The manifestations of strongly coupled Quark-Gluon Plasma at RHIC

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Outline:

- Why strongly coupled QGP?
- Collective flows: radial and elliptic, systematics: => viscosity
- Does charm flows?
- Where the energy of jets go? A ``conical flow”
- How strong is ``strongly coupled”? Quasiparticles, potentials and bound states at T>Tc
- Colored bound state and EoS
- A 1.5-2 GeV rho,omega,phi mesons?

Why strongly coupled QGP?

- 1a: Because hydro works well, and the viscosity is very low (Teaney,ES,Heinz,Kolb…01)
- 1b: Because parton cascade requires very large cross sections (Molnar-Gyulassy)

(a comment: they are not the same => a cascade makes no sense in a strongly coupled regime, while hydro only works better)

Why strongly coupled QGP?

- 2a: Because at 3Tc>T>Tc the interaction is strong enough to make multiple bound states (ES+Zahed, 03), most of them colored. hadron-like states lead to hadron-size cross sections
- 2b: Marginal states with small binding may lead to even larger cross sections (ES+Zahed, 03), confirmed by Feshbach resonances in trapped ultracold atoms

Why strongly coupled QGP?

- 3: N=4 SUSY YM theory at strong coupling at finite T shows features very close to sQGP at RHIC:
- 3a: p,e\sim T^4 and even the famous p/p_sb=.8 is well reproduced by large-g series (Klebanov…96,02) (not small-g)
- 3b: viscosity is small: \eta/s=1/4\pi (Son et al,03)
- 3c: quasiparticles are heavy M>>T while their lightest bound states have M=O(T) and can be excited (ES+Zahed,03)

Collective flows: bits of history

Early hydro

- L.D.Landau, 1953
  => first use of hydrodynamics
- L.D.Landau, S.Z.Belenky 1954 Uspechi
  => compression shocks
  => resonance gas (Delta just discovered)
- G.A.Milekhin 1958
  => first numerical solution, emphasis on the transverse flow

My early hydro

- Hydro for e+e- as a spherical explosion PLB 34 (1971) 509

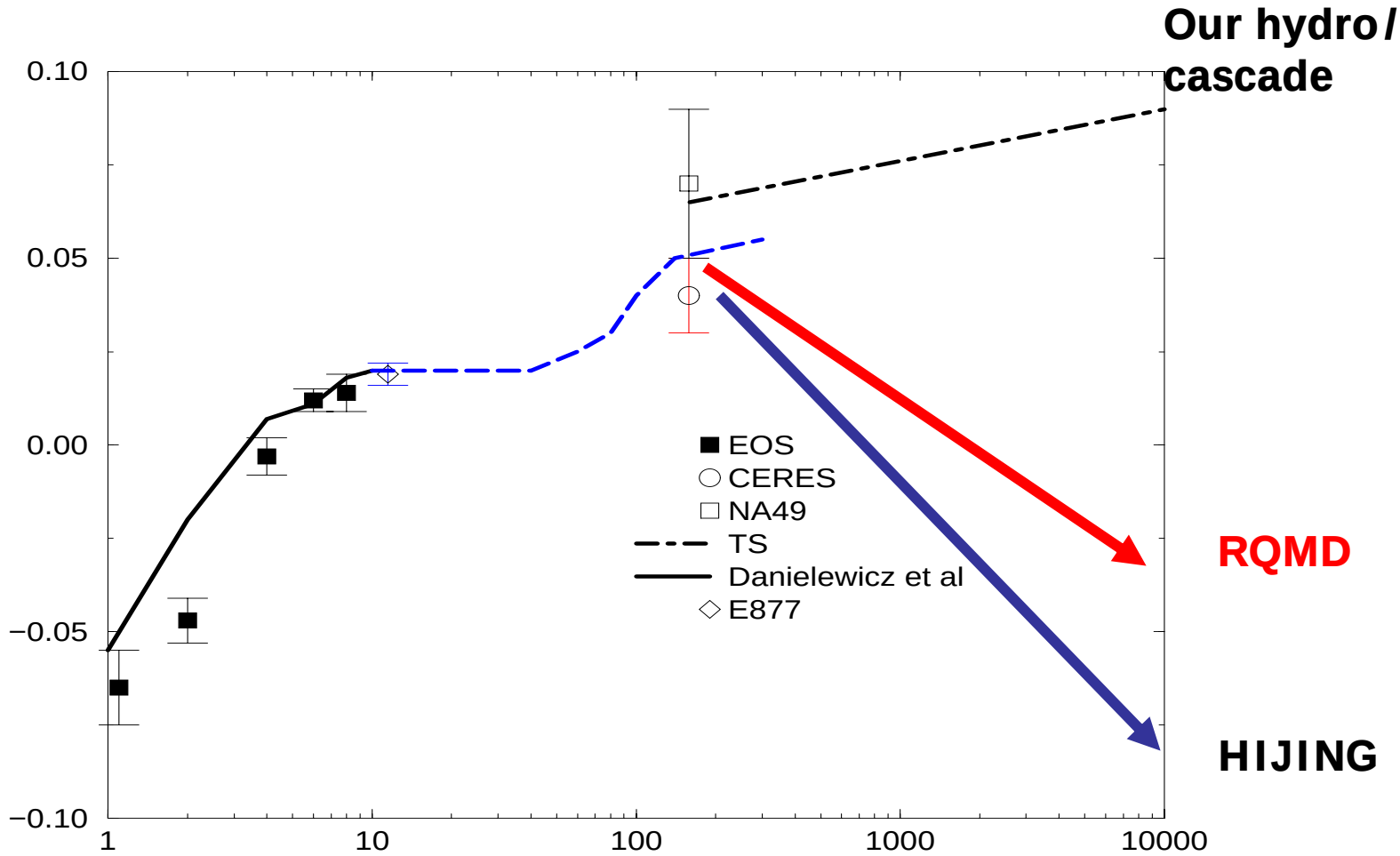
=> killed in 1976 by the discovery of jets in e+e-

- Looking for transverse flow at ISR, ES+Zhirov, PLB (1979) 253

=>Killed by apparent absence of transverse flow in pp

$\Rightarrow$ ES+Hung, prc57 (1998) 1891, radial flow at SPS with correct freezeout surface, correct T_f (centrality) dependence was predicted

Our pre-RHIC (QM99) predictions for v2(energy) (with D.Teaney)



Hydrodynamics is simple and very predictive, but one has to understand few things, and so not all hydros are the same

EoS from Lattice QCD

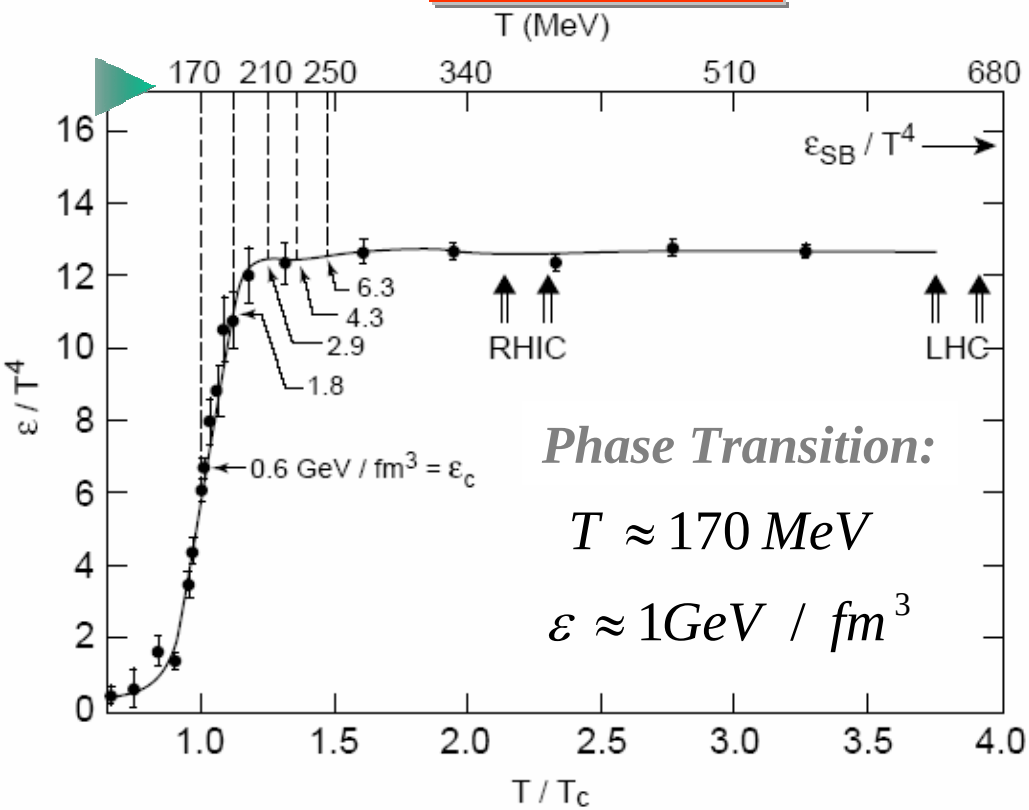
Local Energy-momentum conservation: $\partial_\mu T^{\mu\nu} = 0,$

Conserved number: $\partial_\mu n_i^\mu = 0$

Dynamic Phenomena
- Expansion, Flow
- Space-time evolution of thermodynamic variables

Caveat: Why and when the equilibration takes place is a tough question to answer

Energy density from Lattice QCD:



Phase Transition:

$$T \approx 170\ MeV$$

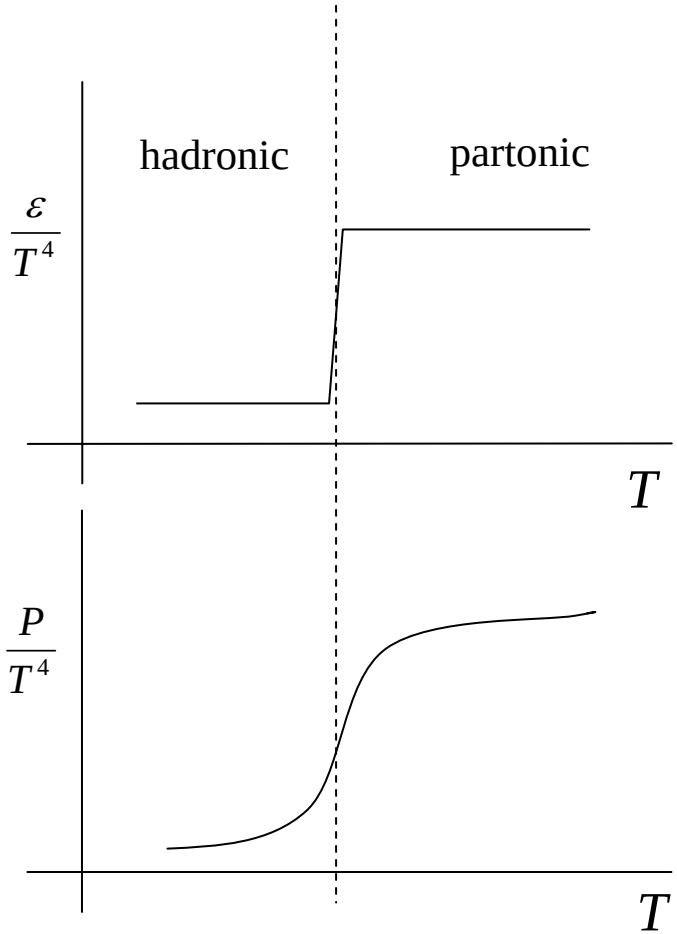
$$\varepsilon \approx 1 GeV\ /\ fm^3$$

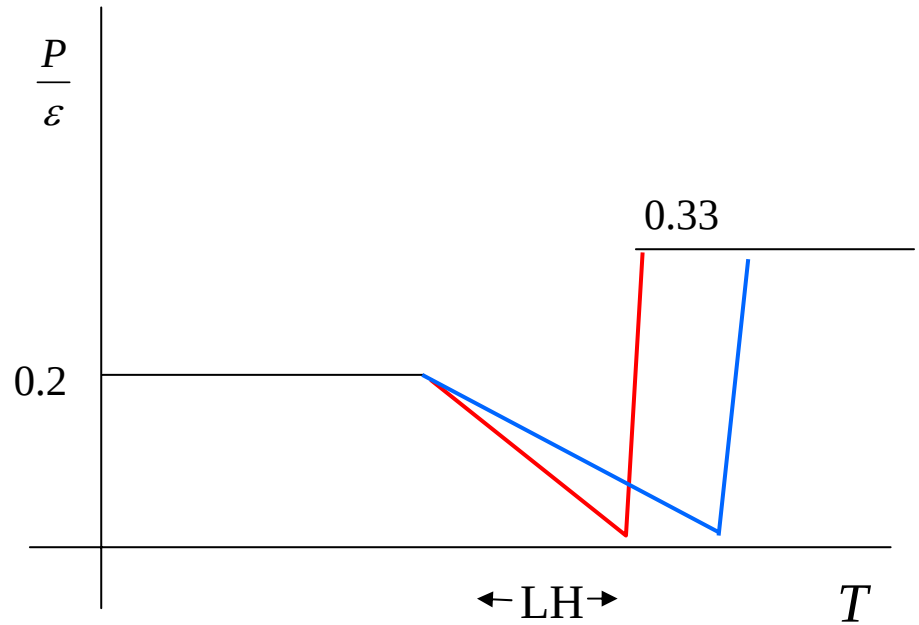
Phase Transition

Putting AGS/SPS/ RHIC/LHC on a map

Thinking About EoS
The Latent Heat and the ``softest point”

(Hung, ES 1995)





Understanding of the freezeouts (which some hydro groups ignored)

- **Chemical freezeout at Tch means that at T<Tch hadronic matter is indeed chemically frozen => different EoS with nonzero mu's**
- **Kinetic freezout at fixed Tf is wrong:**
- **the larger systems cool to LOWER Tf,**
- **one has to calculate the freezeout surface (Hung,ES)**
- **or use an afterburner (RQMD) (Teaney, ES)**

hydro describes both radial and elliptic flows

(from Phenix) v_2=<cos(2 phi)>

proton pion

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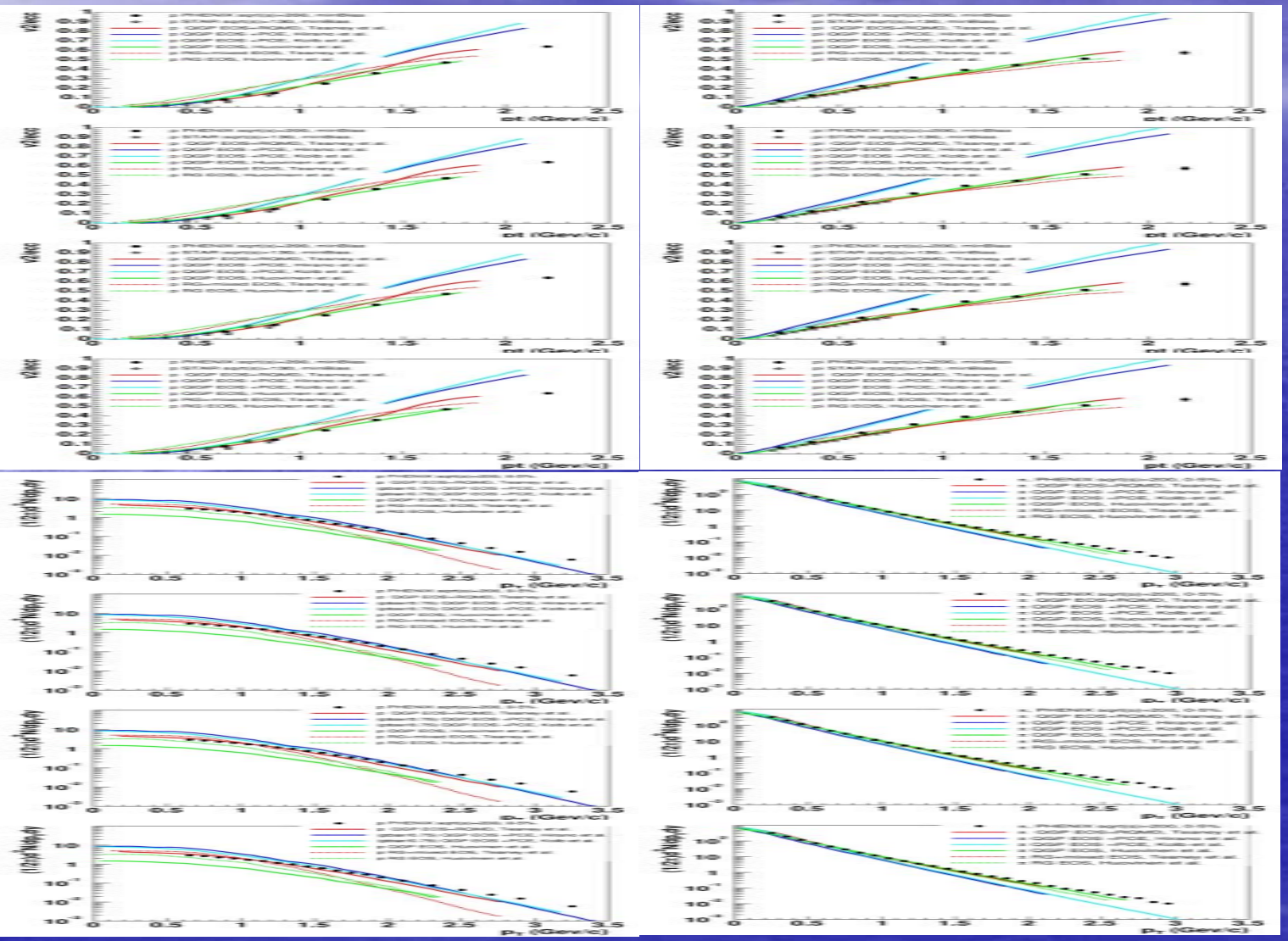


Hydro models:

Teaney
(w/ & w/o RQMD)

Hirano
(3d)

Kolb

Huovinen
(w/& w/o QGP)

V2 systematics: it depends on many variables

- Particle type => y_t^2 m scaling (R.Lacey)
- Collision energy dependence: monotonouse rise with dN/dy then saturation (Teaney+ES,01)
- (pseudo) rapidity (eta) y-dependence: basically the same v2(dN/dy)
- Pt: rapid growth with saturation (?)
- Centrality => v2/s2 scaling (Ollitraut)

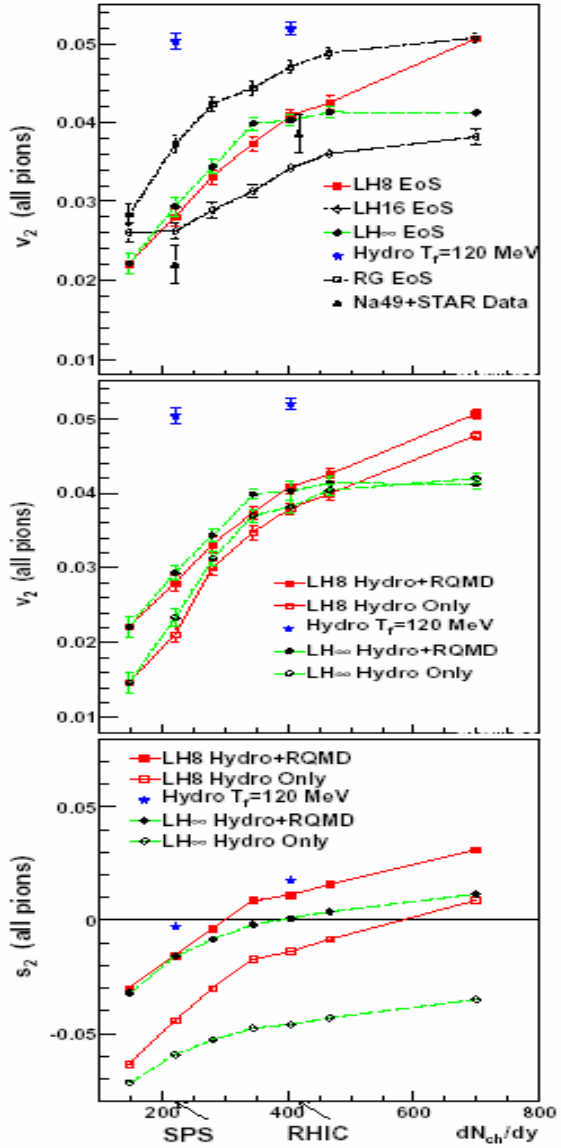


FIG. 24: Panels (a)-(c) show three related quantities as a function of the total multiplicity in a PbPb collision at b = 6fm. (a) shows the integrated elliptic flow v_2 of pions for different EOS and freezeout conditions; (b) shows the integrated elliptic flow v_2 with and without hadronic rescattering; (c) shows the spatial anisotropy s_2 with and without hadronic rescattering. At the SPS, the NA49 v_2 data point is extrapolated to b=6 fm using Fig. 3 in [77]. At RHIC, the STAR v_2 data point is extrapolated to $N_{ch}/N_{ch}^{max} = 0.545$ (b=6 fm in AuAu) using Fig. 3 in [78].

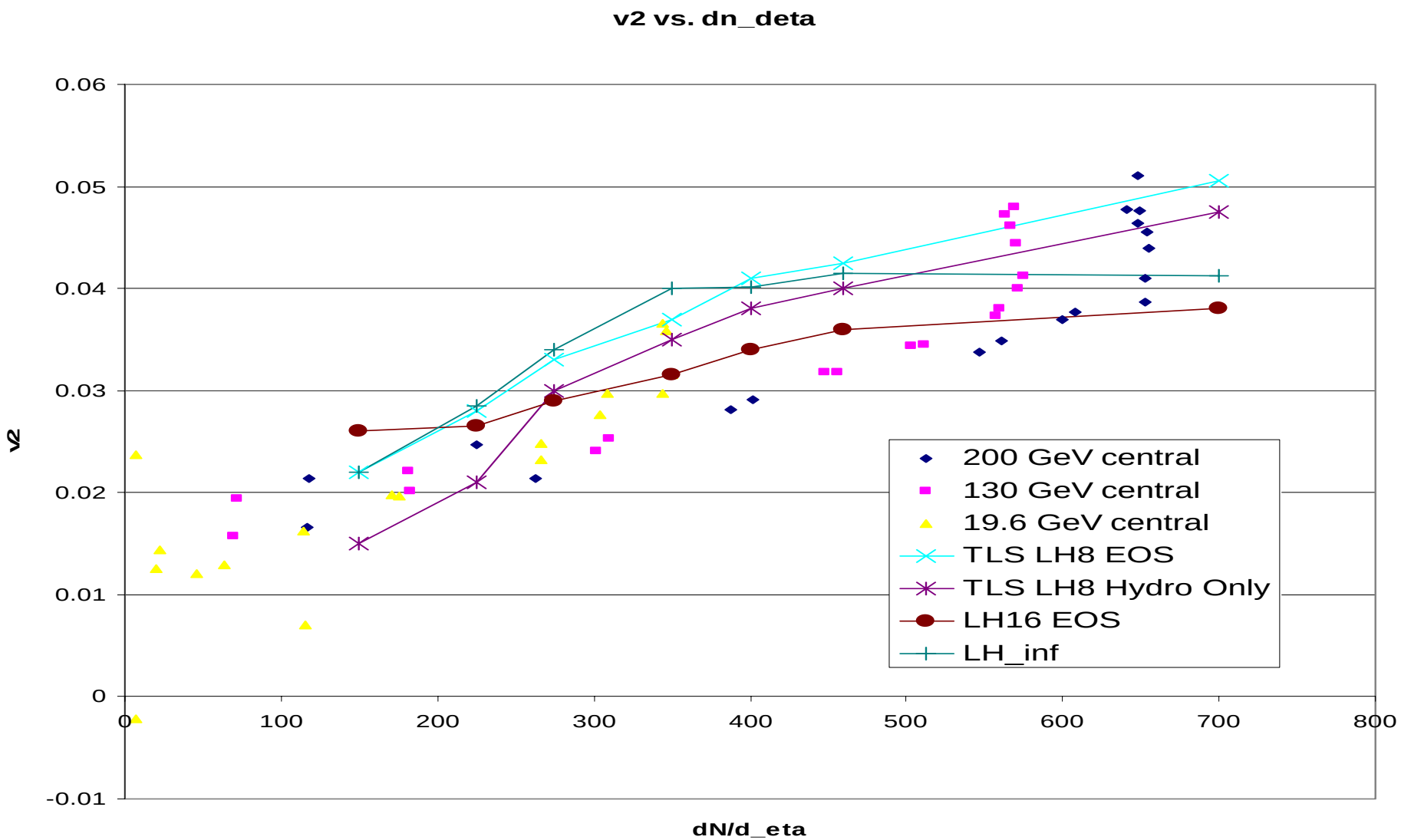
A Hydrodynamic Description of Heavy Ion Collisions at the SPS and RHIC

D. Teaney, J. Lauret, and E.V. Shuryak

nucl-th/0110037 v2 6 Dec 2001

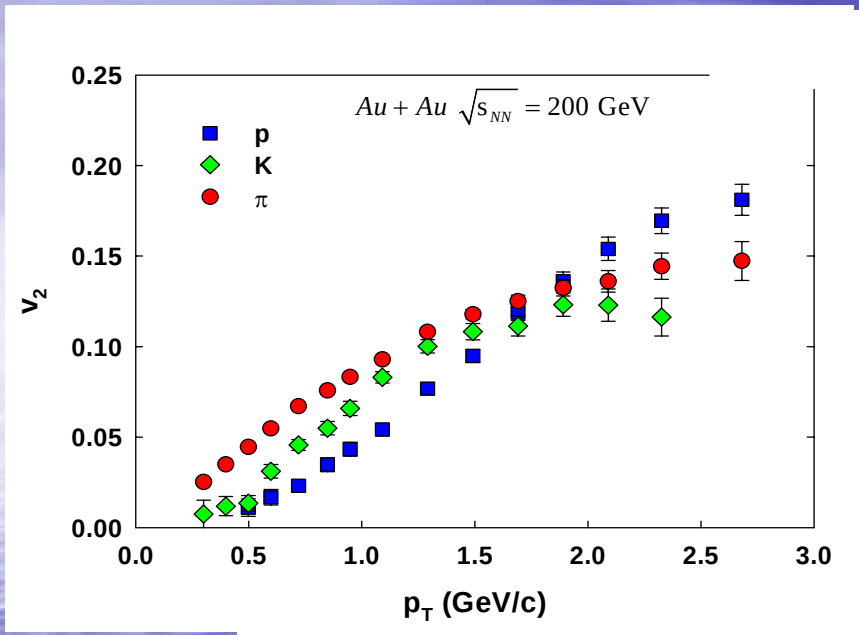
The dependence on dN/dy has a growing trend, with a saturation

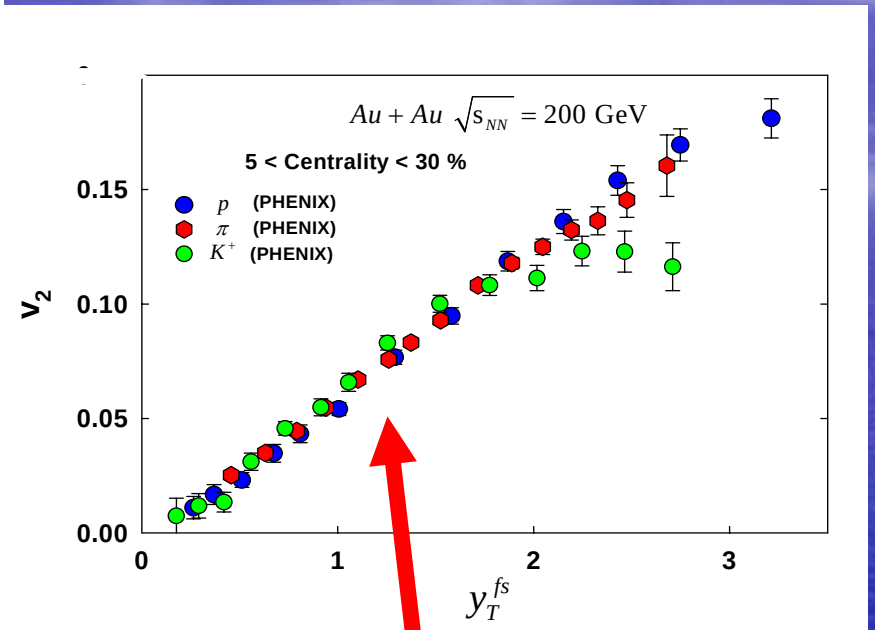
But the trend roughly follows the (BJ-like) hydro predictions, which is is also about s- and y-dependent via local dN/dy

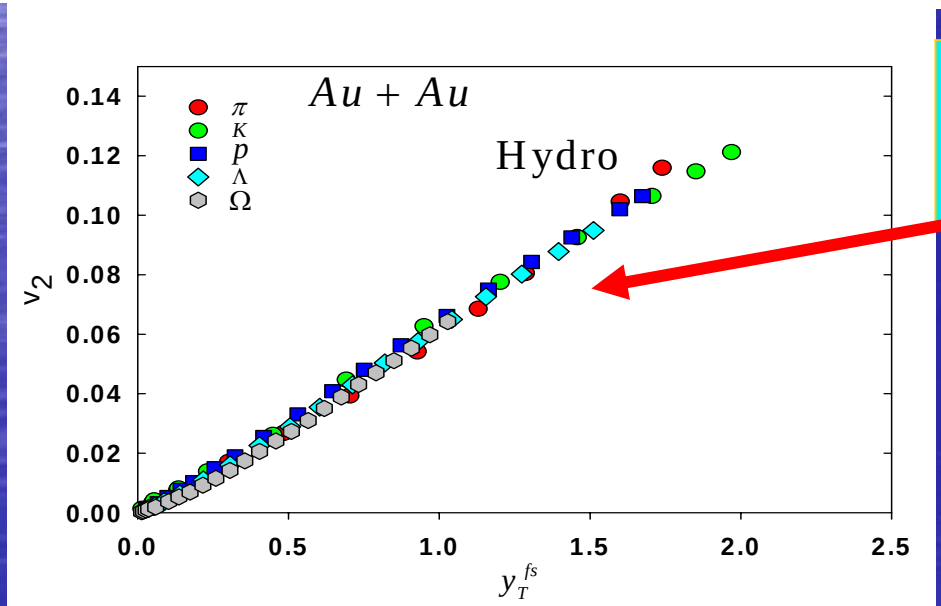


The data scale as hydro:

$$y_T^{fs} \equiv k_m \times y_T^2 m$$







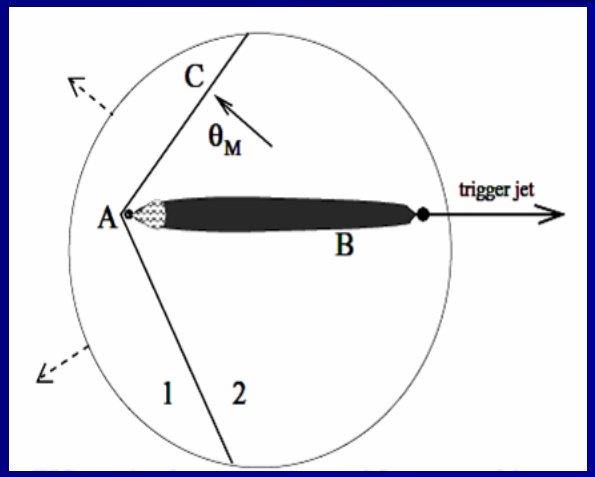
data look like hydro!

R.Lacey

Sonic boom from quenched jets Casalderrey,ES,Teaney, hep-ph/0410067; H.Stocker…

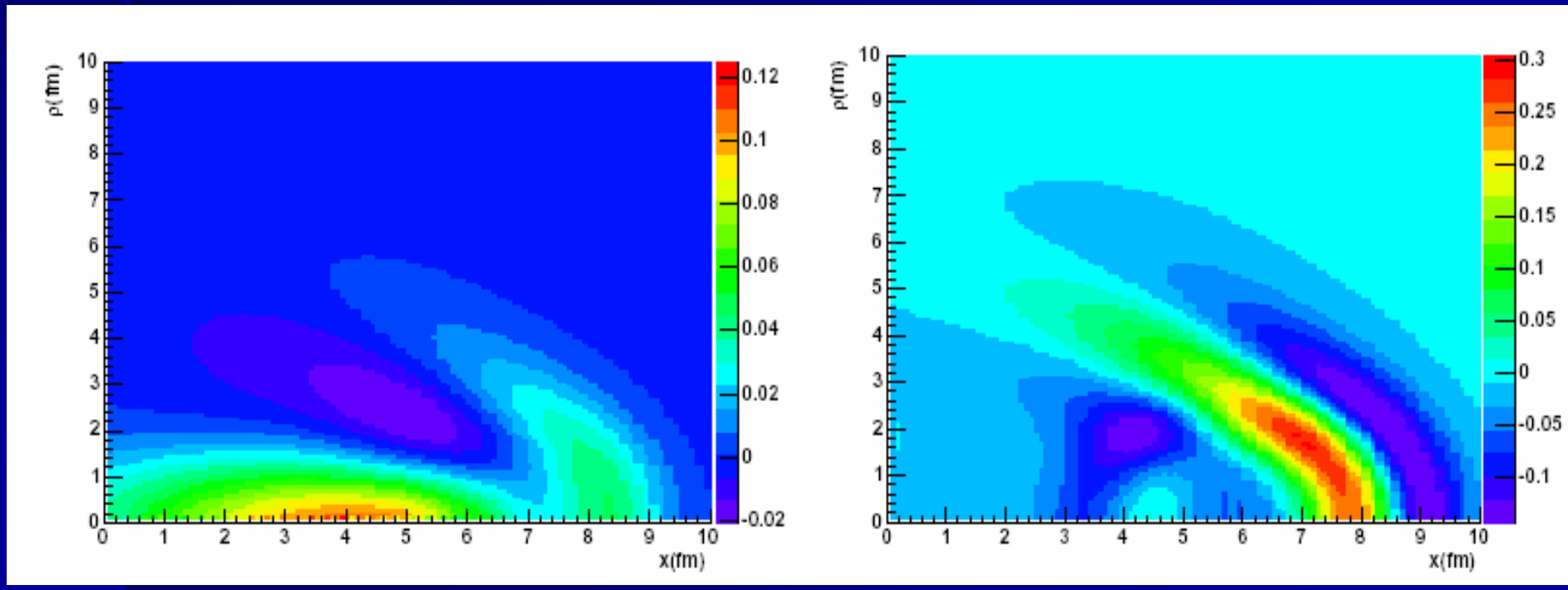
Wake effect or "sonic boom"

- 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
- If there are start and end points, there are two spheres and a cone tangent to both



Two ways to excite matter and two hydro modes: a ``diffuson" and shocks/sound

$$\epsilon_{dt_0}(t=t0,\vec{x}) = e_0(z,r) \quad , \quad \vec{g}_{dt_0}(t=t0,\vec{x}) = g_0(z,r)\delta^{ix} + \vec{\partial} g_1(z,r) \; .$$



Those two lead to quite different spectra, the second with a cone:

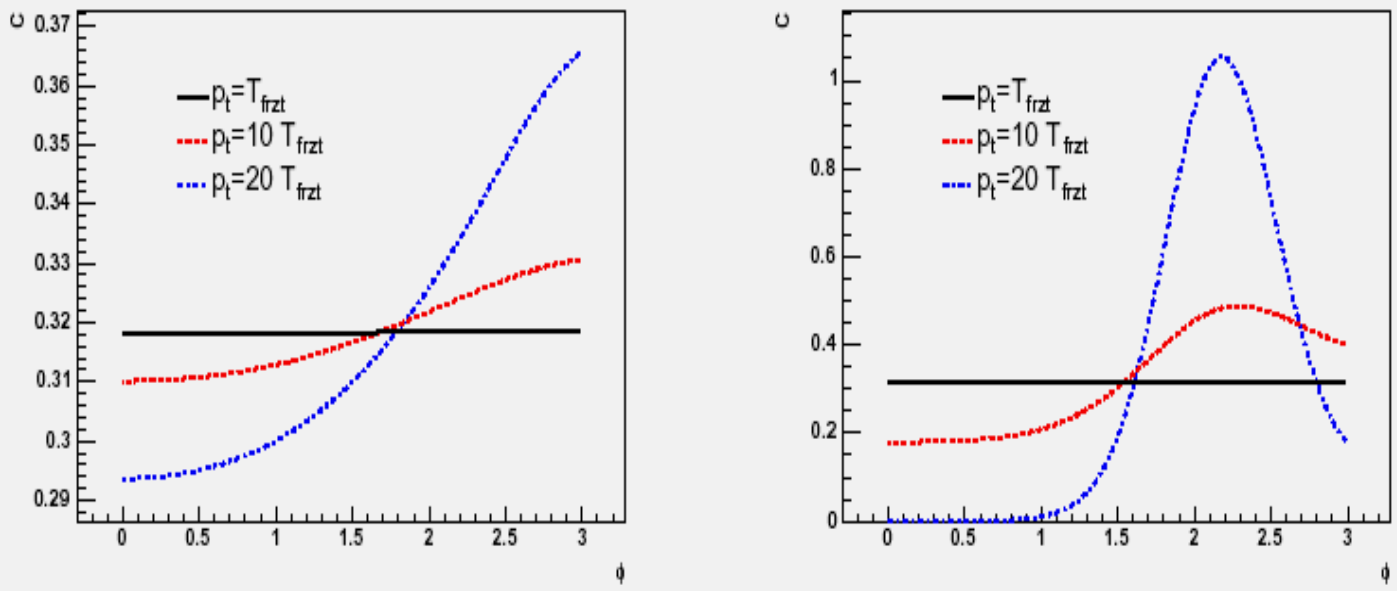


Figure 3. The normalized spectrum of associated secondaries versus the azymuthal angle ϕ. Three curves are for different p_t at $y = 0$ for $c_s^2 = 1/3$, $\Gamma_s = 1/(4\pi T)$, $\sigma = \Gamma_s$. Note the different scales. The jet disappears completely at $t = 7$ fm while the spectrum is calculated at $t = 10$ fm. Two figures (a) and (b) are for scenarios 1 and 2, respectively.

Is such a sonic boom already observed?

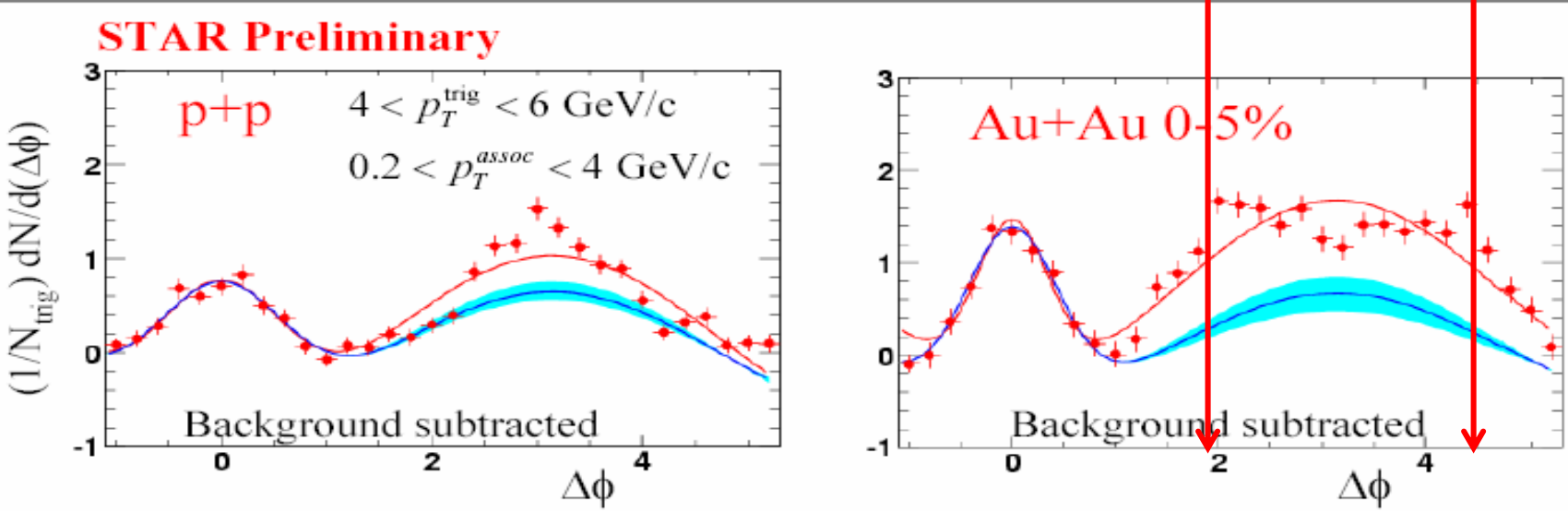
Mean Cs=.33 time average over 3 stages=>

$\phi=\pi$ +/-1.23=1.91,4.37

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

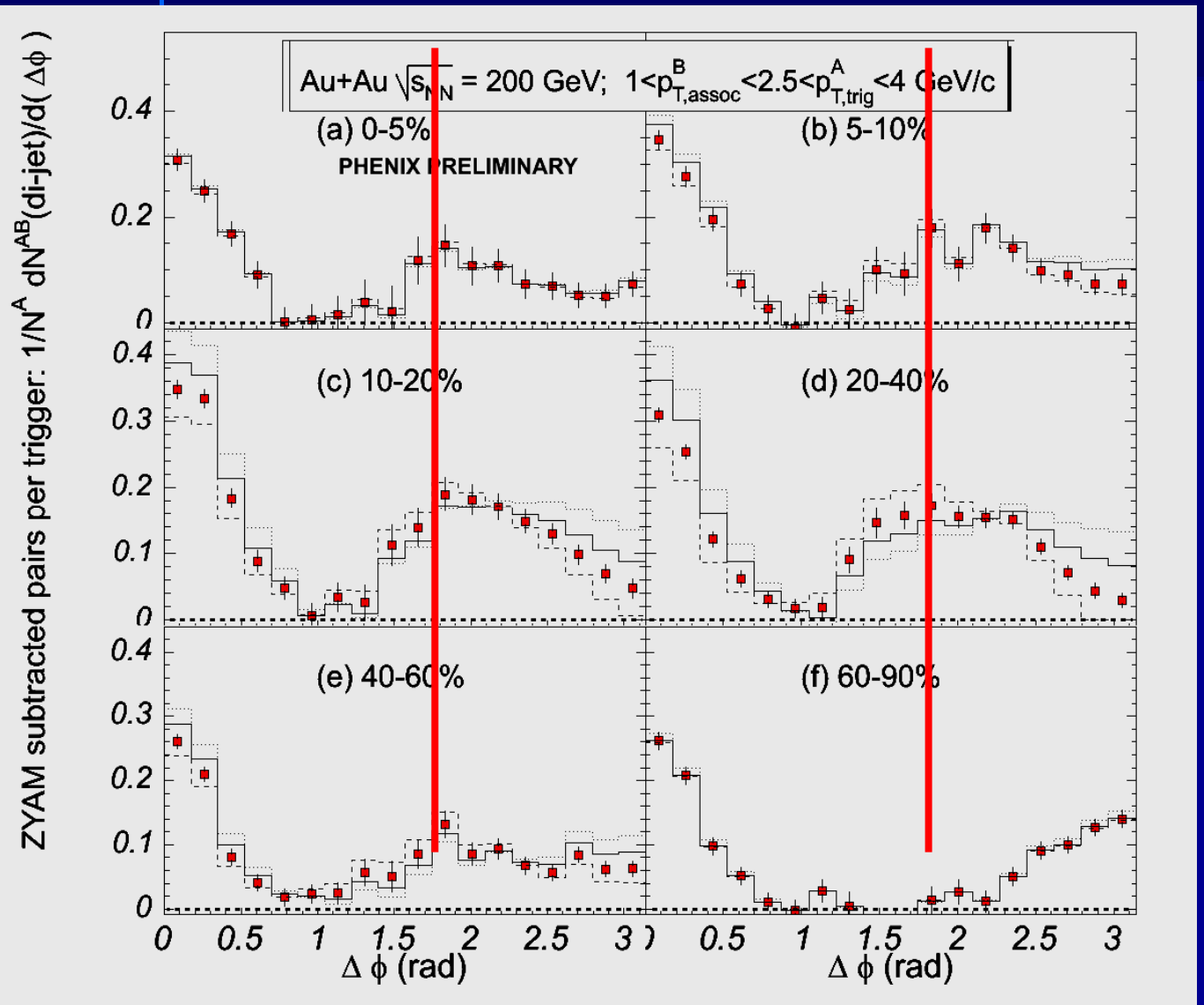
M.Miller, QM04

Is The Away-Side Jet-Like?



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

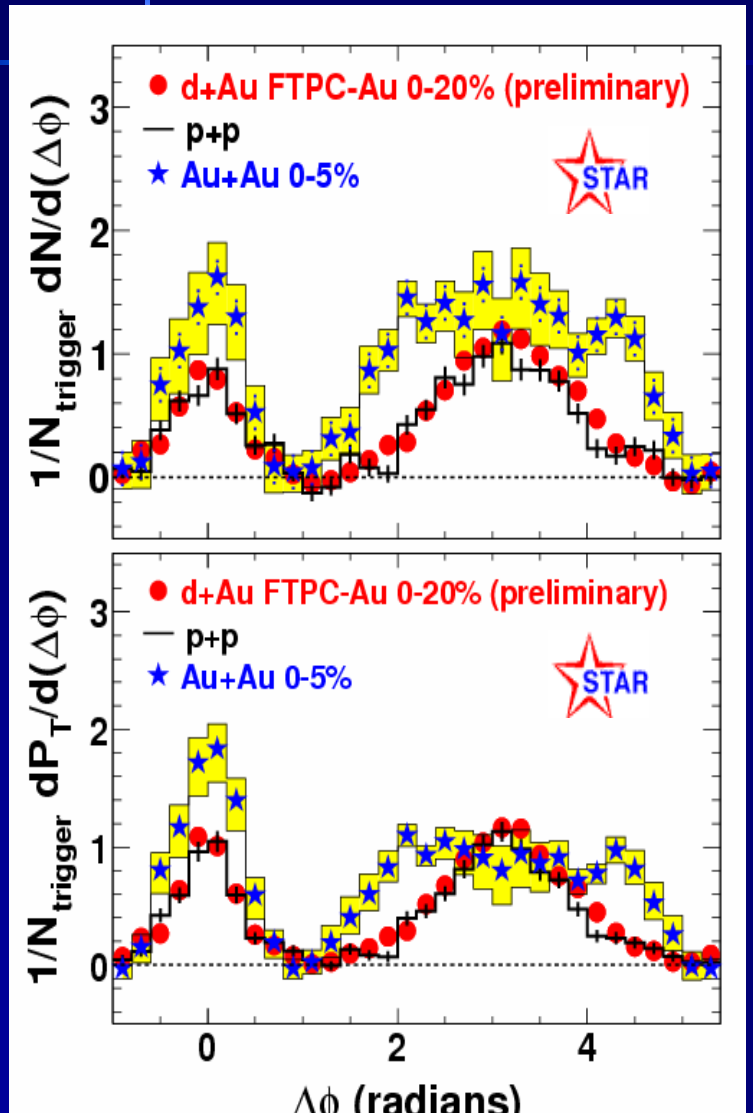
PHENIX jet pair distribution (B.Jacak, Calcutta conf.)

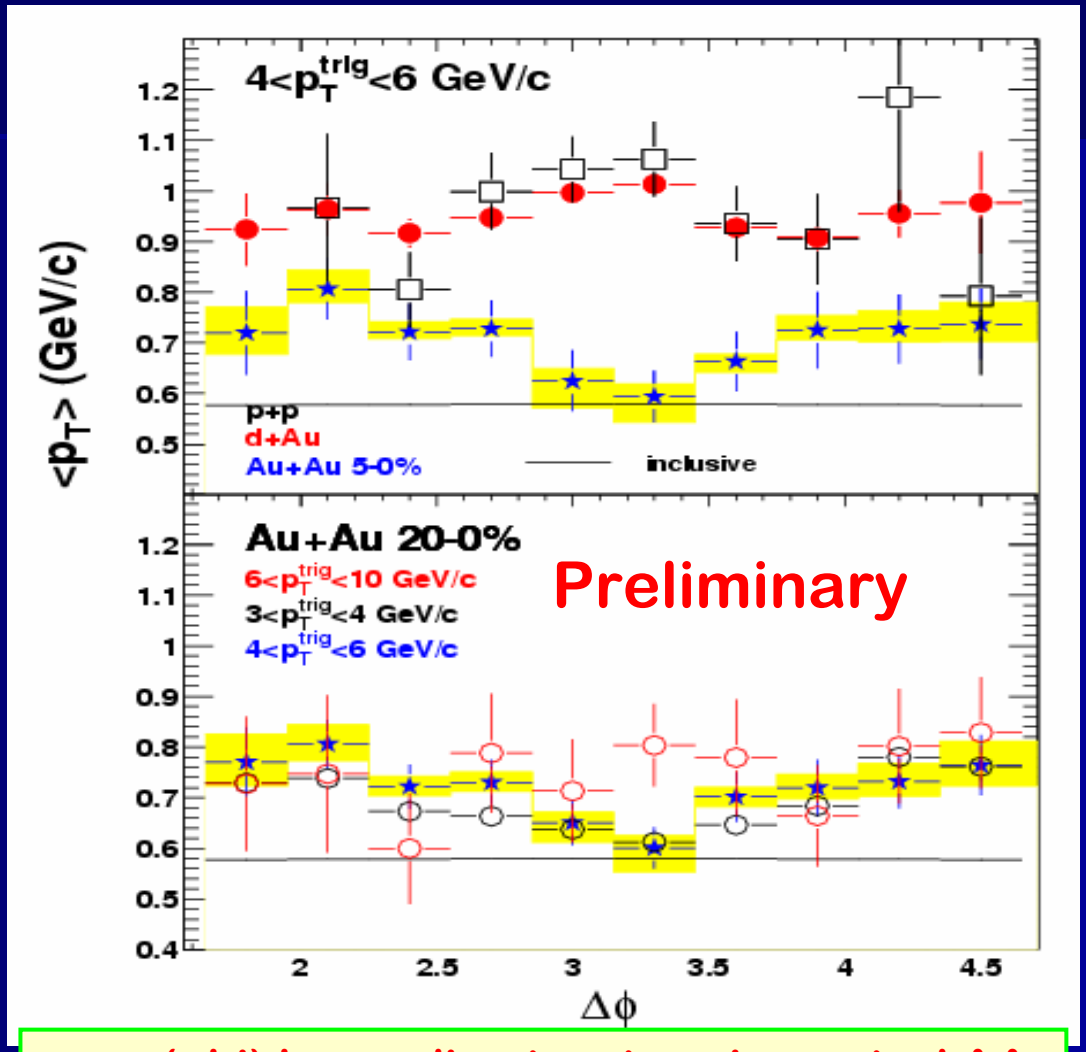


Note: it is only projection of a cone on phi

Note 2: this pt is Larger than in recent data from STAR => stronger peak and smaller background

away <pT> dependence on angle (STAR,preliminary)

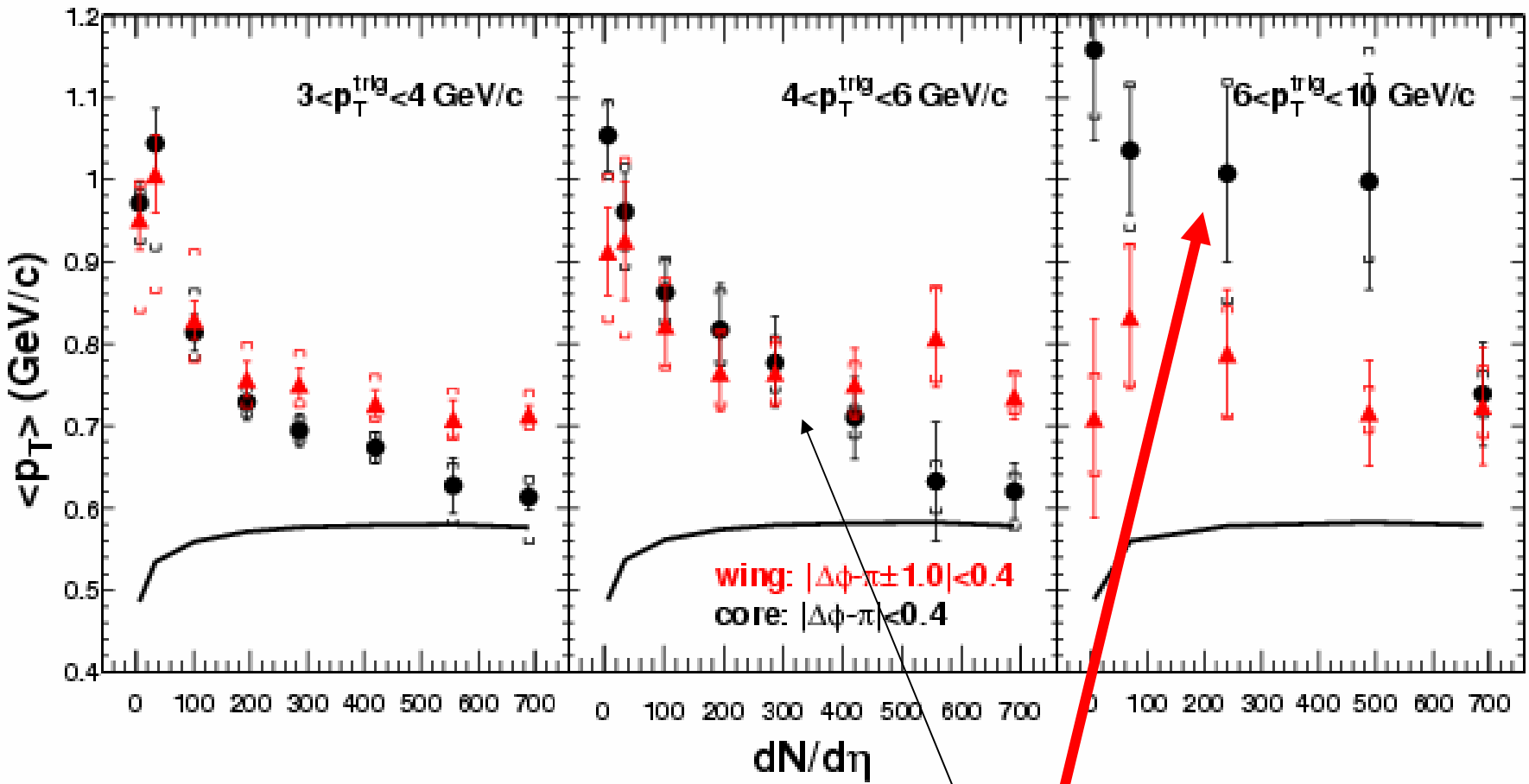




$<p_T>$ (phi) has a dip structure in central AA.

Mach shock wave?

Away $<p_T>$ vs centrality STAR,Preliminary



Away core $<p_T>$ drops with centrality faster than corona <pT>.
Core hadrons almost identical to medium in central collisions.

A punch-though at the highest trigger?

Summary/discussion on conical flow

- Peak is where we expect,
- Well seen in <pt>(phi)
- Next: 3-particle corrlations => high statistics, to fix the rapidity of the away jet... and see if it is a cone or not

Do heavy quarks flow as well?

- The main kinematical argument:

=> one needs Mq/T more collisions

(This is a factor of about

1.5 GeV/.2 GeV, about 7 for charm

and 5/.2 about 20 for b quarks)

heavy quarks: A bit of history:

- Parton model: (e.g. R.Vogt): charm decays will completely dominate single leptons and dileptons
- ES, nuc-th/9605011: if charm would stuck in matter, the dileptons can be observed for M>3 GeV

Whether charm stuck or not makes huge effect on dileptons at RHIC! ES 96

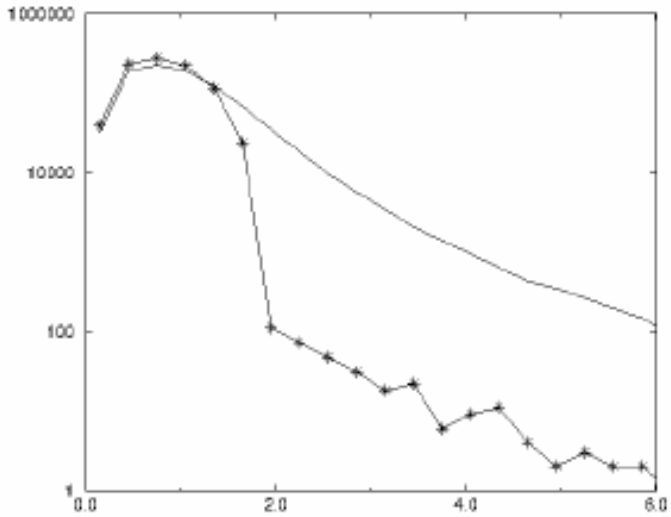


Figure 3: The distribution of dilepton invariant masses produced by a semileptonic decays of charmed quarks, with (stars) and without (histogram) the matter effect due to dE/dx.

Charm observables vs its transport (the diffusion coeff.) D=<x^2(t)>/6t

Moore&Teaney, hep-ph/0412346

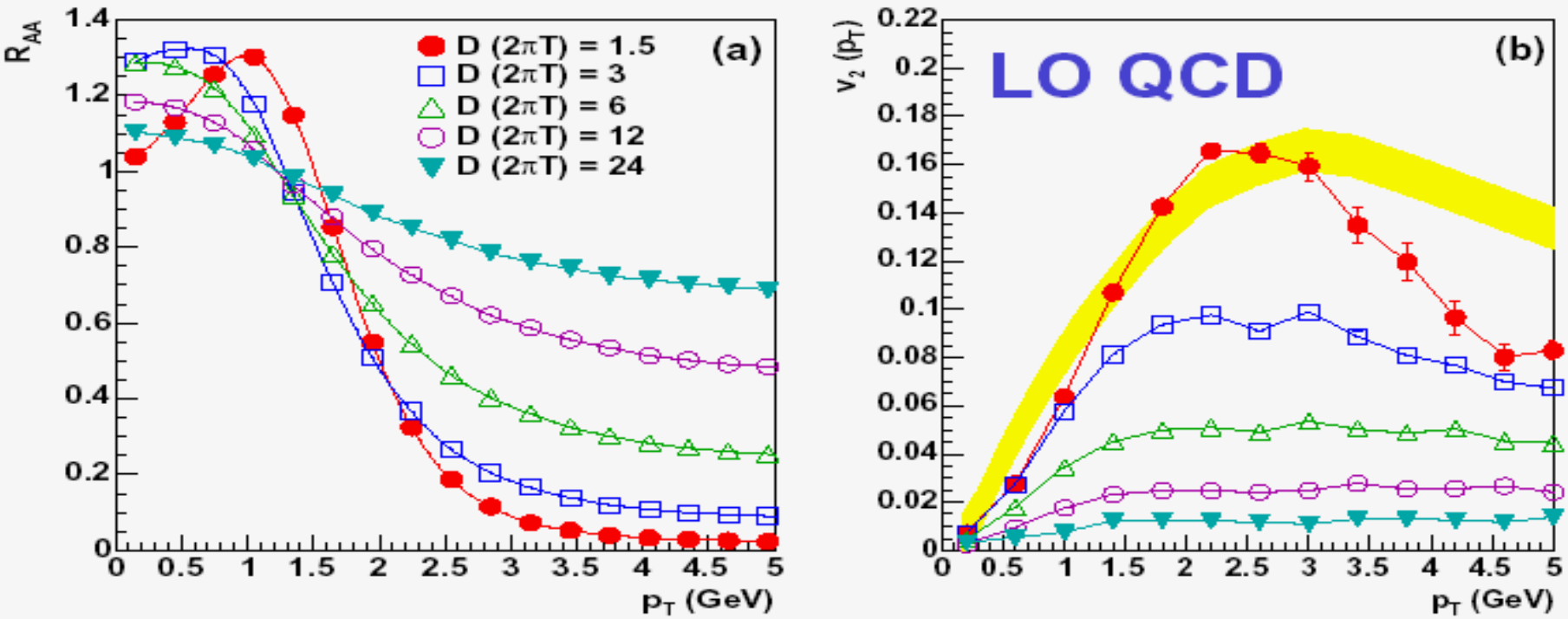


FIG. 4: (Color online) (a) The nuclear modification factor R_{AA} for charm quarks for representative values of the diffusion coefficient. (b) $v_2(p_T)$ for charm quarks for the same set of diffusion coefficients given in the legend in (a). In perturbation theory, $D \times (2\pi T) \approx 6\,(0.5/\alpha_s)^2$. The model for the drag and fluctuation coefficients is referred to as LO QCD in the text. The band estimates the light hadron elliptic flow for impact parameter $b = 6.5$ fm using STAR data [2].

nucl-ex/0502009

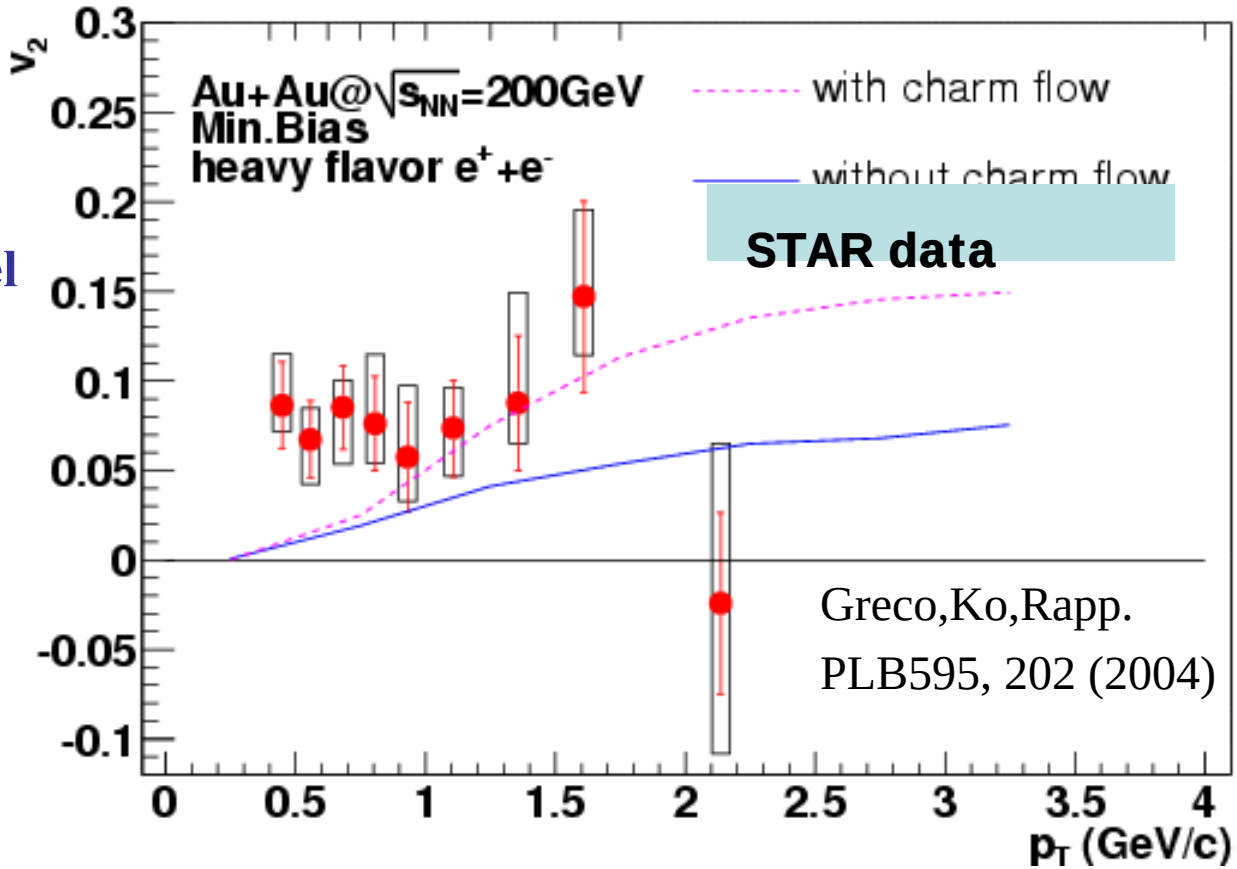
PHENIX measures v_2 of non-photonic e±

- electron ID in Au+Au via RICH + EMCAL
- measure and subtract photonic sources

$v_2 \neq 0$ at 90% confidence level

data consistent with heavy q thermalization

***but large errors; run4 will tell**



Conclusions on charm

- R_AA and v2 of charm suggest

a small diffusion coeff. for c ,

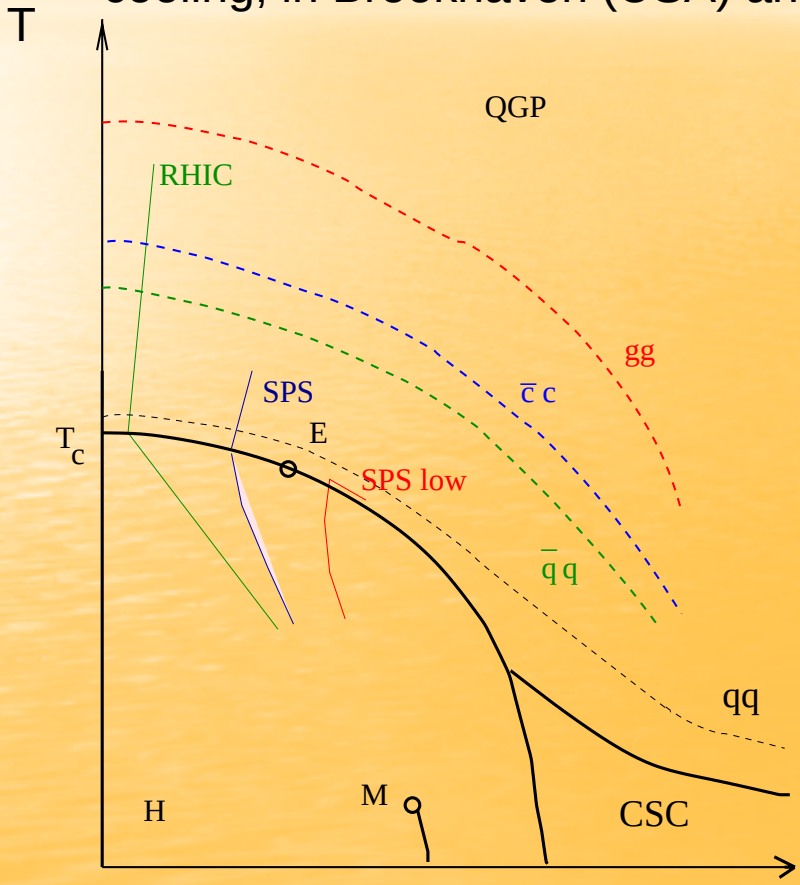
Maybe an order below of what pQCD suggests

- Q: at pt>4GeV we suppose to see b-quark dominance for e, so ???
- Q: what is the dilepton background?

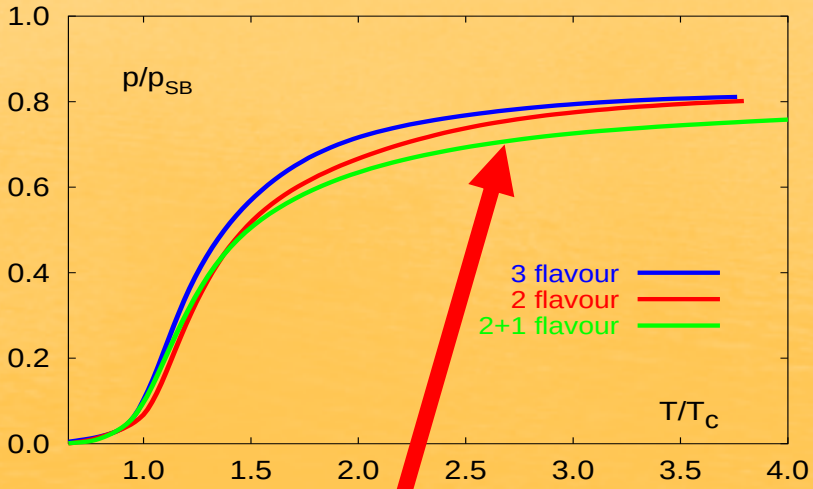
Theory and phenomenology of sQGP

The map: the QCD Phase Diagram

The lines marked RHIC and SPS show the paths matter makes while cooling, in Brookhaven (USA) and CERN (Switzerland)



Chemical potential mu

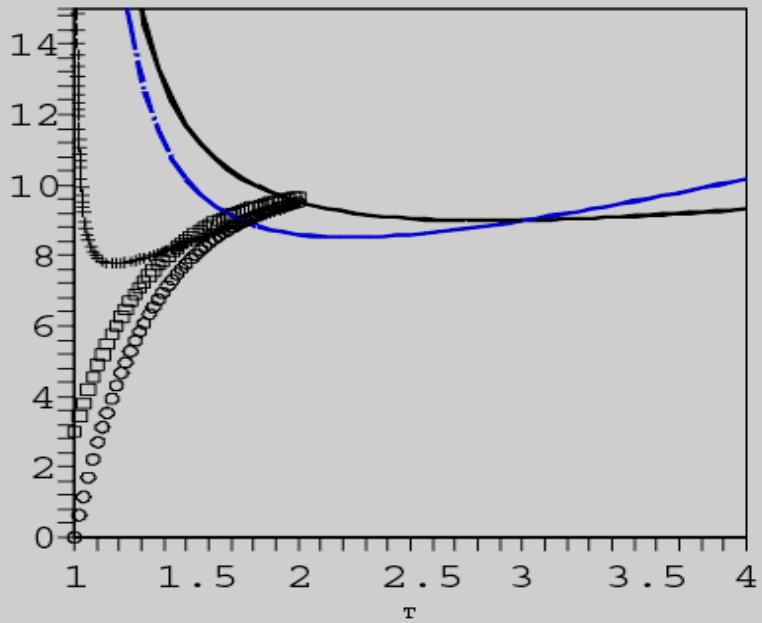


Theory prediction (numerical calculation, lattice QCD, Karsch et al) the pressure as a function of T (normalized to that for free quarks and gluons)

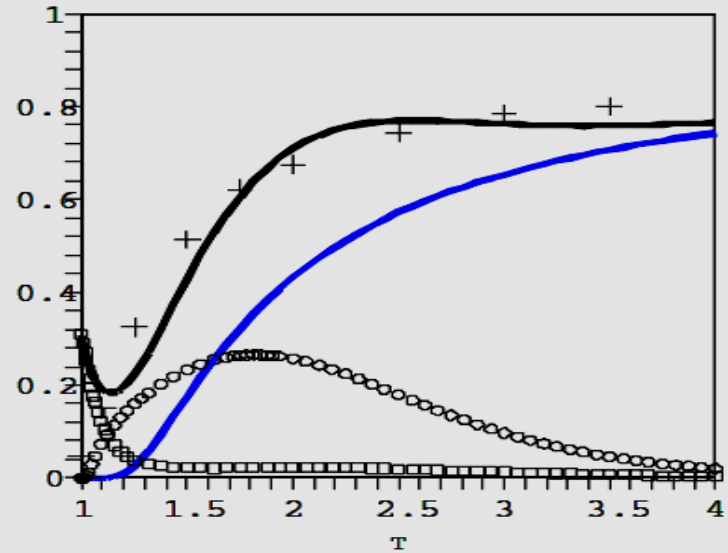
p/psb=.8

weak or strong coupling?

The pressure puzzle is resolved!



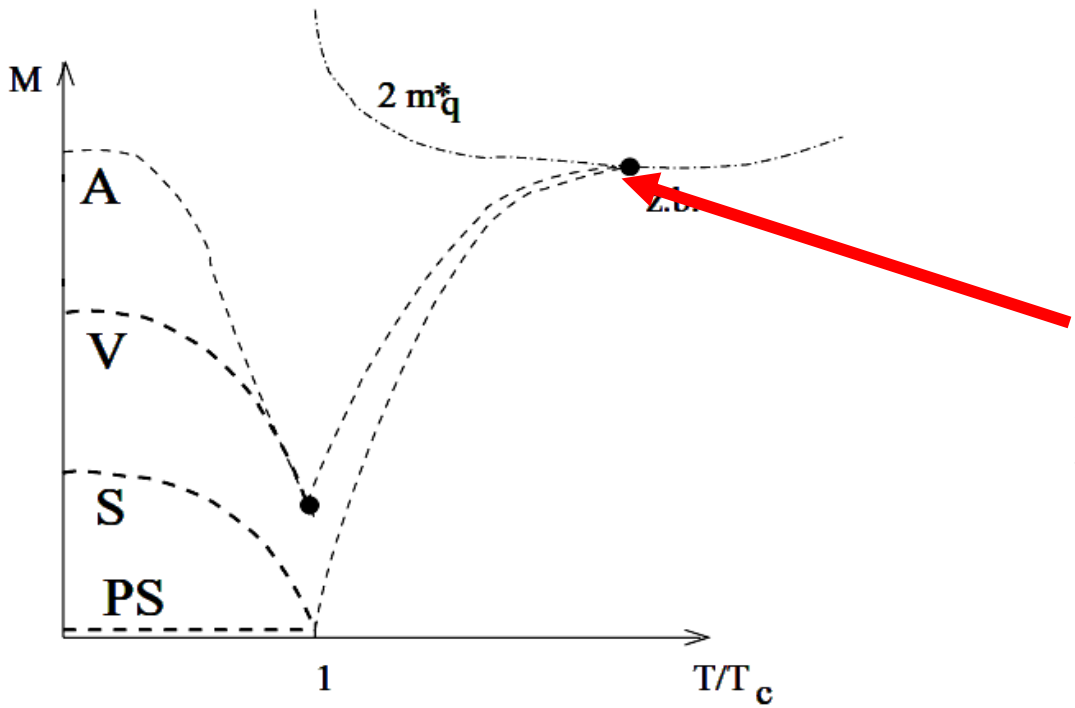
$2M_q(T), 2M_g(T)$ fitted to (Karsch et al) quasiparticle masses, as well as example of "old" $M_\pi(T)$ and "new" octet $M^8_{gg}(T)$



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 existence of bound states at T>Tc experimentally?

Dileptons from sQGP:



Here, near the minimal quark effective mass we expect to see new peaks

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.

Quark mass and the interaction strength ("α_s") via dileptons

- Three objects can be seen at nonzero p, T,L bound states (at fixed $T<T_{z.b.}$ about 2 T_c) and the near-threshold enhancement (``bump"), 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 Gamow parameter for small velocity

$z=\pi\ (4/3)\alpha_s/v$; can be > 1,

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

a nonrelativistic approach with realistic potentials (Jorge Casalderrey +ES,2004)

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

to

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

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*:

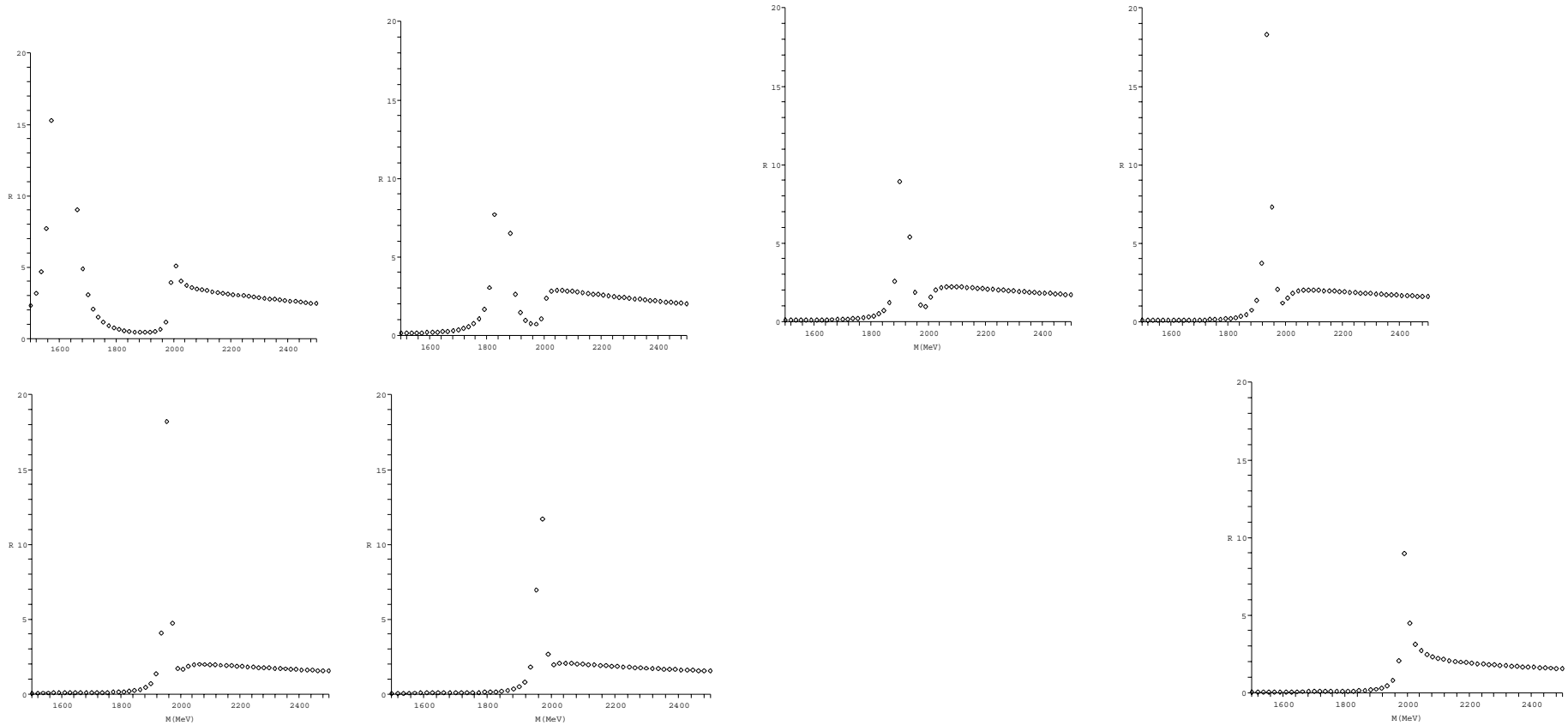
$$[-\frac{1}{m}\vec{\nabla}^2 + V(\vec{r}) - (E+i\Gamma)]G_{E+i\Gamma}(r,\bar{r}) = \delta^3(\vec{r}-\vec{\bar{r}}) \qquad (6)$$

Following the methods developed for t quark

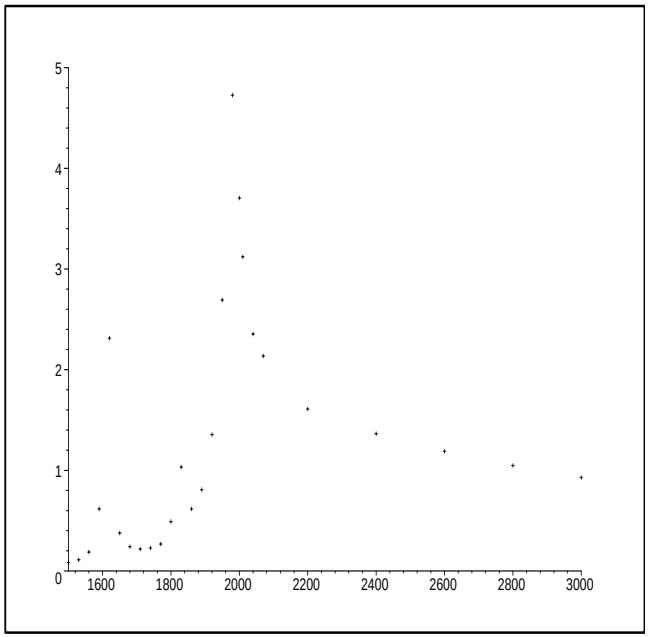
- Khose and Fadin: sum over states, then Strassler and Peskin: Green function can be formed of 2 solutions
- We get 2 solutions numerically and checked that published t-pair production for Coulomb is reproduced up to .2 percent!
- Then we used it for ``realistic” potentials

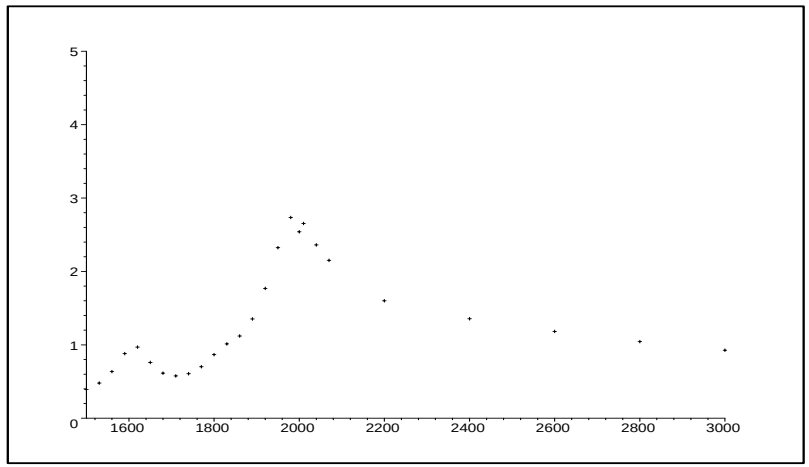
Study of near-endpoint annihilation rate using non-rel. Green function, for lattice-based potential (+ instantons) $\mathrm{Im}\Pi(M)$ for $T=1\ldots 2\,T_c$

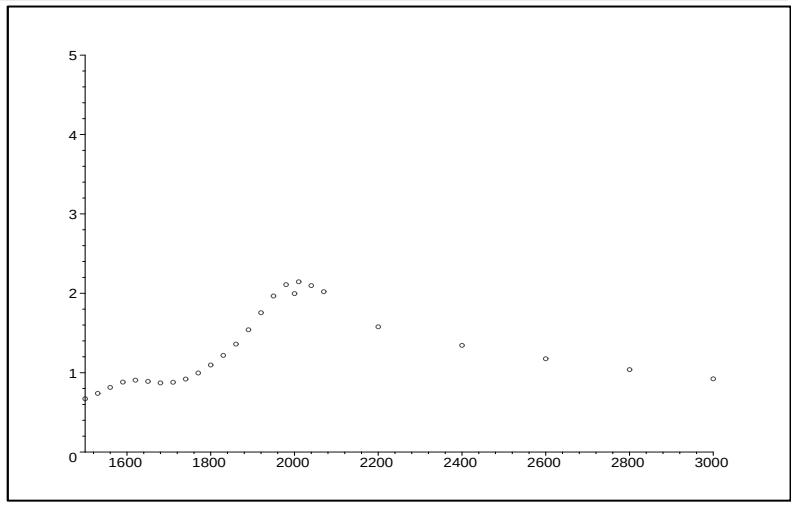
(a warning: very small width)



Total width is 20,100 or 200 MeV

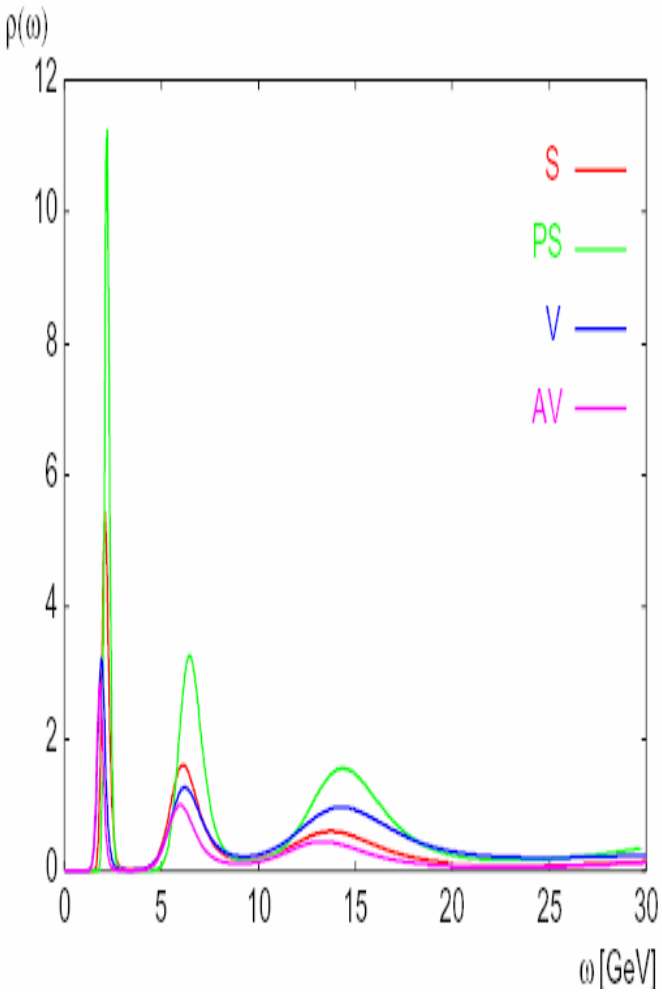






Width is not to be trusted !

Asakawa-Hatsuda, $T=1.4T_c$



Karsch-Laerman, T=1.5 and 3 Tc

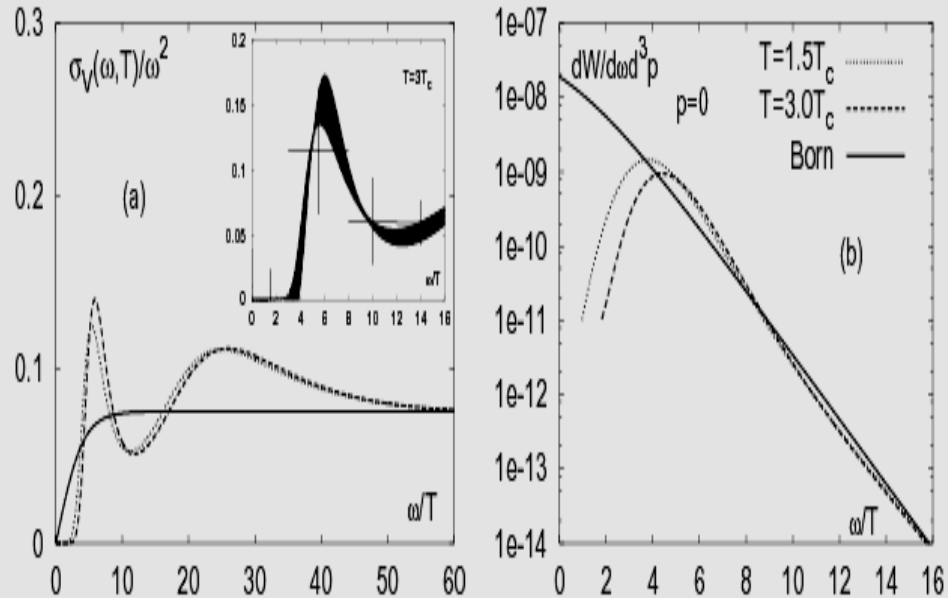


Figure 2: Reconstructed vector spectral function σ_V in units of ω^2 at zero momentum (a) and the resulting zero momentum differential dilepton rate (b) at $T/T_c = 1.5$ (doted line) and 3 (dashed line). The solid lines give the free spectral function (a) and the resulting Born rate (b). The insertion 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).

Scattering amplitudes for quasiparticles

M. Mannarelli. and R. Rapp hep-ph/05050080

\bar q q scattering no q - gluon scattering yet

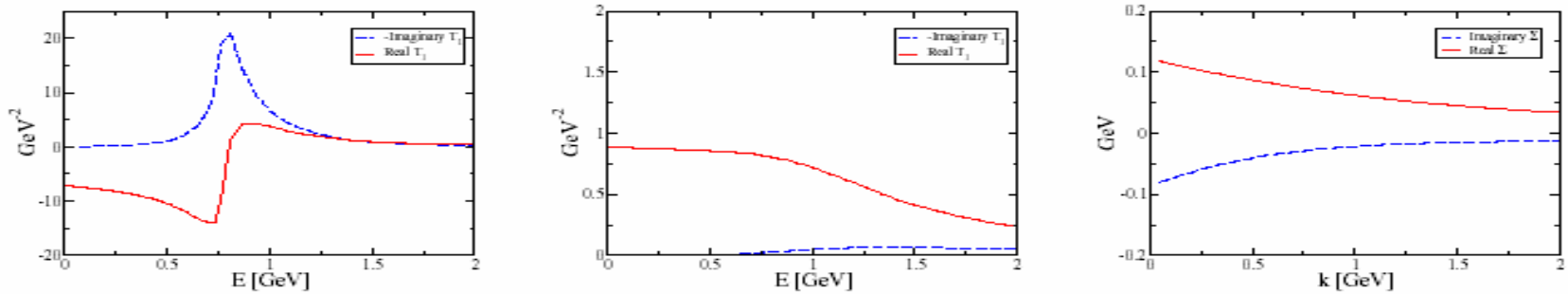


FIG. 8: Real (full line, red) and imaginary (dashed line, blue) parts of the T-matrix in the color-singlet channel (left panel), color-octet channel (central panel) and corresponding (singlet+octet) self-energy (right panel) at a temperature $T = 1.5\,T_c$ using a "gluon-induced" mass term of $m = 0.25$ GeV.

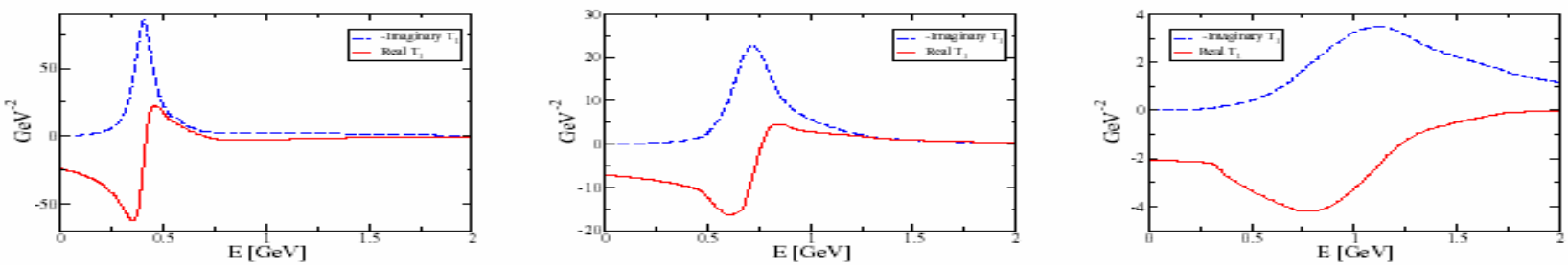
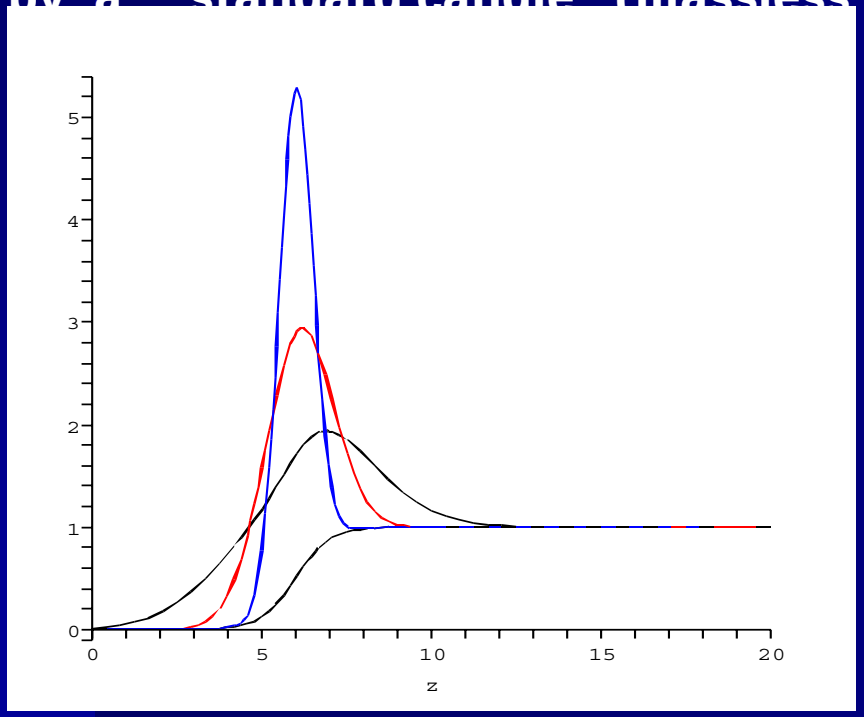


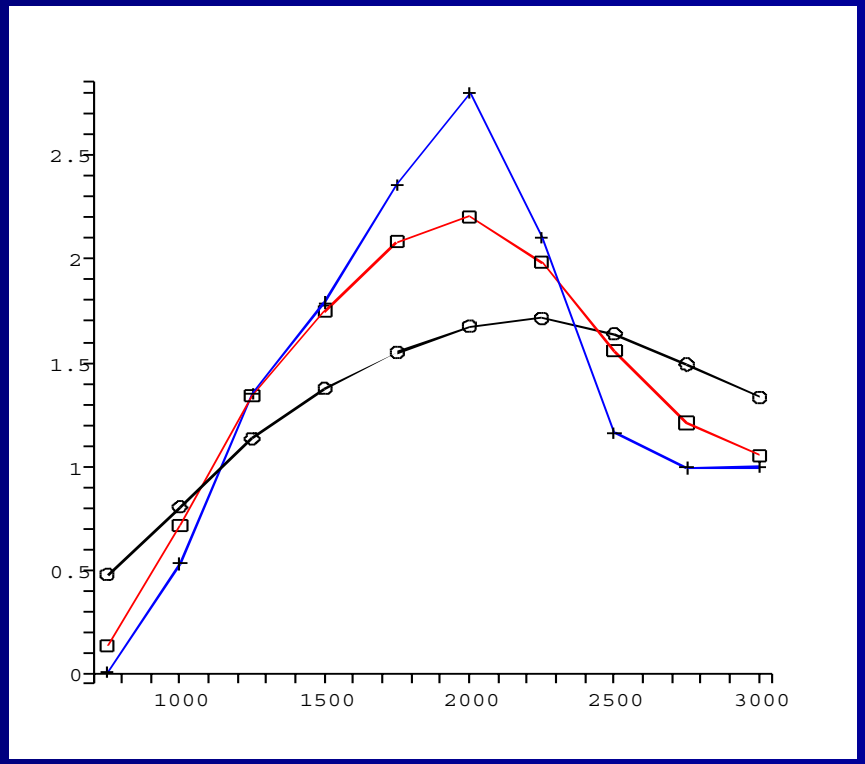
FIG. 5: Real (full red line) and (absolute value of the) imaginary part (dashed blue line) of the light-quark (on-shell) T-matrix (in units of GeV^{-2}) in the singlet channel at temperatures $T = 1.2\,T_c$, $T = 1.5\,T_c$ and $T = 1.75\,T_c$ (left, middle and right panel, respectively) as a function of the $q\bar{q}$ CM energy E, with a "gluon-induced" quark-mass term $m = 0.1$ GeV.

QUARK-HADRON DUALITY AND BUMPS IN QCD: A simple exercise with all M scaling as T (the worse case scenario)

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)





Summary on dileptons

- In general, 3*3 objects (for each rho, omega and phi states):L,T vectors plus a near-threshold bump
- Most observable is probably T=Tc when Vs are about .5-.8 GeV in mass
- Possibly observable enhancement is in the region 1.5-2 GeV, where 2Mq is about constant in a wide T interval. Not to be present at SPS but at RHIC
- Realistic potential predicts quite interesting shapes, but the width (and resolution) issue is so far not quite quantitive

Conclusions

- QGP as a “matter” in the usual sense, not a bunch of particles, has been produced at SPS/RHIC
- It shows very robust collective flows => sQGP is the most ideal fluid known

  eta/hbar s=.1-.2 <<1

And seem to have many bound states

(New PD Tables?)

- Sonic boom from quenched jets?
- Charm of even bottom flows?
- New peaks in dilepton spectra, where rho,omega,phi die?

Collective flows
=>collisional regime
=> hydrodynamics
The main assumption:

$$l << L$$

(the micro scale) << (the macro scale)

(the mean free path) << (system size)

(relaxation time) << (evolution duration)

In the zeroth order in l/L it is **ideal hydro with a local stress tensor.** Viscosity appears as a first order correction l/L, it has velocity gradients. Note that it is inversely proportional to the cross section and thus is (the oldest) strong coupling expansion

Viscosity of QGP

QGP at RHIC seem to be the most ideal fluid known, viscosity/entropy =.1 or so

water would not flow if only a drop with 1000 molecules be made

- viscous corrections

1st order correction to dist. fn.:

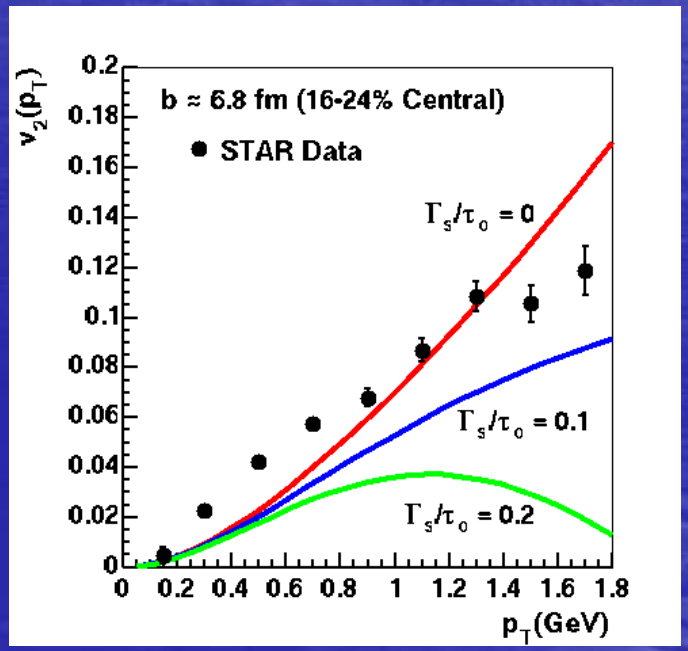
$$\delta f \propto \frac{\Gamma_s}{T^2} f_0(1+f_0) p^\mu p^\nu X_{\mu\nu}$$

Γ_s :Sound attenuation length

$X_{\mu\nu}$ Velocity gradients

$$R^{-1} \approx \Gamma_s/\tau$$

Nearly ideal hydro !?



D.Teaney('03)

How to get 20 times pQCD σ?

(Zahed and ES,2003)

- Quark-antiquark bound states don't all melt at Tc (charmonium from lattice known prior to that…)
- Many more colored channels
- all q,g have strong rescattering qqbar $\Leftrightarrow$ meson

Resonance enhancements

Huge cross section due to resonance enhancement causes elliptic flow of trapped Li atoms

Bound states in sQGP

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 about 2T
- If $\alpha(M_d)$ indeed runs and is about ½-1, it is large enough to bind charmonium till about $T=3T_c$ (above the highest T at RHIC)
- Since q and g quasiparticles are heavy,

M about 3T, they all got bound as well !

Fitting F to screened Coulomb

- 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

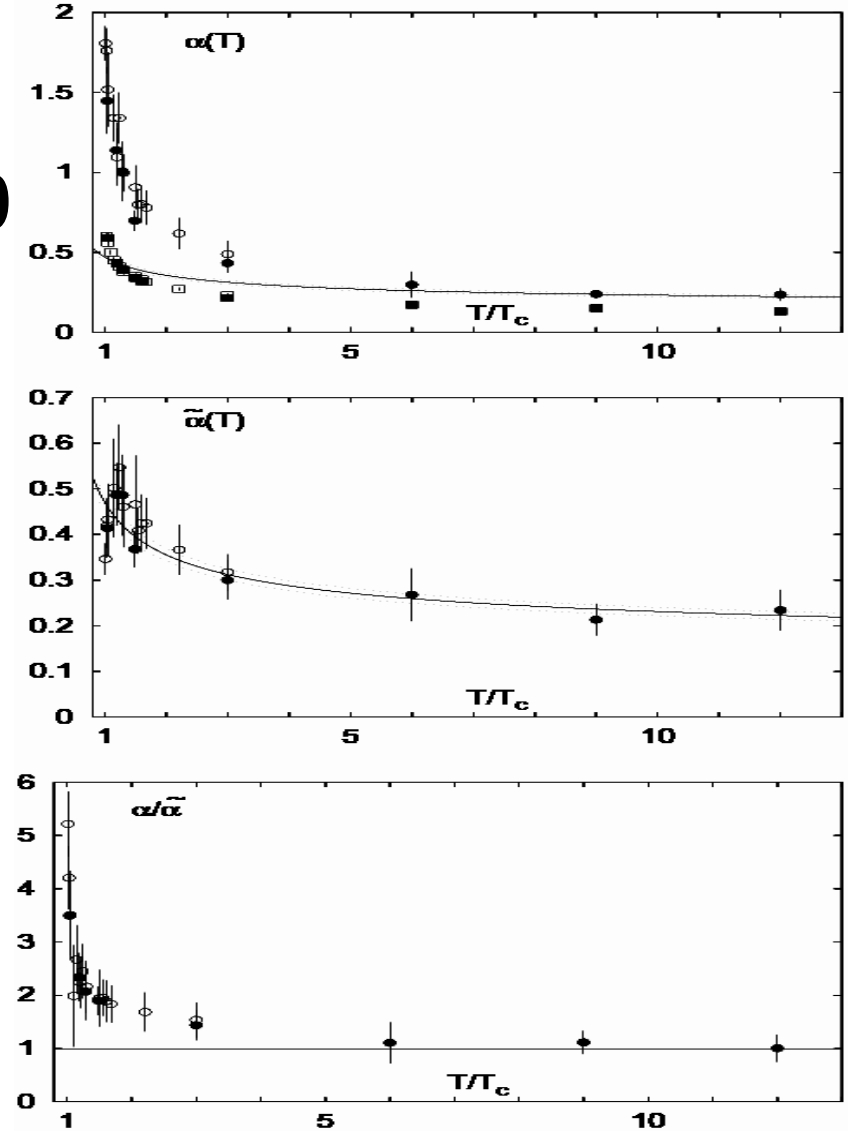
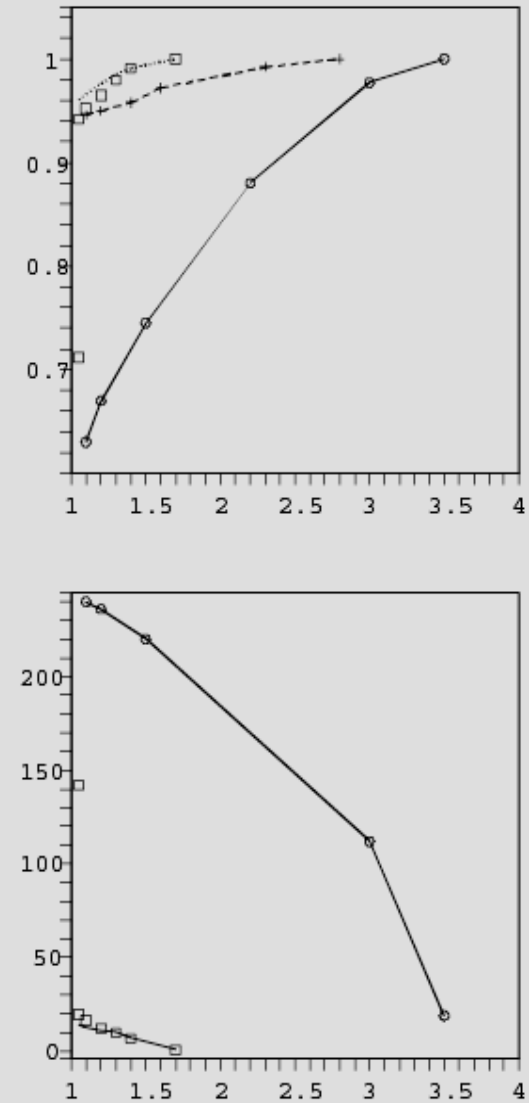


FIG. 6: The temperature dependent running coupling determined from the large distance behavior of the singlet free energy on lattices with temporal extent $N_\tau = 4$ (open symbols) and $N_\tau = 8$ (filled symbols). The upper figure shows $\alpha(T) \equiv g^2(T)/4\pi$ (dots) and the value $\alpha_{\rm qq}(r_{\rm scream}, T)$ (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.

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

- 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

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

- **In QGP there is no confinement =>**
- **Hundreds of colored channels should 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.

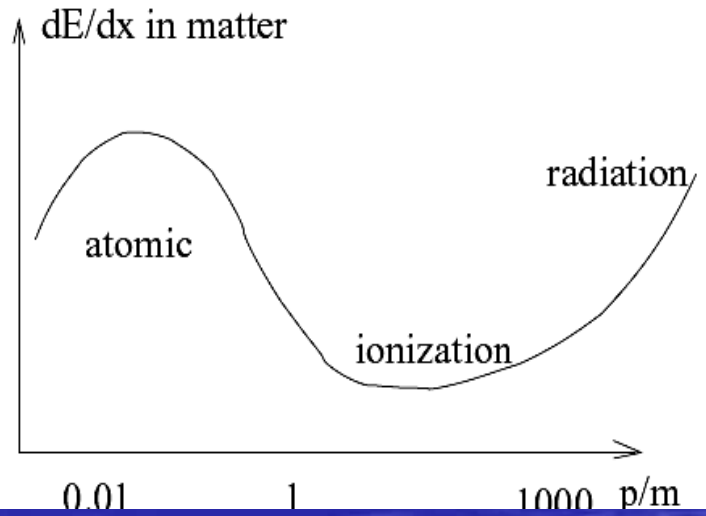
Jet quenching by ``ionization'' of new bound states in QGP?

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

Very recent idea (IZ+ES) of ''ionization losses'' for minijets at $p_t \sim few\, GeV$.

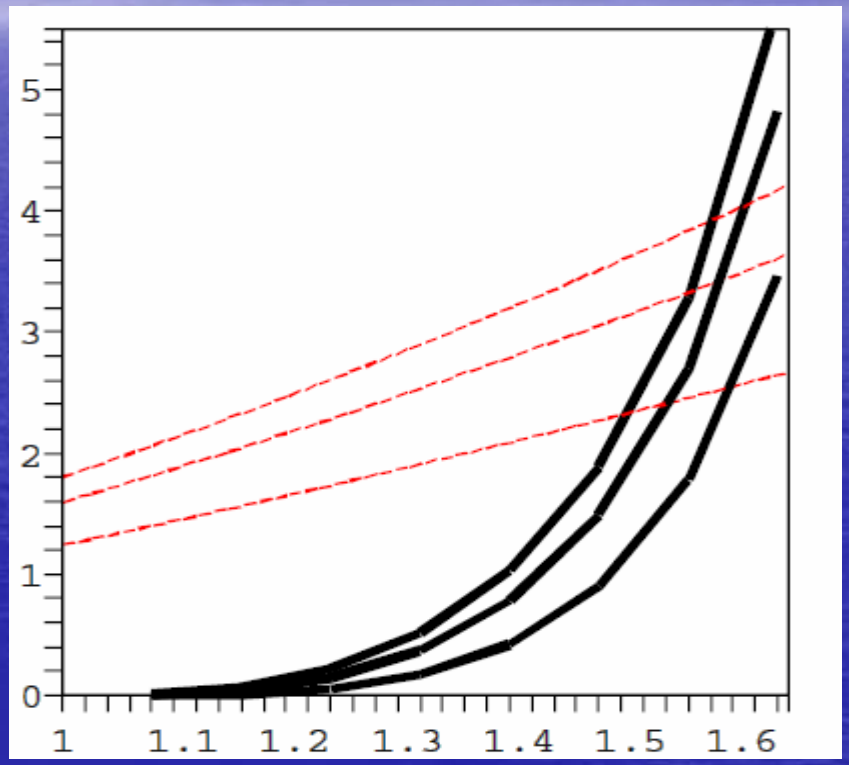
Cannot work in hadronic phase - cofinement

If it is true, the ''lost energy'' can never be recovered (unlike for radiative losses)



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)

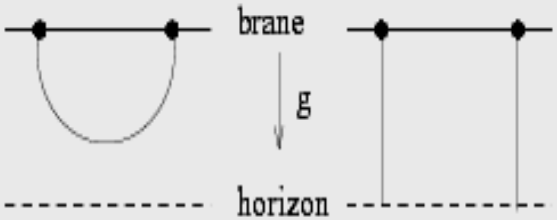


dE/dx in GeV/fm vs T/T_c for a gluon 15,10,5 GeV.
Red-elastic, black -ionization

Theoretical sQGP in N=4 SUSY YM and AdS/CFT

A gift by the 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)



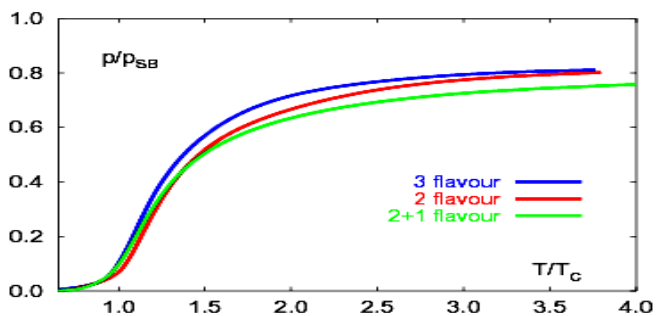
$$V(L) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{L}$$

- becomes a sreened potential at finite T

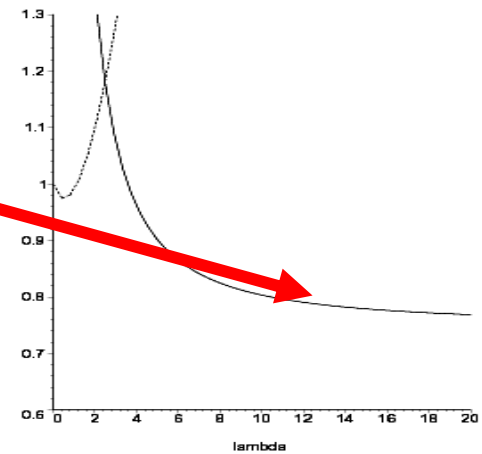
The viscosity/entropy => 1/4Pi is very small and about as observed at RHIC (D.Son et al 2003)

QCD vs CFT: let us start with EoS (The famous .8 explained!)

- CFT free energy at large λ is $F = (3/4 + O(1/\lambda^{3/2}))F_{free}$ (I.Klebanov et al 1996...)



- Lattice results (Bielefeld group) for QCD thermodynamics: pressure normalized to Stephan-Boltzmann value



- Weak (5 terms) vs. strong $(3/4 + const/\lambda^{3/2})$ coupling for the CFT: the ratio of the pressure to Stephan-Boltzmann value vs the 't Hooft coupling $\lambda = g^2 N$.

Bound states in AdS/CFT

(ES and Zahed, PRD 2004)

- The quasiparticles are heavy

M_q =O(sqrt(lambda) T) >> T

- But there are light binary bound states with the mass = O(M_q/sqrt(lambda))=O(T)

Out of which the matter is made of!

A complete ``gravity dual" for RHIC from 10-d GR? (ES,Sin,Zahed, in progress)

- Black Holes + Howking rad. Is used to mimic the finite T
- How black hole is produced can be calculated from GR (tHooft … Nastase)
- Entropy production => black hole formation, falling into it is viscosity
- Moving brane => hydro expansion