Consistent μ_{π} ? Apply to other hadrons.
- Recombination (hard-soft) as medium contribution to fragmentation function (**E. Wang**).



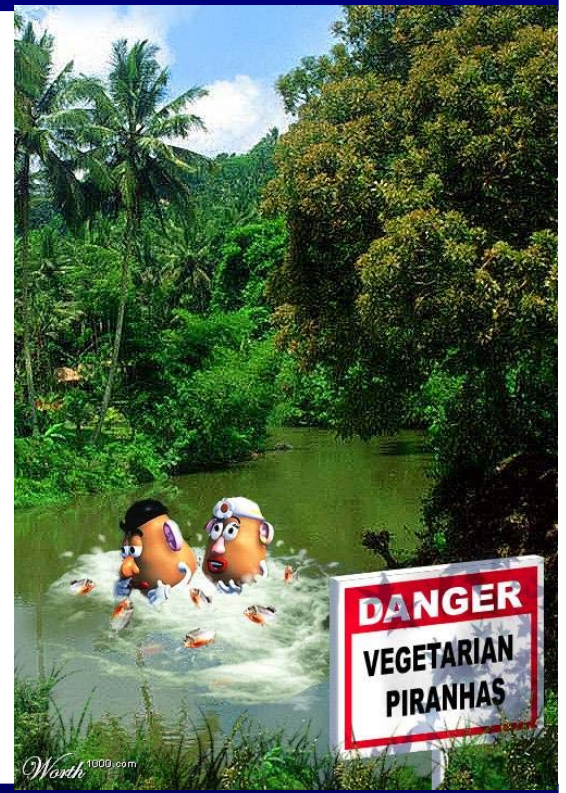
fragmentation



recombination

GOOD
(AND NOT SO GOOD)

OLD IDEAS



3-D Hydrodynamics

- New 3-D relativistic hydro code (SPheRIO) with continuous freeze-out available (**Hama**).
- 3-D hydro code with partial hadrochemical equilibrium (**Hirano**). Understanding of $v_2(\eta)$ requires improved treatment of hadronic freeze-out.
- 3-D hydro code with transition to hadronic cascade at $T_f < T_c$ (“hydro+micro” approach – **Nonaka**).
- We now need to see systematic studies of AA phenomenology: flow, hadron spectra, imbedded hard probes (photons, jets).
- Immediate goal is determination of EOS and $s(x,t)$ from data.
- How far can we go without QGP viscosity?

Parton transport

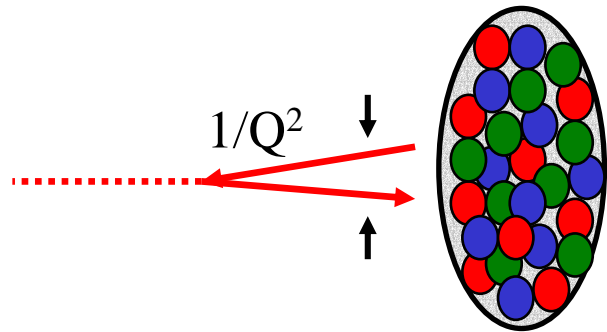
- Connection between shear viscosity and charm energy loss / flow (**Teaney**). Collisional Langevin equation for charm quark:

$$\frac{dp}{dt} = \eta_D p + \xi(t) \quad \text{with} \quad \eta_D = \frac{T}{MD}, \quad \langle \xi_i(t) \xi_k(t') \rangle = \frac{2T^2}{3D} \delta_{ik} \delta(t-t')$$

$$\text{pQCD: } D \approx \frac{6}{8\pi\alpha_s^2 T} \approx 6 \frac{\eta}{sT} \xrightarrow[\text{Data}]{\text{PHENIX}} D = \frac{3 \cdots 6}{2\pi T} \Leftrightarrow \frac{\eta}{s} = \frac{1 \cdots 2}{4\pi}$$

- Scattering on “D-meson” like bound states in the plasma (**Rapp**).
- Radiative energy loss implies $R_{AA}(e) > 2R_{AA}(\pi)$ (**Djordjevic**).
- Parton cascade with $gg \leftrightarrow ggg$ and detailed balance equilibrates rapidly (**Xu**). More efficient than σ_{tr} would naively suggest.
- Are parton cascades with huge σ 's (**Molnar, Zhang**) really telling us anything useful, except the obvious, or are they misleading?

Gloun saturation & CGC



Color glass condensate (CGC)

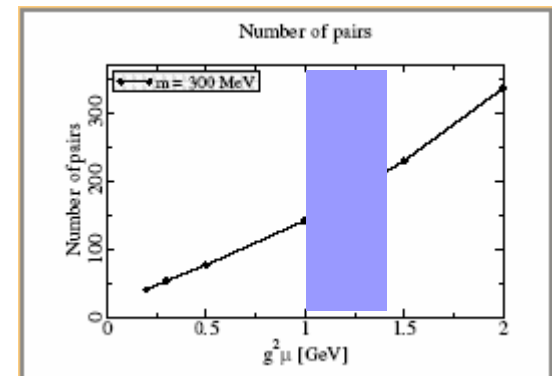
= universal form of saturated gluon fields

$$Q_s^2(x, A) \sim A^{1/3} x^{-\lambda}$$

Review of status of CGC field ([Itakura](#))

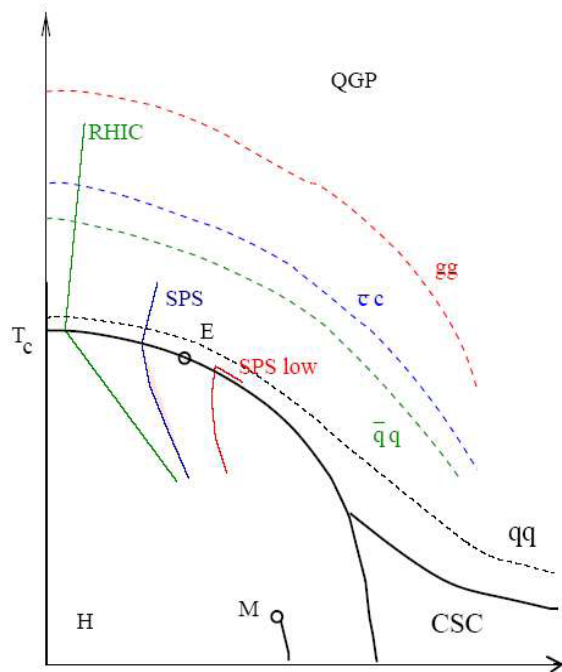
Relevant to forward hadron production in d+Au ([Jalilian-Marian](#)) ?

Quark pair production in strong CGC fields ([Lappi](#)): Very efficient – maybe more light quarks than gluons ! Most pairs produced by colliding gluon CGC sheets, not equilibrating gluon fields.



Crossing the road...

...to the Bound State QGP



Chicken on the way to the BS-QGP side of the road.

Testing the BS-QGP idea

1. Baryon number – strangeness correlation (Koch):

$$C_{BS} = -3 \frac{\langle \delta B \cdot \delta S \rangle}{\langle (\delta S)^2 \rangle} = -3 \frac{\langle BS \rangle}{\langle S^2 \rangle}$$

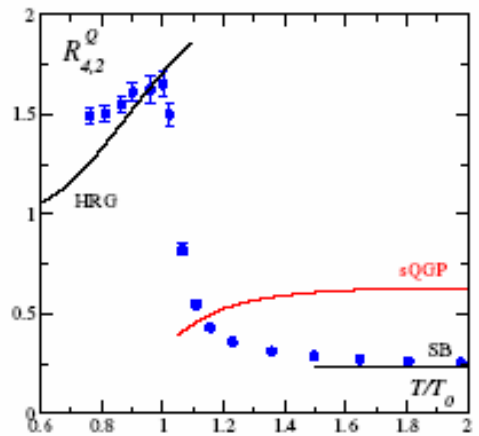
$$\text{pQGP: } C_{BS} = 1 \text{ [s]}$$

$$\text{HG } (T_c): C_{BS} = 0.66 \text{ [K, } \Lambda, \dots]$$

$$\text{BS-QGP } (1.5T_c): C_{BS} = 0.61 \text{ [s-qbar]}$$

$$\text{Lattice: } C_{BS} = -\frac{1}{3} \frac{\langle \frac{1}{3}(u+d+s)(-s) \rangle}{\langle (-s)^2 \rangle} = 1 + \frac{\chi_{us} + \chi_{ds}}{\chi_{ss}} = 1 + \frac{0.00(3)}{0.53(1)}$$

2. Baryon number – electric charge (BQ) correlation (Karsch):
Probes for qq states.



Conclusion:

(qq) and (q-qbar) ruled out. Can this method be extended to (qg) & (gg), maybe by means of γ_g ?

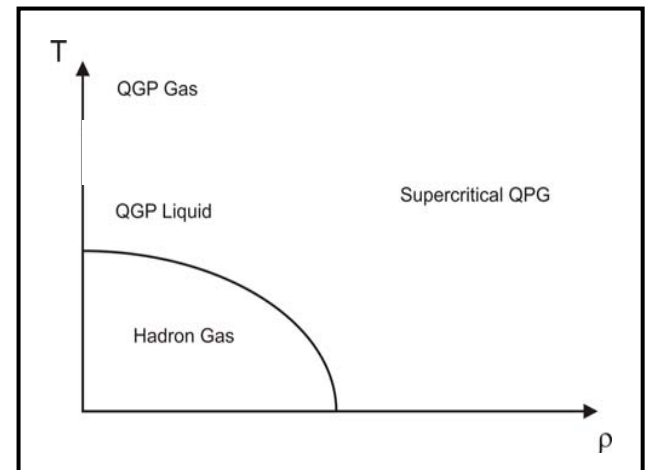
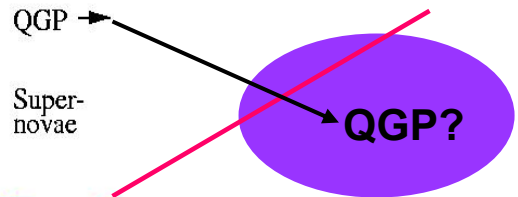
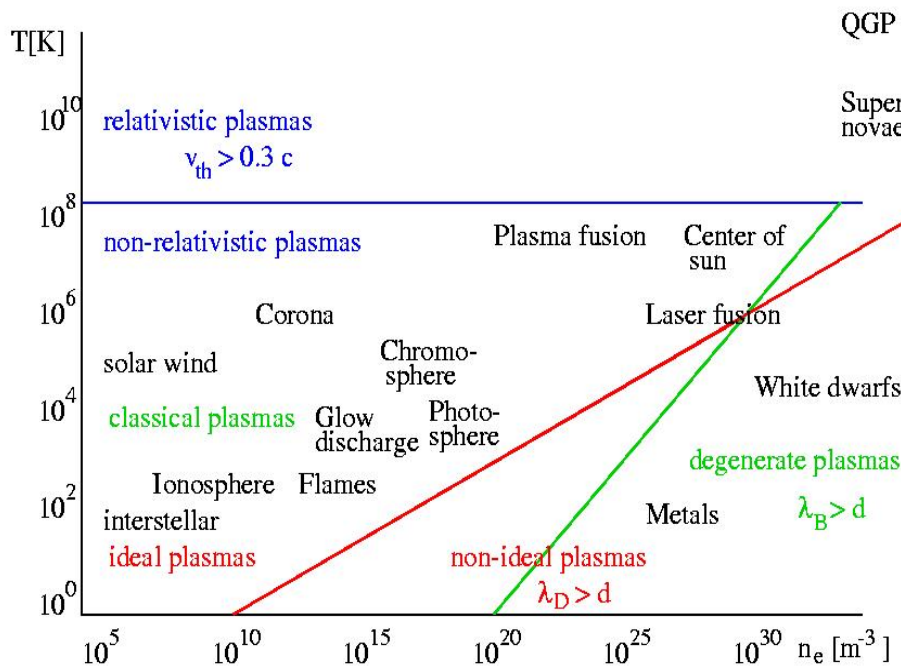
The sQGP challenge

Strongly coupled EM plasmas may provide guidance (Thoma).

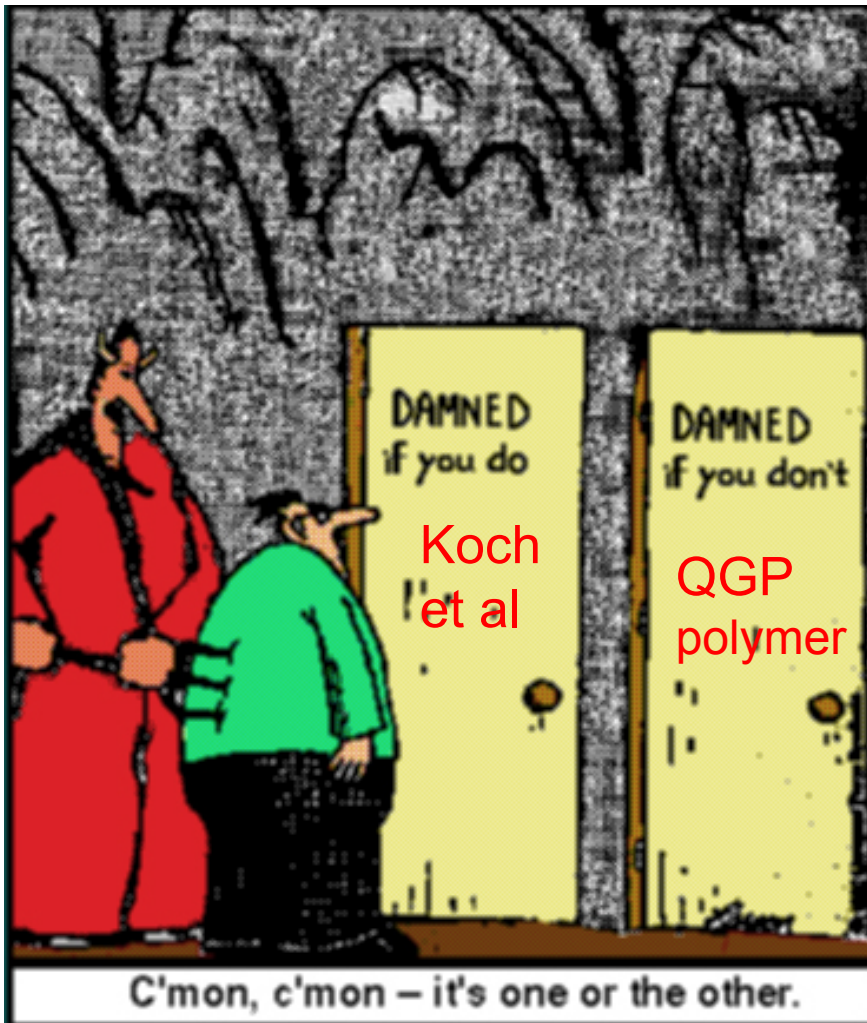
$$\Gamma = \frac{Q^2}{dT} \rightarrow (2) \frac{C_2 \alpha_s}{dT} \geq 1$$

sQGP could be a dense gas or a liquid.

Pair correlation function $g(r)$ will tell.



The prisoner's dilemma...



Prisoner's
RULE #1:

Avoid the
dilemma!!!

QCD molecular dynamics?

$$\frac{dp_i^\mu}{d\tau} = gQ_i^a F^{a\mu\nu} v_{i\nu} \oplus \frac{dQ_i^a}{d\tau} = gf_{abc} A^{a\mu} Q_i^c v_{i\mu}$$

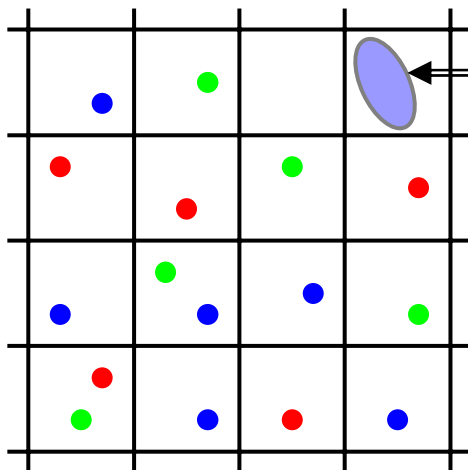
Wong

$$\partial_\mu F^{a\mu\nu} = j^{a\nu} \equiv \int d\tau \sum_i gQ_i^a v_i^\nu \delta(x - \xi_i(\tau))$$

Heinz

Reproduces HTL pert. th. at weak coupling (Kelly, Liu, Lucchesi, Manuel)

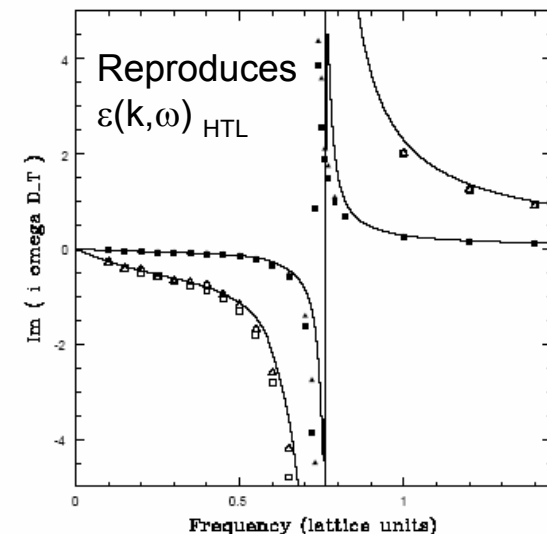
Lattice/particle formulation exists (Hu, BM, Moore, also Dumitru, Nara)



Collisions of particles within the same cell could be easily added

Well suited for studies of equilibrium properties.

Hartmann, Shuryak



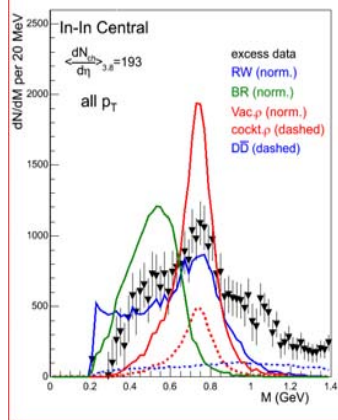
Phenomenology



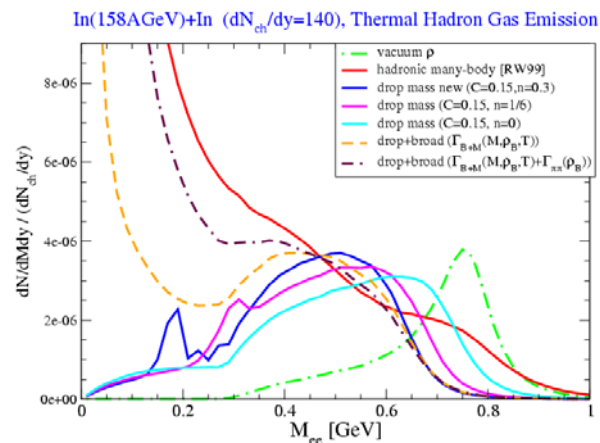
EM probes

- Beautiful review (Gale) – little to add.
- Photons: Good (improvable) theory can be a powerful tool !
- Lepton pairs: The fun starts now !
 - Can we rule out certain models, e.g. ρ mass shift only?

NA60



Courtesy: R. Rapp



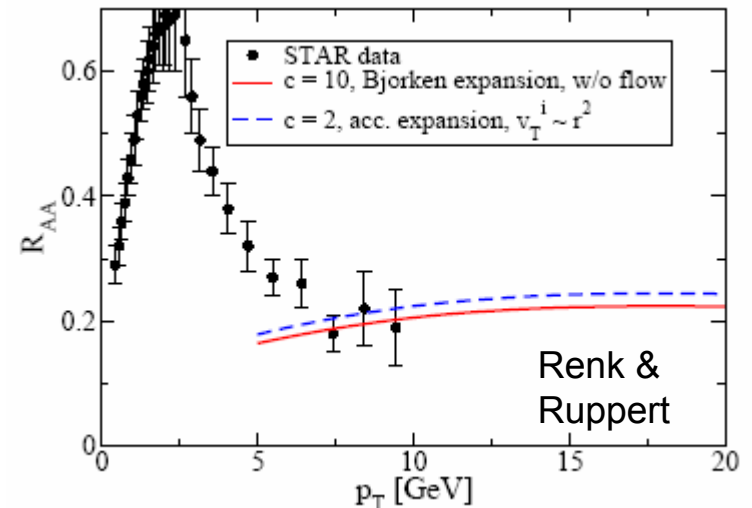
Useful to incorporate general predictions of QCD (no Δm without Γ) and to explore implication for broader questions:

What is the path to chiral symmetry restoration and deconfinement?

Jets & energy loss

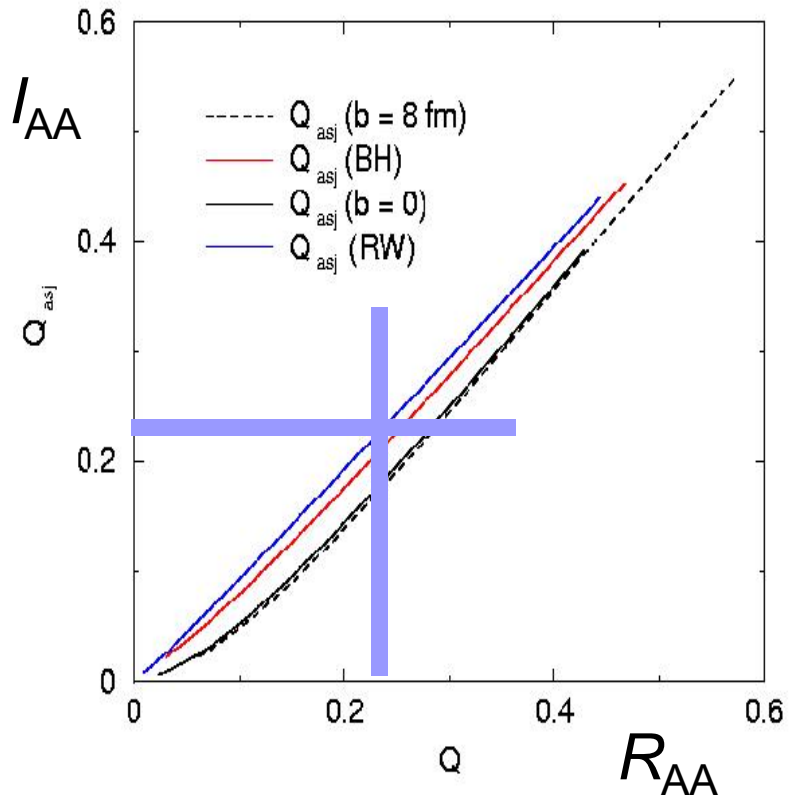
- Medium modified splitting functions in MLLA (**Borghini**): Excellent description of STAR data !
- Di-hadron fragmentation functions (**Majumder**).
- Quantitative predictions for LHC from RHIC (Armesto).

- Flow effects can be important:
 - Longitudinal flow (Bjorken or not)
 - Transverse flow, for tangential emission
- Important to compare calculations



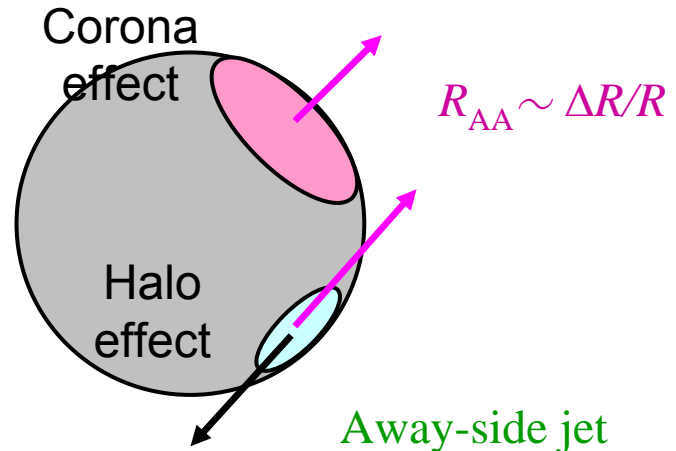
R_{AA} versus I_{AA}

BM, Phys. Rev. C67:061901,2003



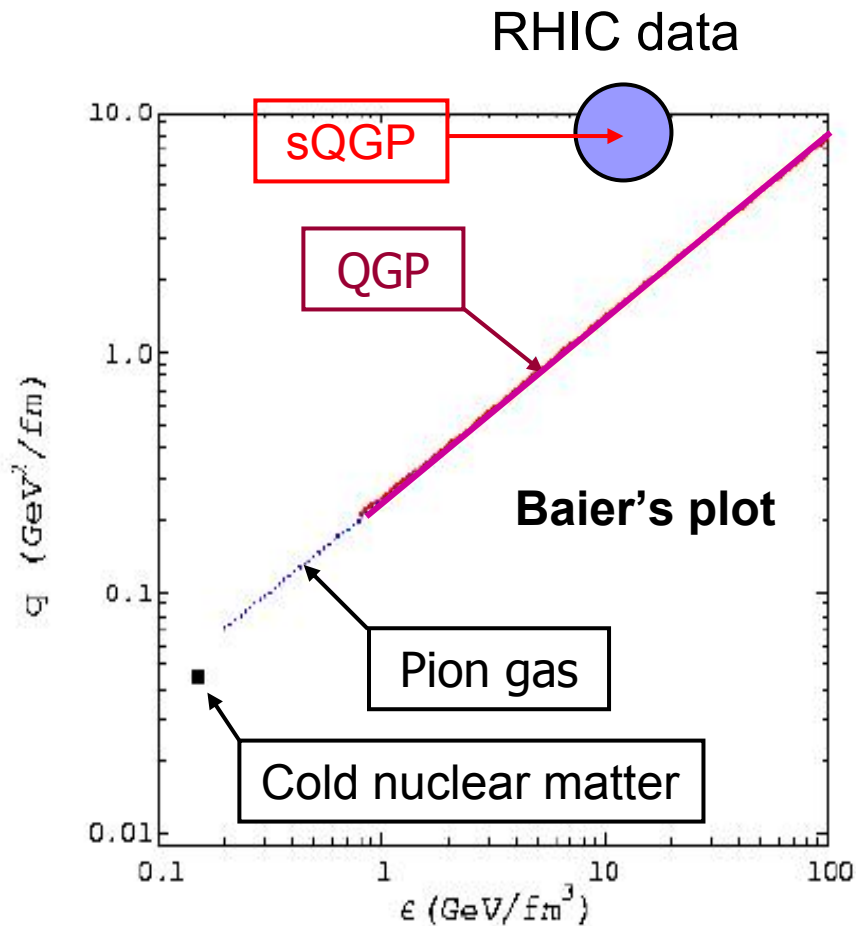
STAR result: di-jet suppression

$$R_{AA} \approx I_{AA} \approx 0.23$$



$$I_{AA} = R_{AA}^{dijet} / R_{AA} \sim \Delta R/R$$

Jet quenching



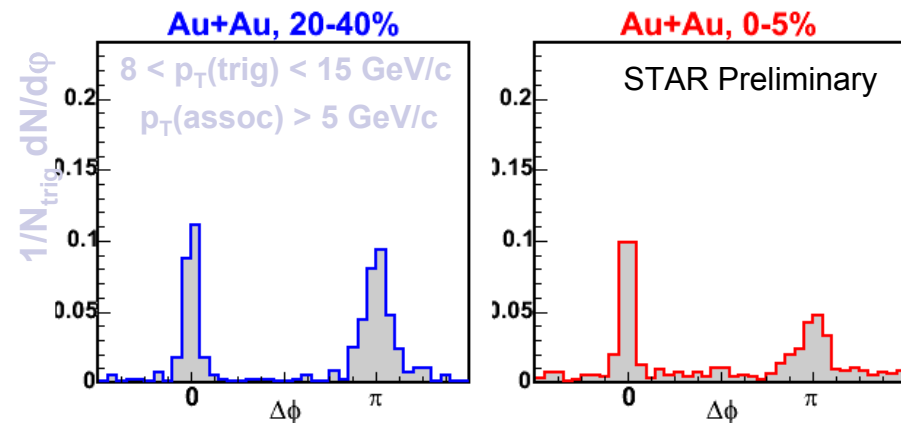
Density of scatterings

Range of color force

$$\hat{q} = \rho \sigma \langle k_T^2 \rangle = \frac{\mu^2}{\lambda}$$

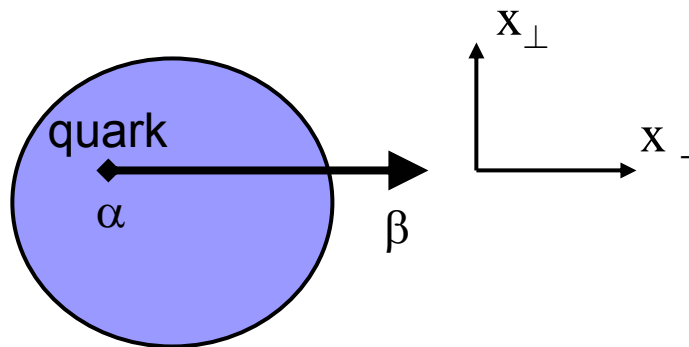
$$= 5 - 15 \text{ GeV}^2/\text{fm}$$

Emergence of away-side jet will make determination of \hat{q} easier.



Eikonal formalism

Kovner, Wiedemann



$$|q_{\alpha}(x_{\perp})\rangle \rightarrow W_{\alpha\beta}(x_{\perp}; L) |q_{\beta}(x_{\perp})\rangle$$

$$W(x_{\perp}; L) = \mathcal{P} \exp \left[i \int_0^L dx_{-} A^{+}(x_{\perp}, x_{-}) \right]$$

Gluon radiation:



$$N_g(k) = \frac{\alpha_s C_F}{2\pi} \int dx_{\perp} dy_{\perp} e^{ik(x_{\perp}-y_{\perp})} \frac{x_{\perp} \cdot y_{\perp}}{x_{\perp}^2 y_{\perp}^2} [1 - C(x_{\perp}, 0) - C(0, y_{\perp}) + C(x_{\perp}, y_{\perp})]$$

with
$$C(x_{\perp}, y_{\perp}) = \frac{\langle \text{Tr}[W_A^{\dagger}(x_{\perp}; L) W_A(y_{\perp}; L)] \rangle}{N_c^2 - 1}$$

Eikonal form. II

$$\begin{aligned} C(x_{\perp}, y_{\perp}) &= \frac{\langle \text{Tr}[W^{\dagger}(x_{\perp}; L)W(y_{\perp}; L)] \rangle}{N_c^2 - 1} \\ &\approx \frac{1}{2}(x_{\perp} - y_{\perp})^2 \int_0^L dx_- \int_0^{x_-} dx'_- \langle F^{+i}(x_-)W(x_-, x'_-)F_i^+(x'_-)W^{\dagger}(x_-, x'_-) \rangle \\ &\sim \frac{1}{2}(x_{\perp} - y_{\perp})^2 L \langle F^{+i}F_i^+ \rangle \xi_F \rightarrow \frac{1}{2}(x_{\perp} - y_{\perp})^2 L \hat{q} \end{aligned}$$

Can $\langle F^{+i}(x)F_i^+(0) \rangle$ be computed for $x^2 = 0$ on the lattice

Not unlike calculation of gluon structure function, maybe moments are calculable using euclidean techniques.

Charmonium

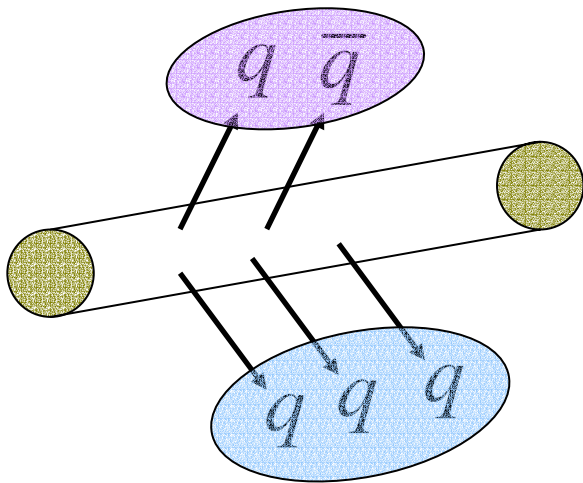
- Review of J/Ψ suppression theory (Nardi).
- Still no generally accepted theoretical framework. Since m_c sets a hard scale, eikonal techniques (as in parton energy loss) might serve as basis of unified framework.
- No quantitative agreement between lattice (spectral function) and potential approaches to disappearance of heavy quarkonia (Mocsy, Petreczky).
- Detailed calculations of J/Ψ regeneration are needed.
- Plenty of room for improvements !

Don't get confused by irritating details....the obvious may be true!



© 2000.com
"Wait! Wait! ... Cancel that, I guess it says 'help.'"

Hadronization

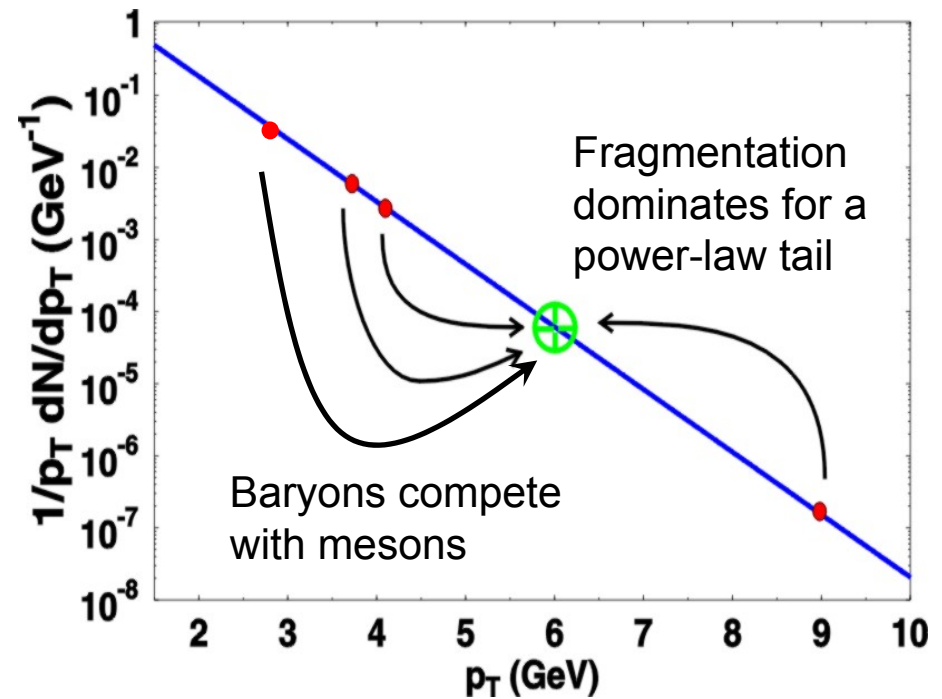


Recombination

$$\frac{\text{Baryon}}{\text{Meson}} \approx 1$$

$$p_M \approx 2p_Q \quad p_B \approx 3p_Q$$

Recombination always dominates over fragmentation for thermal quark spectrum.



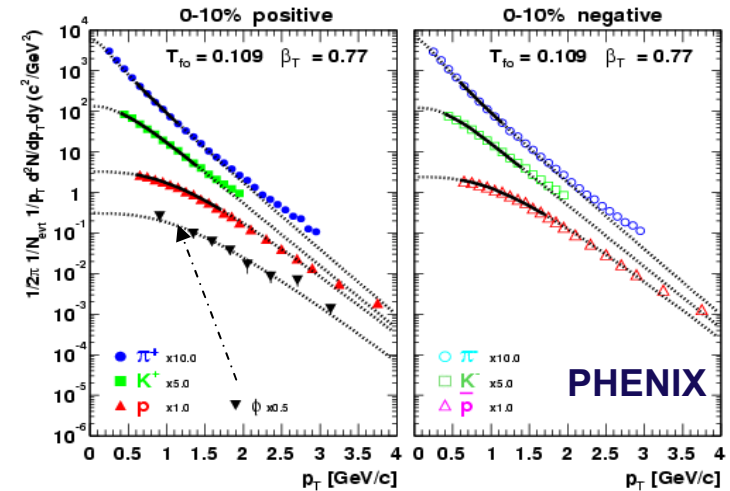
Constituent vs. current quarks ?

Hadronization

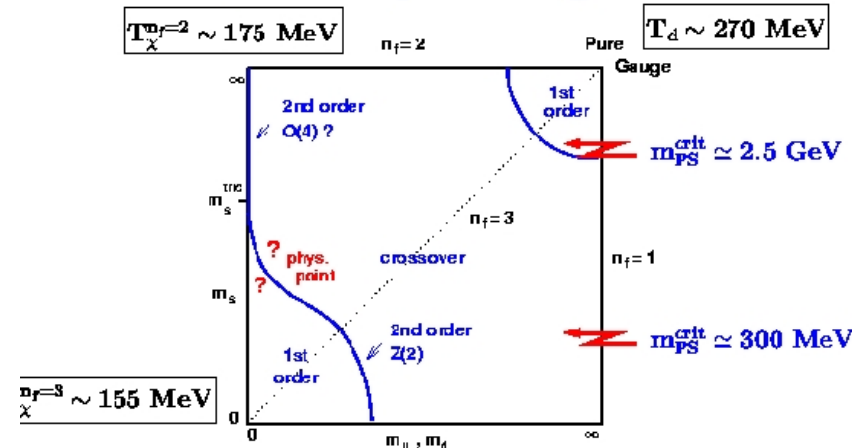
- Question of joint or separate chemical and kinetic freeze-out remains unresolved (**Florkowski**).
- Need to do sophisticated freeze-out calculations using opacity, reach a consensus on freeze-out physics.
 - Does a fit of the ϕ spectrum with $T = 109$ MeV really make sense?
 - Could we detect m_ϕ shift or σ_ϕ change in medium?

Data suggest $\gamma_s = 1$ at RHIC. But excellent fits with $\gamma_s > 2$ exist (**Letessier & Rafelski**). And γ_s can be different in QGP and HG \rightarrow Determine γ_s as function of p_T ?

Explore QCD phase diagram as function of γ_s (Taylor expansion?). Could influence order of transition (just like N_f)!

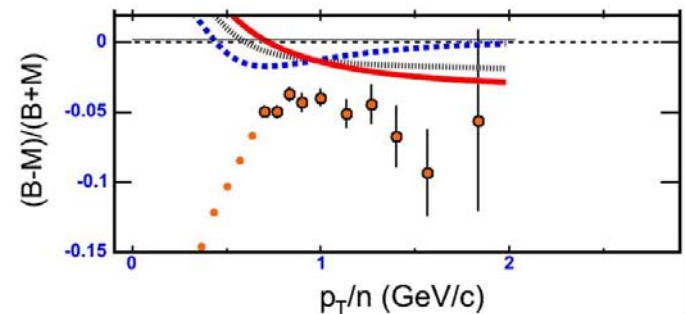
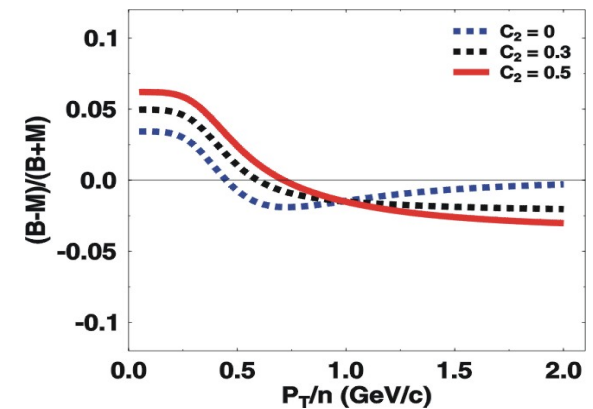
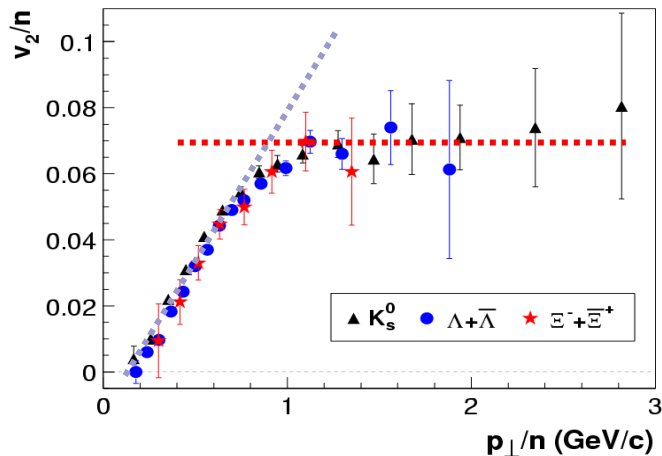


3-flavour phase diagram



Recombination

- Recombination model works amazingly well:
 - Transition to common RAA at $p_T \sim 6$ GeV/c.
 - Systematic deviation from quark number scaling in v_2 predicted from higher Fock space admixture is observed (at 5% level - [Sorensen](#)).
- Dihadron correlations ([Bass](#))
- Pedestal and correlation effect ([Hwa](#))



The perfect ink...

- Is brilliantly dark and opaque
- Yet flows smoothly and easily

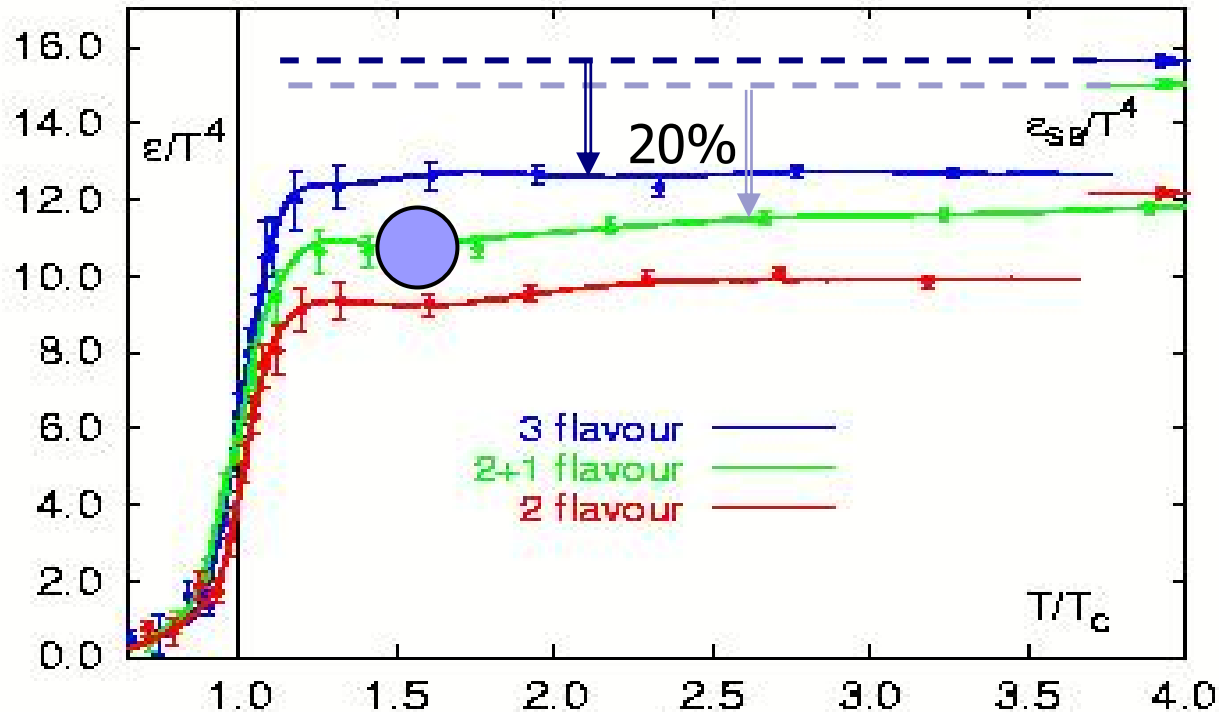
- A challenge to fountain pen designers

- A challenge to physicists:
 - What is the limit of perfection?
 - Strong coupling limit of $N = 4$ SUSY-YM (**Starinets**):
 - Does limit apply to QCD ?



$$\frac{\eta}{s} = \frac{1}{4\pi} \left(1 + \frac{135 \zeta(3)}{8(2g^2 N_c)^{3/2}} \right)$$

QCD equation of state



New generation of calculations with realistic quark masses and for $N_t=6$.

New result (Katz):

$$T_c = 191 \pm 8 \text{ MeV}$$

Can we put a “data” point on this diagram?

Measuring ν

$$s = \nu \frac{2\pi^2}{45} T^3$$

Determine s from multiplicity and upper limit on T from photon spectrum.

OR:

BM & K. Rajagopal, hep-ph/0502174

Eliminate T from ε and s :

$$\left. \begin{aligned} \varepsilon &= \nu \frac{\pi^2}{30} T^4 \\ s &= \nu \frac{2\pi^2}{45} T^3 \end{aligned} \right\} \nu = \frac{1215}{128\pi^2} \frac{s^4}{\varepsilon^3} \approx 0.96 \frac{s^4}{\varepsilon^3}$$

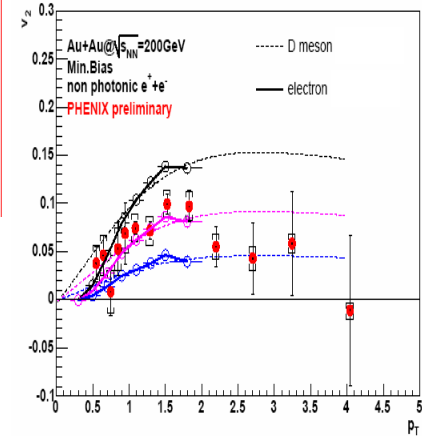
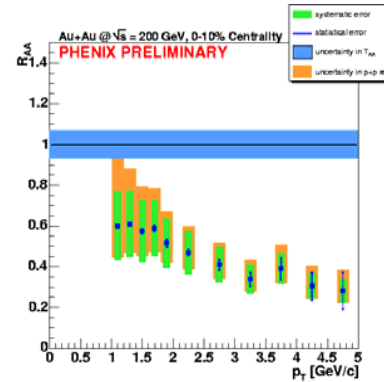
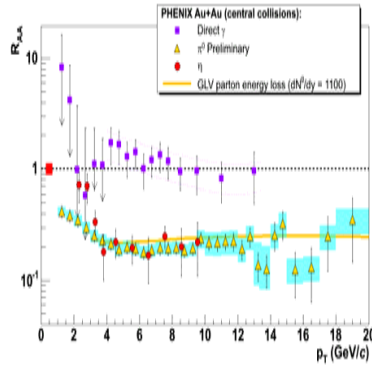
Lower limit on ν requires lower limit on s and upper limit on ε .

Measuring s and ε

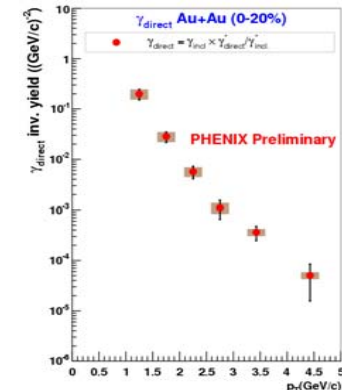
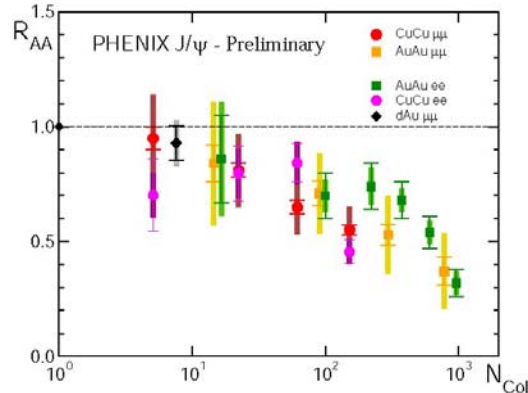
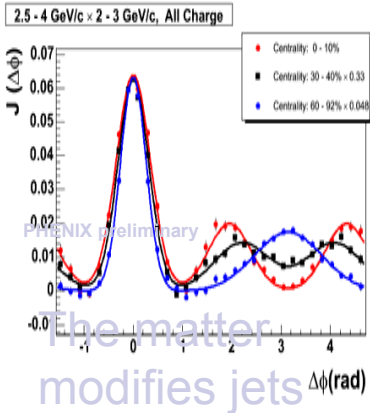
- Entropy is related to produced particle number and is conserved in the expansion of the (nearly) ideal fluid:
 $dN/dy \rightarrow S \rightarrow s = S/V.$
- Two approaches:
 - 1) Use inferred particle numbers at chemical freeze-out from statistical model fits of hadron yields;
 - 2) Use measured hadron yields and HBT system size parameters as kinetic freeze-out (Pratt & Pal).
- Good news: results agree within errors:
 - $dS/dy = 5100 \pm 400$ for Au+Au (6% central, 200 GeV/NN)
 $\rightarrow s = (dS/dy)/(\pi R^2 \tau_0) = 33 \pm 3 \text{ fm}^{-3}$ (at $\tau_0 = 1 \text{ fm}/c$)
- Energy density from parton energy loss ?



An offer too good to refuse...



We look forward to working with the theory community to extract the properties of the matter





The End

Peter & Tamas:

THANK YOU!

See you all in Shanghai!