

Heavy Ions at RHIC: an Experimental Cornucopia

Collisions of heavy ions at high energies:

AGS at Brookhaven, SPS at CERN

Relativistic Heavy Ion Collider (RHIC) at Brookhaven

Large Hadron Collider (LHC) at CERN: from Nov. 9!

Wealth of results: for large nuclei, with atomic number $A \sim 200$,

“Central” AA collisions are *very* unlike $A * \text{proton-proton collision}$

Several *robust* signals for new “stuff”: but *what* stuff?

A Quark-Gluon Plasma (QGP)? *Not the QGP we expected...*

Golden age for *experimental* HE Nuclear Physics

Theorists awash in data, a “horn of plenty” =>

Lattice simulations *essential*



Hunt for the Quark Gluon Plasma



QGP as a “Unicorn”. Experimentalists as hunters,
so (in *this* field), “All theorists are...”

AA collisions at high energies

Collide:

AA, nuclei on nuclei. Atomic # “A”: 60 => 200, Cu -> Au. “Hot” nuclei.

pp, protons on protons. Benchmark for “ordinary” QCD.

dA, deuteron on nucleus. QCD in “cold” nuclei

Why AA? $A \sim 200$, linear size $A^{1/3} \sim 6$. Transverse area $A^{2/3} \sim 36$.

Total energy in the center of mass, per nucleon, $\sqrt{s}/A = \sqrt{s_{NN}}$

AGS@BNL => 5 GeV

SPS @ CERN 5 => 17 GeV

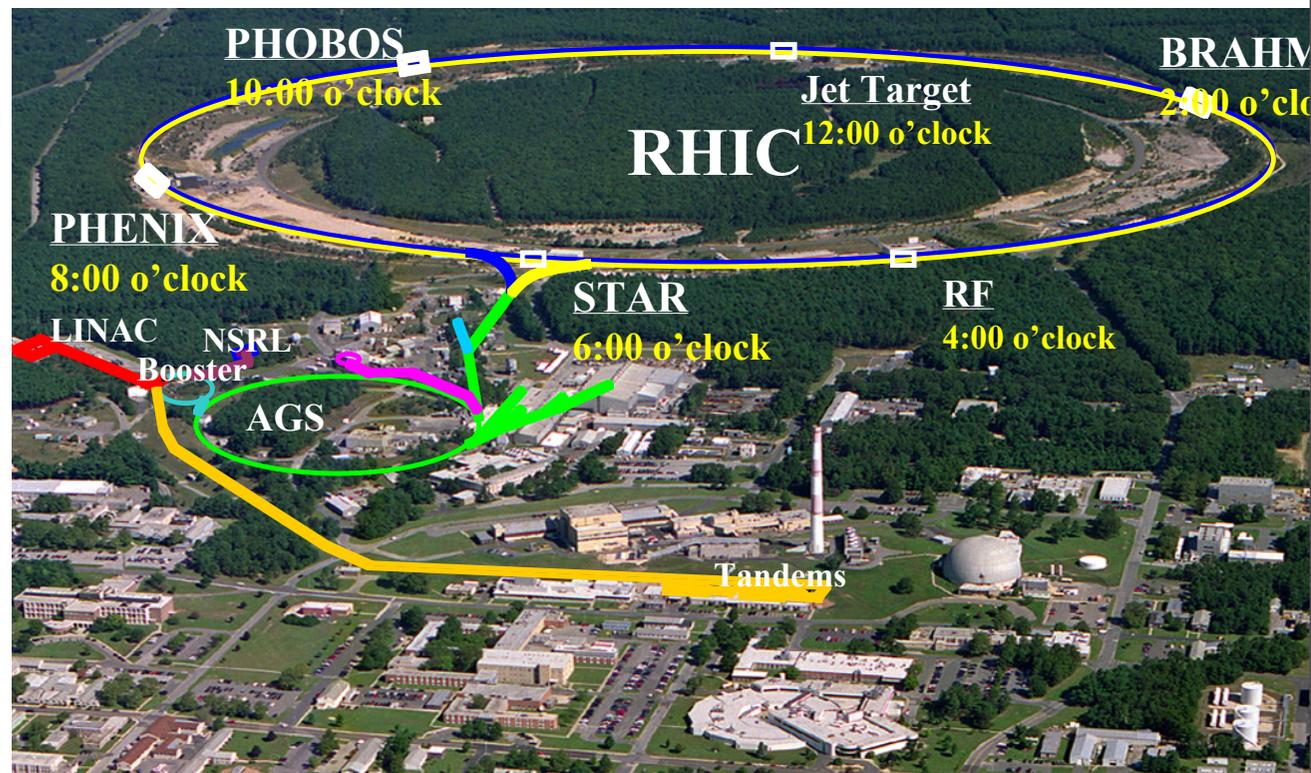
RHIC @ BNL 20 => 200 GeV

LHC @ CERN 5500 GeV

AGS, SPS Fixed Target

RHIC, LHC Colliders

LHC: from Nov. 9, 2010



Au-Au collisions @ RHIC: *low multiplicity*

Total # particles/unit rapidity ~ 900 ($A \sim 200$)

$\sim 1.30 \times A \times (\# \text{ particles/unit } y)$ in pp
Not much entropy generated.

Experiments @ RHIC:

“Big”: ~ 400 people.

STAR & PHENIX

“Small”: ~ 50 people.

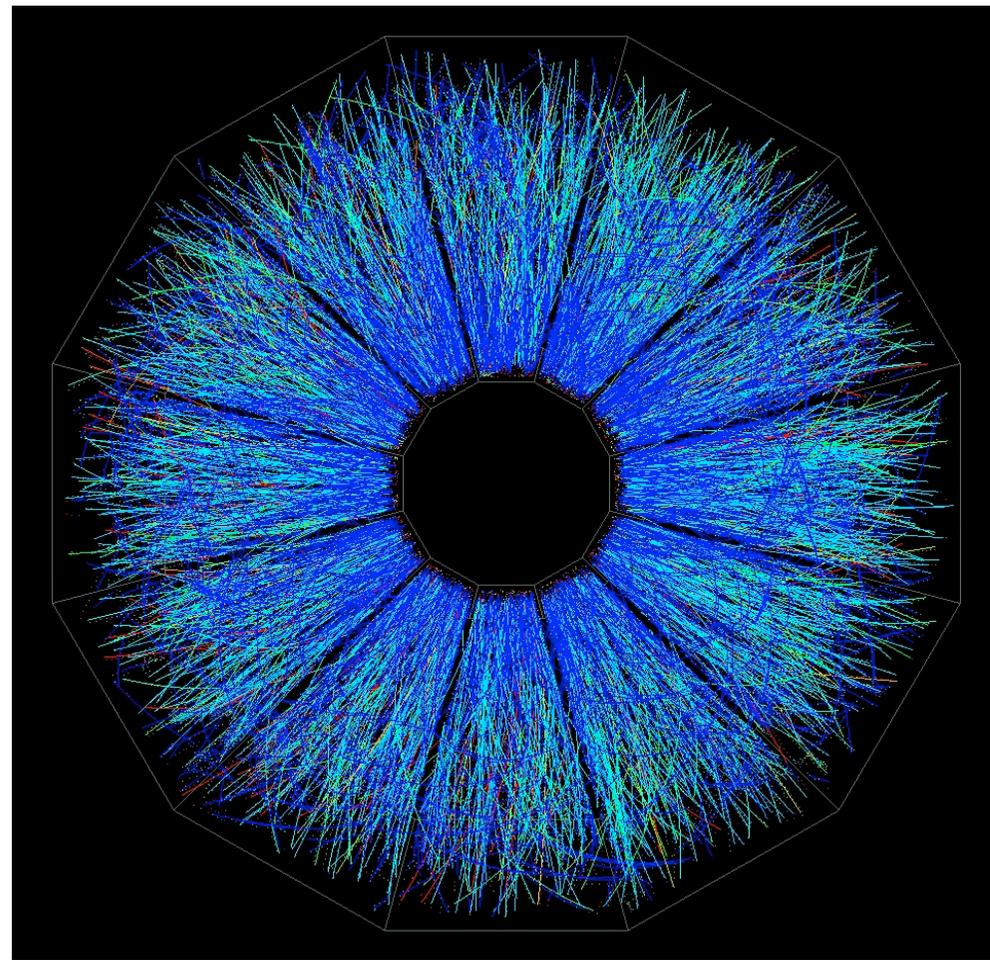
PHOBOS & BRAHMS

total # particles \sim total # experimentalists

$\sim \log(\text{total energy})$

theorists $\sim \log(\log(\text{total energy}))$.

(Need hunters more than...)



Narrow central plateau first arises at RHIC:

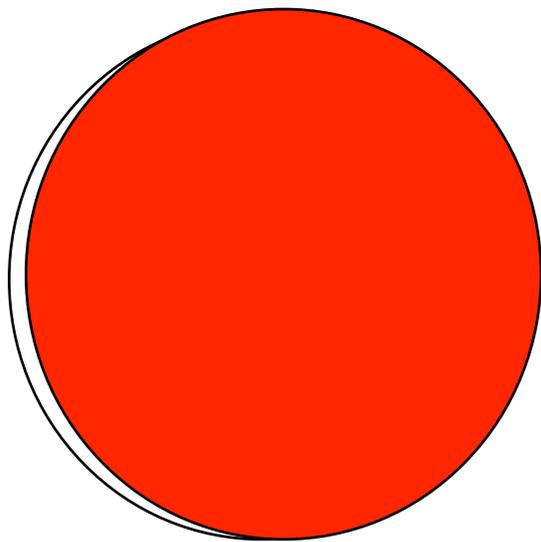
dN/dy and $\langle p_t \rangle$ constant over $\pm .5$ in y , out of ± 5.0 (STAR & BRAHMS)

Central vs peripheral collisions

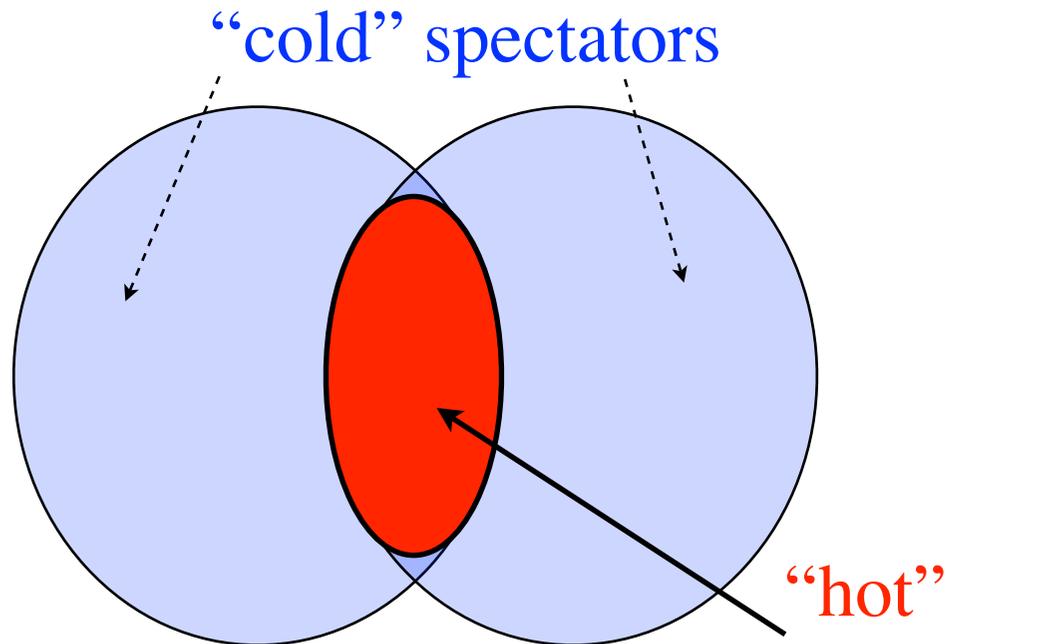
Nuclei overlap completely: central collision (Beam *into* the plane)

Nuclei overlap partially (“almond”): peripheral collision

Exp.’y, can determine # *participants* when > 100 ; maximum 400 for $A \sim 200$



central
collision



peripheral
collision:

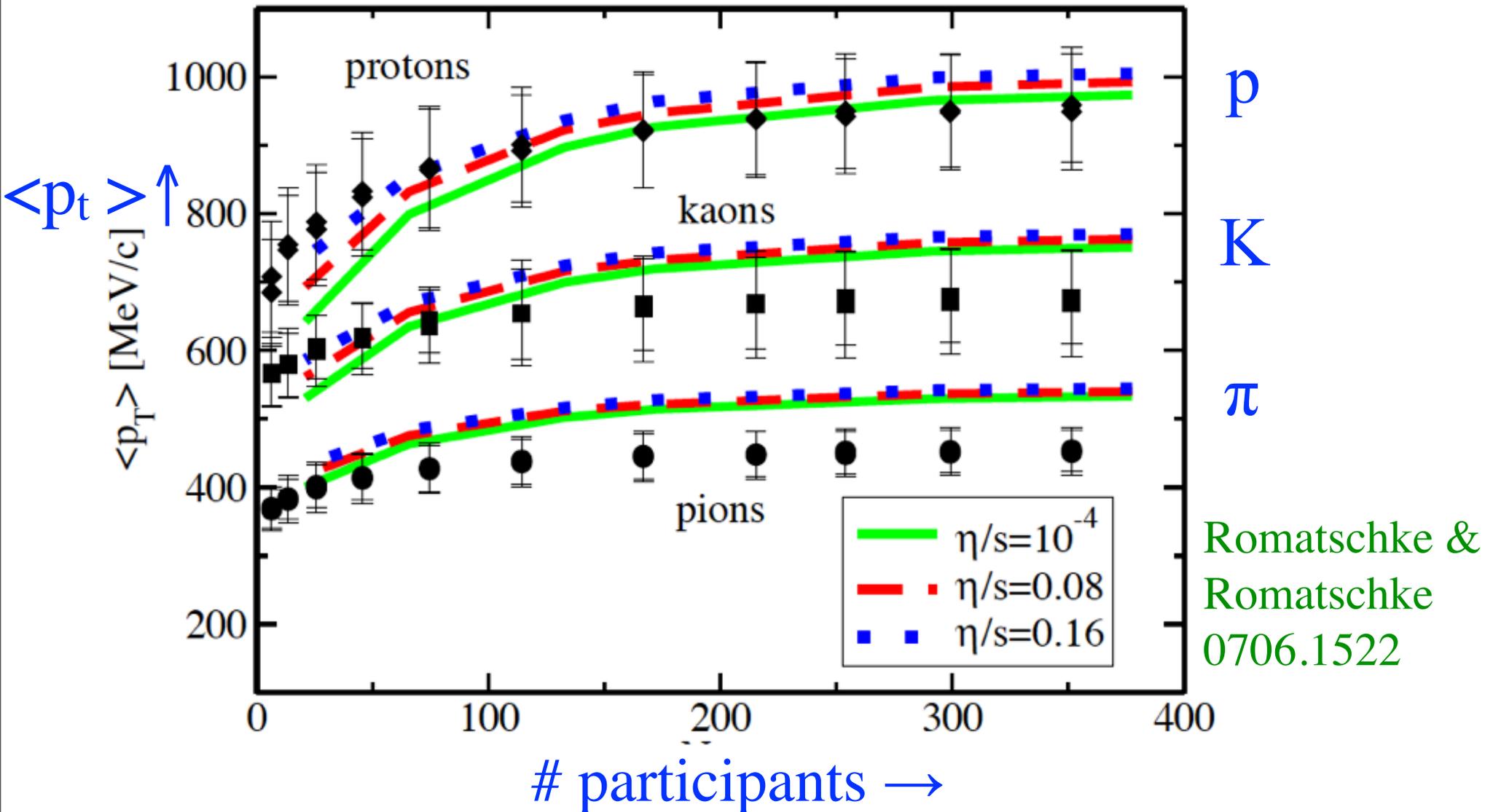
participants in “hot” almond

Hydrodynamics: single particle spectra

Large # particles, so hydrodynamics reasonable.

Non-ideal hydro. : depends upon η/s = shear viscosity/entropy.

Not very restrictive for $\langle p_t \rangle$. Hydro. still gives too big $\langle p_t \rangle$ for pions.

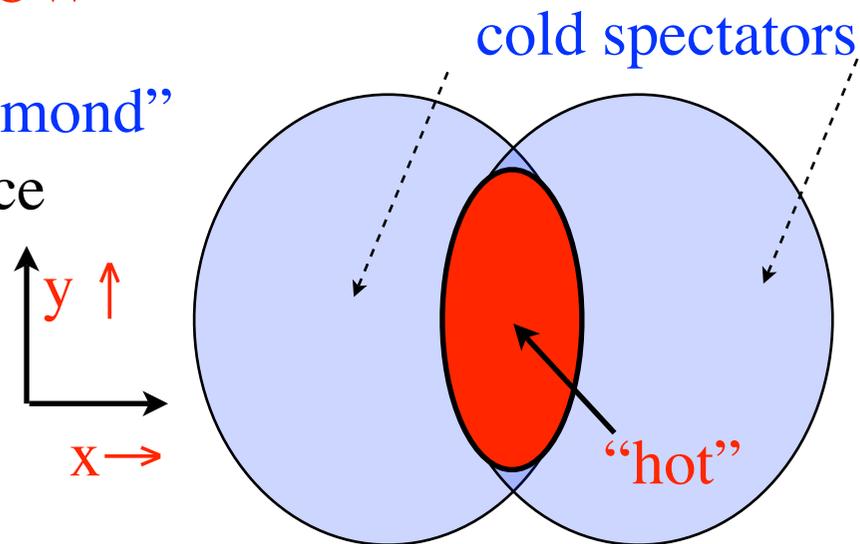


“Elliptic Flow”

For peripheral collisions, overlap region is “almond” in coordinate space, sphere in momentum space

So start with spatial anisotropy,

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

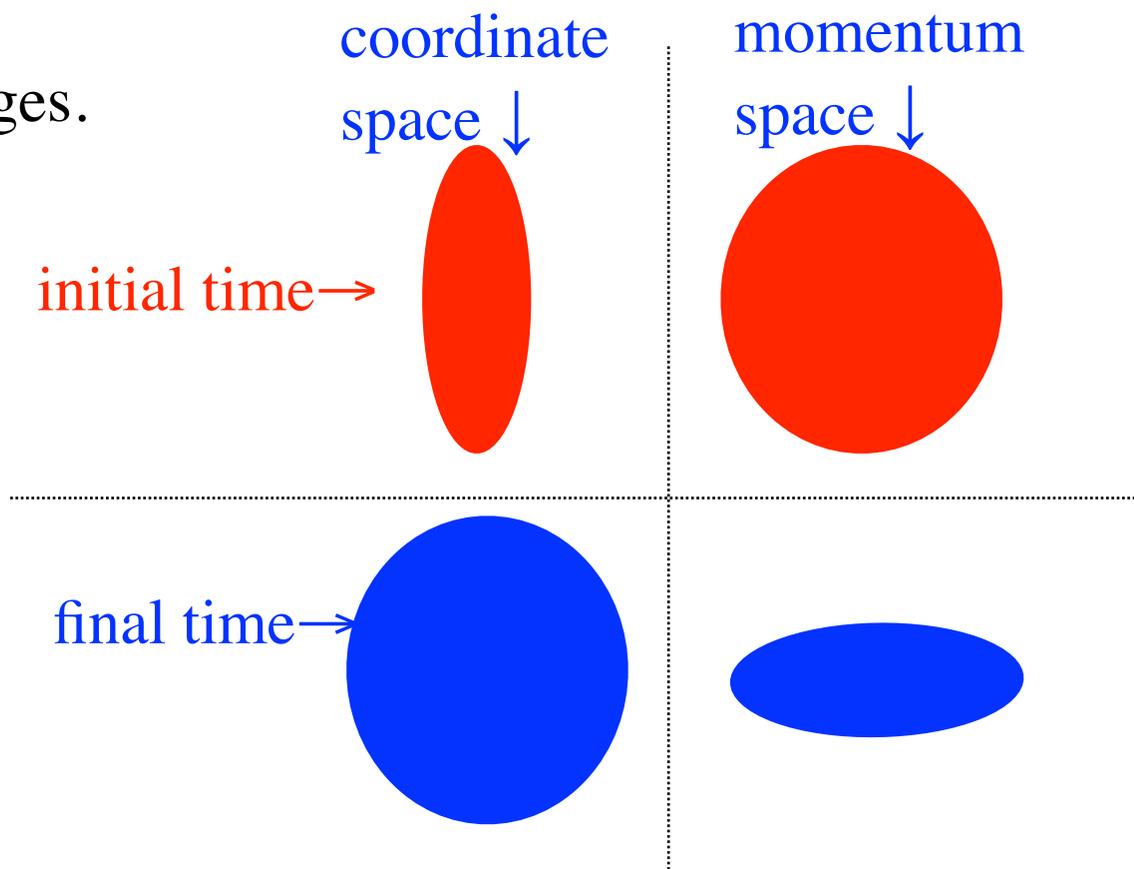


If particles free stream, nothing changes.

If collective effects present, end up with sphere in coordinate space, almond in momentum space:

“elliptic flow”

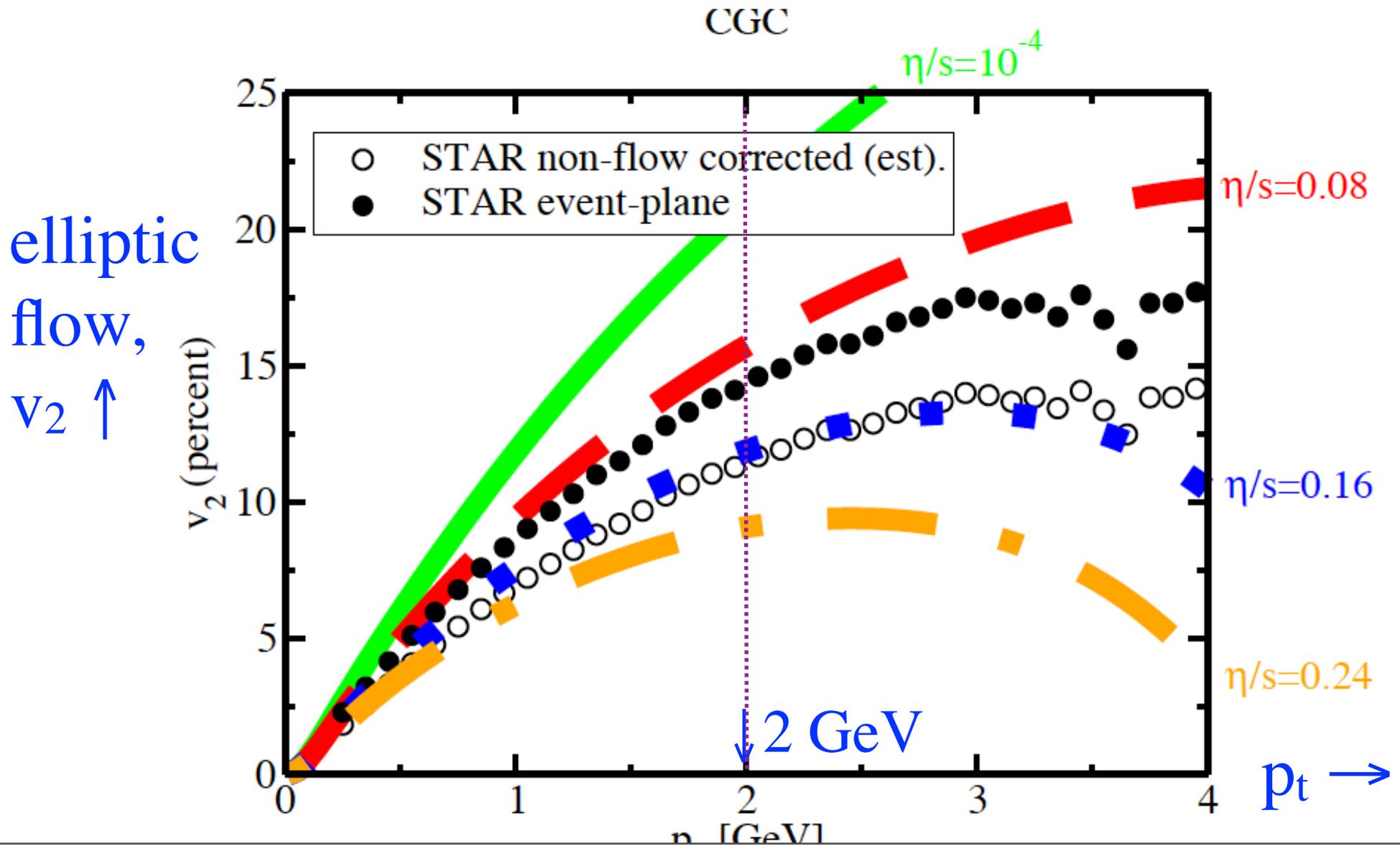
$$v_2 = \frac{\langle p_y^2 - p_x^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$



Elliptic flow: bound on η/s

Elliptic flow *strongly* constrains $\eta/s =$ shear viscosity/entropy.

$\eta/s = 0.1 \pm 0.1$ (theory) ± 0.1 (exp.) Luzum & Romatschke 0804.4015



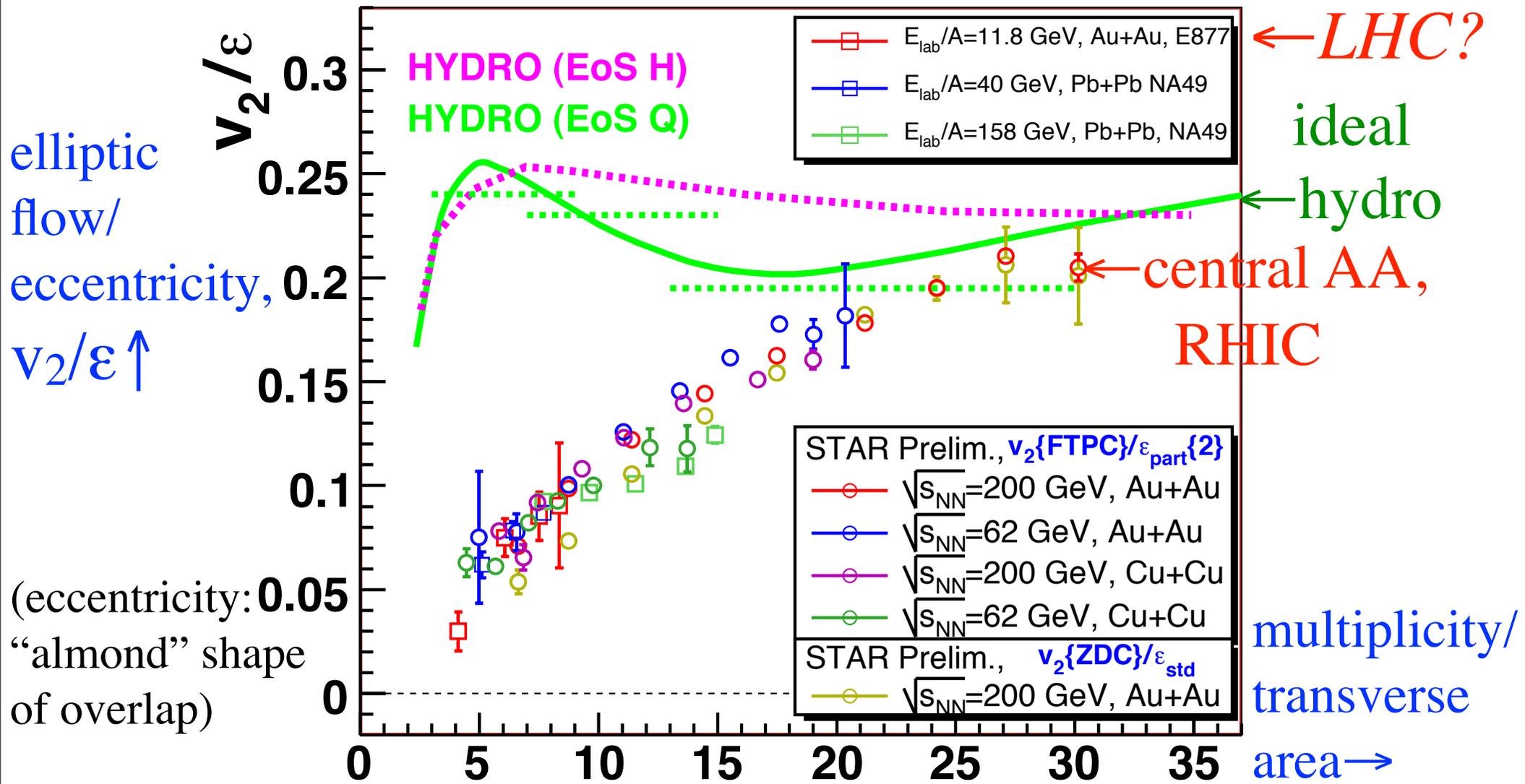
Elliptic flow: SPS to RHIC (*LHC?*)

Central AA at RHIC: good fit to v_2 with ideal hydrodynamics

Does *not* work at lower energies. Song & Heinz 0805.1756

Below: energies AGS, SPS, RHIC. $A \sim 60, 200$.

Where is LHC?



RHIC and the “most perfect fluid on earth”

Experimental bound on η/s appears valid.

Order of magnitude smaller than *any* non-relativistic system.

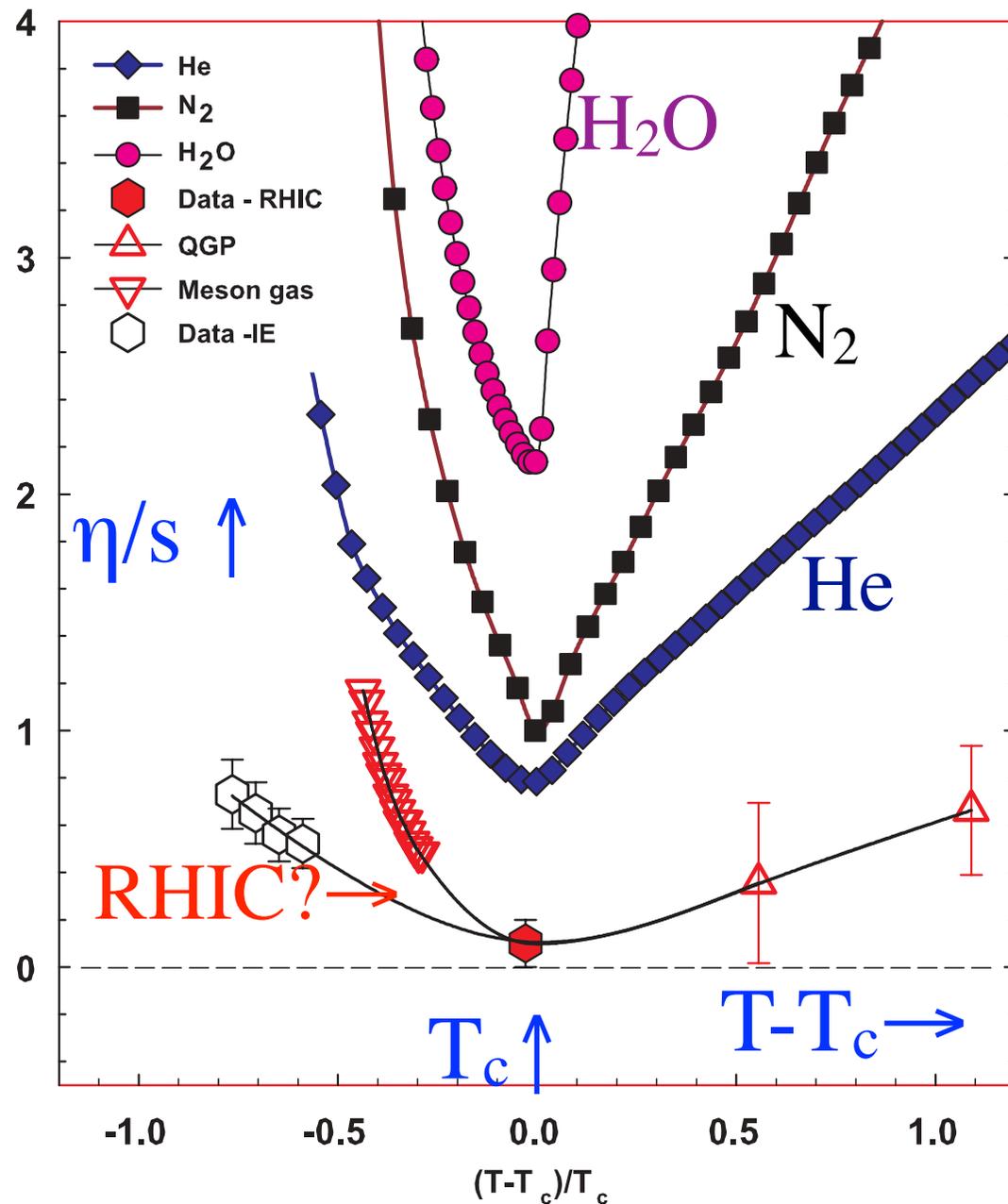
Close to conjectured bound from

$$\mathcal{N} = 4 \text{ SU}(\infty)? \quad \left. \frac{\eta}{s} \right|_{\text{SUSY}} \sim \frac{1}{4\pi}$$

Exp. value is ~ 10 *smaller* than in perturbation theory,

$$\left. \frac{\eta}{s} \right|_{\text{pert.}} \sim \frac{1}{\alpha_s^2} \sim 1.0$$

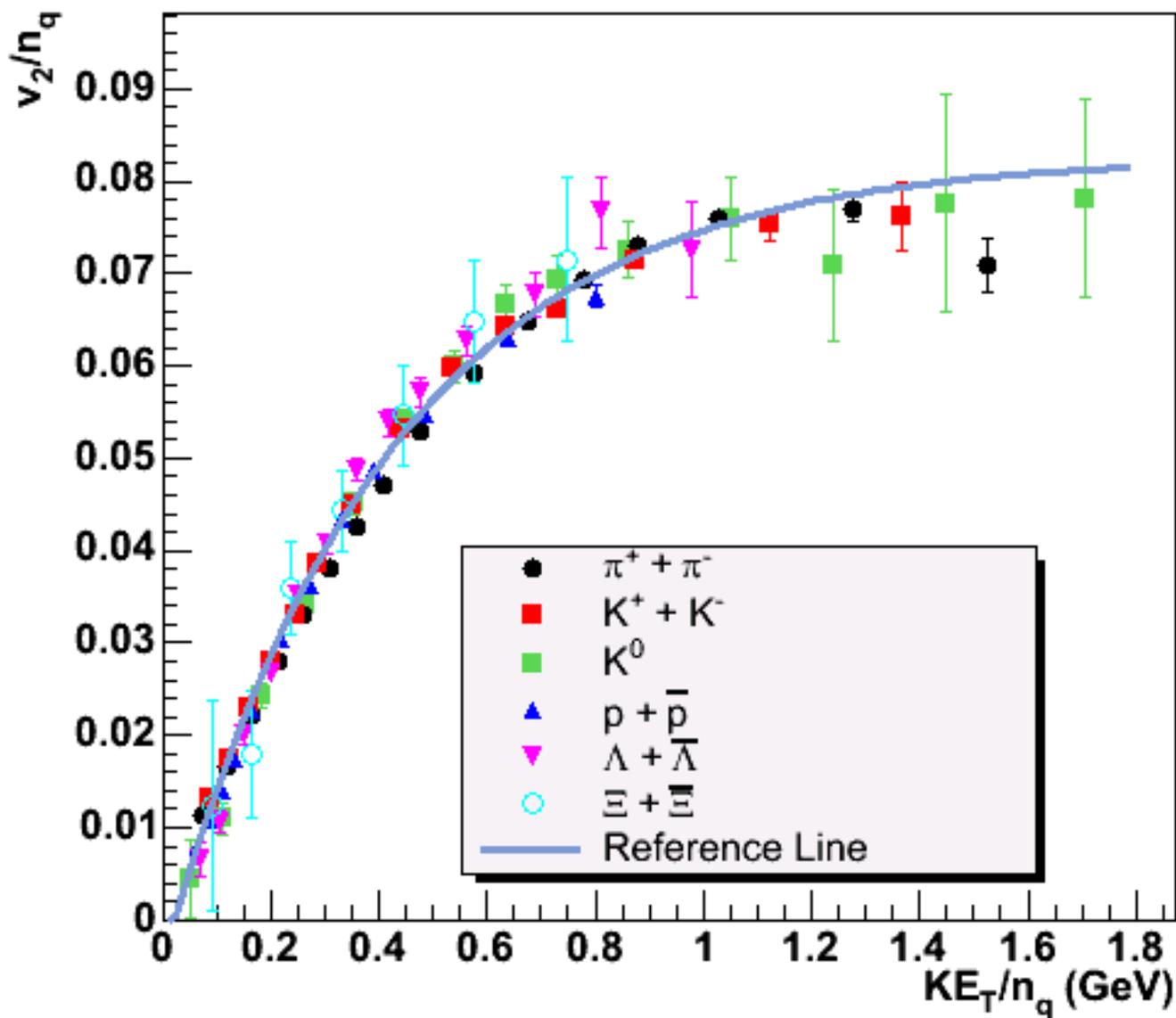
Evidence of *strong coupling* near T_c ?



Universal curve for elliptical flow

Exp.y, elliptical flow/# quarks satisfies a *universal* scaling, with respect to transverse *kinetic energy*/ # quarks (kinetic?)

elliptic
flow/
quarks
 $v_2/n_q \uparrow$



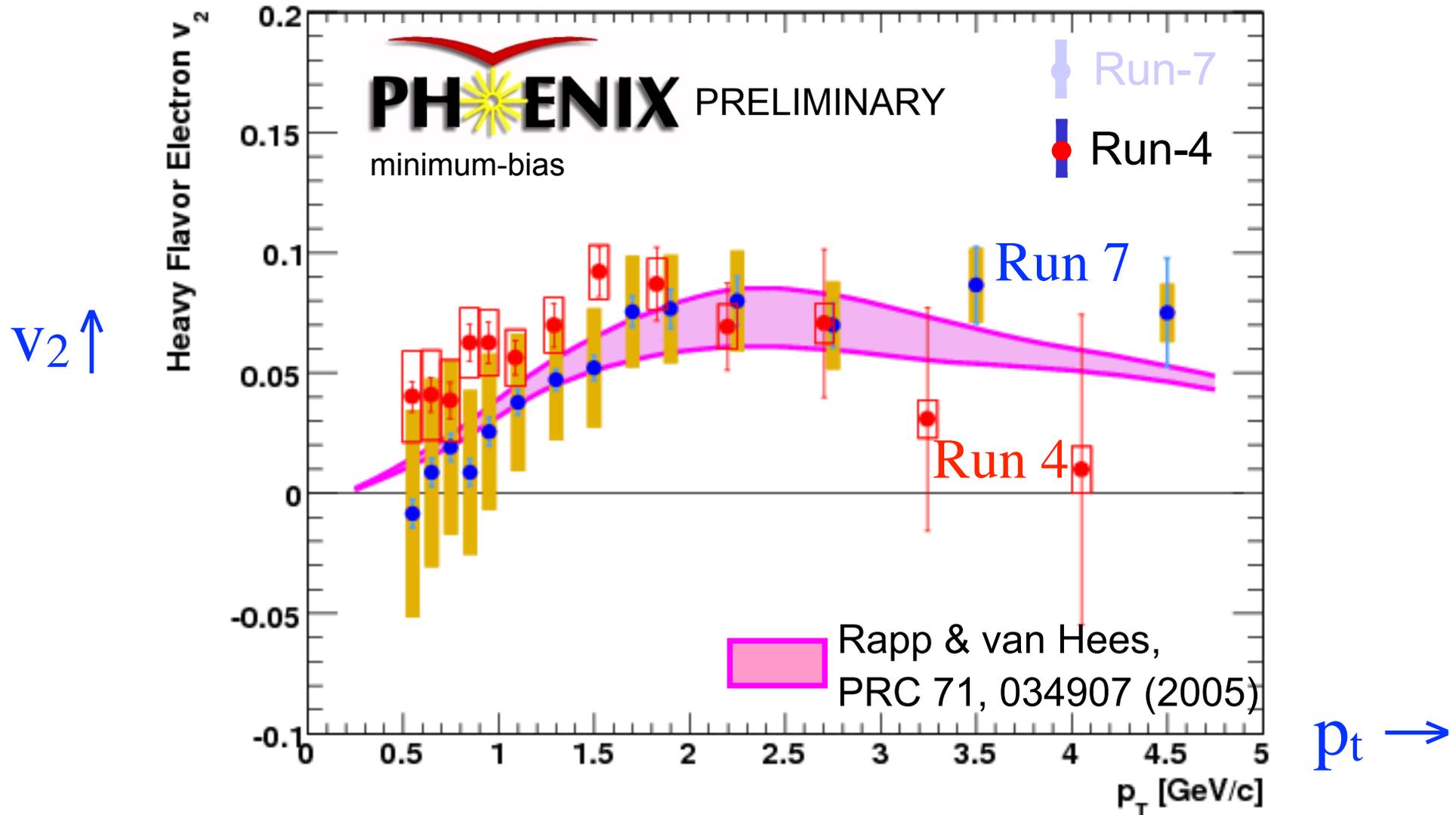
$KE_{tr}/n_q \rightarrow$

Elliptic flow even for *charm* quarks

Look at charm quarks through single electrons.

Find *large* elliptic flow: *no* suppression due to large mass.

Heavy quarks “flow” ~ *same* as light quarks! *Weird*.

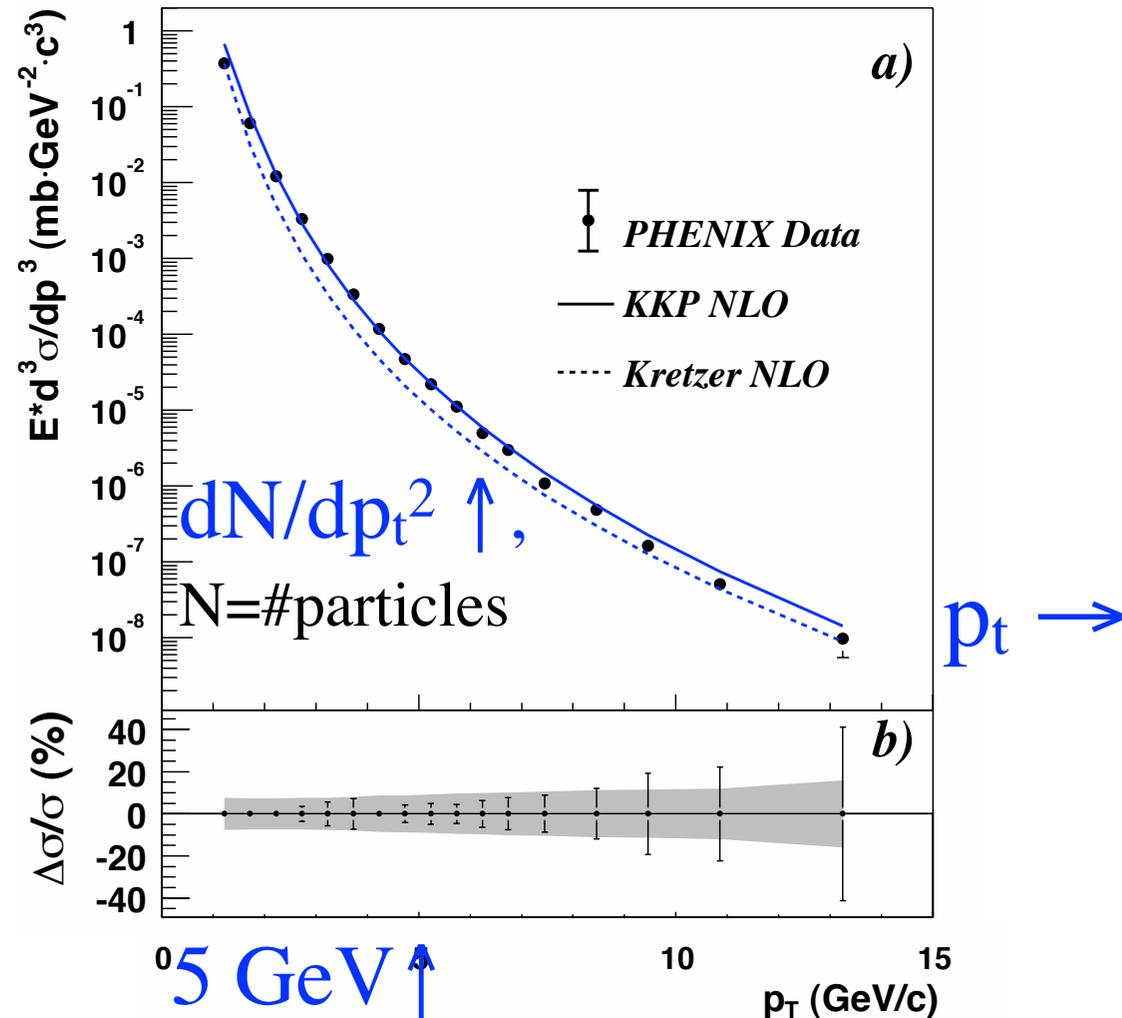
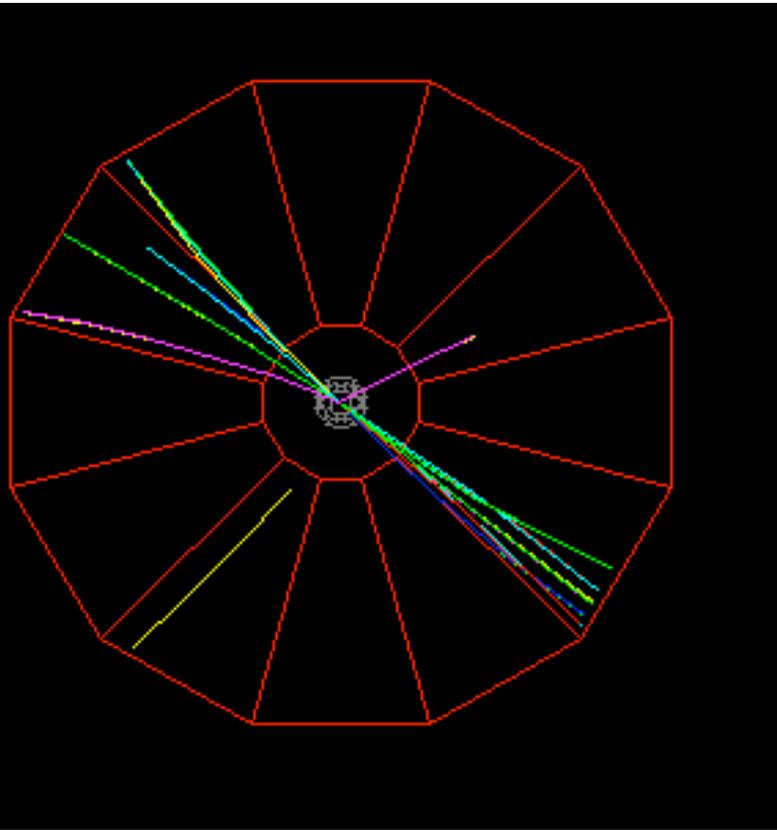


Jets at RHIC, pp and AA

← At RHIC, clearly see jets in pp collisions.

For each jet, there is always an away side jet.

Can compute perturbatively at high p_t ↓



In AA collisions, how to pick out jets, over a background with high multiplicity?

Need *statistical* measures.

R_{AA} and jet suppression

For any species:

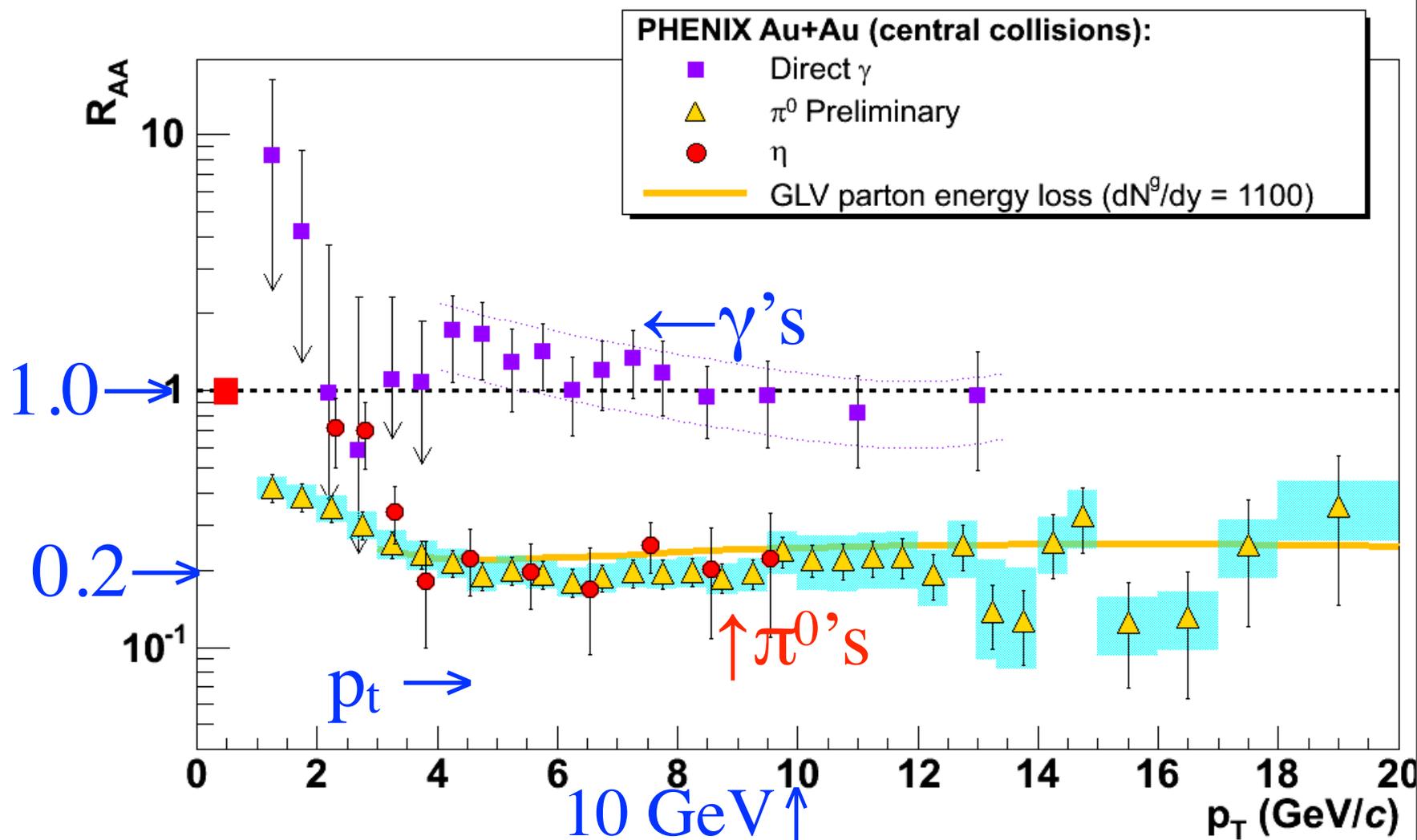
$$R_{AA}(p_t) = \frac{\# \text{ particles central AA}}{A^2 \# \text{ particles pp}}$$

A^2 : # hard collisions.

For γ 's, $R_{AA} \sim 1.0$, $p_t > 2$ GeV.

For π^0 's, $R_{AA} \sim 0.2$, $p_t : 4 \rightarrow 20$ GeV. As if jets emitted *only* from surface!

R_{AA} : \uparrow
 $A=200$,
 $\sqrt{s}=200$ GeV



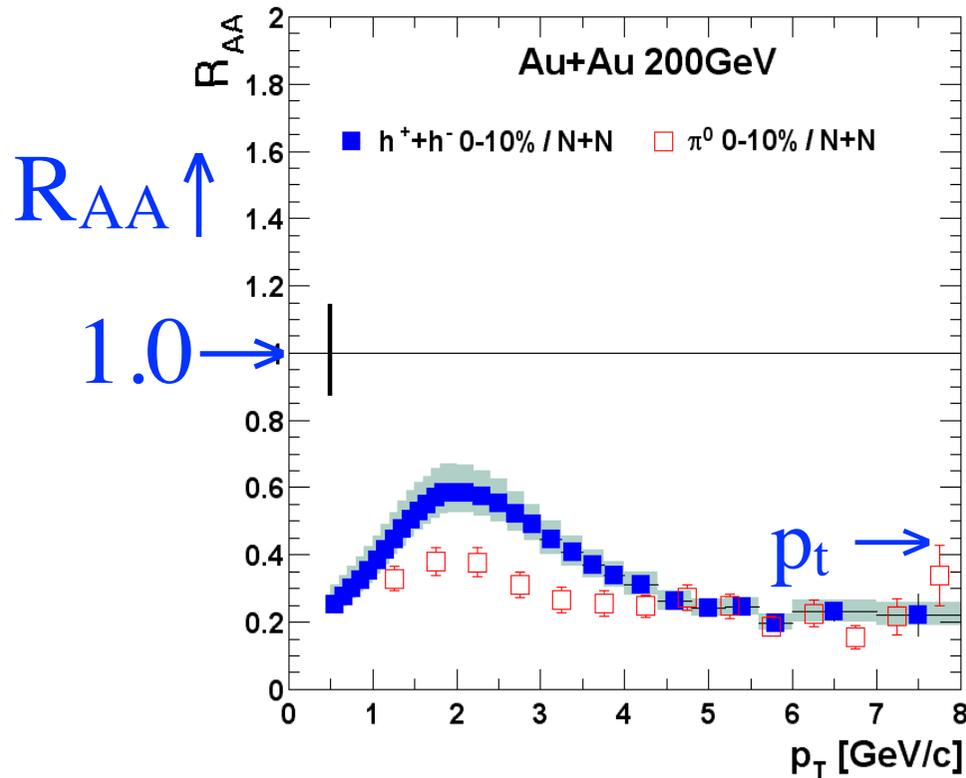
R_{AA} final state effect: *not* in R_{dA}

For dA coll.'s: $R_{dA} \sim \# \text{ particles in dA} / (2A \# \text{ pp})$. At zero rapidity:

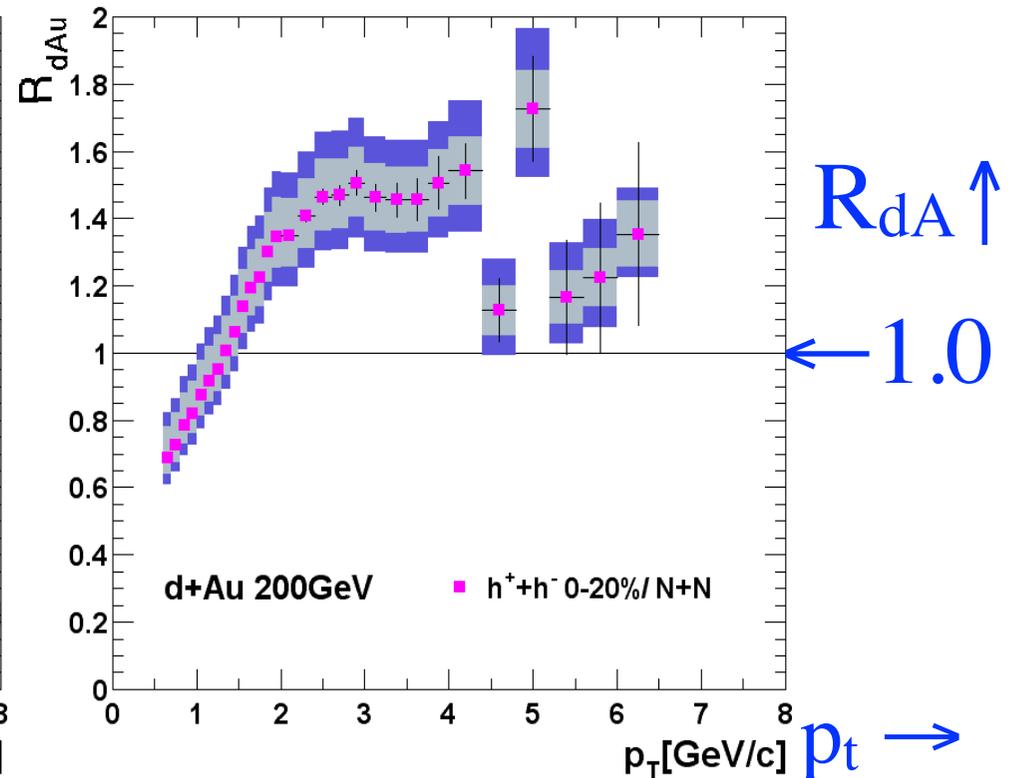
dA: *enhancement*, from initial state (Cronin) effect ($R_{dA} \rightarrow 1, p_t > 8 \text{ GeV}$)

AA: *suppression* => *final state effect*

Suppression in dA in d-fragmentation regime: Color Glass



Suppression in AA \uparrow

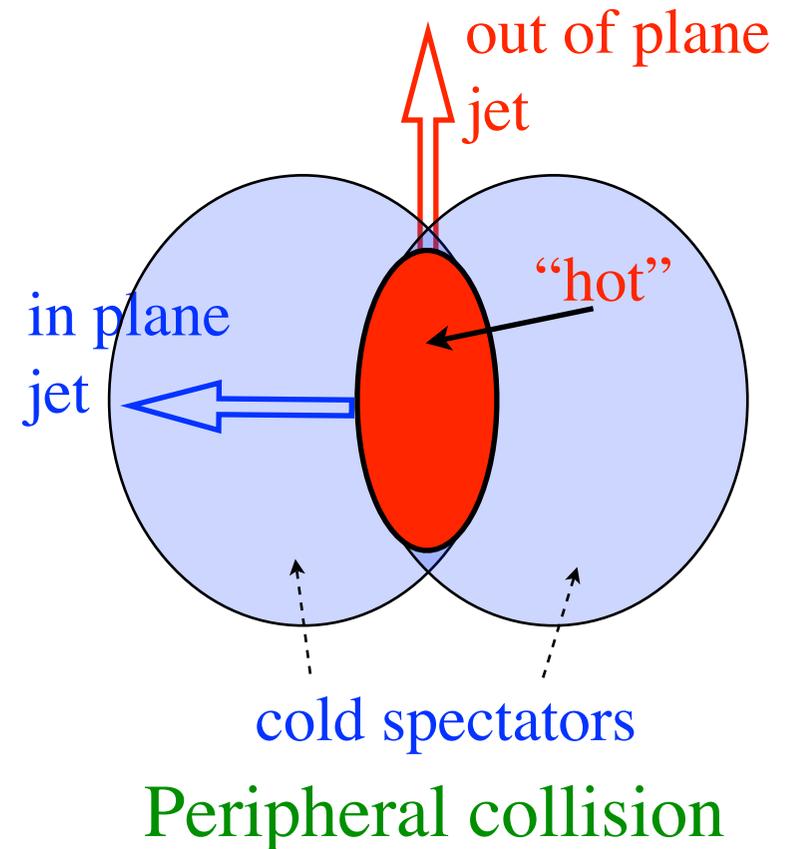
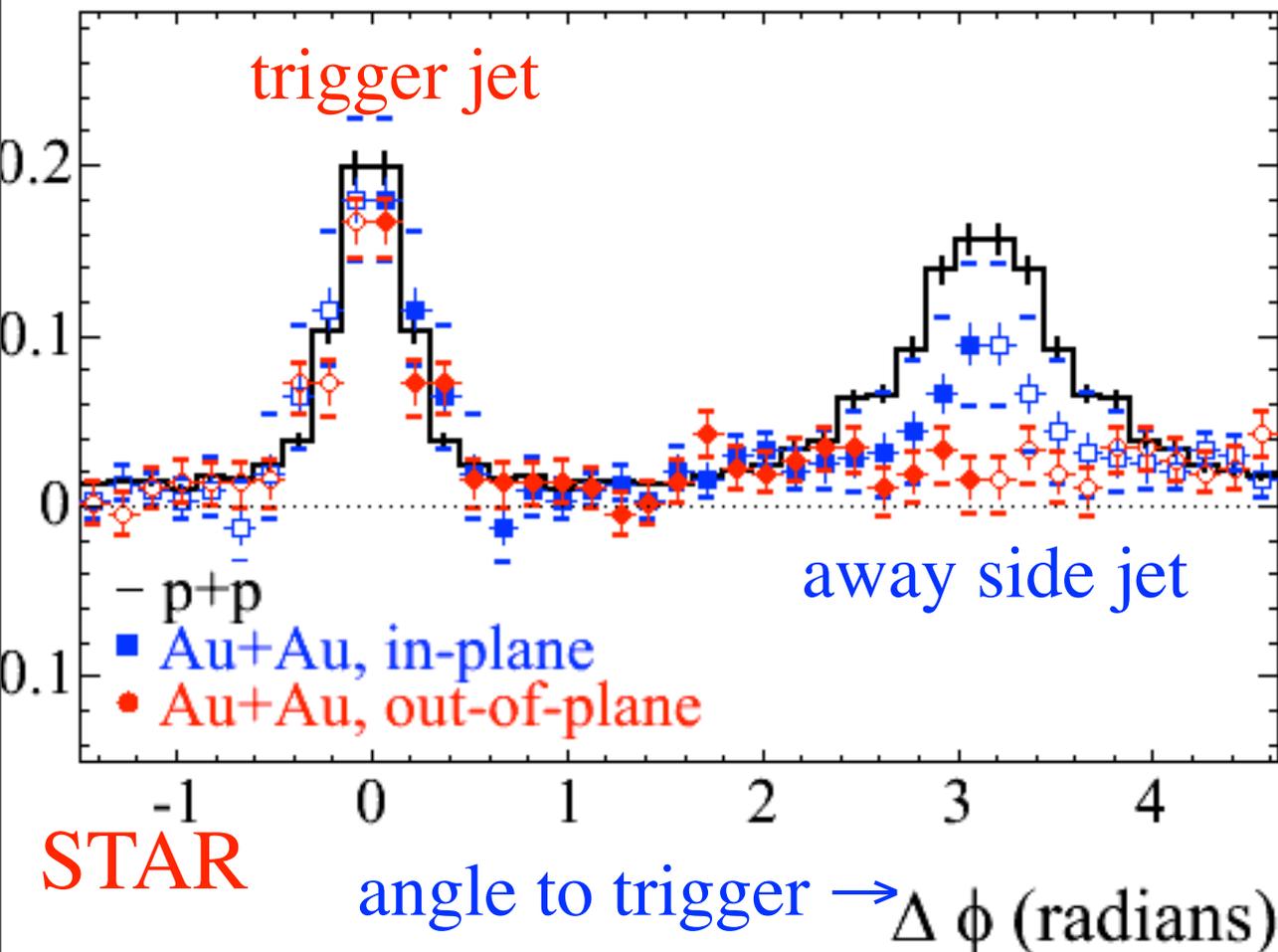


Enhancement in dA \uparrow

Geometrical test of jet suppression

Peripheral collisions: “hot stuff” forms “almond”. In vs. out of reaction plane
Out: more “hot stuff”. *In*: less hot stuff, more cold nuclear matter

Exp.’y: away side jet more strongly suppressed *out* of plane than *in* plane

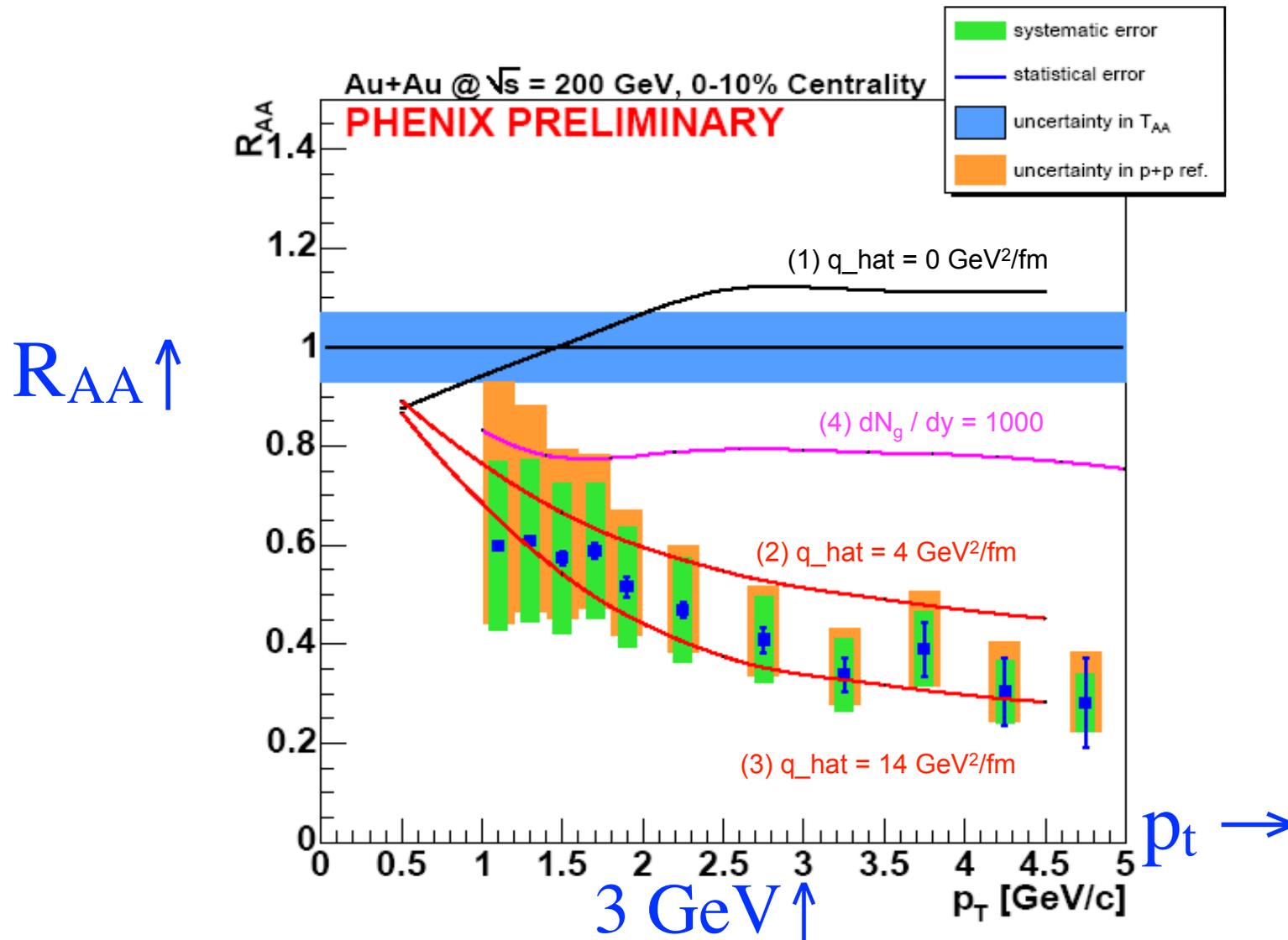


Suppression of heavy quarks \sim light.

PHENIX: direct e^- 's from decay of heavy quarks

R_{AA} charm quarks \sim light quarks! But $T/m_{\text{charm}} \sim 1/8$: not *less* suppression?

Appears true even for *bottom* quarks: \sim same suppression. *Weird.*



“Ridge” in rapidity

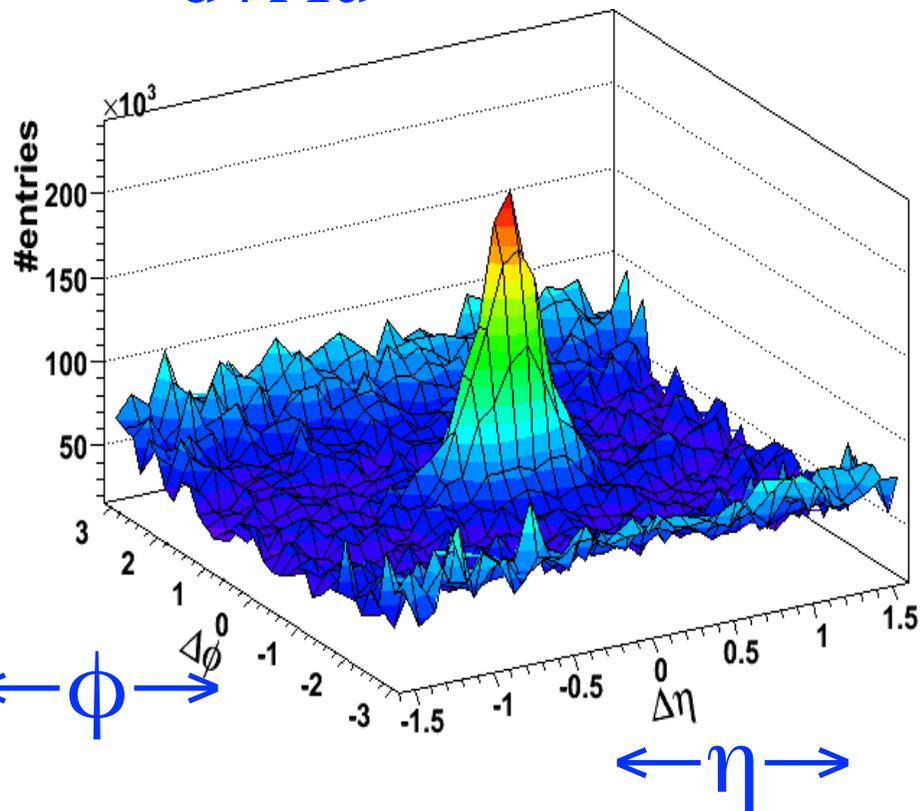
Shape of trigger jet modified in central AA:

Trigger on hard particle, p_t : 3-6 GeV;

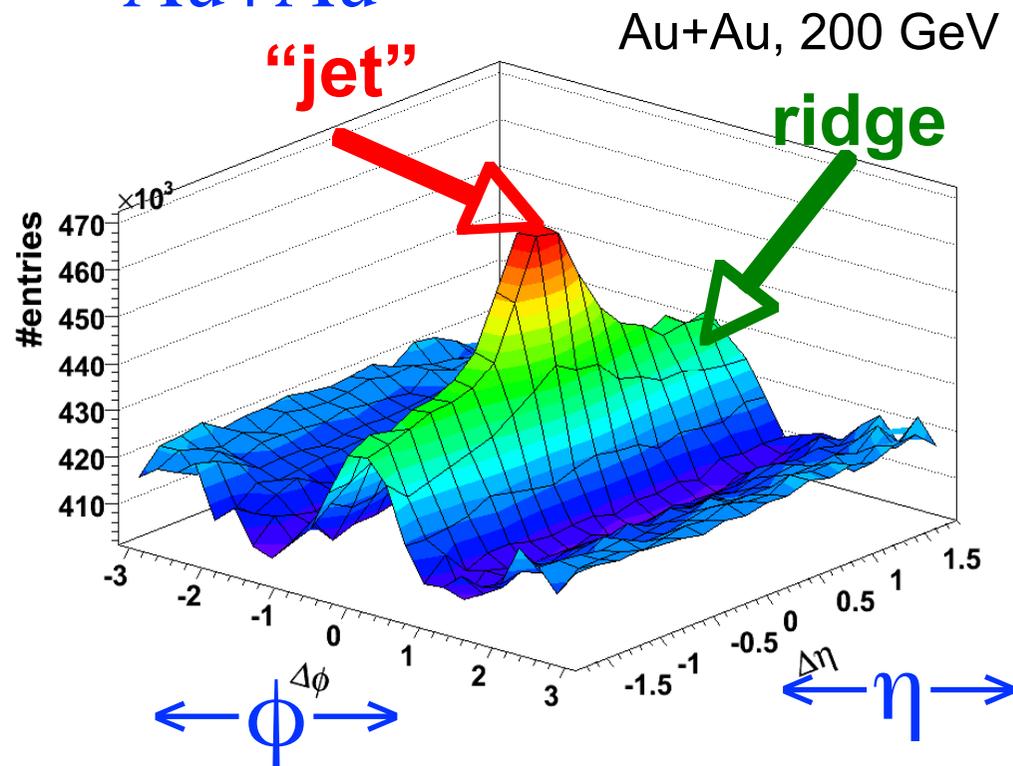
look at soft particles, $p_t > 2$ GeV, in *same* direction.

In pp, or d+Au, 1 unit of rapidity. In central AA, *much* wider, 4 units of rapidity.
Not wider in transverse angle.

d+Au



Au+Au



For Heavy Ions, will LHC be “*like*” RHIC?

1. *Yes*: small increase in elliptic flow, (appropriately scaled) multiplicity
(Nearly) ideal hydro works
Consensus view?
2. *Sorta*: elliptic flow smaller, (scaled) multiplicity higher
Viscous hydro applies: how much does η/s increase?
“Semi”-QGP: *partial* deconfinement near T_c : this talk today
3. *Nothing* like it: elliptic flow *much* larger; (scaled) multiplicity - *much* higher?
Not “Wit-less”: Busza, arXiv: 0907.4719
Terra incognita: *non-equilibrium* distribution
“Abandon all hope ye who enter here”?
Perhaps: use kinetic theory to evolve Color Glass to “jetty” final state?

With Y. Hidaka, arXiv:0803.0453, 0906.1751, 0907.4609, 0912.0940

With A. Dumitru, Y. Guo, Y. Hidaka, C. Korthals-Altes (DGHKP), 1010....

Related: T. Zhang, T. Brauner, & D. Rischke, 1005.2928.

O. Philipsen et al., 1010....

The semi-, versus the complete, Quark Gluon Plasma

Typical plasma in QED: e.g., H atoms

No ionization: gas of H atoms

Completely ionized plasma, e⁻'s and p's move freely of one another

Partially ionized plasma: some H atoms, some free charges.

QCD: deconfinement is the ionization of *color* charge

No color charge ionized: confined phase.

“Complete” Quark-Gluon Plasma (QGP): total ionization of color

“Semi”-QGP: partial ionization of color

Complete QGP: above a “few” times T_c (= temperature for deconfinement)

Semi-QGP: from a little bit *below* T_c , to a “few” times T_c

What is a “few” times times T_c ? What is the width of the semi-QGP?

*If RHIC starts in the semi-QGP, and LHC starts in the complete QGP, then for heavy ions, LHC will *not* be like RHIC.*

(Many, many qualifications: LHC always cools through semi-QGP, etc....)

Summary

Elementary model for confinement

Integrating over an *imaginary* chemical potential

Matrix model of the semi-QGP, versus Polyakov-Nambu-Jona-Lasino models

How to compute: perturbation theory with “birdtrack” diagrams

Fun and games with birdtracks

Dilepton production: not realistic, but illustrative

Energy loss in the semi-QGP: plus *uniform* suppression of color charge

Shear viscosity in the semi-QGP:

shear viscosity decreases, even though the cross section does as well

So how wide *is* the semi-QGP?

Lattice: renormalized Polyakov loops indicate *wide* semi-QGP, to $\sim 4 T_c$.

DGHKP, 1010.... : indirect measures indicate *narrow* semi-QGP, to $\sim 1.5 T_c$.

Experimentalists will know before we (theorists) will.

Elementary model for confinement

Consider the Boltzmann distribution at a nonzero chemical potential, μ :

$$n_B(E - \mu) = e^{-(E - \mu)/T}$$

Let μ be imaginary, $\mu = iQ$:

$$n_B(E - iQ) = e^{-(E - iQ)/T}$$

Q is clearly periodic, and runs from 0 to $2\pi T$.

Now assume that the distribution in Q is *flat*. Then the integral over Q vanishes,

$$\int_0^{2\pi T} n_B(E - iQ) dQ = e^{-E/T} \int_0^{2\pi T} e^{iQ/T} dQ = 0$$

which is confinement.

For Bose-Einstein (+) or Fermi-Dirac (-) statistics, do Boltzmann expansion:

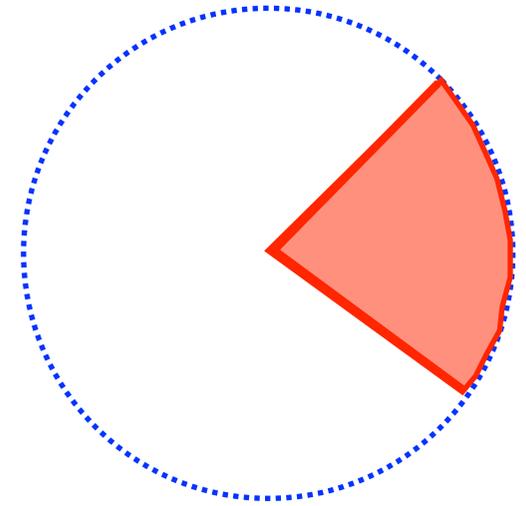
$$n_{\pm}(E - iQ) = \frac{1}{e^{-(E - iQ)/T} \mp 1} = e^{(E - iQ)/T} \pm e^{-2(E - iQ)/T} \dots$$

For a flat distribution, the integral of *every* term vanishes, so $\langle n_{\pm}(E - iQ) \rangle = 0$.

Elementary model for partial *deconfinement*

Take a distribution which is flat, but only in a wedge:

$$\rho_x(Q) = \frac{1}{2\pi x} \theta \left(\pi x - \frac{|Q|}{T} \right)$$



This is a normalized density,

$$\int_0^{2\pi T} \rho_x(Q) dQ = 1$$

$x=0$: only $Q = 0$. “*Complete*” Quark-Gluon Plasma.

$x=1$: flat distribution of Q 's. *Confined phase*, all distribution functions vanish.

$1 < x < 0$. Q 's flop around. *Partial* suppression of distribution functions.
“*Semi*”-QGP, partial deconfinement.

N.B.: The suppression of colored fields is *independent* of mass or momentum:
why R_{AA} for charm quarks is $\sim R_{AA}$ for light quarks (pions)?

Matrix model for semi-QGP

Color? Thermal Wilson line $\mathbf{L} \rightarrow$

\mathbf{L} is gauge variant, eigenvalues gauge *invariant*.

For $SU(N_c)$, N_c-1 eigenvalues.

$$\mathbf{L} = \mathcal{P} \exp \left(ig \int_0^{1/T} A_0 d\tau \right)$$

To represent non-trivial \mathbf{L} , perform a

semi-classical expansion in *intermediate* coupling about $\rightarrow (A_0^{cl})^{ab} = \delta^{ab} \frac{Q^a}{g}$

Q^a : $a=1\dots N_c$. with $\sum_{a=1}^{N_c} Q^a = 0, \text{ mod } 2\pi T$.

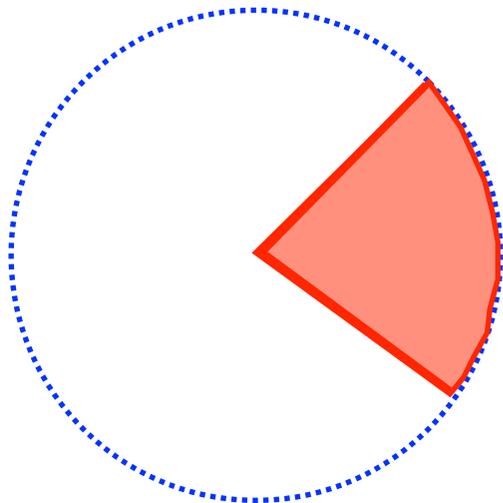
At infinite N_c , the sum over eigenvalues becomes an *integral* over Q .

Matrix model of the semi-QGP. (Like $SU(\infty)$ on femtosphere:

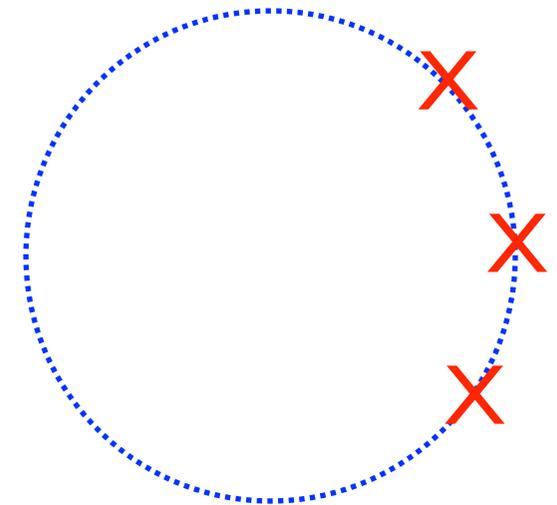
Sundborg, hep-th/9908001; Aharony, Marsano, Minwalla,

Papadodimas, & Van Raamsdonk, hep-th/0310285 & 0502149)

$N_c = \infty$



$N_c = 3$



Computing in the semi-QGP: energies with color

Generalize 't Hooft's double line notation to finite N_c .

BTW, can derive *any* group theory identity by drawing "birdtracks"

P. Cvitanovic, <http://www.birdtracks.dk/>

$$(t^{ab})_{cd} = \begin{array}{c} \text{a} \\ \uparrow \\ \text{---} \rightarrow \text{---} \\ \text{c} \end{array} \begin{array}{c} \text{b} \\ \downarrow \\ \text{---} \rightarrow \text{---} \\ \text{d} \end{array} = \frac{1}{N} \begin{array}{c} \curvearrowright \\ \text{---} \rightarrow \text{---} \end{array}$$

Computing semi-class.'y about A_0^{cl} is *easy*: energy p_0 acquires color indices: one for fields in the fundamental representation, two for those in the adjoint.

$$\begin{array}{c} \text{---} \rightarrow \text{---} \\ \text{---} \rightarrow \text{---} \end{array} = \frac{1}{N} \begin{array}{c} \curvearrowright \\ \text{---} \rightarrow \text{---} \\ \curvearrowleft \end{array}$$

quark:

$$p_0^a = p_0 - Q^a$$

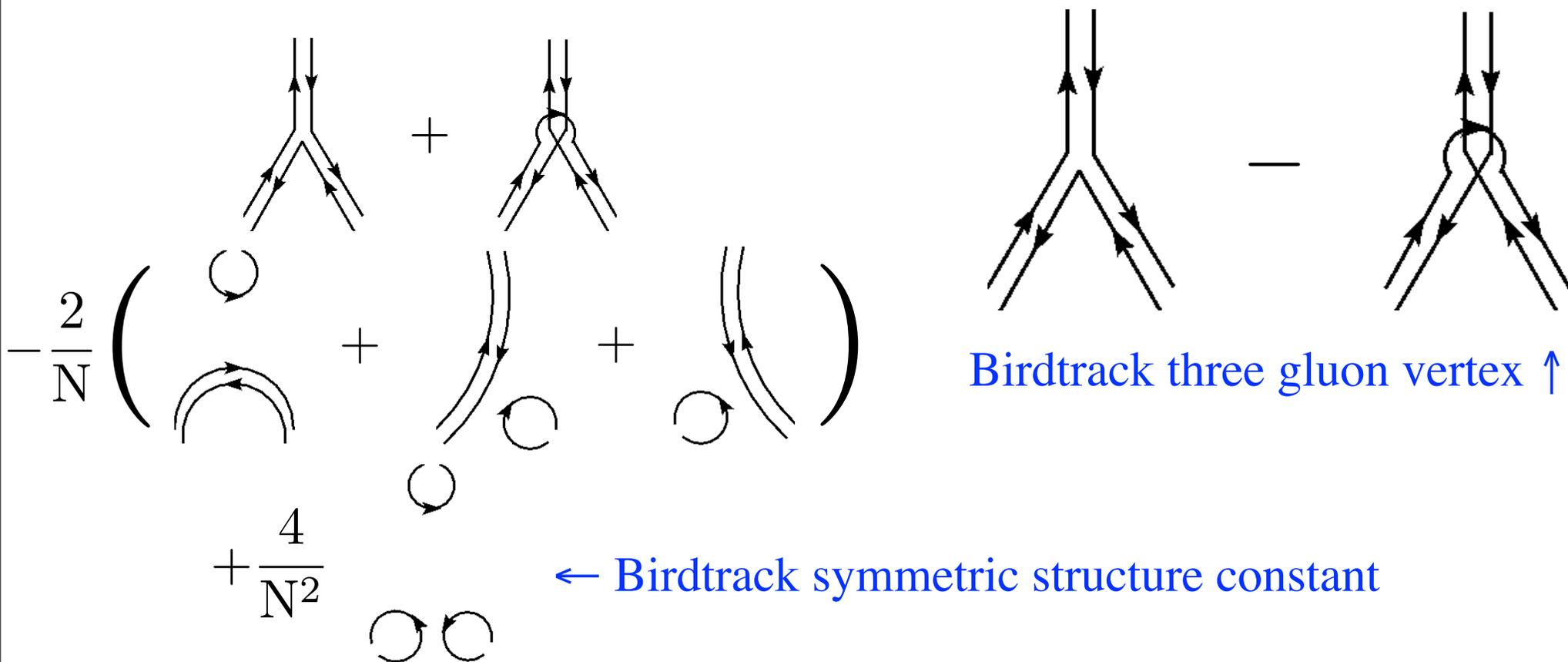
gluon:

$$p_0^{ab} = p_0 - Q^a + Q^b$$

Computing with ease in the semi-QGP

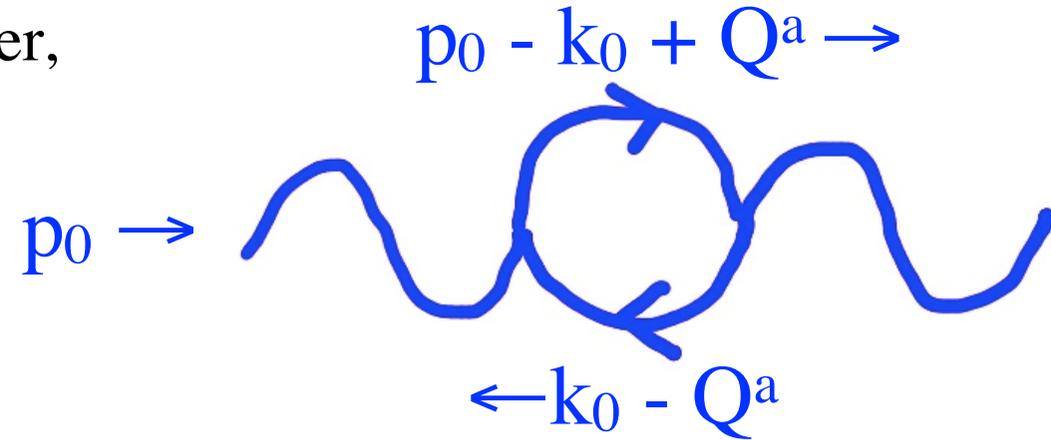
Perturbation theory is as usual, except there is an imaginary (color) chemical potential, which shifts the energy, p_0 . Propagators in imaginary time, τ :
 energy $p_0 = 2 \pi n T$, $n = 0, \pm 1, \pm 2 \dots$

$$\Delta_Q(\tau, E) = T \sum_{n=-\infty}^{+\infty} \frac{e^{-ip_0\tau}}{(p_0 + Q)^2 + E^2} = \sum_{s=\pm} \frac{s}{2E} (1 + n(sE - iQ)) e^{-sE\tau}$$



Dilepton production in the semi-QGP, 1

Compute the usual diagram at lowest order, just adding Q 's to the propagators:



Loop momenta = k ; $E_1 = E_k$, $E_2 = E_{k-p}$.
Result is $\sim \int d^3k R_Q$:

$$R_Q = n_-(E_1 - iQ) n_-(E_2 + iQ)$$

Standard identity:

$$R_Q = n_+(E_1 + E_2) (1 - n_-(E_1 - iQ) - n_-(E_2 + iQ))$$

Doing Boltzmann expansion,

$$R_Q = n_+(E_1 + E_2) \left(1 - \sum_{j=1}^{\infty} \frac{(-1)^{j+1}}{N_c} (e^{-jE_1} \text{tr} \mathbf{L}^j + e^{-jE_2} \text{tr} (\mathbf{L}^\dagger)^j) \right)$$

Still have to integrate over Q 's. Easy to evaluate for arbitrary Q -distribution.

Dilepton production in the semi-QGP, 2

Complete QGP: $Q = 0$, usual product of Fermi-Dirac distribution functions

$$R_{Q=0} = n_-(E_1) n_-(E_2)$$

Confined phase: flat Q -distribution.
At $N_c = \infty$, $\text{tr } \mathbf{L}^j = 0$ for $j \geq 1$, so

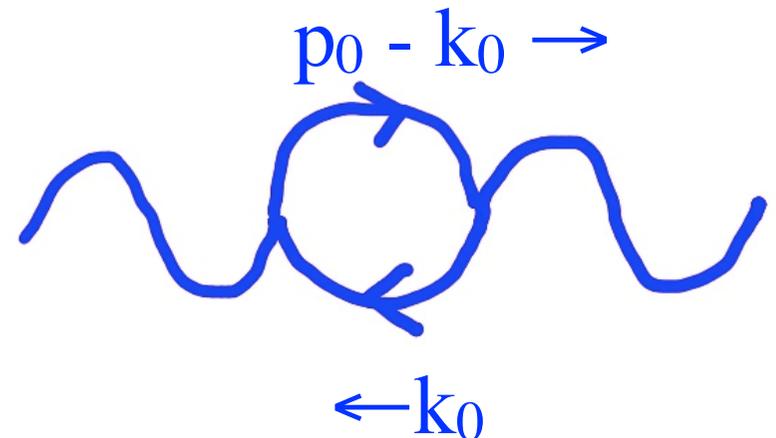
$$R_{\text{confined}} = n_+(E_1 + E_2)$$

At low momenta, $E_1 + E_2 \ll T$, $R_{\text{confined}} \sim (E_1 + E_2)/T$, while $R_{Q=0} \sim 1$
Bose enhancement in the confined phase, but *not* in the complete QGP.

Confined phase gives *more* (very soft) dileptons than the QGP!

Contrast to FWpPNJL model
(Fukushima-Weise-pisarski-Polyakov)NJL:

Each quark line $\sim l = \text{tr } \mathbf{L}/N_c$,
so R suppressed, $\sim l^2$ as $l \rightarrow 0$.



Not like a matrix model, where there is *enhancement*

Energy loss in the semi-QGP

Damping rate for a fast or heavy quark: add Q's to the propagators.

Need Hard Thermal Loops (HTLs) in background Q-field:

Blue: hard momenta, $p \sim T$. Red: soft momenta, $p \sim g T$. Blob = HTL resummed



Again, result is a function of the Q's, $F(Q)$
times the perturbative result:

$$\gamma = c g^2 N_c \log(1/g) \mathcal{F}(Q)$$

By definition, in the complete QGP, $Q = 0$, $F(0) = 1$.

Near T_c , where $l \rightarrow 0$, $F(Q) \sim l$.

Energy loss \sim damping rate, so it is suppressed *linearly* near T_c .

Suppression of energy loss very different from dilepton production!

Plus: uniform suppression of color charge, $\sim \langle loop \rangle$: R_{AA} for heavy quarks?

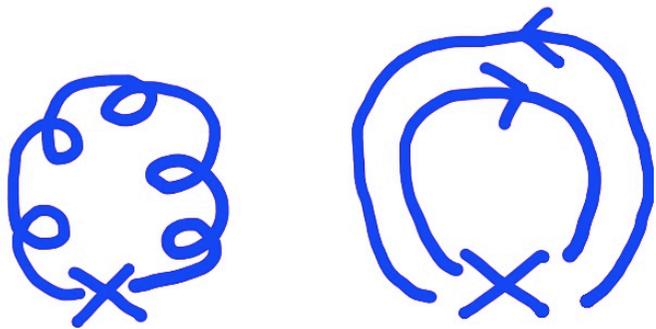
Shear viscosity in the semi-QGP, 1

Shear viscosity, η , in the complete QGP: [Arnold, Moore & Yaffe, hep-ph/0302165](#)

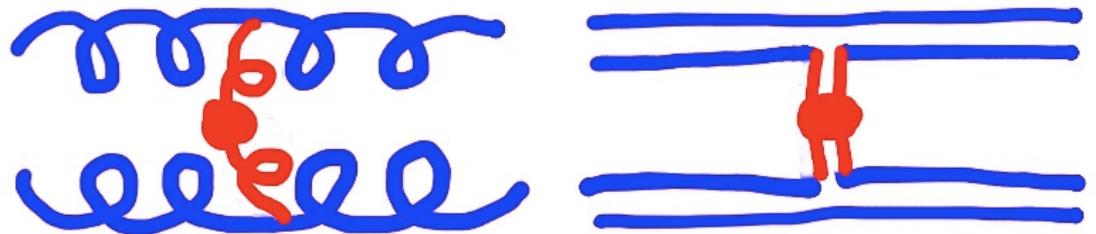
In the semi-QGP: Boltzmann equation in a *background* field, $Q \neq 0$.

$$\eta = \frac{S^2}{C} \quad S = \text{source term}, C = \text{collision term.}$$

Start first with pure glue, for *small* values of the Polyakov loop, $l = \text{tr } L/N_c$:



$$S_{\text{glue}} \sim l^2$$

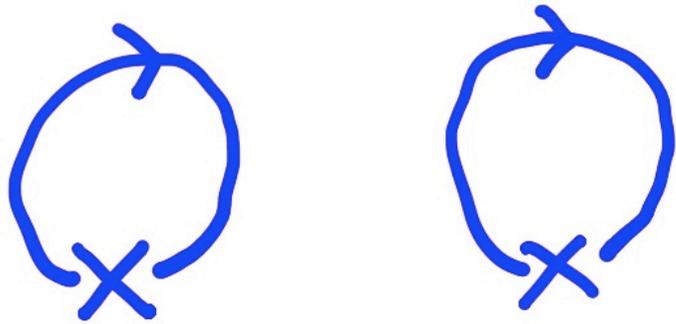


$$C_{\text{glue}} \sim l^2$$

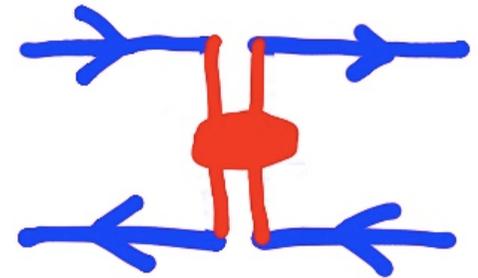
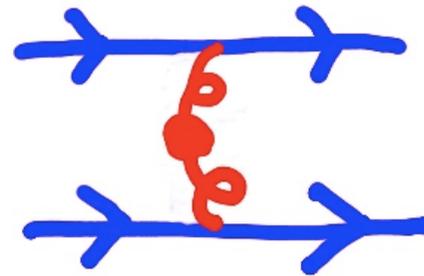
$$\eta_{\text{glue}} \sim \frac{S_{\text{glue}}^2}{C_{\text{glue}}} \sim \frac{(l^2)^2}{l^2} \sim l^2$$

Shear viscosity in the semi-QGP, 2

With N_f flavors of dynamical quarks, taking $N_f \sim N_c \rightarrow \infty$:



$$S_{\text{qk}} \sim l$$



$$C_{\text{qk}} \sim 1$$

$$\eta_{\text{qk}} \sim \frac{S_{\text{qk}}^2}{C_{\text{qk}}} \sim \frac{l^2}{1} \sim l^2$$

Thus $\eta \sim l^2$ as $l \rightarrow 0$ in all cases.

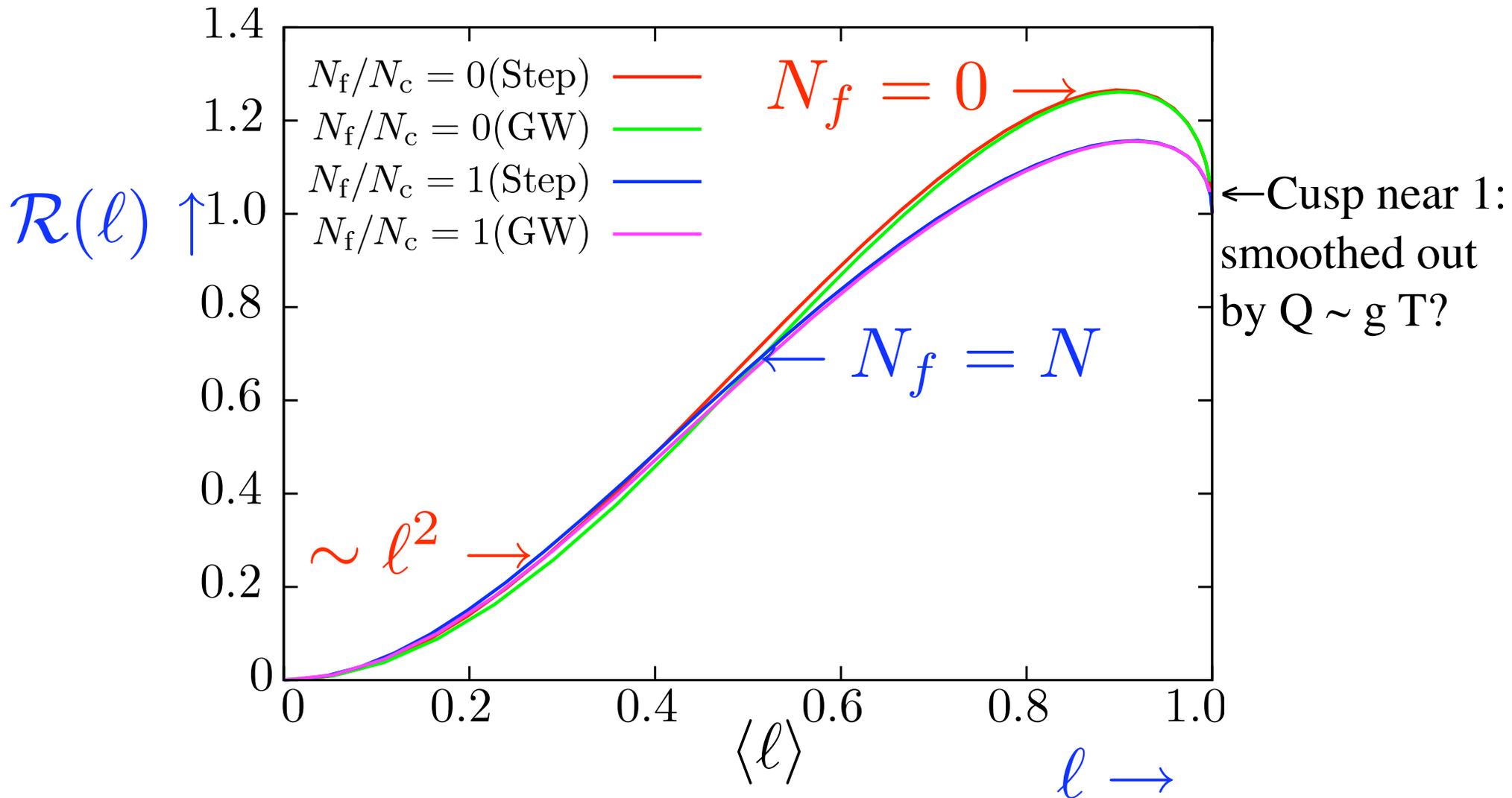
Away from small l , quark and gluon scattering enter, terms mix.

Not like ordinary kinetic theory: η small not because of large coupling, but because density of fields vanishes. *Special* to deconfining transition.

Shear viscosity in the semi-QGP, 3

$R(l)$ = ratio of shear viscosity in
 semi-QGP/pert.-QGP for the *same* value of g
 c_1, c_2 #'s from **Arnold, Moore, & Yaffe**
 As $l \rightarrow 0, R(l) \sim l^2$. e.g., $R \sim 0.3$ for $l \sim 0.3$

$$\eta = \frac{c_1 T^3}{g^4 \log(c_2/g)} \mathcal{R}(l)$$

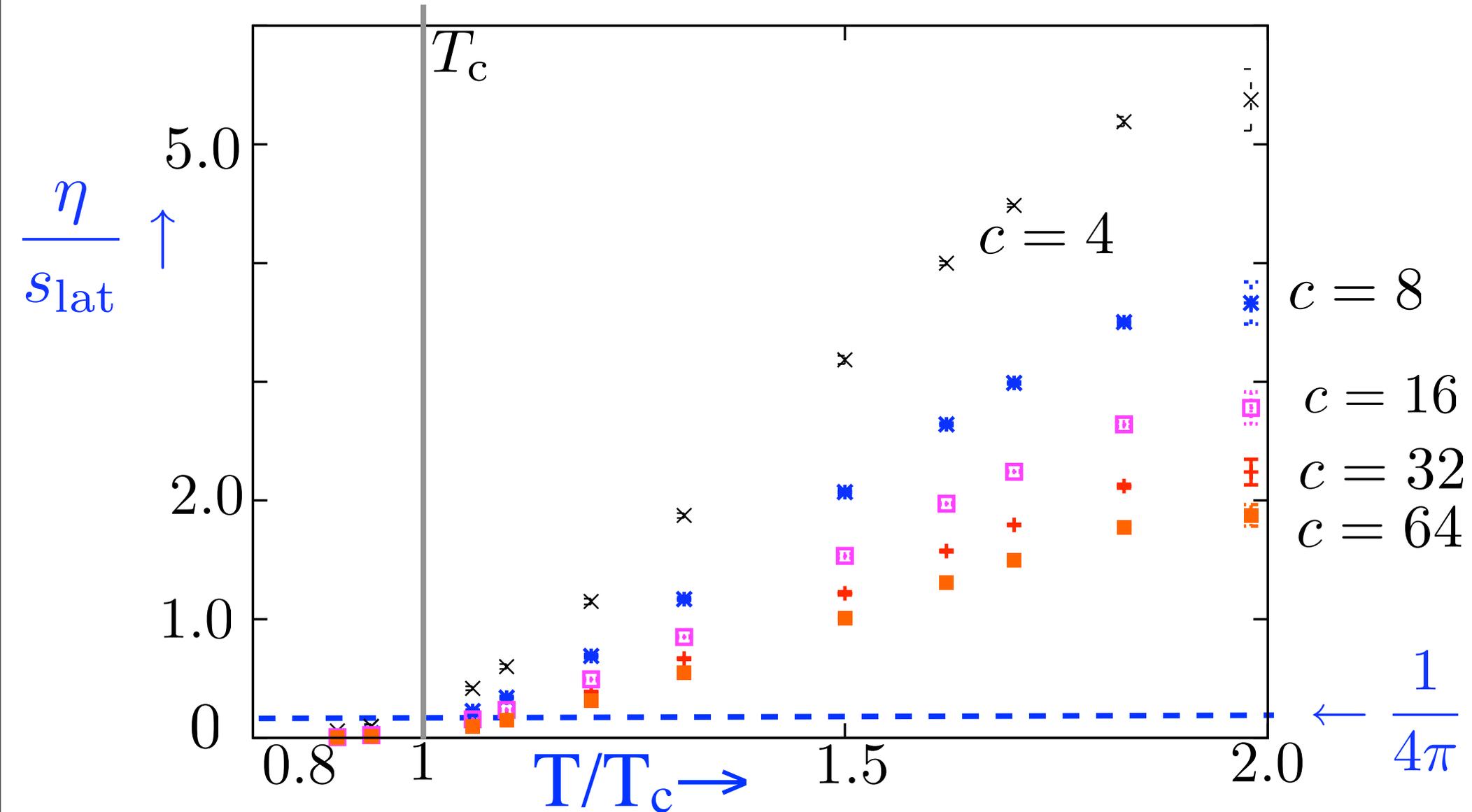


Shear viscosity in the semi-QGP, 4

Leading log shear viscosity/lattice entropy. $\alpha_s(T_c) \sim 0.3$.

Large increase from T_c to $2 T_c$. Clearly need results beyond leading log.

Also need to include: quarks and gluons below T_c , hadrons above T_c . Not easy.

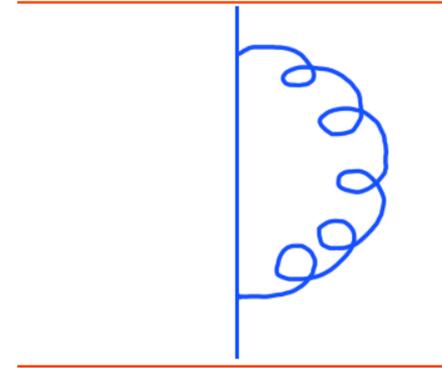


Renormalized loops

Polyakov '80, Dotsenko & Vergeles '81 +...

Dumitru, Hatta, Lenaghan, Originos, & RDP hep-ph/0311223

Gupta, Hubner & Kaczmarek 0711.2251 = GHK



Bare loop UV divergent. At one loop =>

In 3+1 dim.'s, linear divergence with lattice spacing "a":

(R = representation, Casimir C_R)

$$\langle \ell_R^{\text{bare}} \rangle = \exp \left(- \# C_R g^2 (1 + \dots) \frac{1}{aT} \right) \langle \ell_R^{\text{ren}} \rangle$$

Renormalized loop:

$N_t = 1/aT = \#$ time steps:

$$\langle \ell_R^{\text{bare}} \rangle = \mathcal{Z}_R (g^2)^{N_t} \langle \ell_R^{\text{ren}} \rangle$$

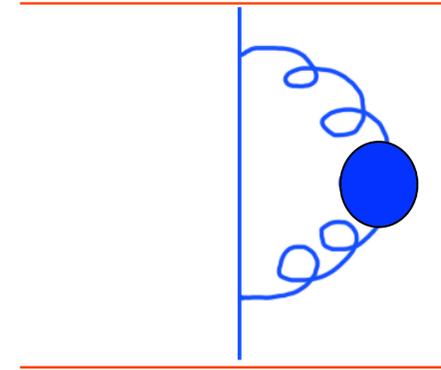
Can choose $\langle \ell \rangle \rightarrow 1$, $T \rightarrow \infty$

Also choose zero point energy $E_0 = 0$: RDP & YK 0907.4609

At high T, ren'd loops approach 1 from above

Gava & Jengo '81:

Compute perturbatively,
fold Debye mass, m_D , into propagator for A_0 :



$$\langle \ell_R^{\text{ren}} \rangle - 1 \sim (-) \frac{C_R g^2}{T} \int d^3 k \frac{1}{k^2 + m_D^2} \sim (-) \frac{C_R g^2}{T} (-) \sqrt{m_D^2}$$

Sign of the integral is *negative*; like subtracting $1/k^2$ propagator.

$$\langle \ell_R^{\text{ren}} \rangle - 1 \sim (+) \frac{C_R}{N} \frac{(g^2 N)^{3/2}}{8\pi\sqrt{3}}$$

Zero point energy & renormalized loops

RDP & YK 0907.4609: renormalization valid for arbitrary Wilson loops:

$$\mathcal{W} = \text{tr} \mathcal{P} e^{ig \oint A_\mu dx^\mu} \quad ; \quad \mathcal{W}_{\text{bare}} = \mathcal{Z}_{\text{div}} \mathcal{W}_{\text{ren}}$$

Two ambiguities:

$$\mathcal{Z}_{\text{div}} = e^{E_0 L} \mathcal{Z}_0 \mathcal{Z}(g^2 \dots)^{L/a} \quad ; \quad \mathcal{W}_{\text{ren}} \rightarrow e^{-E_0 L} \mathcal{Z}_0^{-1} \mathcal{W}_{\text{ren}}$$

Overall scale trivial: $\mathcal{Z}_0 = 1$ by requiring $\langle \text{loop} \rangle \rightarrow 1$ as $T \rightarrow \infty$.

E_0 = ground state energy for potential from Wilson loop: $E_0 = \# \sqrt{\sigma}$. # ?

Can *define* $E_0 = 0$ order by order in perturbation theory with *any* regulator.

$E_0 = 0$ also in string model: Nambu-Goto *plus* extrinsic curvature terms.

Ambiguity present also for calc.'s on small sphere

Lattice provides *non-perturbative* way to *define* $E_0 = 0$.

However, $E_0 = 0$ *only* for straight loops, and *not* for “smeared” loops.

Renormalization of smeared loops: S. Capitani and O. Kaczmarek, in progress.

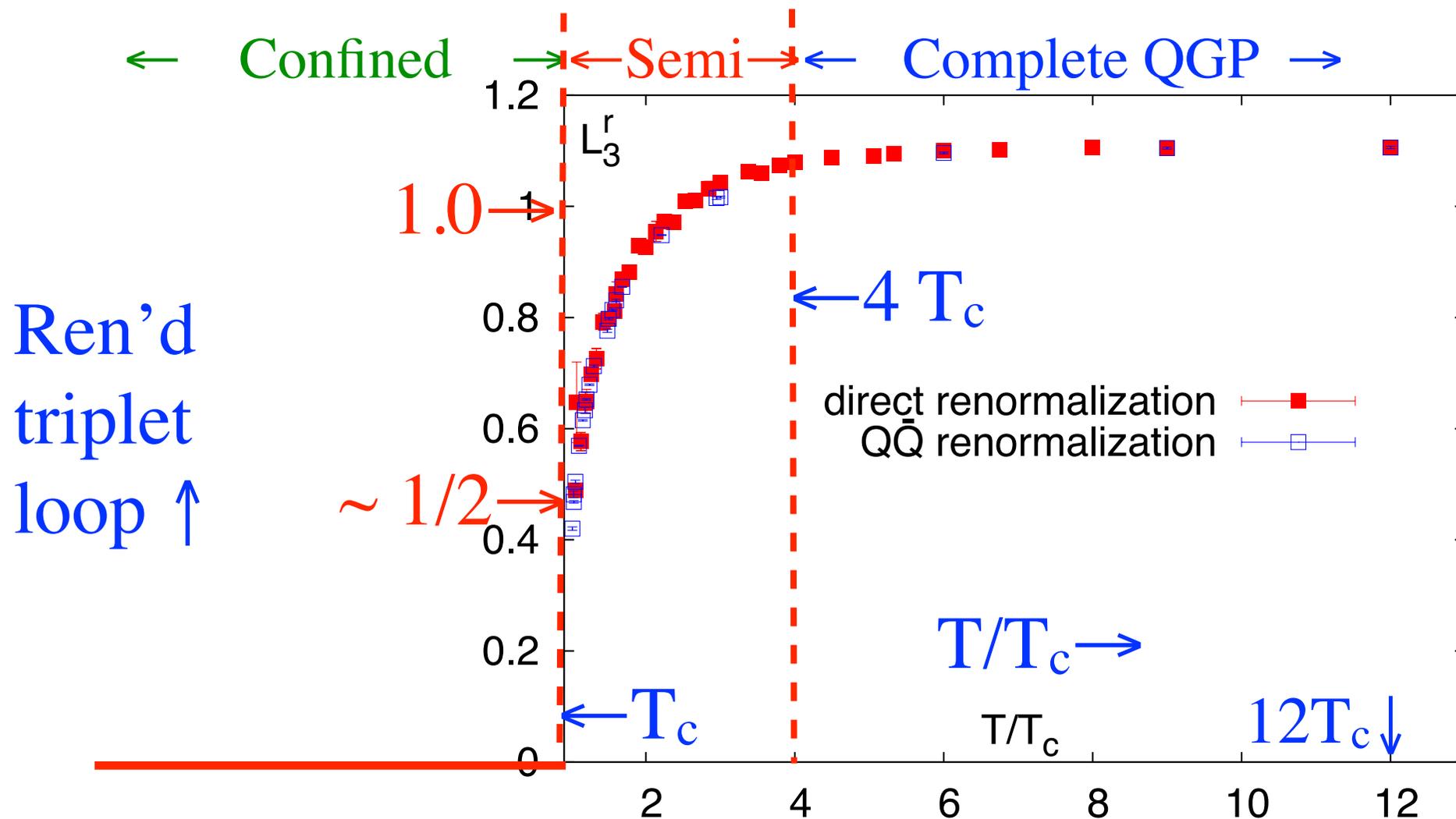
Lattice: renormalized loop, c/o quarks

GHK: Lattice SU(3), *no* quarks. Two ways of getting ren'd loop agree.

$\langle \text{triplet loop} \rangle \sim 1/2$ at T_c^+ . N=3 close to Gross-Witten point?

semi-QGP: from (*exactly*) T_c^+ to 2 - 4 T_c (?). $\langle \text{loop} \rangle \sim$ constant above 4 T_c .

$\langle \text{adjoint loop} \rangle \sim 0.01$ just below T_c . *Only* natural in matrix model.

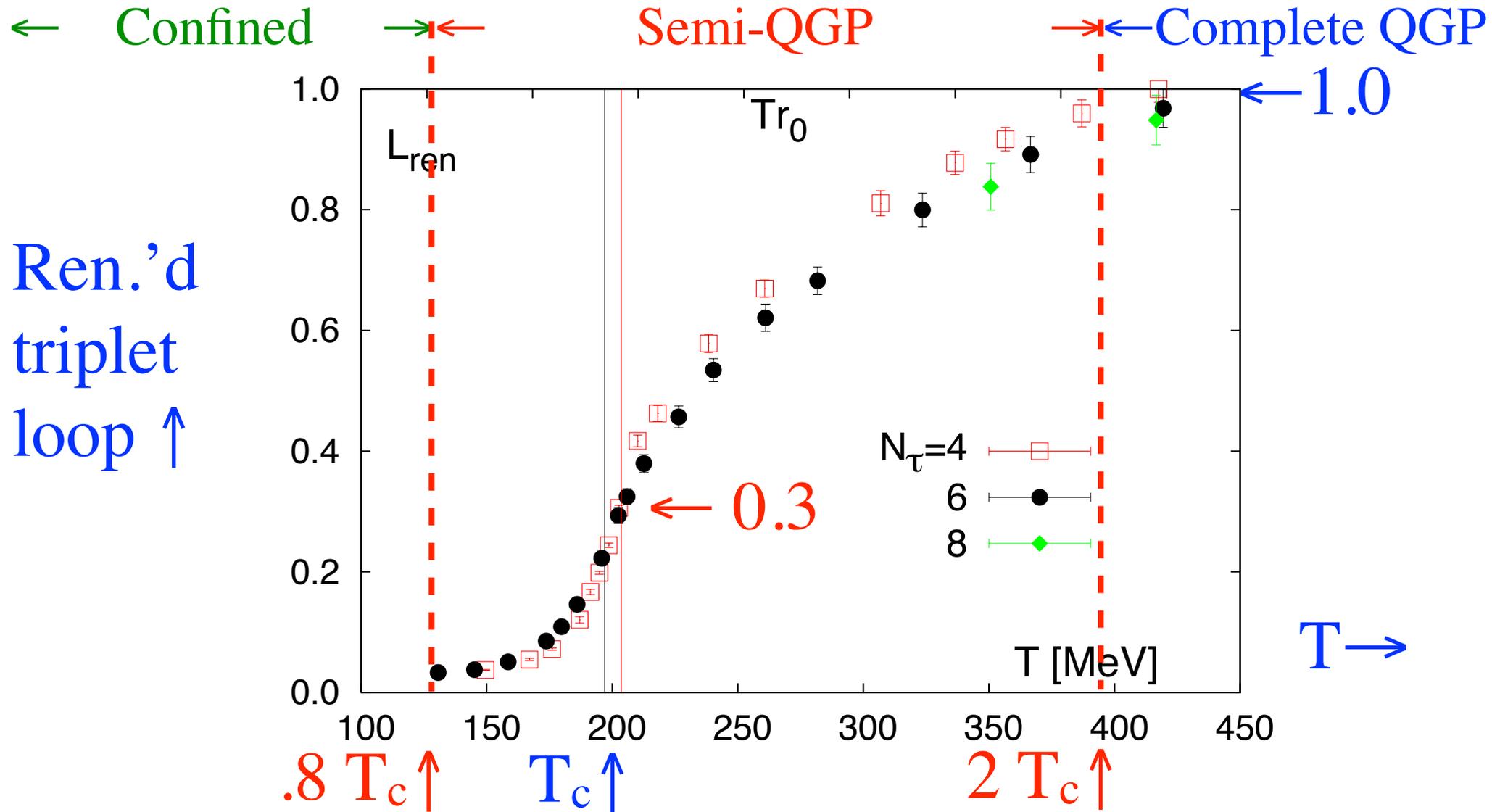


Lattice: renormalized loop, with quarks

Cheng et al, 0710.0354: \sim QCD, 2+1 flavors. $T_c \sim 190$ MeV, crossover.

$\langle loop \rangle$: nonzero from $\sim 0.8 T_c$; ~ 0.3 at T_c ; ~ 1.0 at $2 T_c$.

Semi-QGP from $\sim 0.8 T_c$ (below T_c) to $\sim 2-3 T_c$ (?). $\langle loop \rangle$ small at T_c .



Effective potential for the semi-QGP, 1

At one loop order, there is a potential for $A_0^{\text{cl}} = Q/g$:

Gross, Yaffe, & RDP, '81; N. Weiss, '81

$$\mathcal{V}_{\text{pert.}} = \# T^4 q^2 (1 - q)^2, \quad Q = 2\pi T q$$

Necessary: in the pure glue theory, lifts the degeneracy in q .

This potential enters the computation of the tunneling between $Z(N_c)$ vacua,
= $Z(N_c)$ interface tension.

Meisinger, Miller, & Ogilvie (MMO), hep-ph/0108009:

add a *non-perturbative* potential, $\sim T^2$

Terms $\sim T^2$ “Fuzzy Bag”: RDP, hep-ph/0612191

$$\mathcal{V}_{\text{non-pert.}} = \# T^2 q(1 - q)$$

Must have terms $\sim q$ as $q \rightarrow 0$: else have a phase transition

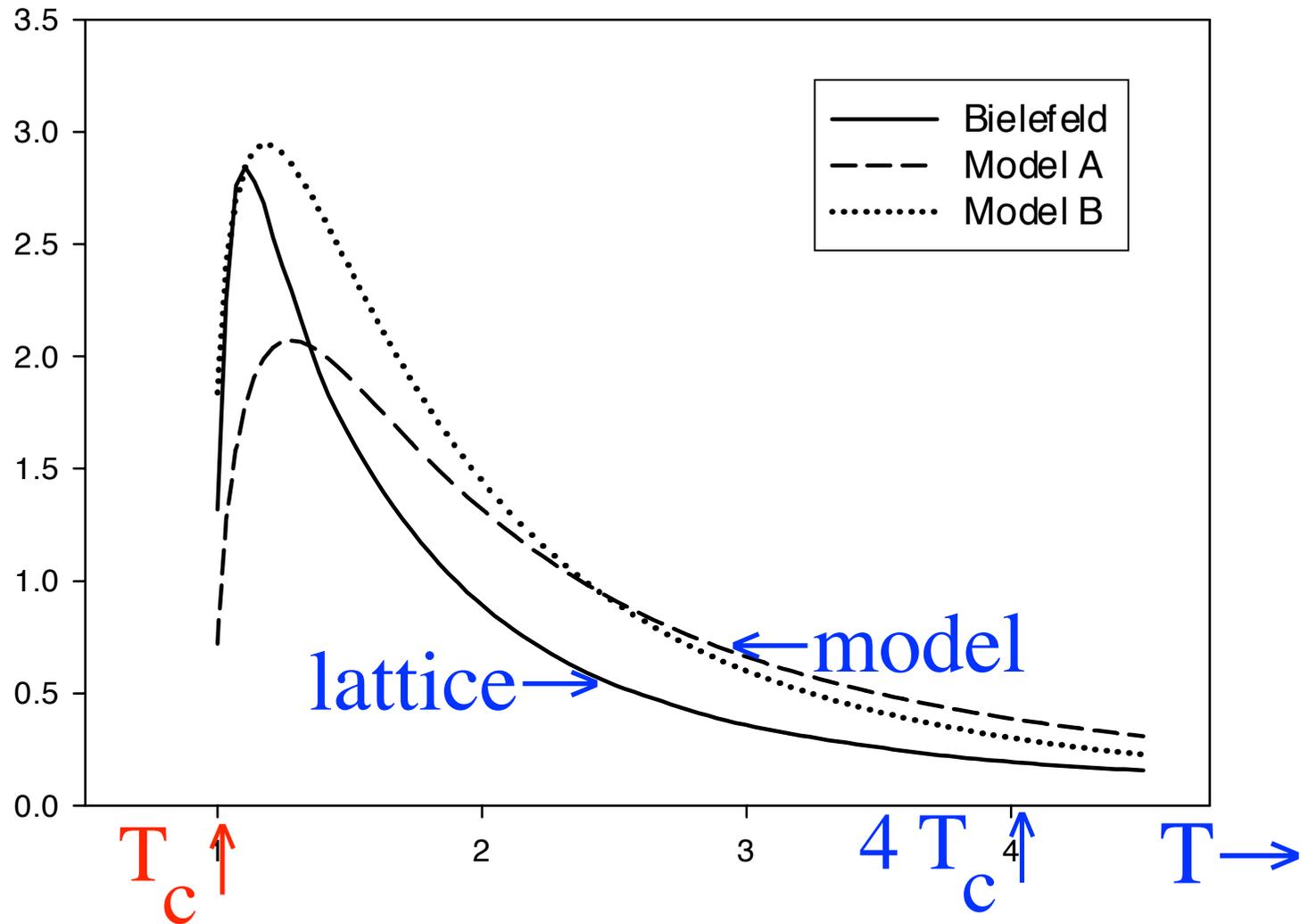
(either 1st or 2nd order), in going from the *complete* QGP, to the semi- QGP.

Lattice finds only *one* transition, at T_c , and *not* a second transition above T_c .

Effective potential for the semi-QGP, 2

MMO fit the pressure with reasonable accuracy:

$$\frac{e - 3p}{T^4} \uparrow \Delta$$



But the renormalized Polyakov loop is *nothing* like the lattice:
it is near one by $\sim 1.5 T_c$!

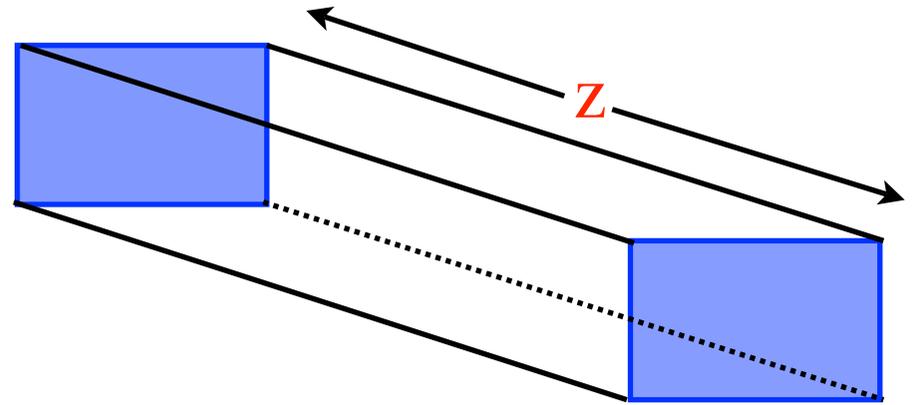
Dumitru, RDP, & Zschiesche, '05, unpublished: *no* effective potential fits
both the pressure *and* the renormalized loop.

Z(N) interfaces = 't Hooft loop

Z(N) interface: Z(N) “twist” in z-direction. A_{tr} = transverse area.

$$A_0^{\text{cl}} = \frac{2\pi T}{gN} q(z) t_N$$

$$\langle L \rangle = \mathbf{1}$$



$t_N = \text{diag}(1_{N-1}, -N+1)$. $A_0 \sim$ “coordinate” $q(z)$.

$\mathcal{L}_{\text{eff}} =$ classical + 1 loop potential, for *constant* A_0

$$\langle L \rangle = e^{2\pi i/N} \mathbf{1}$$

$$\mathcal{L}_{\text{eff}} = \frac{4\pi^2 (N-1) T^3}{\sqrt{3g^2 N}} A_{\text{tr}} \int dz \left(\left(\frac{dq}{dz} \right)^2 + q^2 (1-q)^2 \right)$$

Bhattacharya, Gocksch, Korthals-Altes & RDP, hep-ph/9205231

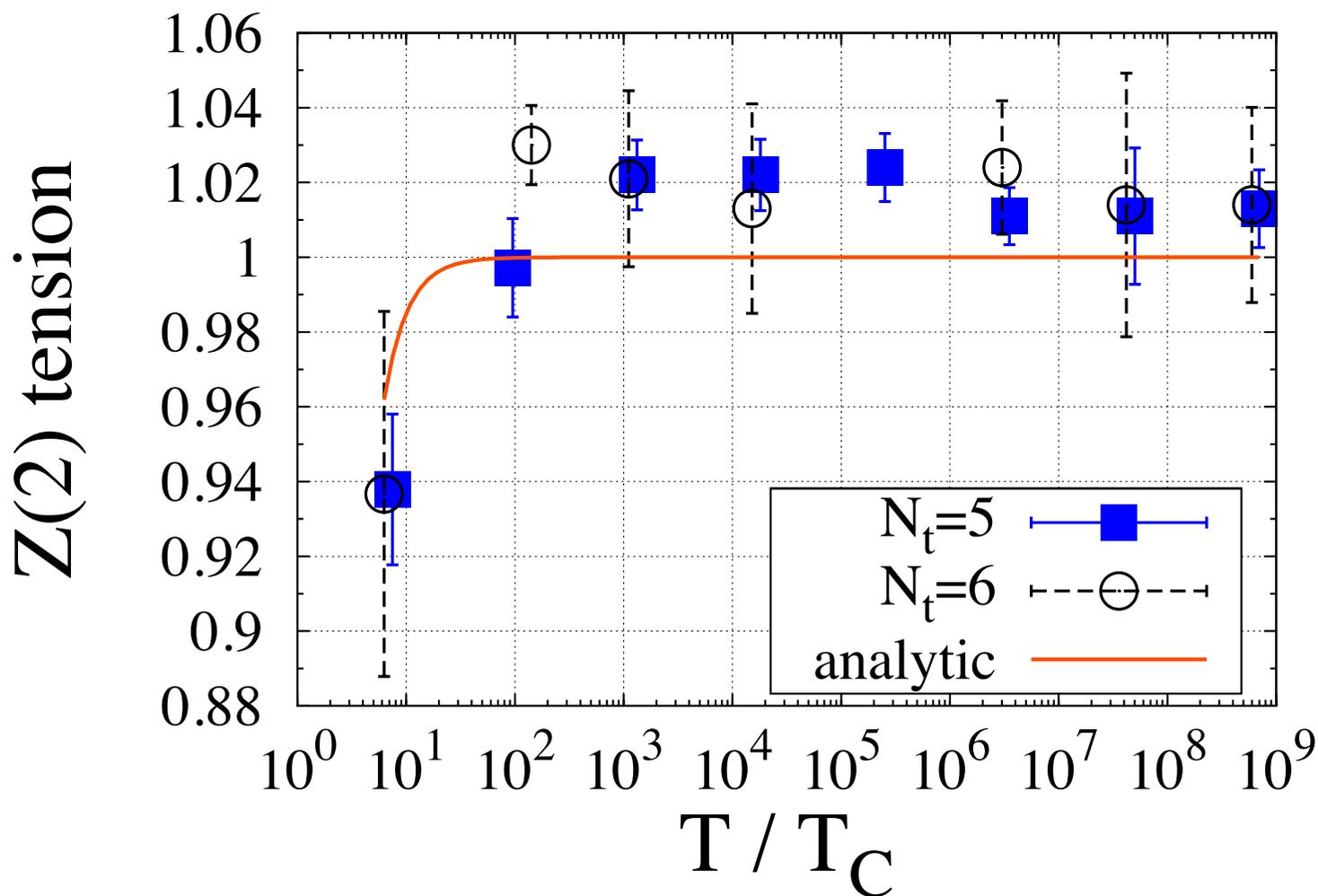
Interface = 't Hooft loop: Korthals-Altes, Kovner & Stephanov, hep-ph/9909516

Corrections $\sim g^3$: Giovannangeli & Korthals-Altes hep-ph/0412322

$\sim g^4$: Korthals-Altes, Schroder, & Vuorinen, in progress

Interface tension for the semi-QGP

In pure glue $SU(N_c)$ theory, global $Z(N_c)$ symmetry implies N_c degenerate vacua
Tunneling between degenerate N_c vacua is interface tension (aka 't Hooft loop)
Semi-classical computation of interface tension works *well* above ~ 10 GeV,
but *not* below: $SU(2)$ lattice, [de Forcrand & Noth hep-lat/0506005](#)
[DGHKP, 1010....](#): With “fuzzy bag” term of MMO, works well right down to T_c !



Two types of gluon masses in the semi-QGP

DGHKP, 1010....: two point function of gluons. In coordinate space,
 (energy $p_0 = 2 \pi n T$, $n = 0, \pm 1, \pm 2...$)

$$\langle A_0^{ab}(\vec{x}) A_0^{ba}(0) \rangle \sim \int \frac{d^3 p}{(2\pi)^3} e^{i\vec{p}\cdot\vec{x}} \sum_{n=-\infty}^{+\infty} \frac{e^{-ip_0\tau}}{(\vec{p})^2 + (p_0 + Q^a - Q^b)^2 + m_D^2(Q)}$$

Off-diagonal color fields *heavy*:

$$\sim |p_0 + Q^a - Q^b| \sim 2 \pi T$$

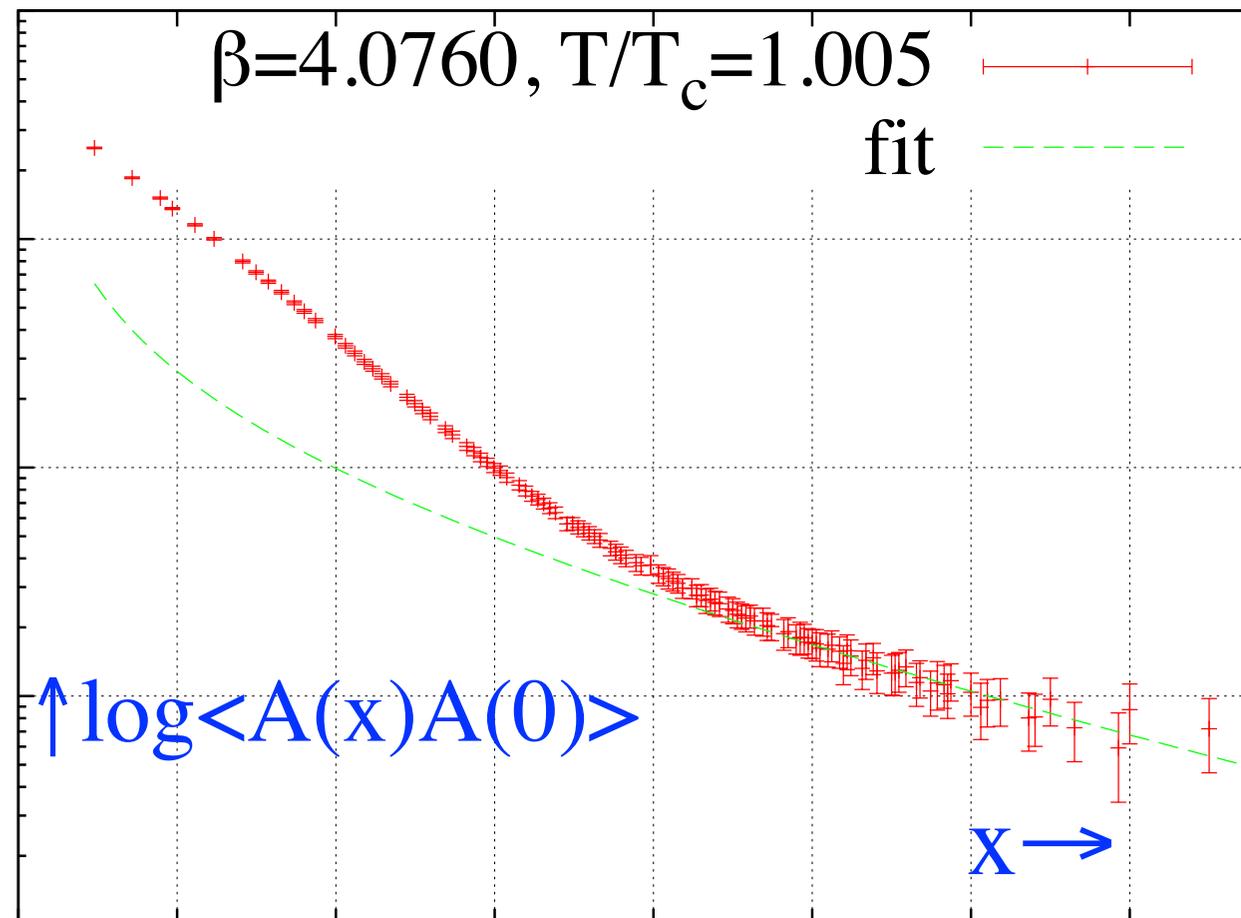
Diagonal color fields *light*:

$$\sim \text{Debye mass, } m_D(Q) \sim g T$$

Unique prediction in semi-QGP:
two types of gluon masses

O. Kaczmarek, unpublished:
 evidence from lattice SU(3):
 two slopes in $\log\langle A(x)A(0) \rangle$

Only below $\sim 1.5 T_c$, not above



Conclusions

RHIC: (mainly) in the semi-QGP?

LHC: deep in the complete QGP?

Shear viscosity *increases* going from the semi- QGP,
to the complete QGP.

Today: the width of the semi-QGP is *narrow*, from $\sim T_c$ to $\sim 1.5 T_c$,
and *not* broad, $\sim T_c$ to $\sim 4 T_c$.

John Harris: “Expect the Unexpected”