How can we probe a Strongly Coupled QGP?

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Pre-history, what would be in this talk in 2003:

- Radial and elliptic flows for all secondaries $\pi..\Omega$=> QGP seem to be the most perfect fluid known $\eta/s \approx .1-.2 << 1$
- how strong is strong? => When bound states occure (es+Zahed,2003) or even falling on a center…
- Zero binding lines => Resonances =>large cross sections => hydro behavior
- Many colored bound states => solution to

several lattice puzzles =>high mutual concistency of lattice data

- Relation to other strongly coupled systems, from atomic experiments to string theory

Outline cont: new ideas

- **Bound states (ρ,ω,ϕ) in L and T forms, and a near-threshold bump in QGP => dileptons =>**

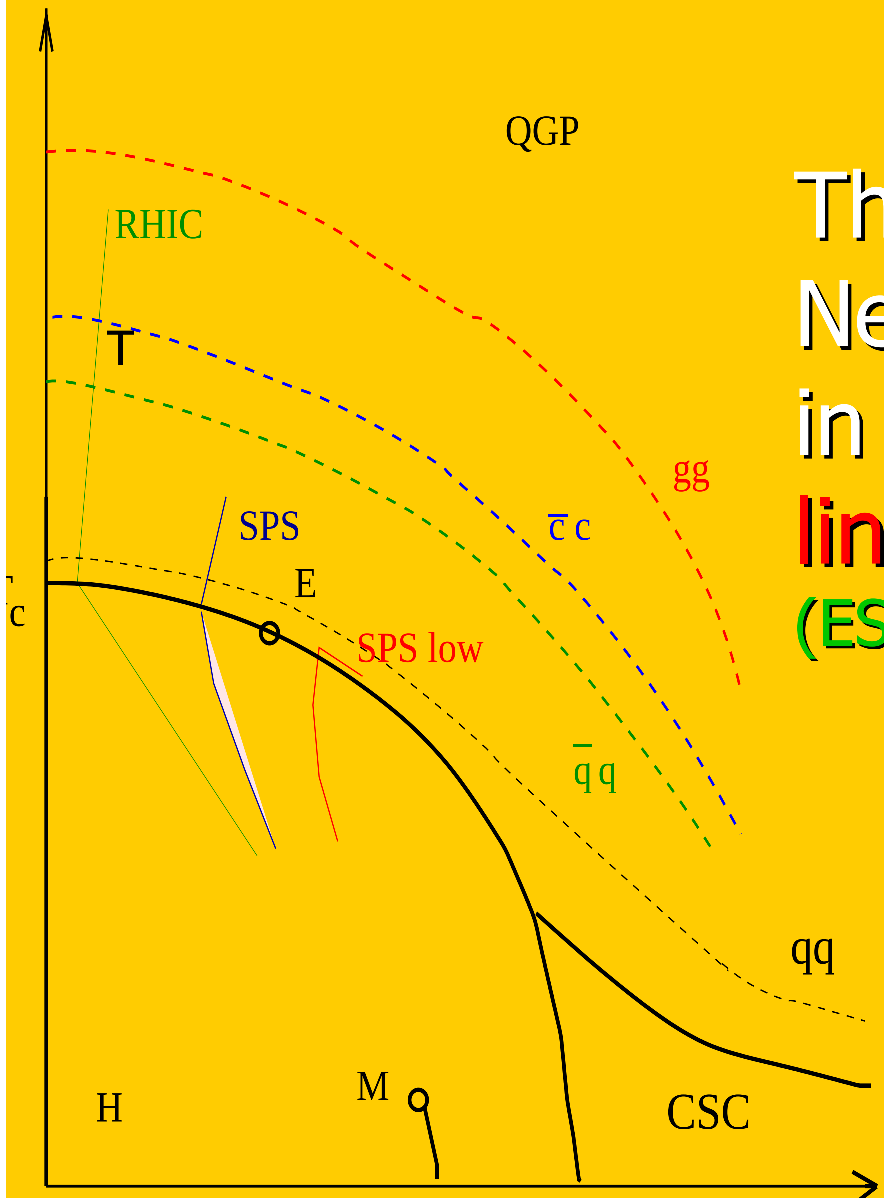
quasiparticle masses and the interaction strength

(Jorge Casalderrey +ES)

- **Conical flow from quenched jets (Casalderrey, ES,Teaney)**
- **Jet quenching due to ``ionization" of new bound states**

(I.Zahed+ES)

- **One more strongly coupled liquid: ordinary QED plasmas**



Chemical potential μ_B

The beginning of sQGP: a New QCD Phase Diagram, in which ``zero binding lines" first appeared

(ES+I.Zahed hep-ph/030726, PRC)

The lines marked RHIC and SPS show the adiabatic cooling paths

Why is hydro description so good ?

=> near zero binding provides large objects ,

maybe large cross sections? (ES+Zahed,03, same)

This is how small mean free path (viscosity) and zero binding lines and can be related!

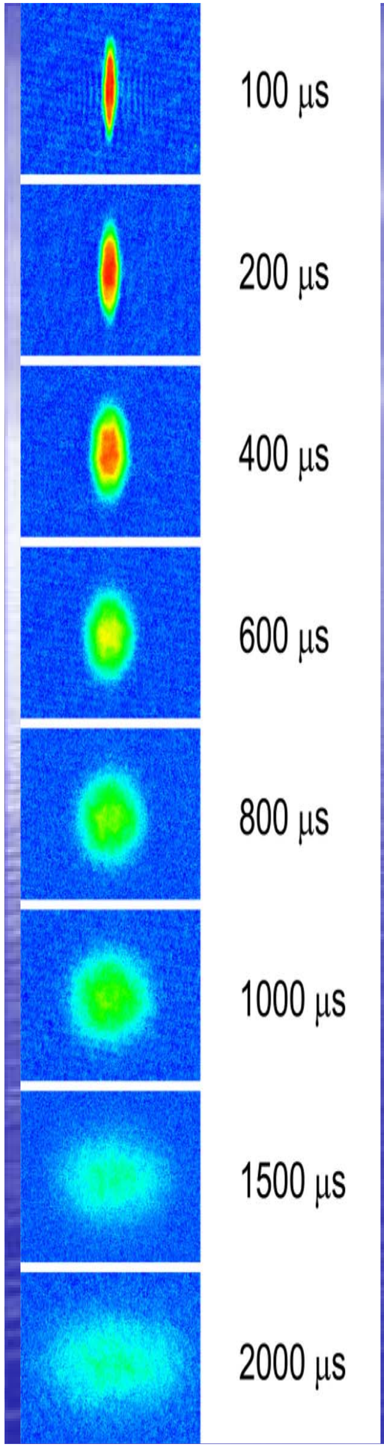
(SZ) (q.p.+ q.p. <=> bound state): a resonance

$$\sigma(k) \sim \frac{4\pi}{k^2} \frac{\Gamma_i^2/4}{(E-E_r)^2 + \Gamma_t^2/4}$$

For $E - E_r \approx 0$ the in- and total widths approximately cancel: the resulting "unitarity limited" scattering is determined by the quasiparticle wavelengths which can be very large.

Can this scenario work?

Well, it was shown to work for strongly coupled atoms



The coolest thing on Earth, T=10 nK or 10^(-12) eV can actually produce a Micro-Bang !

Elliptic flow with ultracold trapped Li6 atoms, a=> infinity regime via the so called Feshbach resonance

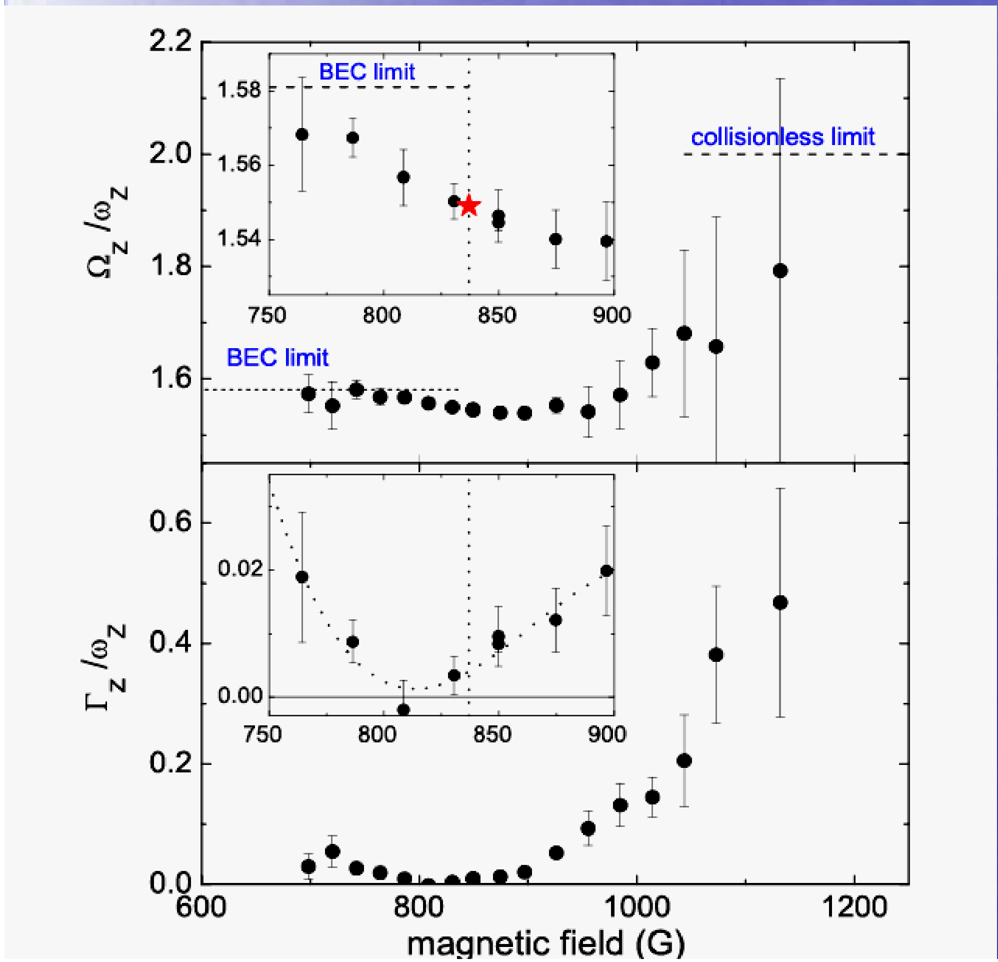
The system is extremely dilute, but cit still goes into a hydro regime, with an elliptic flow

(Similar mechanism as proposed by Zahed and myself) for QGP, a pair of quasiparticles is near the "zero binding lines")

- Hydro works for up to 1000 oscillations!

Ω agrees with hydro (red star) at resonance

Viscosity has a strong minimum there



B.Gelman, ES,I.Zahed
nucl-th/0410…

The most ideal cold liquid Must be

$\eta/(\sim n)>1/6\pi$

In reality it is

¼ .5§ .3 at the experimental minimum.

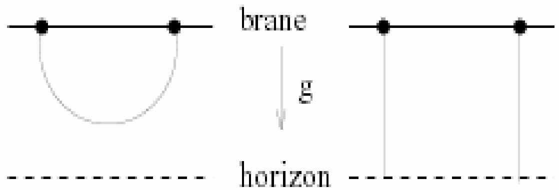
About as perfect as sQGP!

Bartenstein et al
cond-mat/0403716

Unexpected help from string theorists, AdS/CFT correspondence

- The $\mathcal{N}=4$ SUSY Yang Mills gauge theory is conformal (CFT) (the coupling does not run). At finite T it is a QGP phase at ANY coupling. If it is weak it is like high-T QCD => gas of quasiparticles. What is it like when the coupling gets strong $\lambda = g^2 N_c \gg 1$?
- AdS/CFT correspondence by Maldacena turned the strongly coupled gauge theories to a classical problem of gravity in 10 dimensions
- Example: a modified Coulomb's law (by Maldacena)

$$V(L) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{L}$$



- becomes a sreened potential at finite T

- The viscosity/entropy => $1/4\pi$ when g^2N_c! 1, (D.Son et al 2003), as small as at RHIC!

- Multiple Coulomb bound states with l» $g^2 N_c$ (ES+Zahed, PRD 04)

Where the energy of quenched jets go? The ``conic” flow

(appropriate for a hard probe conference…)

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Sonic boom from quenched jets
(J.Casalderrey, ES, D.Teaney, in progress)

- **the energy deposited by jets into liquid-like strongly coupled QGP must go into conical shock waves, similar to the well known sonic boom from supersonic planes.**
- **We solved relativistic hydrodynamics and got the flow picture behind the shocks.**

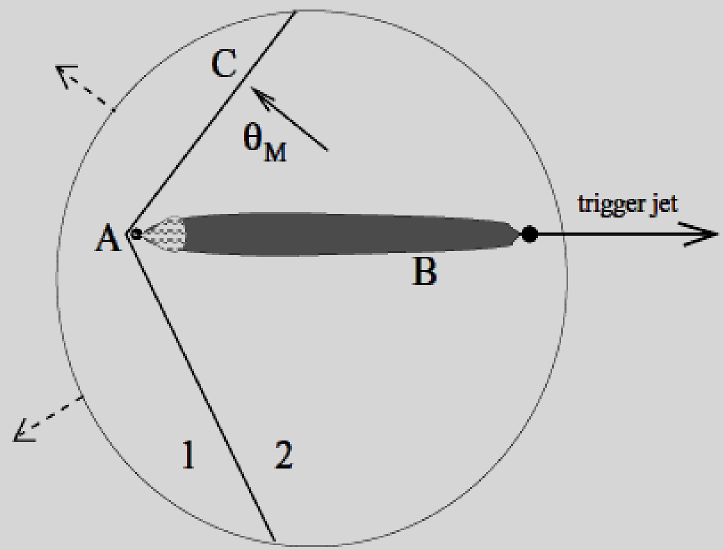


FIG. 1. A schematic picture of flow created by a jet going through the fireball. The trigger jet is going to the right from the origination point (the black circle). Its observation biased it to be emitted near the surface and move outword. Its companion jet is moving to the left, heating the matter and thus creating a cylinder of additional matter (light grey area). The head of the jet is a "nonhydrodynamical core" of the QCD gluonic shower, formed by the original hard parton (black dot). The solid arrow shows a direction of flow normal to shock cone and having an angle θ_M with the jet, the dashed arrows show the direction of the flow after shocks hit the edge of the fireball

How to observe it?

- the direction of the flow **is normal to Mach cone,** defined entirely by ratio of the speed of sound to that of light
- So, unlike for QCD radiation, **the angle is not shrinking with increase of the momentum of the jet**

Has a sonic boom from quenched jets been already observed?

$$\theta_{emission} = arccos(c_s/c) \approx 1.1 rad = 63^o$$

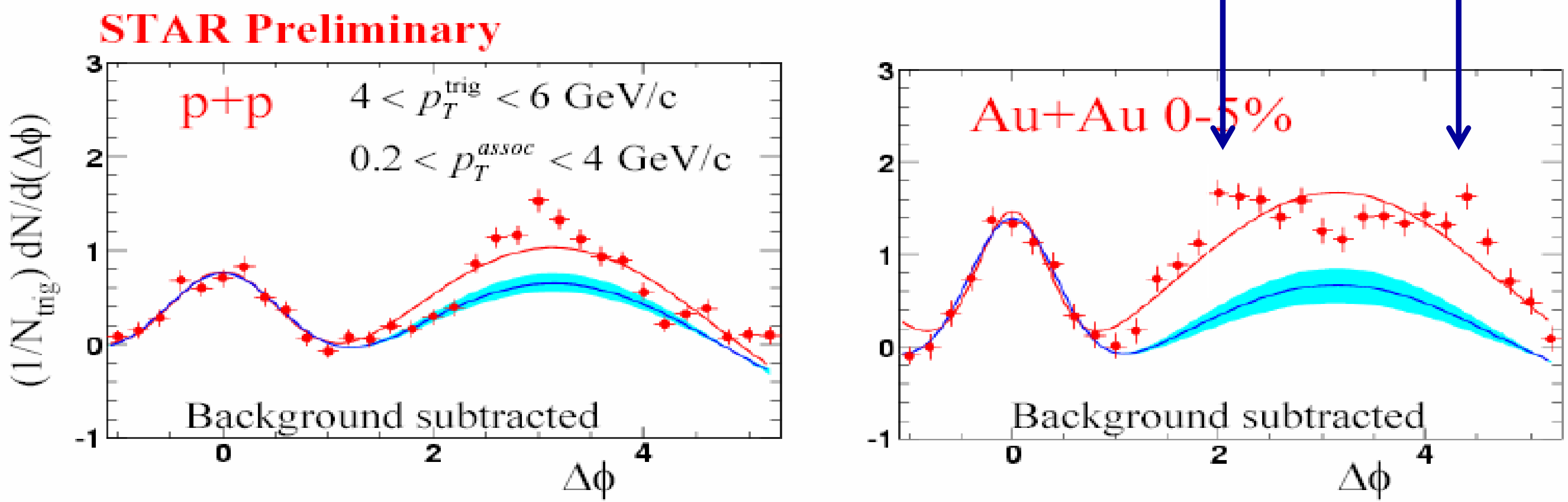
$\phi=\pi$ § 1.1=2.0,4.2

flow of matter normal to the Mach cone seems to be observed! See data from STAR,

(PHENIX also sees two bumps but cannot show)

M.Miller, QM04

Is The Away-Side Jet-Like?



Away-side looks jet-like in p+p, not central Au+Au!

Determining the speed of sound=EoS, but at what time?

- At kinetic freezeout, τ=12-15 fm/c, and that is why we used c_s^2=.16-.2 for resonance gas
- That was because we considered central collisions (to awoid complications with elliptic flow subtraction) in which a jet has to go about a diameter of Au
- One can use semi-peripheral and play with

Jet orientation relative to collision plane and change timing

lattice puzzles

- Since Matsui-Satz and subsequent papers it looked like even $J/\psi, \eta_c$ dissolves in QGP (thus it was a QGP signal) and yet it is now found (Asakawa-Hatsuda,Karsch et al) that they seem to exist up to $T=2T_c$. or more. Why????
- How can pressure be high at $T=(1.5\text{-}2)T_c$

while q,g quasiparticles are quite heavy? (it gets parametric in the N=4 SYM as quasiparticles in strong coupling are infinitely heavy m»λ^1/2 T)

How strong is strong?

For a screened Coulomb potential, Schr.eqn.=>a simple condition for a bound state

- $(4/3)\alpha_s\ (M/M_{Debye}) > 1.68$
- M(charm) is large, M_{Debye} is not, ¼ 2T
- If $\alpha(M_d)$ indeed runs and is about ½-1, it is large enough to bind charmonium till about $T=2T_c=340$ MeV

(accidentally, the highest T at RHIC)

- Since q and g quasiparticles are heavy,

M» 3T, they all got bound as well !

Digression :Relativistic Klein-Gordon eqn has a critical Coulomb coupling for **falling onto the center** (known since 1920's)

What happens is that the particle starts falling towards the center. Indeed, ignoring at small r all terms except the V^2 term one finds that the radial equation is

$$R'' + \frac{2}{r}R' + \frac{\alpha^2}{r^2}R = 0 \qquad (10)$$

which at small r has a general solution

$$R = Ar^{s_+} + Br^{s_-}, \qquad s_\pm = -1/2 \pm \sqrt{1/4 - \alpha^2} \qquad (11)$$

that for $\alpha \to 1/2$ is just $1/r^{1/2}$. At the critical coupling *both* solutions have the same (singular) behavior at small r. For $\alpha > 1/2$ the falling starts, as one sees from the complex (oscillating) solutions.

- $(4/3)\alpha_s=1/2$ is too strong, a critical value for Klein-Gordon (and it is 1 for Dirac).

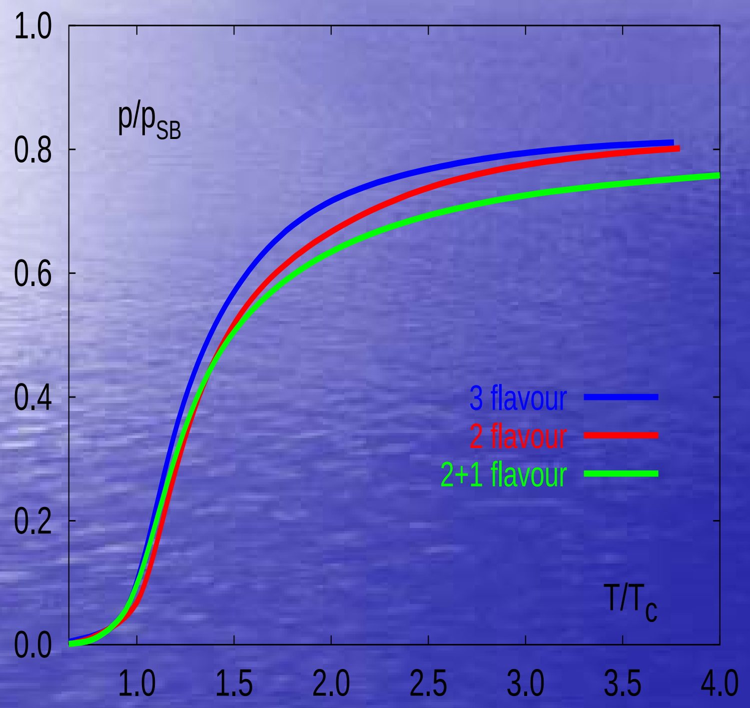
Solving for the bound states ES+I.Zahed, hep-ph/0403127

- **In QGP there is no confinement =>**
- **Hundreds of colored channels may have bound states as well!**

channel	rep.	charge factor	no. of states
gg	1	9/4	9_s
gg	8	9/8	$9_s * 16$
$qg + \bar{q}g$	3	9/8	$3_c * 6_s * 2 * N_f$
$qg + \bar{q}g$	6	3/8	$6_c * 6_s * 2 * N_f$
$\bar{q}q$	1	1	$8_s * N_f^2$
$qq + \bar{q}\bar{q}$	3	1/2	$4_s * 3_c * 2 * N_f^2$

- gg color 8*8=64=27+2*10+2*8+1: only the 2 color octets $(gg)_8$ have $(16 * 3_s * 3_s = 144)$ states.

The pressure puzzle

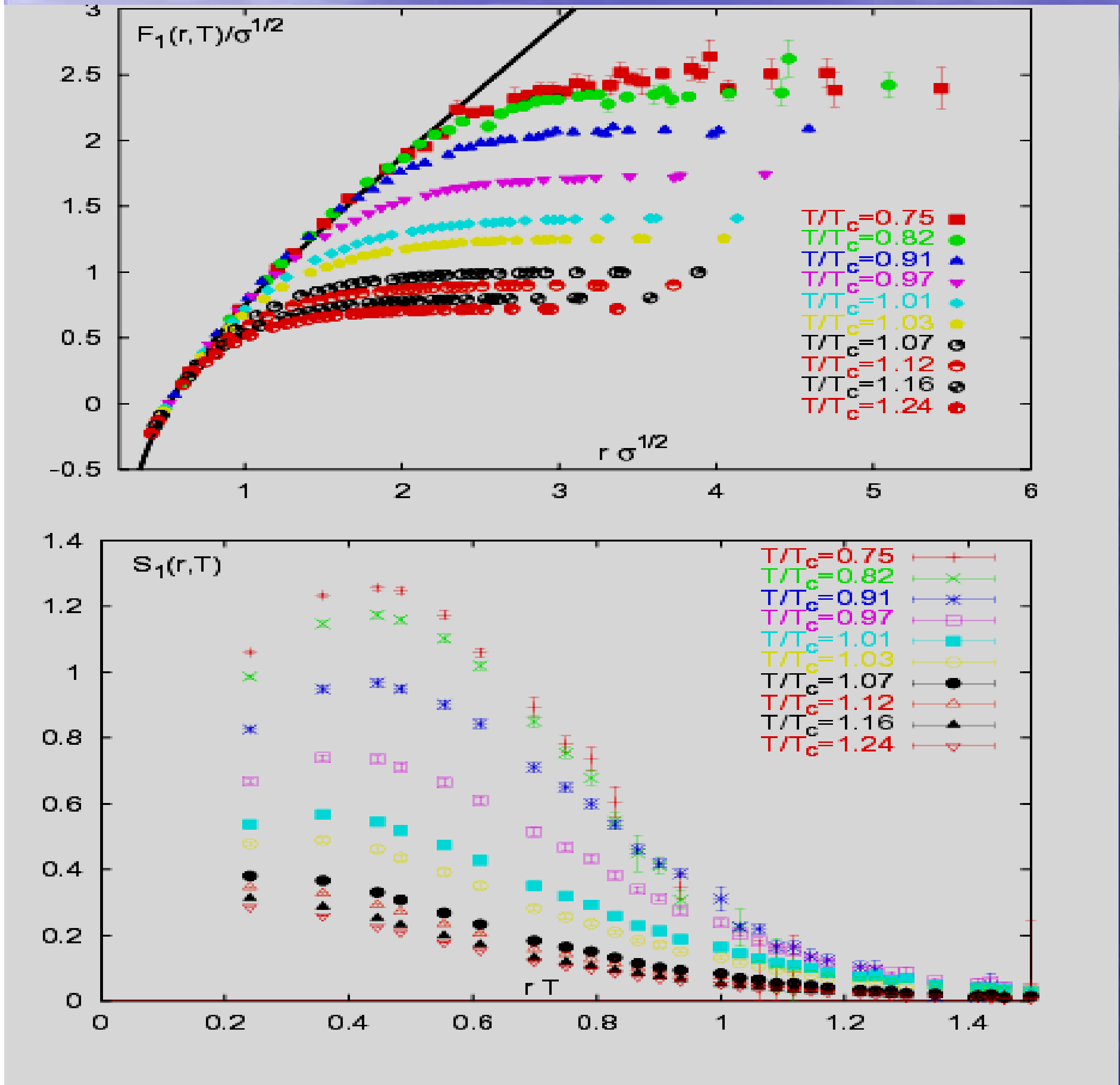


Well known lattice prediction (numerical calculation, lattice QCD, Karsch et al) the pressure as a function of T (normalized to that for free quarks and gluons)

- **This turned out to be the most misleading picture we had, fooling us for nearly 20 years**
- p/p(SB)=.8 from about .3 GeV to very large value. Interpreted as an argument that interaction is relatively weak (0.2) and can be resumed, although pQCD series are bad…

BUT: we recently learned that storng coupling leads to about 0.8 as well!

New ``free energies” for static quarks (from Bielefeld)



- **Upper figure is normalized at small distances: one can see that there is large ``effective mass” for a static quark at T=Tc.**
  - **Both are not yet the potentials!**
- **The lower figure shows the effective coupling constant**

mb

- Fit from Bielefld group hep-lat/0406036

$$\frac{F_{\rm fit}(r,T)}{T} = \frac{4\alpha(T)}{3rT}\exp\{-\sqrt{4\pi\tilde{\alpha}(T)}rT\} + c(T)$$

•Note that the Debye radius corresponds to \`\`normal” (enhanced by factor 2) coupling, while the overall strength of the potential is much larger

•It becomes still larger if V is used instead of F, see later

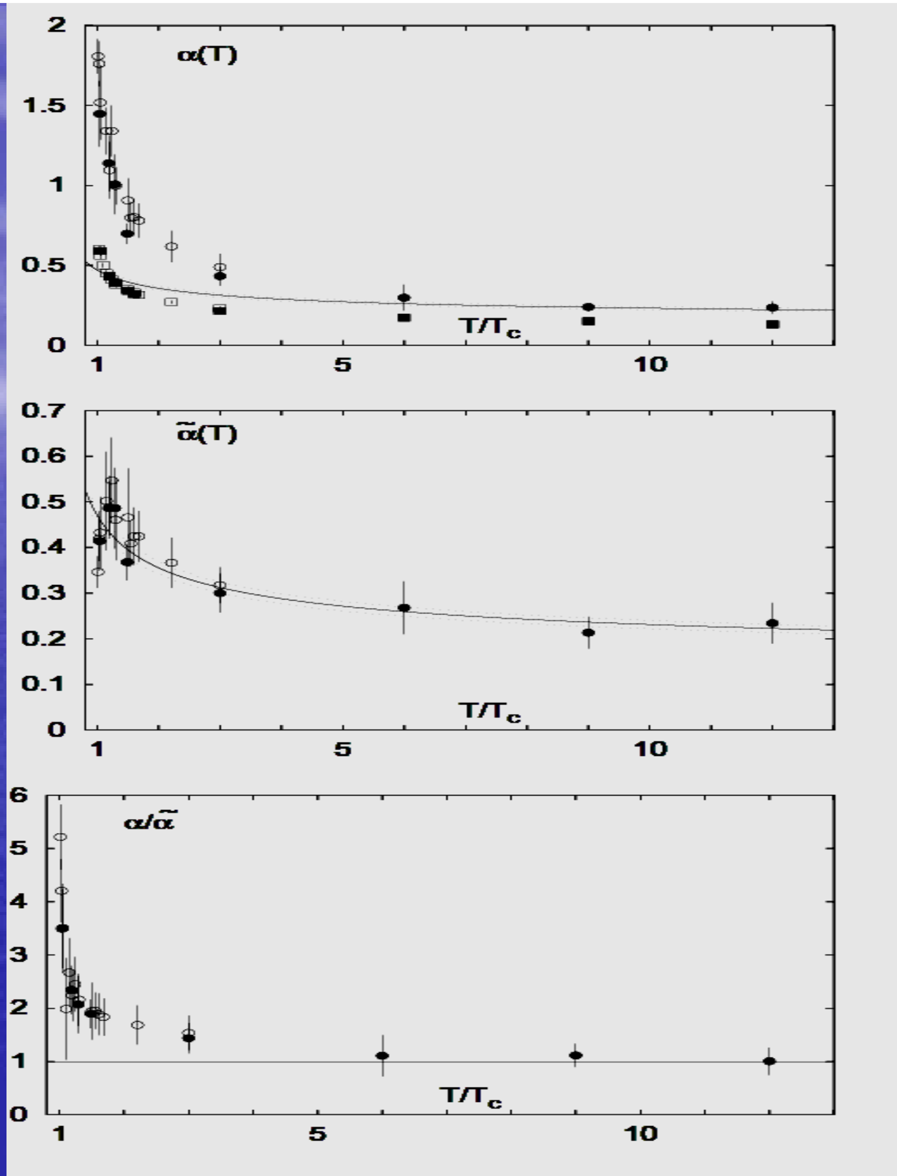
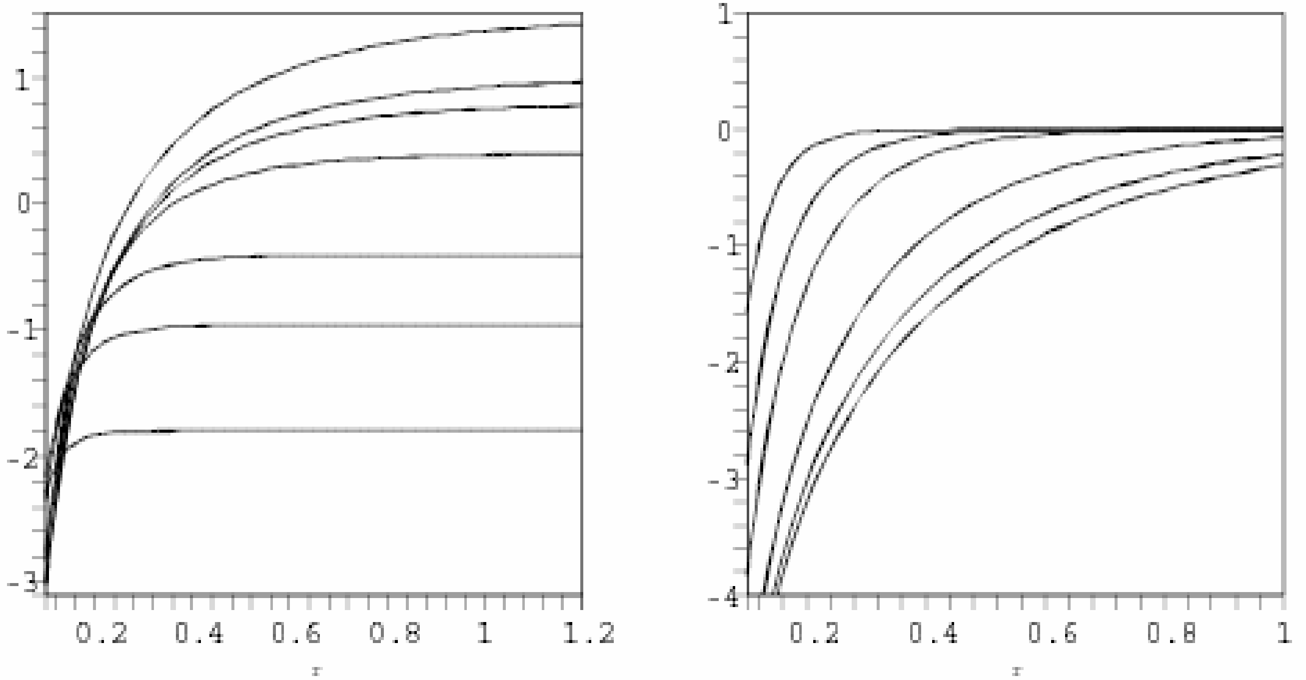


FIG. 6: The temperature dependent running coupling determined from the large distance behavior of the singlet free energy on lattices with temporal extent $N_\tau = 4$ (open symbols) and $N_\tau = 8$ (filled symbols). The upper figure shows $\alpha(T) \equiv g^2(T)/4\pi$ (dots) and the value $\alpha_{qq}(r_{screen}, T)$ (squares) determined from the short distance behavior of the singlet free energy (see Fig. 3). The figure in the middle shows $\tilde{\alpha}(T) \equiv \tilde{g}^2(T)/4\pi$ and characterizes the temperature dependence of the screening mass. The lower figure gives the ratio of both fit parameters. The solid lines with the dotted error band are discussed in the text.

New potentials should have the **entropy term is subtracted,**
which makes potentials deeper still



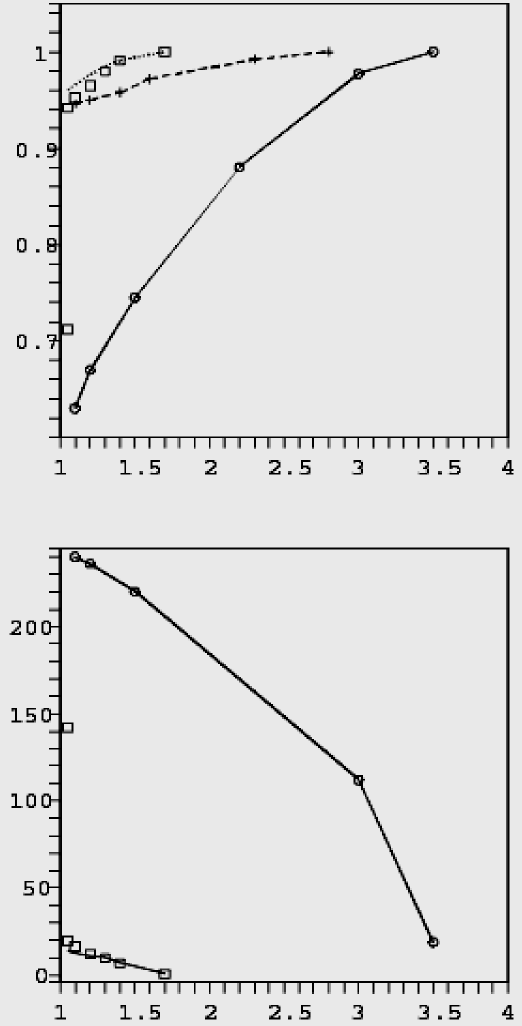
this is how potential I got look like for T = 1; 1.2; 1.4; 2; 4; 6; 10Tc, from right to left, from ES,Zahed hep-ph/0403127

Here is the binding and |psi(0)|^2

So J/\psi is indeed bound till nearly 3 Tc

- Our results (IZ+ES,hep-ph/0403...) for binding then reproduce the binding region from Asakawa-Hatsuda and Bielefeld group (using the Maximal Entropy Method MEM), found bound $J/\psi, \eta_c$ till $2.2T_c$:

(a) The energy of the bound state $E/2M$ vs T/T_c from $V(T,r)$, for charmonium (crosses and dashed line), singlet light quarks $\bar{q}q$ (solid line) and gg (solid line with circles). Squares show the relativistic correction to light quark, a single square at $T = 1.05T_c$ is for $\bar{q}q$ with twice the coupling, which is the maximal possible relativistic correction. (b) $|\psi(0)|^2/T_c^3$ of the bound states vs T/T_c.



E/2M
Vs T/Tc

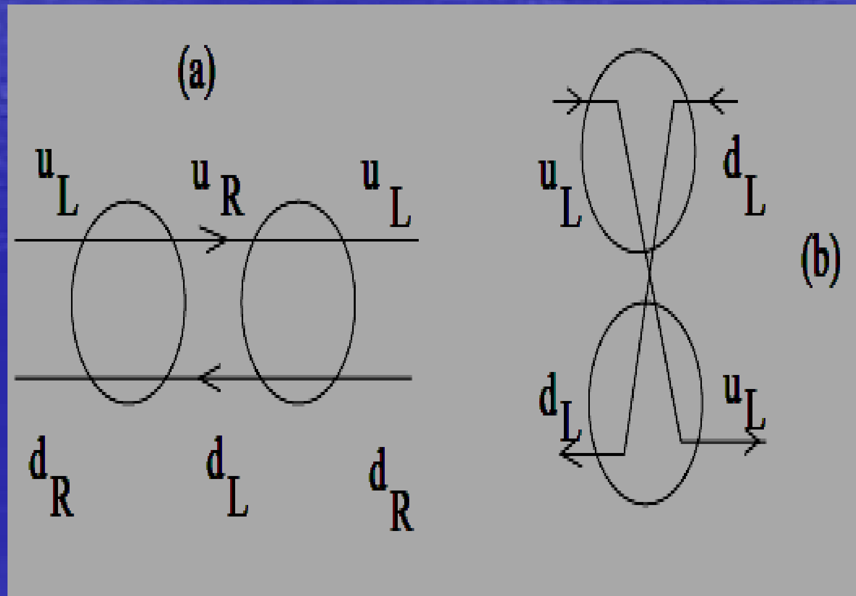
If a Coulomb coupling is too strong, falling onto the center may occur: but it is impossible to get a binding comparable to the mass

But we need massless pion/sigma at T=>Tc !

- Brown,Lee,Rho,ES hep-ph/0312175 : near-local interaction induced by the ``instanton molecules”

(also called ``hard glue” or ``epoxy”, as they survive at $T>T_c$

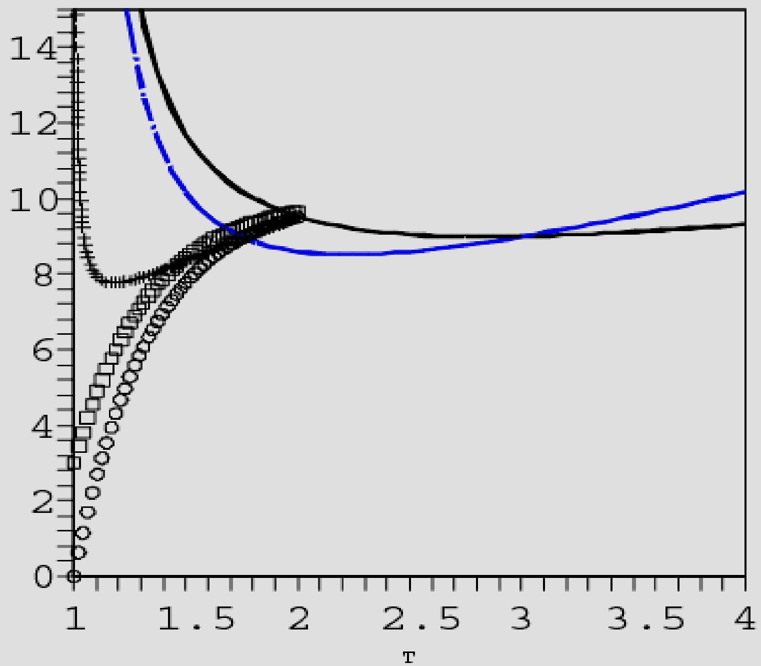
- Their contribution is » $|\psi(0)|^2$ which is calculated from strong Coulomb problem



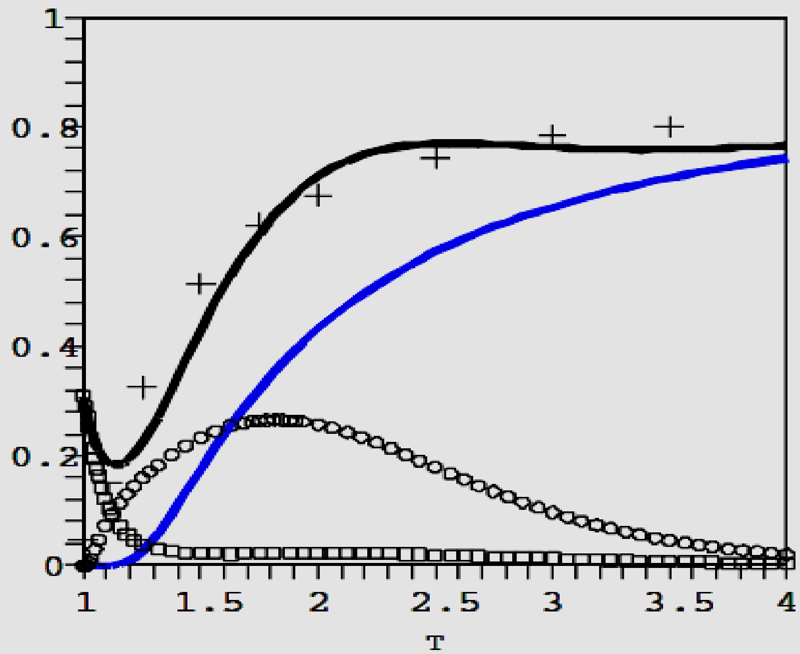
The pressure puzzle is resolved!

Masses, potentials and EoS from lattice are mutually consistent

M/Tc vc T/Tc and p/p$_{SB}$ vs T/Tc



$2M_q(T), 2M_g(T)$ fitted to (Karsch et al) quasiparticle masses, as well as example of "old" $M_\pi(T)$ and "new" octet $M^8_{gg}(T)$



The QGP pressure: crosses are lattice thermodynamics for $N_f = 2$ (Bielefeld,2000), the lines represent the contributions of $q + g$ quasiparticles, "mesons" $\pi - \rho ...$, colored exotics (gg_8, qg_3) and total (the upper curve).

Can we verify it experimentally?
Dileptons from sQGP:

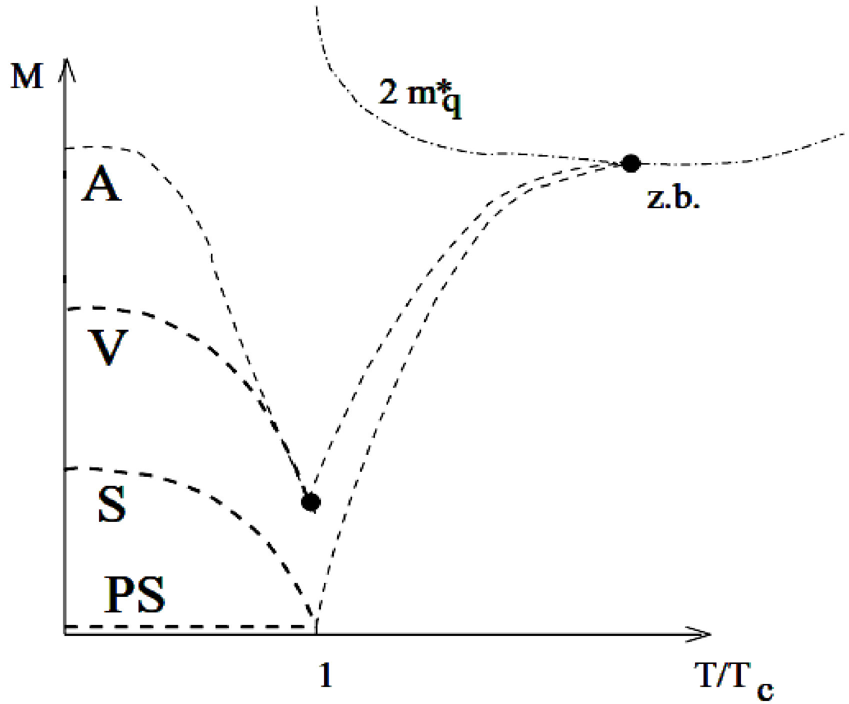


FIG. 1. Schematic T-dependence of the masses of $\bar{q}q$ states. A, V, S and PS stand for axial, vector, scalar and pseudoscalar states. The dash-dotted line shows a behavior of twice the quasiparticle mass. Two black dots indicate places where we hope the dilepton signal may be observable.

A near-threshold enhancement (``bump") should exist at any T

- Why bump? Because attraction between anti-q q in QGP enhances annihilation

- Example: pp(gg) -> t t at Fermilab has a bump near threshold ($2m_t$) due to gluon exchanges.
- The nonrelat. Gamow parameter for small velocity $z=\pi\,(4/3)\alpha_s/v > 1$,

Produces a bump: the Factor $z/(1-\exp(-z))$ Cancels v in phase space

dilepton rate: a nonrelativistic approach with realistic potentials

(Jorge Casalderrey +ES,hep-ph/0408128)

$$\sigma_{LO} = \frac{4\pi\alpha_{QED}^2 e_t^2}{3s} N_c \sqrt{(1 - \frac{4m_t^2}{s})(1 + \frac{2m_t^2}{s})} \quad (4)$$

to

$$\sigma = \frac{4\pi\alpha_{QED}^2 e_t^2}{3s} N_c \frac{24\pi \Im G_{E+i\Gamma_t}(0,0)}{s} \quad (5)$$

Where E is the center of mass energy and Γ_t is the width of the top quark. $G_{E+i\Gamma_t}(r,\bar{r})$ is the Green´s function of the *Schrodinger equation*:

$$[-\frac{1}{m}\vec{\nabla}^2 + V(\vec{r}) - (E + i\Gamma)]G_{E+i\Gamma}(r,\bar{r}) = \delta^3(\vec{r} - \vec{\bar{r}}) \quad (6)$$

The annihilation rate divided by that for free massless quarks using non-rel. Green function, for lattice-based potential (+ instantons)

$\mathrm{Im}\Pi(M)$ for T=1.2,1.4,1.7, 3 T_c

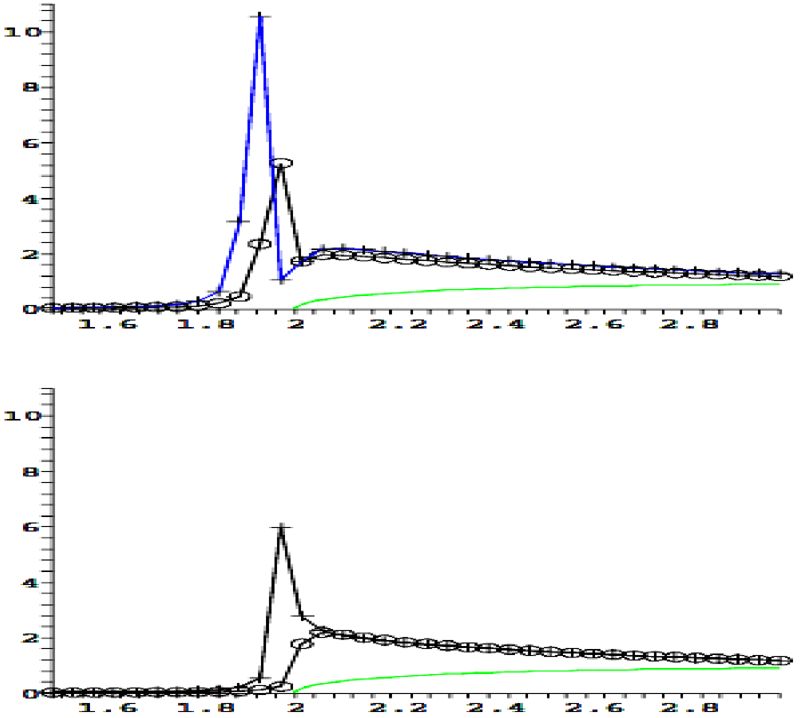
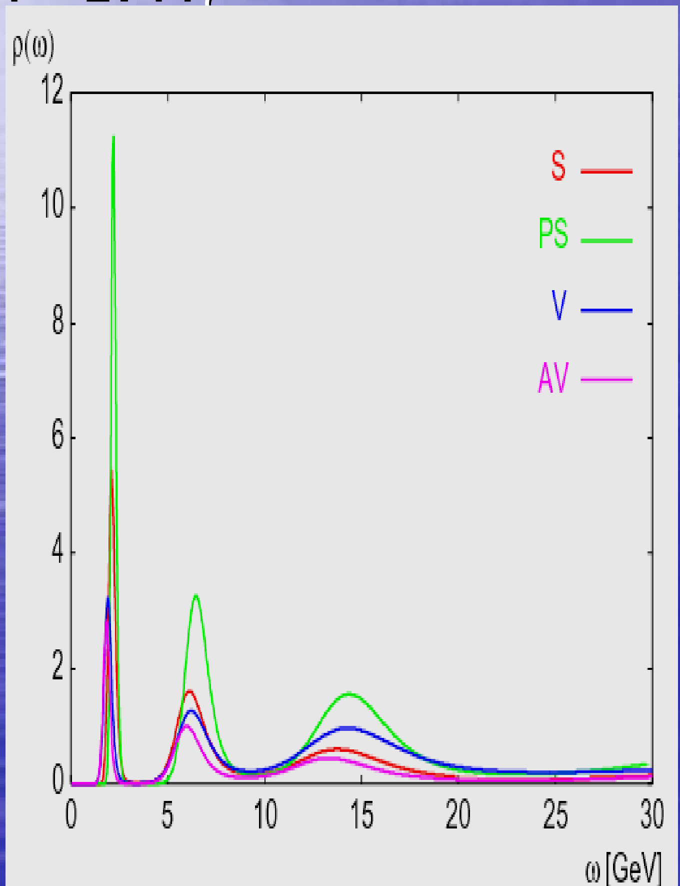


FIG. 5. Modification of the spectral density versus the in-
riant mass in M_q units for different temperatures: (a) 1.2
: (cross) and 1.4 Tc (circle), (b) 1.7 Tc (cross) and 3 Tc
ircle) and the correction due to quark mass (line).

The widths of these states are being calculated… But one sees these peaks on the lattice!

Karsch-Laerman, T=1.5 and 3 Tc

Asakawa-Hatsuda, $T=1.4T_c$



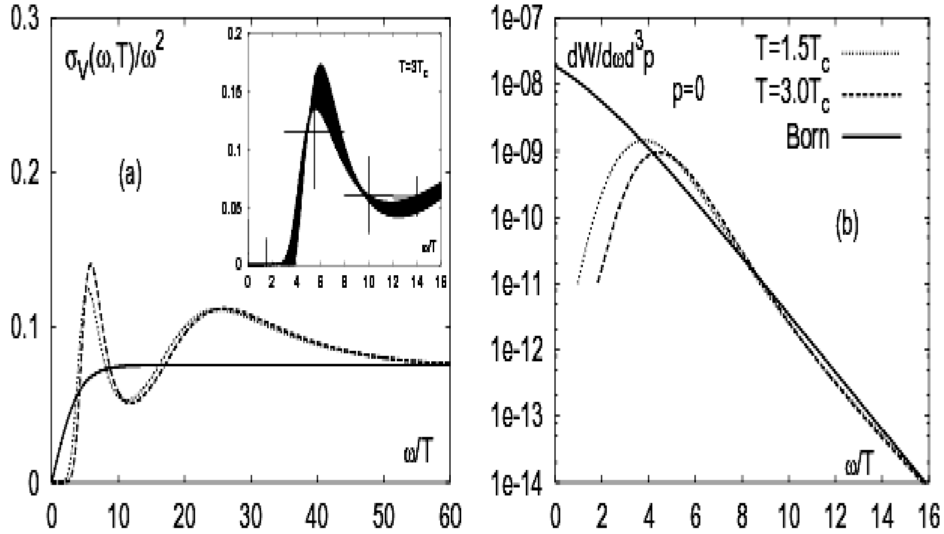


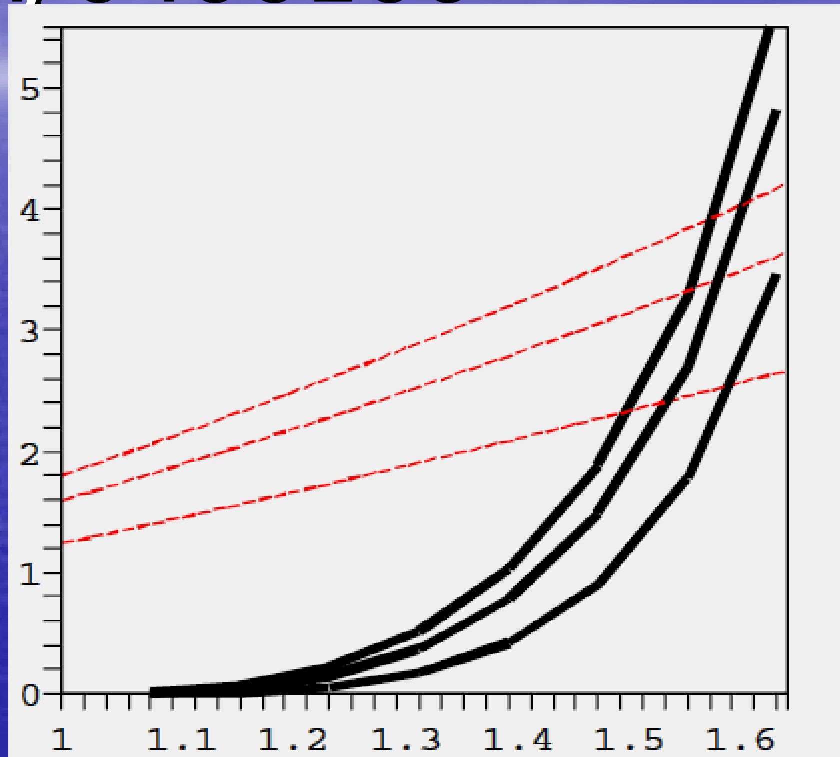
Figure 2: Reconstructed vector spectral function σ_V in units of ω^2 at zero momentum (a) and the resulting zero momentum differential dilepton rate (b) at $T/T_c = 1.5$ (doted line) and 3 (dashed line). The solid lines give the free spectral function (a) and the resulting Born rate (b). The insertion in (a) shows the error band on the spectral function at $3T_c$ obtained from a jackknife analysis and errors on the average value of $\sigma_V(\omega,T)/\omega^2$ in four energy bins (see text).

Back to jets: dE/dx of two types

- Radiative one is large but energy is going into gluons which are still moving relativistically with v=c
- Heating and ionization losses: this energy goes into matter.
- The second type losses should be equal to hydro drag force in the conical flow

Calculation of the ionization rate ES+Zahed, hep-ph/0406100

- Smaller than radiative loss if L>.5-1 fm
- Is there mostly near the zero binding lines,
- Thus it is different from both radiative and elastic looses, which are simply proportional to density
- Relates to non-trivial energy dependence of jet quenching (smaller at 62 and near absent at SPS)



dE/dx in GeV/fm vs T/T_c for a gluon 15,10,5 GeV. Red-elastic, black -ionization

Summary

- QGP at RHIC is in a strong coupling regime => **New spectroscopy:** many old mesons plus hundreds of exotic colored binary states
- **Lattice potentials, masses and EoS are all consistent ! Puzzles resolved**
- 2 objects (plus another 2 for ss states) can be observed **via dileptons**: the bound vectors plus a near-threshold bump. Most likely in the region 1.5 GeV, where 2Mq stays the same in a wide T interval. The width issue is being studied
- New hydro phenomenon associated with hard jets: **a conical flow**

Additional slides

Energy loss in QED and QCD

- QED:
- Large at v» α_{em}
- Small at relativistic minimum, γ» 1
- Grows at γ» 1000 due to radiation

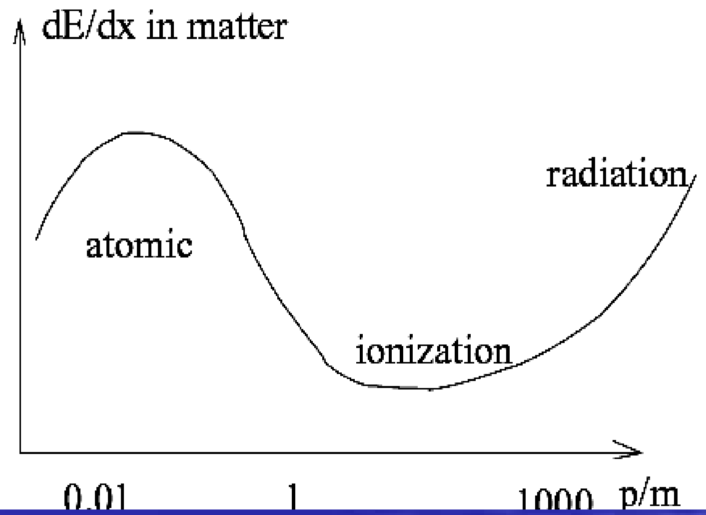
QCD

Only radiative effects were studied in detail: Landau-Pomeranchuck-Migdal effect

Jet quenching by ``ionization" of new bound states in QGP?

- Can we observe (much more multiple) colored states directly?

Very recent idea (IZ+ES) of ''ionization losses'' for minijets at $p_t \sim few\, GeV$.
Cannot work in hadronic phase - cofinement
If it is true, the ''lost energy'' can never be recovered (unlike for radiative losses)



Conclusions

- QGP as a "matter" in the usual sense, not a bunch of particles, shows very robust collective flows.
- QGP seems to be the most ideal fluid known

  η/s ¼ .1 $<<1$

- All of this hints that quenched energy is not dissipated but propagates
- Hydro solution with Mach cones is worked out
- Peaks at about 63 degrees are seen, corresponds to expected Mach angle

Outline :

Motivations:

- Reduced scale => enhanced coupling
- Hydro works and QGP seem to have remarkably small viscosity
- Lattice bound states and large potentials

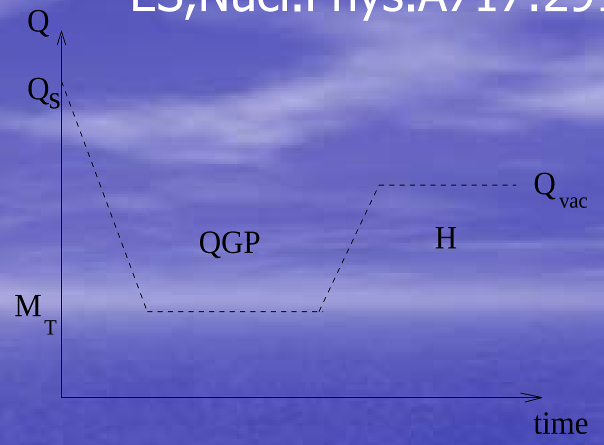
New spectroscopy of sQGP

- Multiple bound states, 90% of them colored, explain lattice puzzles:
- Why resonances in correlators (J/ψ from MEM) at T=(1-2)Tc?
- How can QGP pressure be high, with rather heavy quasiparticles?

How strong is strong?

How large can α_s become in QGP ?

ES,Nucl.Phys.A717:291,2003



- In a QCD vacuum the domain of perturbative QCD (pQCD) is limited by non-pert. phenomena, e.g. by the Qχ» 1 GeV as well as by confinement: so α_s< 0.3
- At high T we get weak coupling because of screening

α<α(gT) ¿ 1 (the Debye mass M_d» gT sets the scale)

- **In between, T_c<T<few T_c, there is no chiral/conf. scales**

While M_{Debye}¼ 2T» 350-400 MeV is not yet large: can $\alpha_s(M_d)$ be » .5-1 (?). If so, binding appears. (ES-

Following the methods developed for t quark

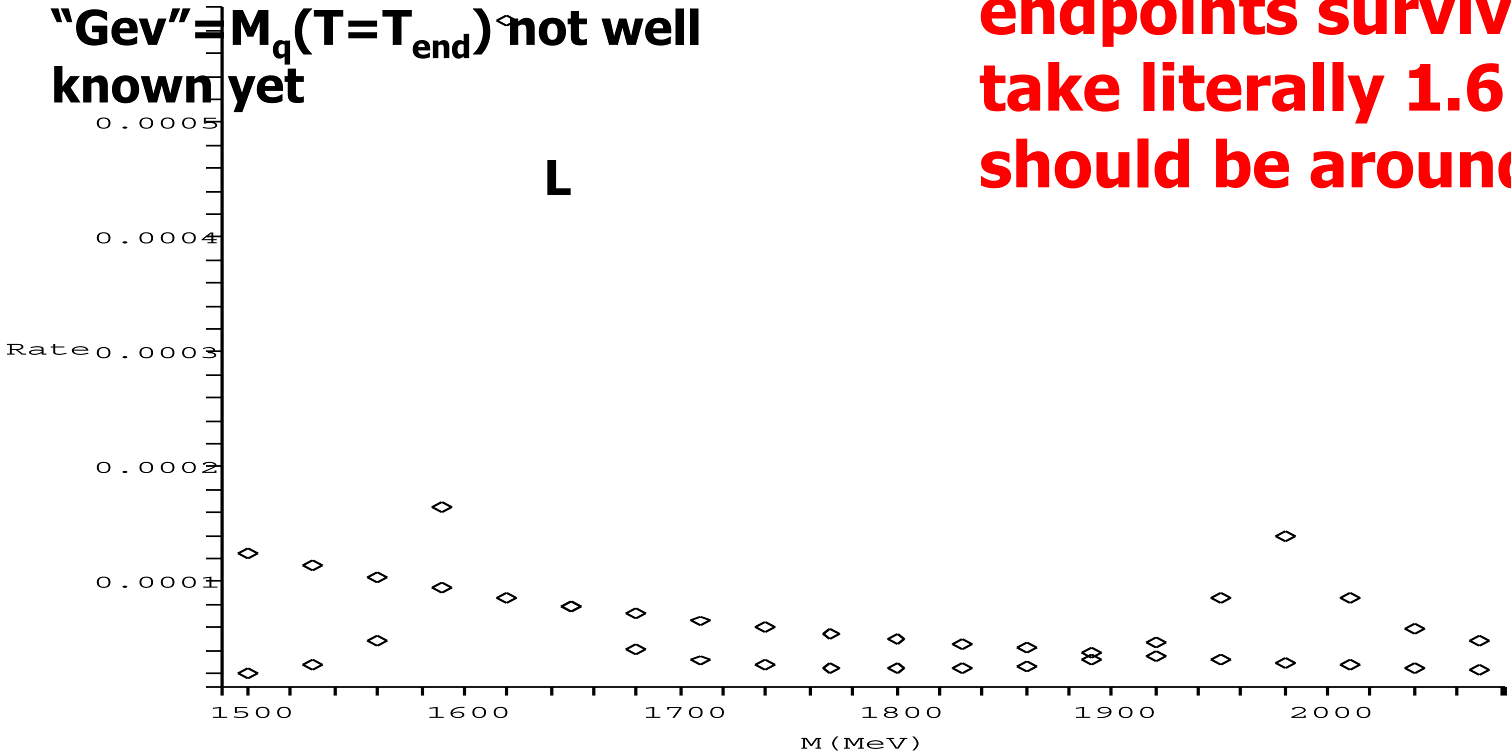
- Khose and Fadin: sum over states, then Strassler and Peskin: Green function can be formed of 2 solutions
- We get 2 solutions numerically and checked that published t-pair production for Coulomb is reproduced up to .2 percent!
- Then we used it for ` `realistic” potentials

(From the lattice)

How those states/bumps look like after one integrates over the expanding fireball?

Smooth curve is our ``standard candle" with massless free quarks

"Gev"=$M_q(T=T_{end})$ not well known yet



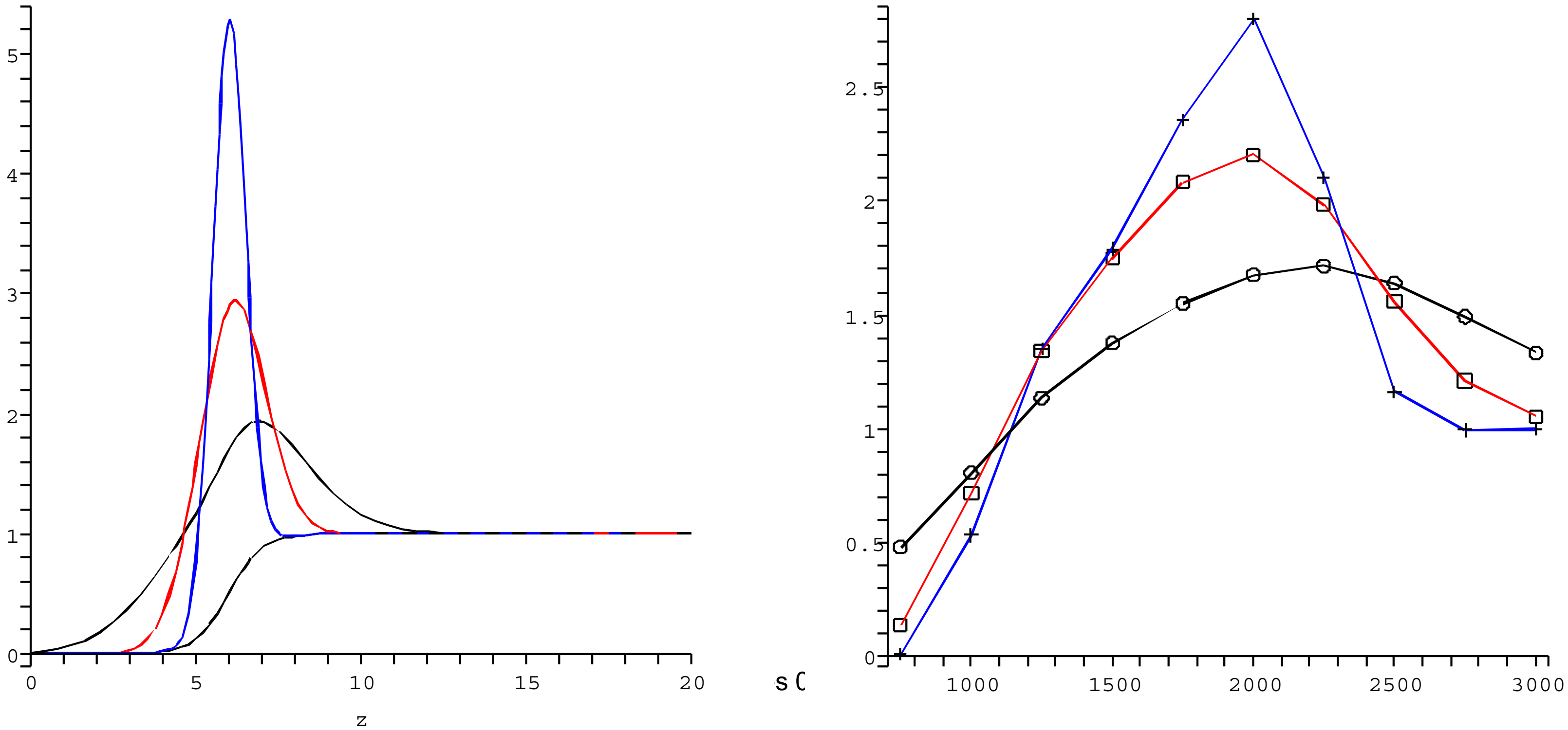
Curves with peaks are for

ρ,ω in sQGP: the endpoints survive (don't take literally 1.6 GeV, should be around .5-.7)

QUARK-HADRON DUALITY AND BUMPS IN QCD:

Operator product expansion tells us that the integral Under the spectral density should be conserved (Shifman, Vainshtein, Zakharov 78).

Three examples which satisfy it (left) the same after realistic time integral Over the expanding fireball (as used in Rapp+ES paper on NA50), divided by a ``standard candle" (massless quarks) (right)



Why study flows in heavy ion collisions?

- **A ``Bang" like other magnificent explosions like Supernova or Big Bang: radial and elliptic flows (which can only be calculated together, from the same EoS)**

- **New form of matter formed, a strongly coupled Quark-Gluon Plasma, a near-perfect liquid in regime with very small dissipative terms η/s».1-.3<<1**

The Big vs the Little Bang

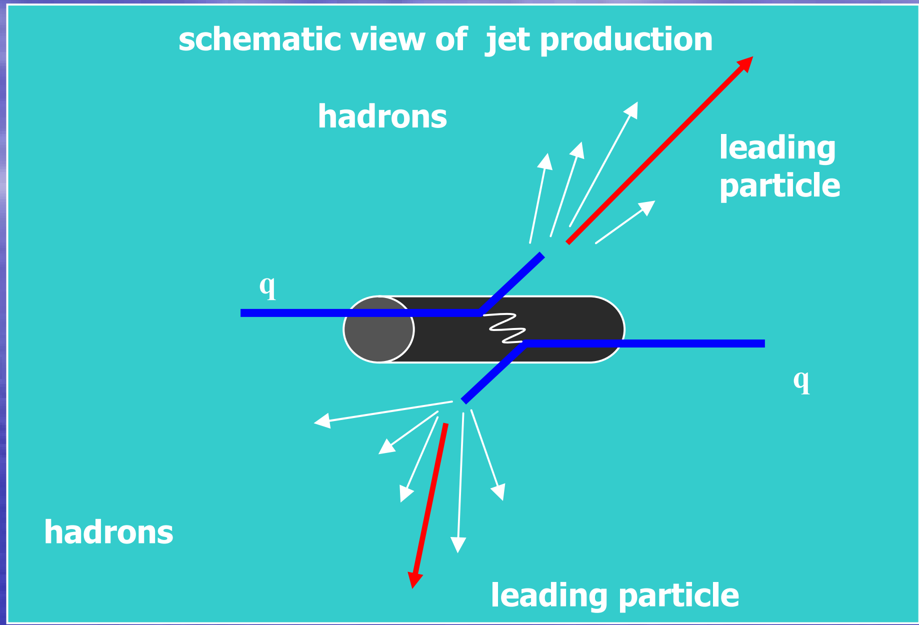
- Big Bang is an explosion which created our Universe.
- Entropy is conserved because of slow expansion
- Hubble law v=Hr for distant galaxies. H is isotropic.
- "Dark energy" (cosmological constant) seems to lead to accelrated expansion

- Little Bang is an explosion of a small fireball created in high energy collision of two nuclei.
- Entropy is also conserved
- Also Hubble law, but H is anisotropic
- The ``vacuum pressure" works against QGP expansion

(And that is why it was so difficult to produce it)

q/g jets as probe of hot medium

Jets from hard scattered quarks observed via fast leading particles or azimuthal correlations between the leading particles



However, before they create jets, the scattered quarks radiate energy (~ GeV/fm) in the colored medium

→decreases their momentum (fewer high p_T particles)
→"kills" jet partner on other side

Jet Quenching