Jet Quenching and Quarkonium Dissociation in Heavy Ion Collisions and String Theory

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28 June 2007

The LHC program

The Standard Model

$L_{QCD} + L_{el-wk}$

How does collectivity emerge from elementary interactions?

p+p @ 14 TeV
ATLAS
CMS
LHCb
ALICE

Heavy Ions @ 5.5 TeV
ALICE
CMS
ATLAS

Beyond the Standard Model

LHC and String theory

The Standard Model

$$L_{QCD} + L_{el-wk}$$

How does collectivity emerge from elementary interactions?

Novel techniques for calculating in non-abelian thermal QFTs

Topic of this talk:

How this may be of use for the phenomenology of heavy ion collisions?

Beyond the Standard Model

String inspired model building

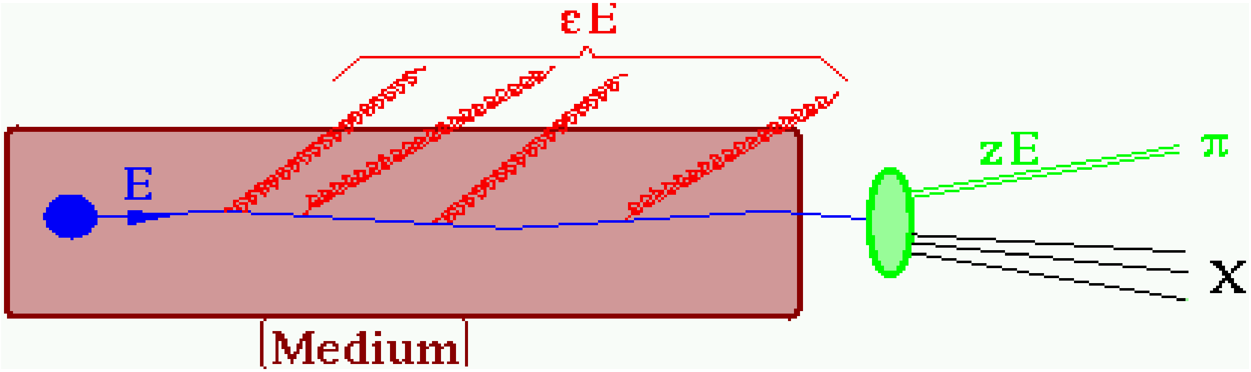
Content

- Some data from RHIC (expectations for LHC)
- Results of QCD-based model calculations and open questions
- Some answers from string theory
- To what extent do the answers address the questions?

What is jet quenching?

(experimentally)

The suppression of high p_T hadron spectra in Au+Au at RHIC



Nuclear modification factor characterizes medium-effects:

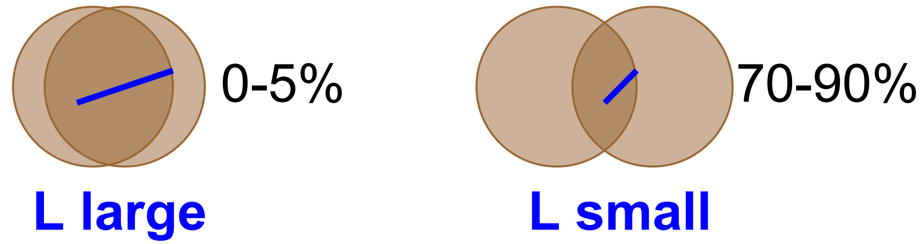
$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{n_{coll}\, dN^{NN}/dp_T}$$

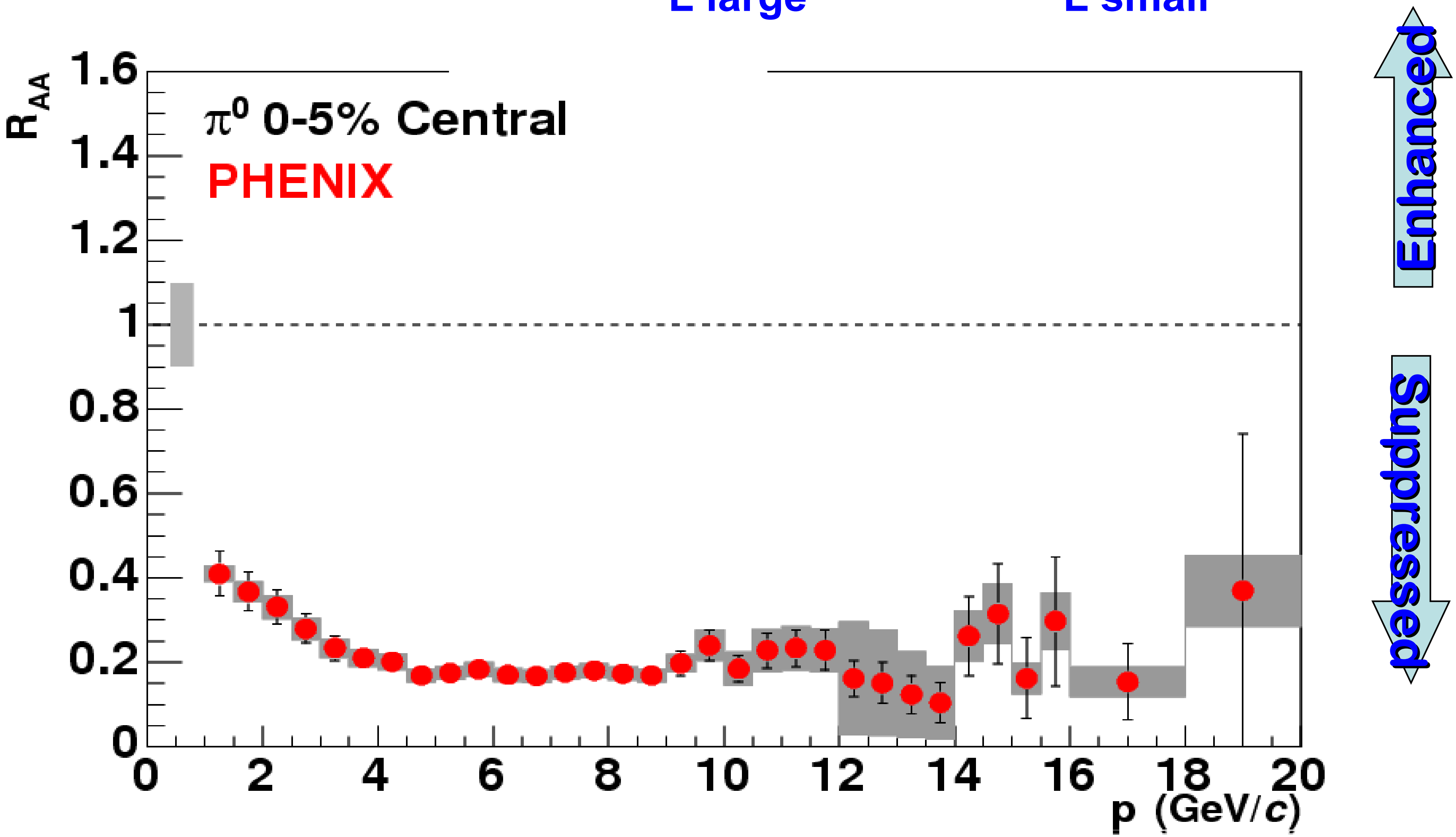
$R_{AA}(p_T) = 1.0$ no suppression

$R_{AA}(p_T) = 0.2$ factor 5 suppression

Strong suppression persists to highest p_T

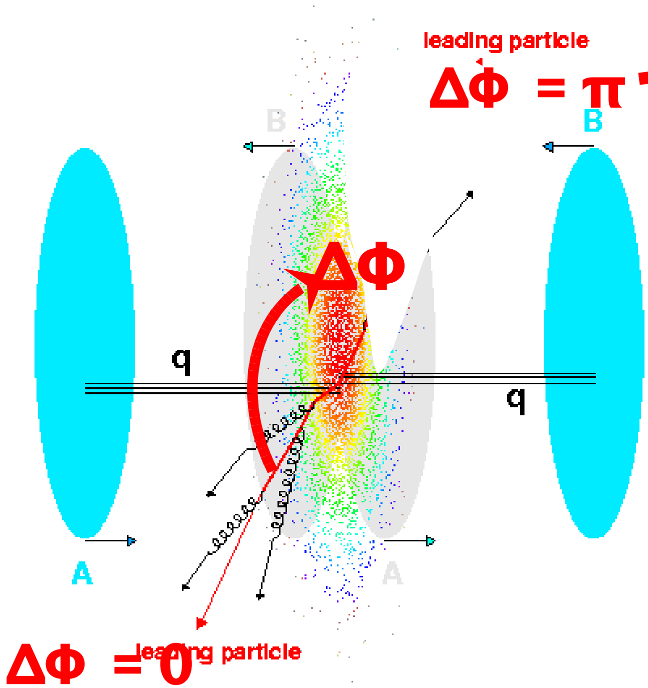
Centrality dependence:

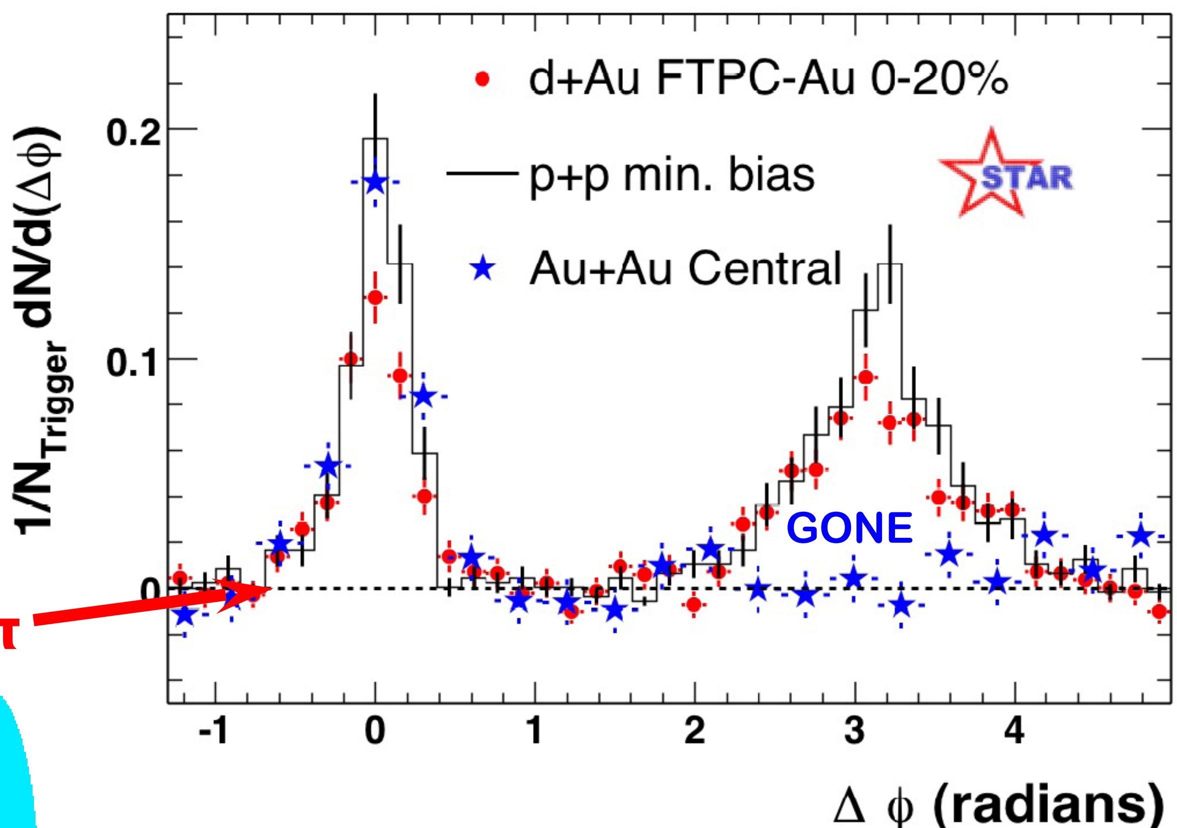




The Matter is Opaque

- STAR azimuthal correlation function shows ~ complete absence of “away-side” jet





Partner in hard scatter is
completely absorbed
in the dense medium

How is jet quenching calculated?

(in QCD)

Parton Propagation in an External Color Field

- In QCD, high-energy scattering can be described by **eikonal Wilson lines**

$$W(x_i) = P \exp\left[i \int dz^- T^a A_a^+(x_i, z_-) \right]$$

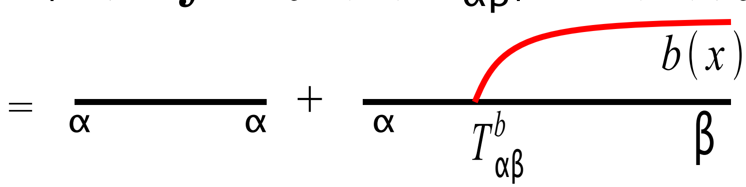
During scattering, transverse coordinates are frozen, **color** rotates

$$Y_{in} = \sum_{\{\alpha_i, x_i\}} y(\alpha_i, x_i) |\alpha_i, x_i\rangle \qquad Y_{out} = \sum_{\{\alpha_i, x_i\}} y(\alpha_i, x_i) \left(P_i W^{r_i}_{\alpha_i \beta_i}(x_i) \right) |\beta_i, x_i\rangle$$

SIMPLIFIED

2. Example: quark-nucleus scattering. Incoming free quark wave function dressed to O(g)

$$Y_{in} = |\alpha\rangle + \int dx\, f(x) T^b_{\alpha\beta} |\beta, b(x)\rangle \qquad f(x) \mu g \frac{\vec{x}}{x^2}$$



Outgoing quark wavefunction, leaving target

$$Y_{out} = W^F_{\alpha g}(0) |g\rangle + \int dx\, f(x) W^F_{\beta g}(0) W^A_{bc}(x) T^b_{\alpha\beta} |g, c(x)\rangle$$

3. Gluon production in quark-nucleus scattering:
Count number of gluons in outgoing wave function

$$|dY\rangle = \left[1 - |Y_{in}\rangle\langle Y_{in}|\right]|Y_{out}\rangle$$

$$N^{qA}(k_T) = \frac{1}{N_c}\sum_{\alpha}\langle dY_{\alpha}|a_d^{+}(k_T)\,a_d(k_T)|dY_{\alpha}\rangle_{Target}$$

Kovchegov Mueller; …

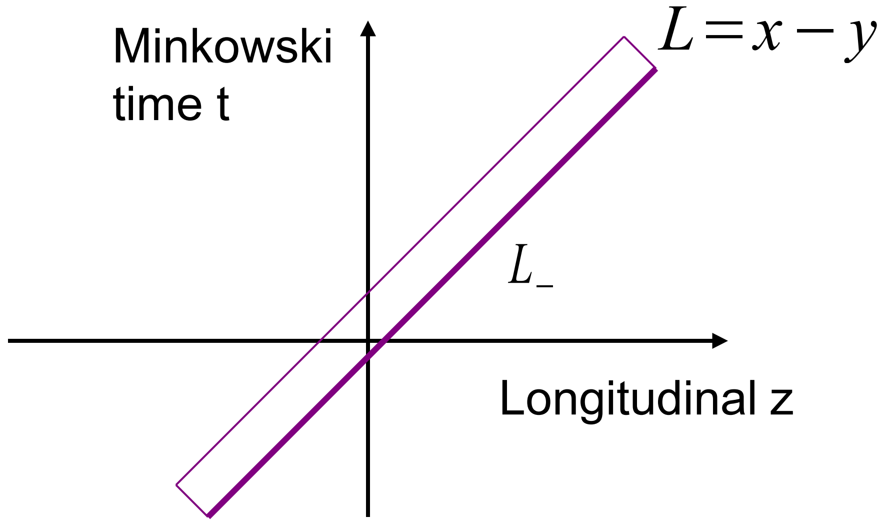
$$\Rightarrow N^{qA}(k_T) \propto \int dx\, dy\, \frac{\vec{x}\cdot\vec{y}}{x^2 y^2}\, e^{-ik_T(\vec{x}-\vec{y})}\left[N(x,0) + N(y,0) - N(x,y)\right]$$

SIMPLIFIED

Information about target encoded in:

$$N(x,y) \equiv 1 - \langle W^{A}(C^{x,y}_{light-like})\rangle_T$$

Light-like Wilson loop



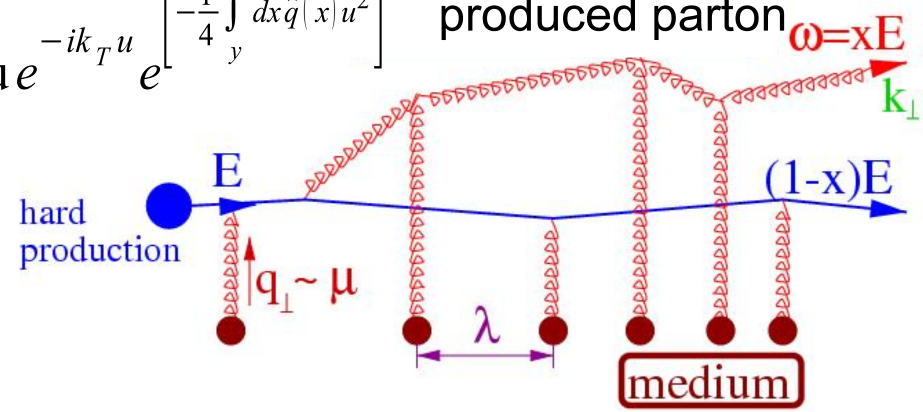
The medium-modified Final State Parton Shower

Baier, Dokshitzer, Mueller, Peigne, Schiff; Zakharov; Wiedemann…

$$\frac{dI}{d\ln\omega\, dk_T} = \frac{\alpha_s C_R}{(2\pi)^2\omega^2}\, 2\,\mathrm{Re}\int_0^\infty dy \int_y^\infty d\bar{y} \int du\, e^{-ik_T u}\, e^{\left[-\frac{1}{4}\int_{\bar{y}}^{\infty} dx\, \hat{q}(x)\, u^2\right]}$$

$$\times \frac{\partial}{\partial u}\cdot\frac{\partial}{\partial s} K(s=0, y; u, \bar{y}|\omega)$$

Radiation off produced parton



Target average determined by **light-like Wilson loop**:

$$K\left(s, y; u, \bar{y}|\omega\right) = \int_{s=\rho(y)}^{u=\rho(\bar{y})} D\rho \exp\left[\int_y^{\bar{y}} dx \left\{\left(\frac{i\omega}{2}\dot{\rho}^2\right) - \frac{1}{4}\hat{q}(x)\rho^2\right\}\right]$$

$$\xrightarrow[\omega\to\infty]{} \exp\left[-\frac{1}{4\sqrt{2}}\hat{q} L_- \rho^2\right] \equiv \left\langle Tr\left[W^{A+}(0)\, W^{A}(\rho)\right]\right\rangle_{tar}$$

BDMPS transport coefficient

- only medium-dependent quantity
- characterizes short transverse distance behavior of Wilson loop

Quenching parameter from QCD pert. modelling

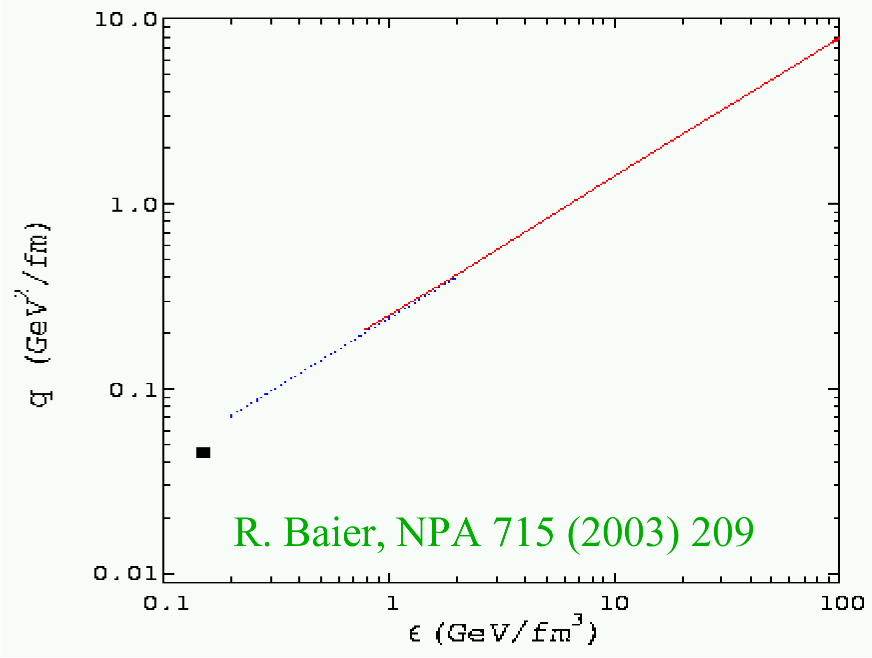
(estimates not based on calculations from Wilson loops)

$$\hat{q} \sim \frac{m^2_{Debye}}{\lambda_{mfp}}$$

$$\mu n_{scatterers}$$

$$» 3.1 \alpha_s^2 N_c^2 T^3$$

$$» 0.9 \frac{GeV^2}{fm}$$

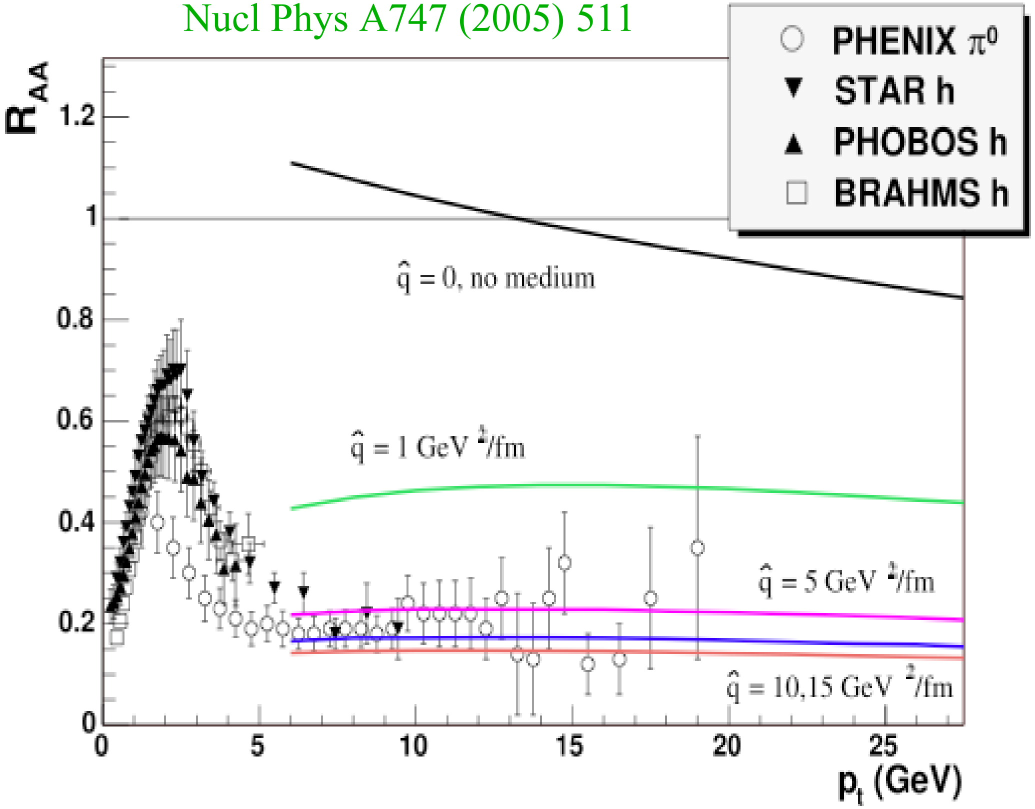


(for $\alpha_s = 1/2, N_c = 3, T = 300$ MeV)

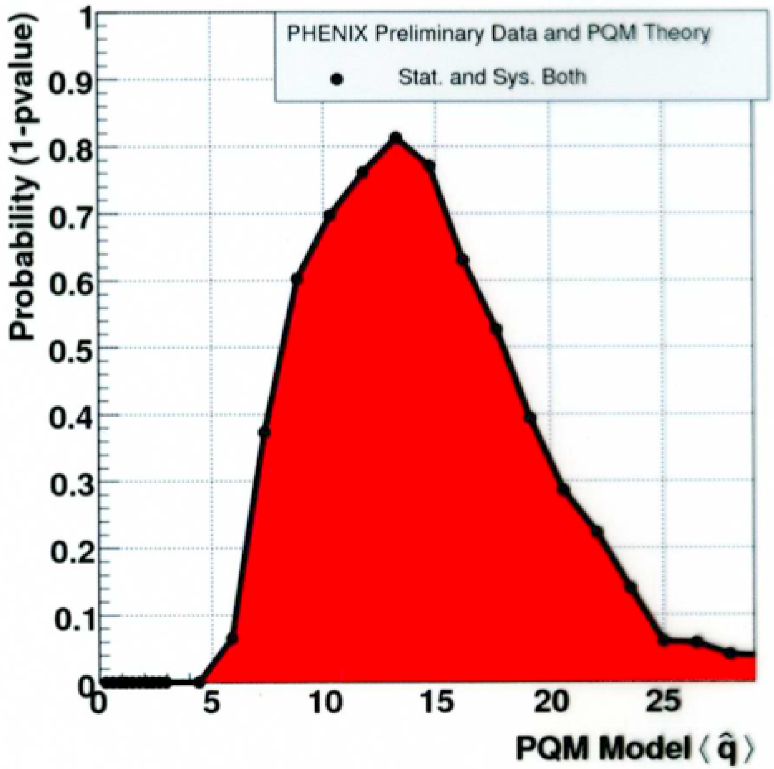
Can we compare such estimates with strong coupling calculations?

Quenching parameter from HI phenomenology

Eskola, Honkanen, Salgado, Wiedemann
Nucl Phys A747 (2005) 511

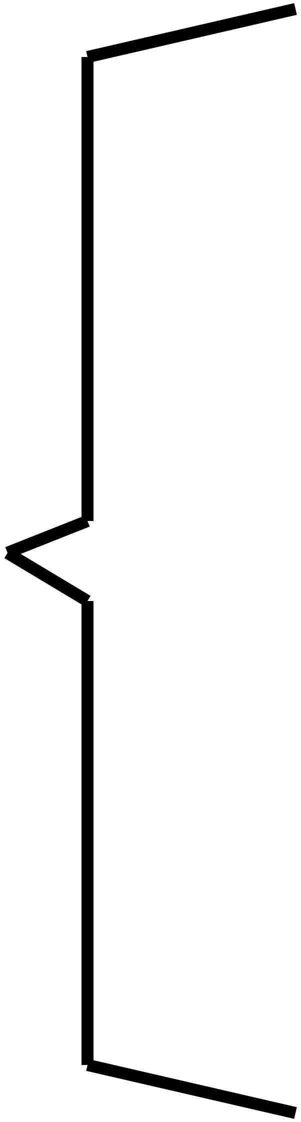


PHENIX Coll, 2006



$$\hat{q}(t=1\ fm/c) > 5\frac{GeV^2}{fm}$$

Can such a large value arise for a medium (in a thermal QFT), which displays a single momentum scale, T~300 MeV say?



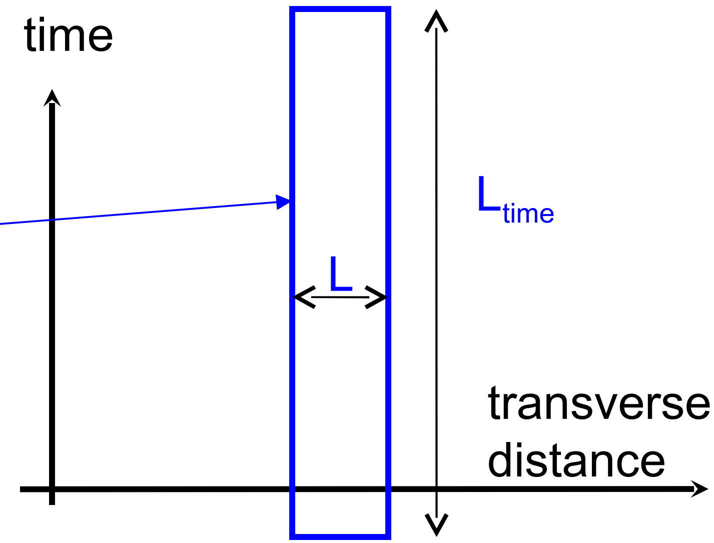
Static quark-antiquark potential E(L)

- For $L_{time} \to$ ¥ define a static quark-antiquark potential

$$W(C) = \frac{1}{N} Tr\left[P \exp\left(i \oint_C A \right) \right]$$

$$\langle W(C) \rangle_T \, \mu \exp\left(-i L_{time} \left(E(L) - E_{ren} \right) \right)$$

Exponent is imaginary

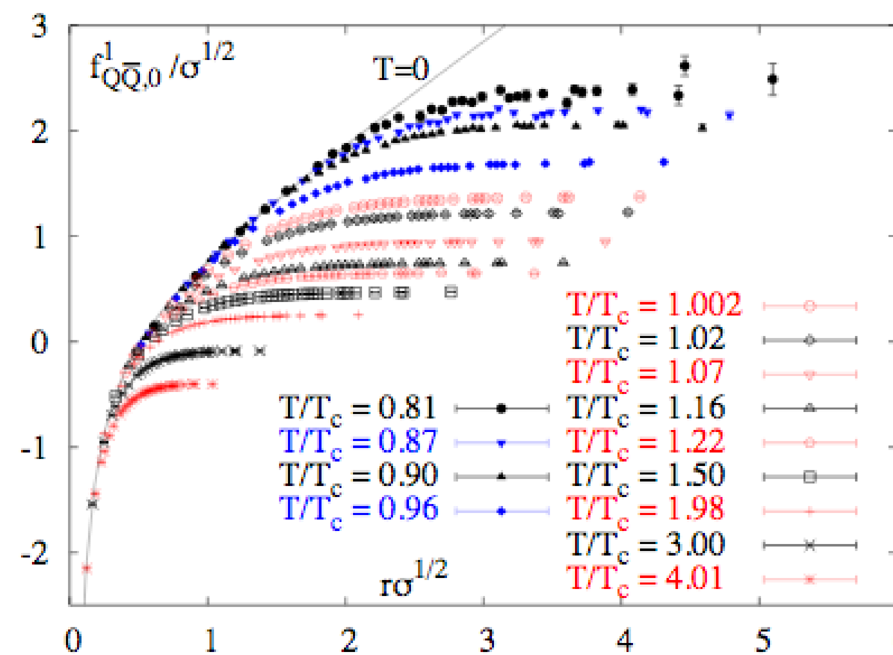


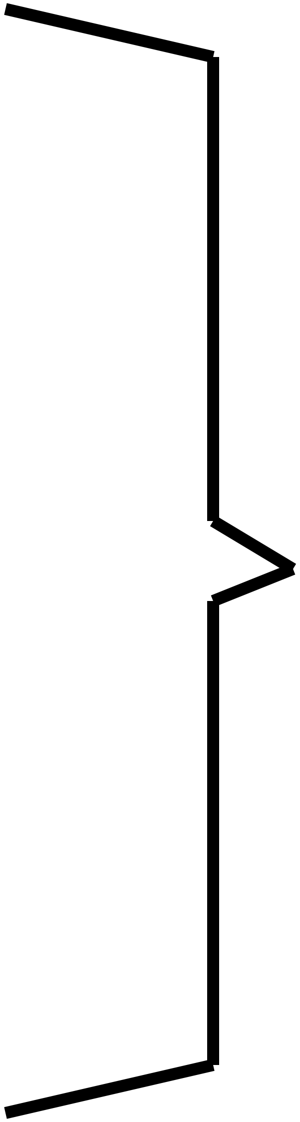
- Recall: quenching parameter sits in **real** exponent

$$\langle W\left(C_{light-like} \right) \rangle \, ^o \exp\left[-\frac{1}{4\sqrt{2}} \hat{q} \, L\_ \, r^2 \right]$$

- The T-dependence of E(L) has been studied in lattice QCD.

Bielefeld Group, hep-lat/0509001





Why turn to AdS/CFT?

- Coupling constant is large for many aspects of heavy ion collisions

$$\alpha_s\left(T_{typ}\right)=\frac{g^2}{4p}\sim 0.5\Rightarrow g^2 N_c=\lambda\sim 20$$

Large t'Hooft coupling seems a good starting point.

Perturbation theory unreliable: $h\sim T^3/g^2\log\left[1/g\right]$ Shear viscosity

$$\hat{q}^{fitted}_{RHIC}\gg\hat{q}_{pert}\sim g^4$$

- Problems involve real-time dynamics

  - imaginary time formalism can be analytically continued but smallest Matsubara frequency is already $2pT$, whereas hydrodynamic limit requires $w\rightarrow 0$

  - lattice techniques are difficult to apply to
    - moving QQbar pairs
    - light-like Wilson lines
    - spectral functions

AdS/CFT correspondence

Maldacena; Witten; Gubser Klebanov Polyakov; ….

N=4 SYM theory

1 gauge field
4 Weyl fermions
6 real scalars
all in adjoint rep

Vanishing beta-function
Two dim-less parameters

$$g^2, N_c$$

Type IIB string theory

Two dim-less parameters:
String coupling and string length

$$g_s, \alpha' = l_s^2$$

Type IIB SUGRA lives in 10-dim space:

$$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\vec{x}^2\right) + \frac{R^2}{r^2} dr^2 + R^2 d\Omega_5^2$$

$$g^2 = 4\pi g_s$$

$$\lambda \equiv \sqrt{g^2 N_c} = \frac{R^2}{\alpha'}$$

For $\lambda \gg 1, g^2$ small, calculating correlation functions is a classical problem

$$Z_{4D}[J] = \exp\left[iS\left[f_{cl}\right]\right] \qquad \lim_{r\to\infty}\left(\frac{r}{R^2}\right)^{\Delta} f_{cl}(r, x) = J(x)$$

Wilson loops from AdS/CFT

- Finite temperature N=4 SYM dual to AdS_5 Schwarzschild black hole:

$$ds^2 = -\frac{1}{2} f\, dt^2 + \frac{r^2}{R^2}\left(dx_1^2 + dx_2^2 + dx_3^2\right) + \frac{1}{f} dr^2 \qquad f \equiv \frac{r^2}{R^2}\left(1 - \frac{r_0^4}{r^4}\right)$$

- Translation into field theoretic quantities:

Hawking temperature is QGP temperature $\quad T_H = \frac{r_0}{\pi R^2} = T$

String tension $\quad 1/4\pi\alpha'$

determines t'Hooft coupling $\quad \lambda \equiv g_{SYM}^2 N \qquad \frac{R^2}{\alpha'} = \sqrt{\lambda}$

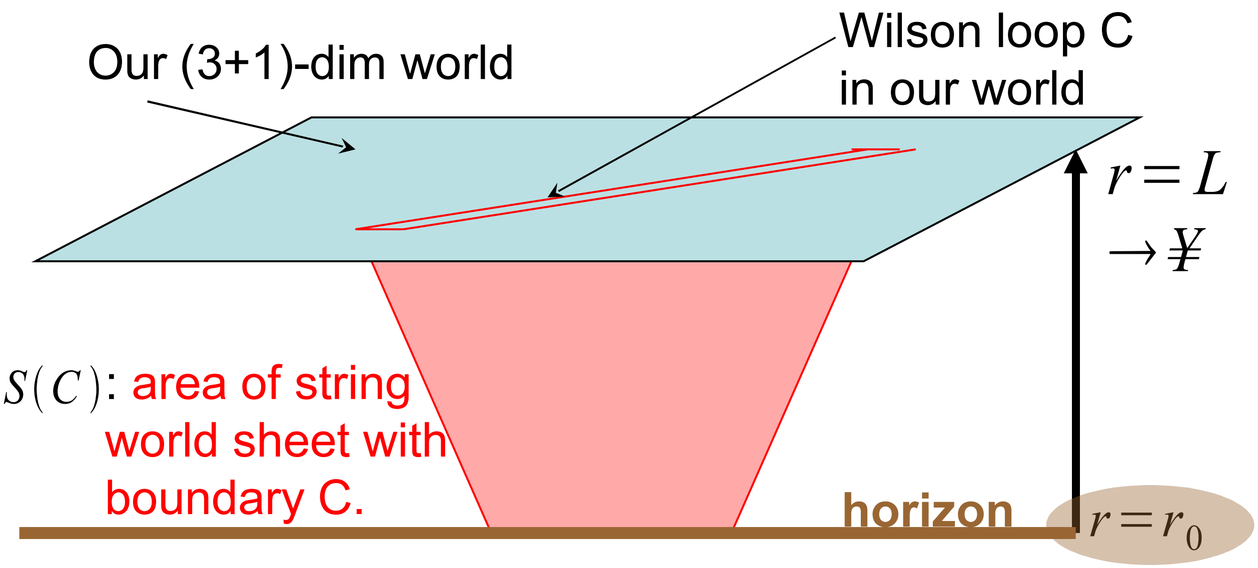
Black hole horizon

Curvature radius

- AdS/CFT - Recipe

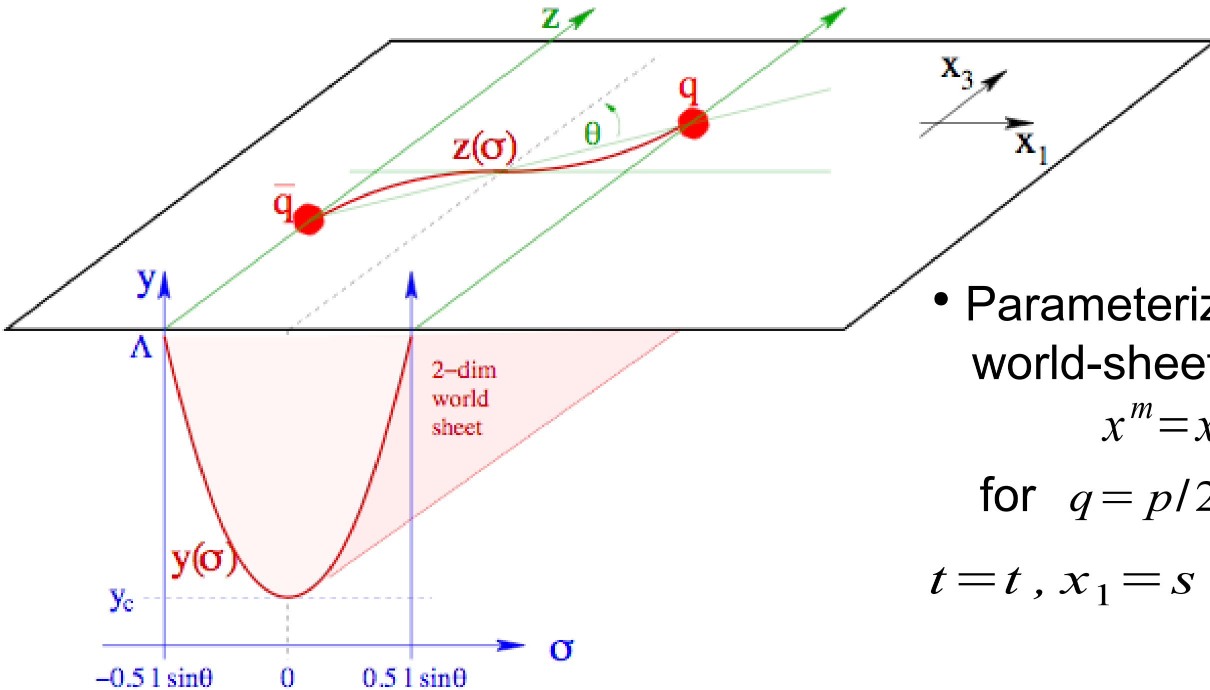
Maldacena; Witten; Gubser Klebanov Polyakov; Rey Lee

$$\langle W^F(C)\rangle_T \equiv \exp\left[iS(C)\right]$$



Calculating the loop in boosted metric

Hong Liu, Rajagopal, UAW



- Parameterization of two-dimensional world-sheet bounded by *C:*

$$x^m = x^m(s,t),\ m = t, 1, 2, 3, r$$

for $q = p/2$

$$t = t,\ x_1 = s \qquad x_2 = const.,\ x_3 = const.$$

$$r^o r_0 y(s)$$

Nambu-Goto action: $S(C) = \frac{1}{4p\alpha'}\int dsdt\sqrt{\det g_{\alpha\beta}} = \sqrt{\lambda}\, TL_{time}\int_0^{l/2} dsL$

Boundary condition: $y\left(\pm\frac{L}{2}\right) = L,\ r^o r_0 y$ $\qquad x_1\left(\pm\frac{L}{2}\right) = \pm\frac{L}{2}$

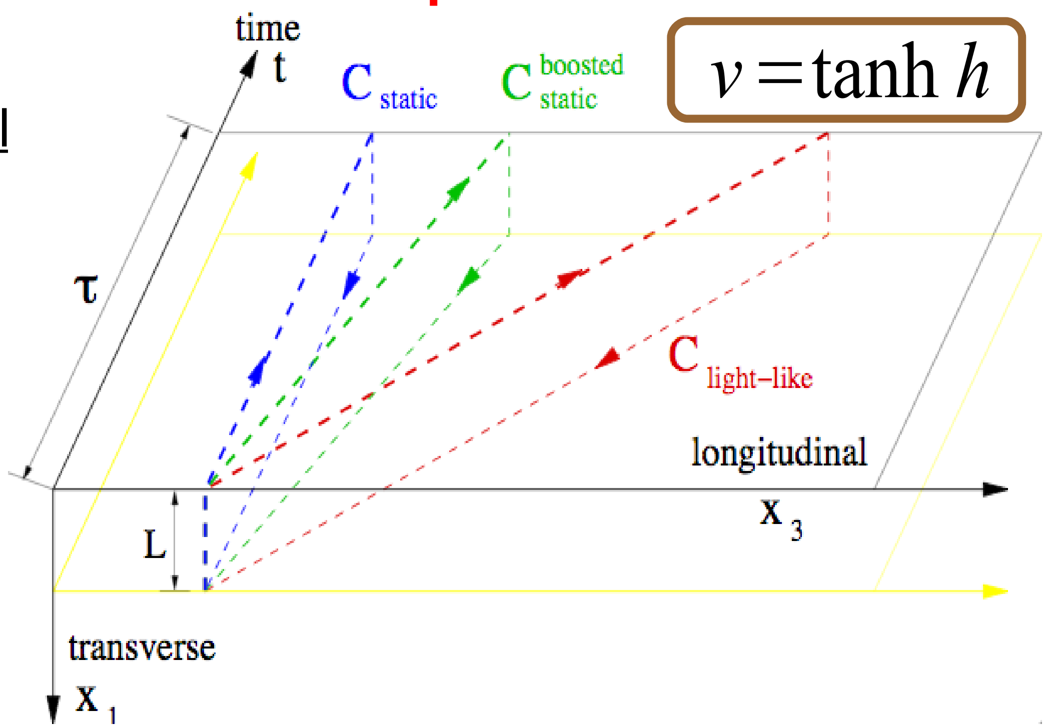
Our task: find catenary

Time-like vs. space-like world sheet

Boosted Q-Qbar potential

$$h = const.$$
$$L \to ¥$$

$$v = \tanh h$$



Light-like Wilson loop

$$h \to ¥,$$
$$L \to ¥$$

(ordered limit)

Time-like world sheet: $\sqrt{\cosh h} < L$

$$y_c^4 = \cosh^2 h + q^2$$

$$S(l) = \sqrt{\lambda}\, T L_{time} \int_1^L dy \frac{y^4 - \cosh^2 h}{\left(y^4 - 1\right)\left(y_c^4 - q^4\right)}$$

$$l = 2q^2 \int_{y_c}^L dy \frac{1}{\sqrt{\left(y^4 - y_c^4\right)\left(y^4 - 1\right)}}$$

Space-like world sheet: $\sqrt{\cosh h} > L$

$$y_m^4 = \cosh^2 h - q^2$$

$$S(l) = i\sqrt{\lambda}\, T L_{time} \int_1^L dy \frac{\cosh^2 h - y^4}{\left(y^4 - 1\right)\left(y_m^4 - q^4\right)}$$

$$l = 2q^2 \int_1^L dy \frac{1}{\sqrt{\left(y^4 - 1\right)\left(y_m^4 - q^4\right)}}$$

action

length

Results for quenching parameter

- The quenching parameter
$$\langle W^A(C_{light-like})\rangle = \exp\left[-\frac{1}{4}\hat{q}\frac{L^-}{\sqrt{2}}L^2\right]$$
$$¿\exp\left[i2S(C_{light-like})\right]$$

  - use: $\langle W^A(C_{light-like})\rangle » \langle W^F(C_{light-like})\rangle^2$

  - consider ordered limit: $h \to ¥\,,\ L \to ¥$

  - expand S(*C*) for small L:

$$\hat{q}_{SYM} = \frac{p^{3/2}G\left(\frac{3}{4}\right)}{G\left(\frac{5}{4}\right)}\sqrt{\lambda}\,T^3 » 26.68\sqrt{\alpha_{SYM}N_c}\,T^3$$

Liu, Rajagopal, UAW

N=4 SYM Numerology

- In QGP of QCD, parton energy loss described perturbatively up to non-perturbative quenching parameter.
- We calculate quenching parameter in N=4 SYM (not necessarily a calculation of full energy loss of SYM)

$$\hat{q}_{SYM} = \frac{p^{3/2} G\left(\frac{3}{4}\right)}{G\left(\frac{5}{4}\right)} \sqrt{\lambda}\, T^3 \text{ » } 26.68 \sqrt{\alpha_{SYM} N_c}\, T^3$$

- If we relate *N*=4 SYM to QCD by fixing $N_c = 3$ $\alpha_{SYM} = 1/2$

$\hat{q}_{SYM} = 4.4 \frac{GeV^2}{fm}$ for T = 300 MeV

$\hat{q}_{SYM} = 10.6 \frac{GeV^2}{fm}$ for T = 400 MeV

This is close to values from experimental fits.

Is this comparison meaningful?

Comment on: Is comparison meaningful?

N=4 SYM theory

- conformal
- no asmptotic freedom
  no confinement
- supersymmetric
- no chiral condensate
- no dynamical quarks, 6 scalar and 4 Weyl fermionic fields in adjoint representation

Physics near vacuum and at very high energy is very different from that of QCD

At finite temperature: Is comparison meaningful?

N=4 SYM theory at finite T	QCD at T ~ few x T_c
• conformal	• near conformal (lattice)
• no asymptotic freedom no confinement	• not intrinsic properties of QGP at strong coupling
• supersymmetric (badly broken)	• not present
• no chiral condensate	• not present
• no dynamical quarks, 6 scalar and 4 Weyl fermionic fields in adjoint representation	• may be taken care of by proper normalization

Explore systematics beyond N=4 SYM

- General CFTs with gravity dual: (large N and strong coupling) $\Omega = 1$

$$\frac{\hat{q}_{CFT}}{\hat{q}_{N=4}} = \sqrt{\frac{a_{CFT}}{a_{N=4}}} = \sqrt{\frac{s_{CFT}}{s_{N=4}}}$$

Liu, Rajagopal, UAW

a central charge
s entropy

- Near conformal theories: corrections small

$$\hat{q} \propto \left(1 - 3.12\left(\tfrac{1}{3} - v_s^2\right)\right)$$

Buchel,

- Finite coupling and N_c corrections: hard

Armesto, Edelstein, Mas

- R-charge chemical potentials:

Corrections small when chemical potentials small

Avramis, Sfetsos;
Armesto, Edelstein, Mas;
Lin, Matsuo; …

What if quark is ‘dragged’ through *N*=4 SYM medium?

- Apply force to maintain momentum p of quark

$$\dot{p} = -mp + F = 0$$

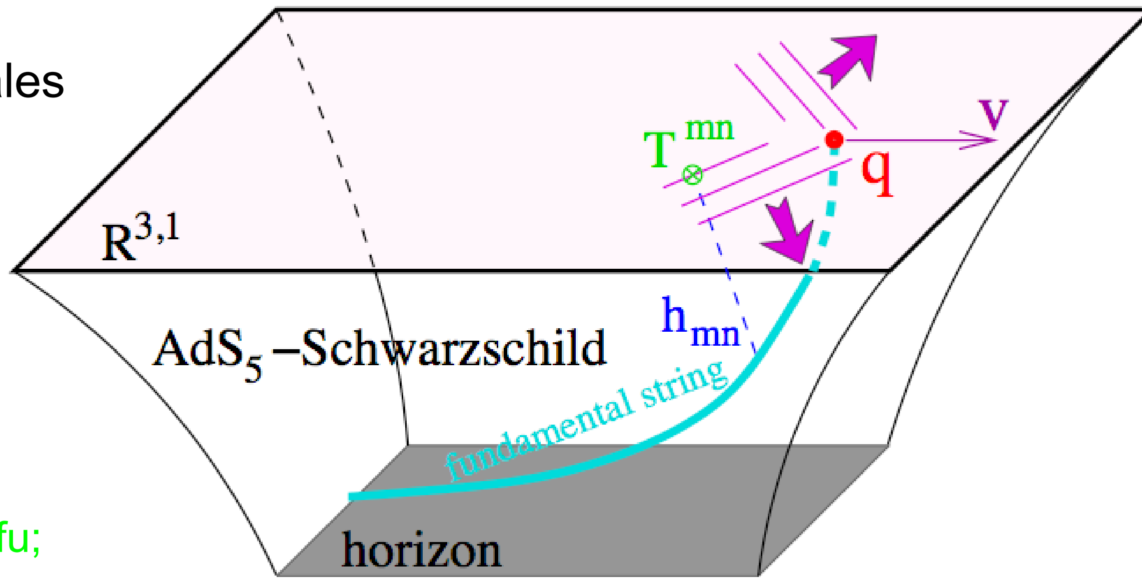
Herzog, Karch, Kovtun, Kozcaz, Yaffe; S. Gubser; Casalderrey-Solana Teaney

- Different from QCD quenching: since strongly coupled on all scales (divergence for v-> 1)

$$\frac{dE_q}{dx} = \frac{p}{2}\sqrt{\lambda}\,T^2 \frac{v}{\sqrt{1-v^2}}$$

Now, lost energy dissipates in **hydrodynamic modes** (Mach cone)

Fries, Gubser, Michalogiorgakis, Pufu; Gubser, Pufu, Yarom; …



- Range of validity of this picture set by Schwinger mechanism

$$F_{crit} \mu \frac{M^2}{\sqrt{\lambda}} \Rightarrow \sqrt{\cosh h} < L$$

Kinematic range does not overlap with that of quenching calculation

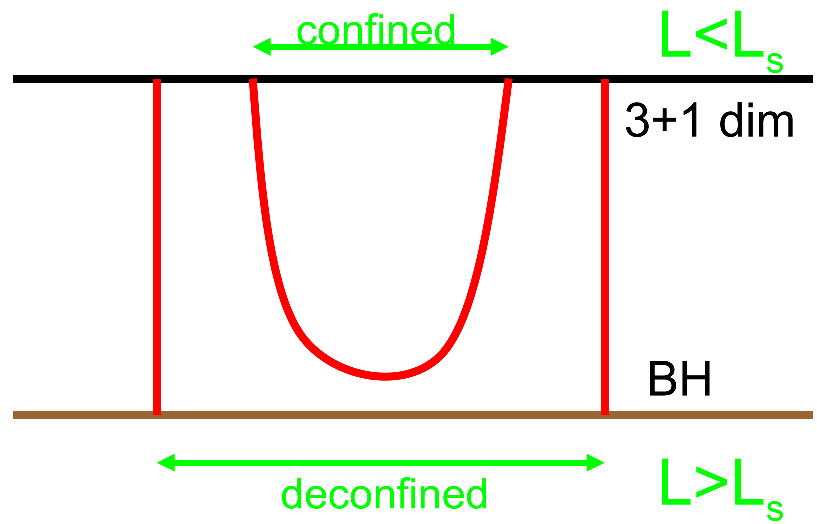
Deconfinement at T>0

- Does the Q-Qbar bound state survive?

  Maldacena; Rey Theisen Yee; Brandhuber
  Itzhaki Sonnenschein Yankielowicz

  - For $L<L_s$: force binds Q and Qbar
  - For $L>L_s$: force is screened
  - For N=4 SYM

$$L_s = \frac{0.277}{T}$$



- The boosted Q-Qbar static potential

  Hong Liu, Rajagopal UAW; Peeters et al;
  Chernicoff et al; Caceres et al; Avramis
  Sfetsos, ..

$$L_s(v,T) = \frac{f(v)}{\pi T}\left(1-v^2\right)^{1/4} \approx L_s(0,T)/\sqrt{\gamma}$$

f depends weakly on η, θ

Suggests that dissociation temperature for bound states,

$$T_{diss}(v) \approx T_{diss}(0)/\sqrt{\gamma}$$

reduced for bound states at high pt.

Towards 'realistic' mesons

- Does velocity-scaling of dissociation temperature persist for realistic mesons?

  - Introduce heavy fundamental quarks (add N_f D7-branes with $N_f << N_c$)

    Karch Katz

  - study 'quarkonia' meson bound states, which dissociate above T_{diss}

    Babington Erdmenger Evans Guralnik Kirsch; Kruczenski Mateos Myers Winters; …

  - study dispersion relation describing moving mesons, analyze

    $$v_{\max}(T) \Leftrightarrow T_{diss}(v)$$

    Ejaz Faulkner Liu Rajagopal UAW, in progress

Confirm that for each T, mesons have a speed limit

$$T_{diss}(v) \cong f(v)\, T_{diss}(0)/\sqrt{\gamma}$$

f depends weakly on η

THANKS

Hong Liu
Krishna Rajagopal

Qudsia Jabeen Ejaz
Thomas Faulkner

THE END
of this talk

- Many chapters on comparing AdS/CFT to QCD written already

  In thermal sector:

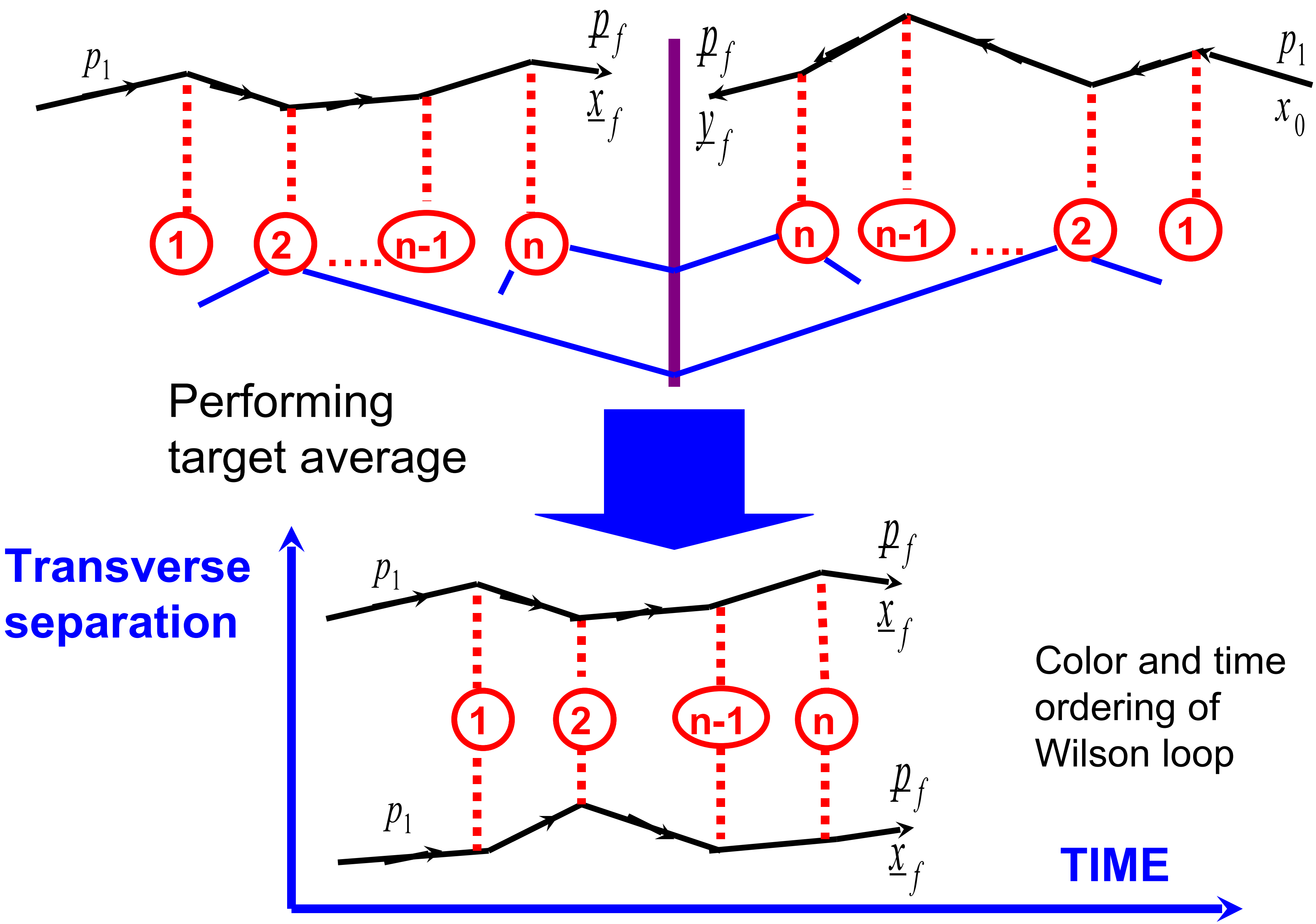
  - Shear viscosity in QCD
  - diffusion constants
  - thermal spectral functions
  - quenching
  - drag
  - quark-antiquark static potential
  - …

- 'Comparison' neither straightforward nor obviously far-fetched
  - rich testing ground for understanding non-perturbative properties of non-abelian thermal gauge field theories

- Many chapters to be written …

BACK-UP

Wilson loops from BDMPS



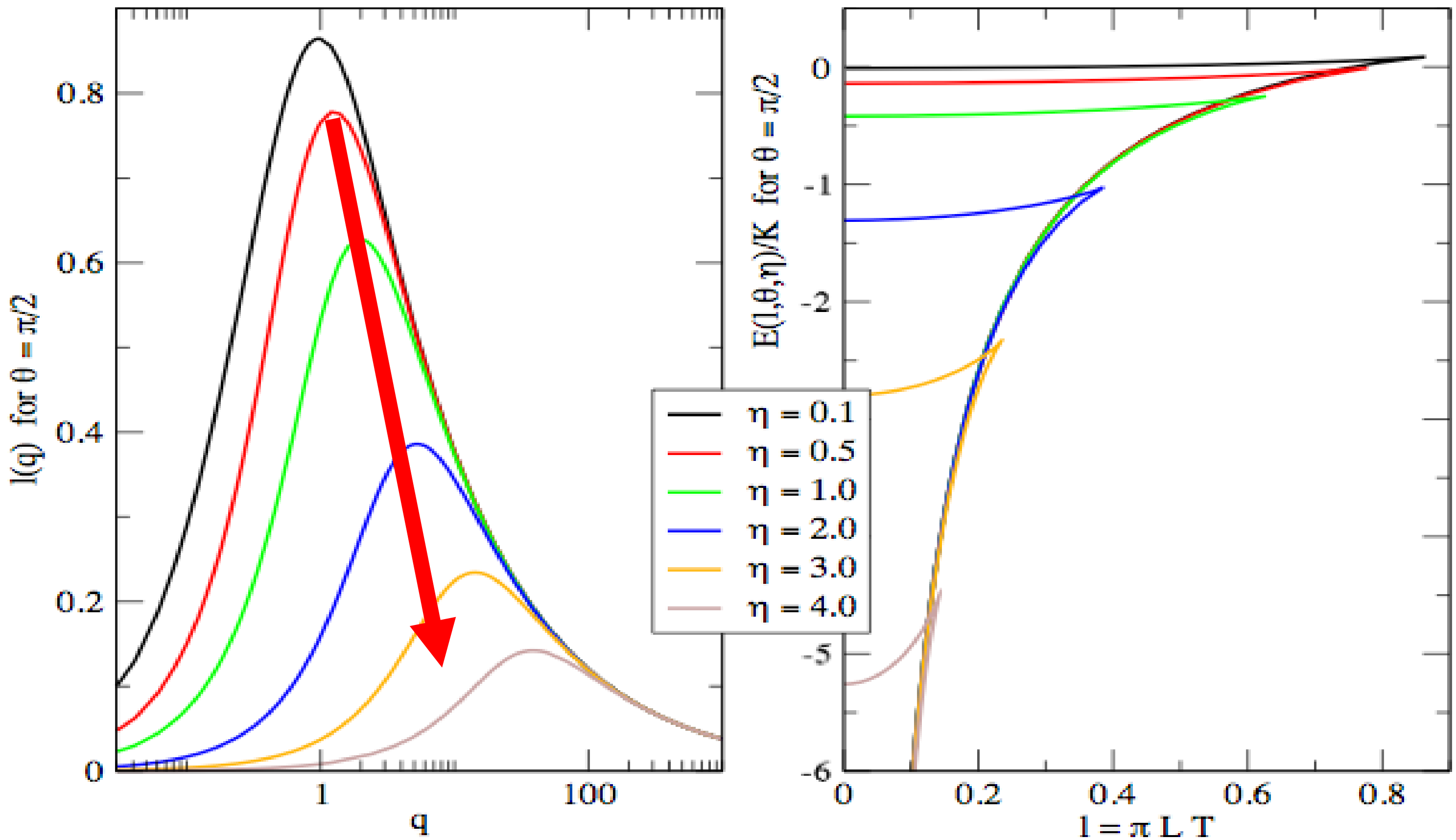
Color and time ordering of Wilson loop

Velocity scaling of static potential

$$l_{\max} = \frac{\sqrt{2p}\, G\left(\frac{3}{4}\right)}{3^{3/4}\, G\left(\frac{1}{4}\right)} \left(\frac{2}{\cosh^{1/2} h} + O\left(\frac{1}{\cosh^{5/2} h}\right)\right)$$

$$L_{\max} = \frac{f(h,q)}{pT\sqrt{\cosh h}}$$

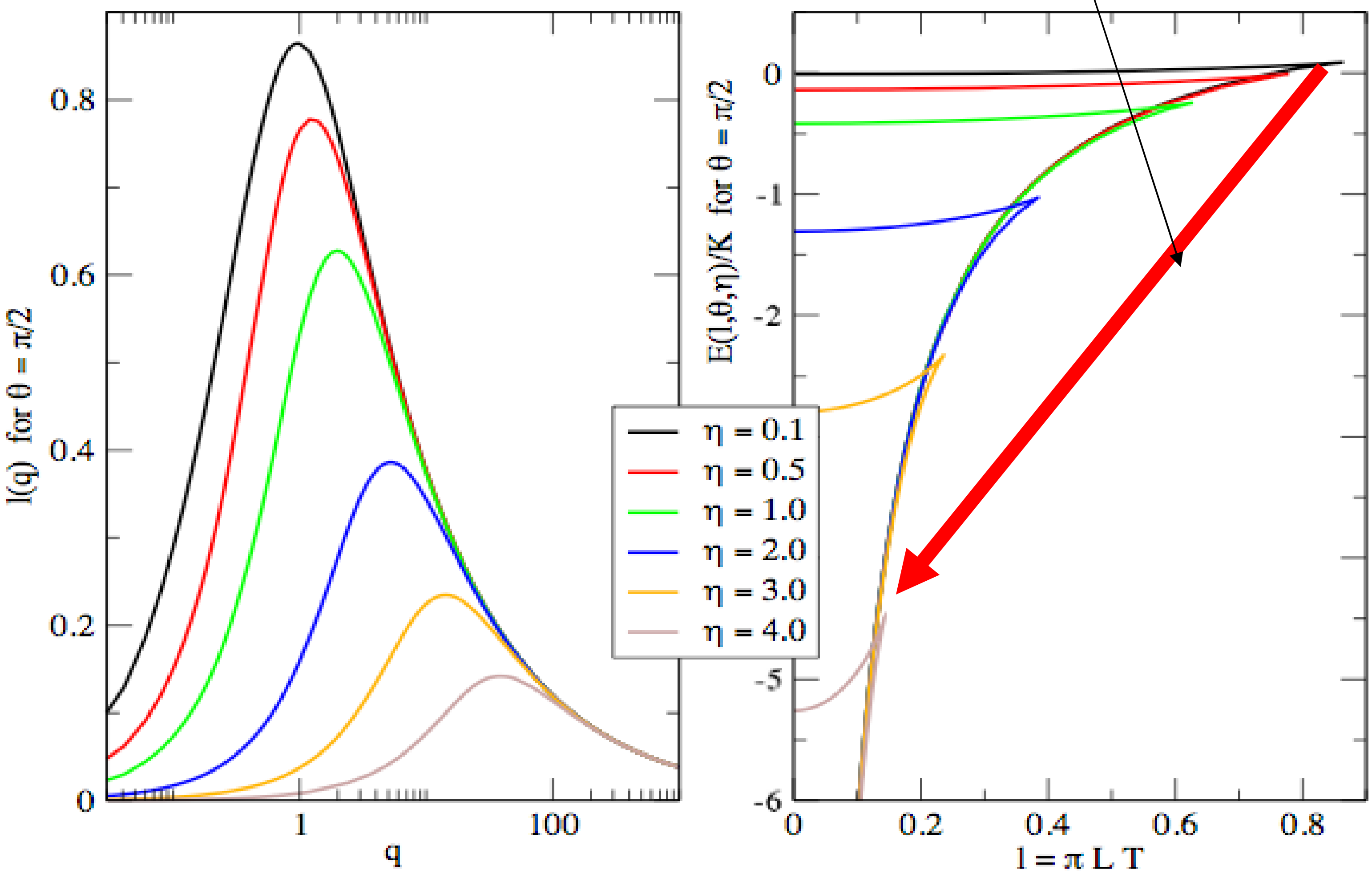
f depends weakly on h, q



Consequences for pt-dependence of quarkonkium suppression at the LHC?

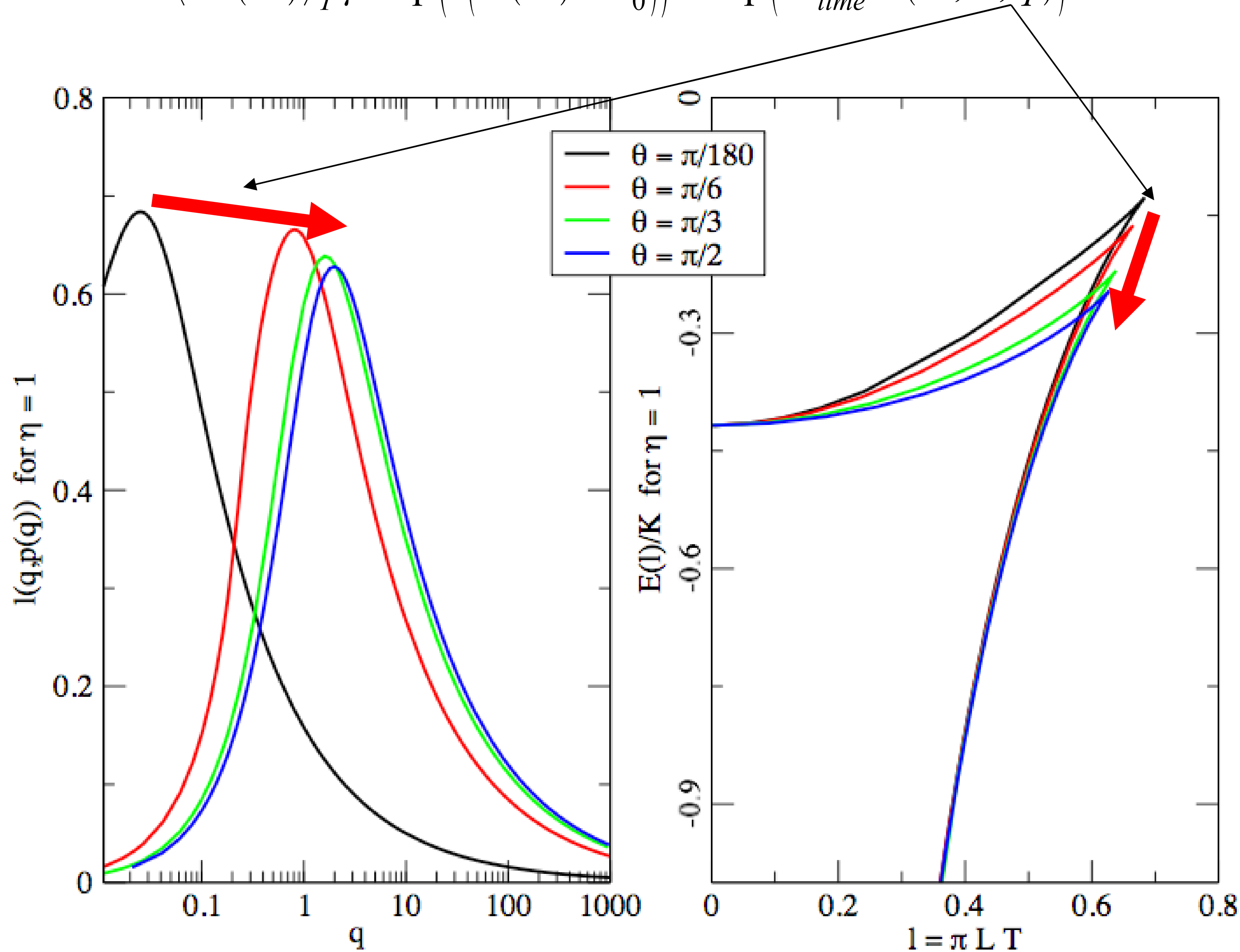
Quark-antiquark static potential

$$\langle W(C)\rangle_T \, \mu \exp\left(i\left(S(L)-S_0\right)\right)=\exp\left(iL_{time}E(L,h,q)\right)$$



Quark-antiquark static potential - angular dep.

$$\langle W(C)\rangle_T \,\mu \exp\left(i\left(S(L)-S_0\right)\right)=\exp\left(iL_{time}E(L,h,q)\right)$$



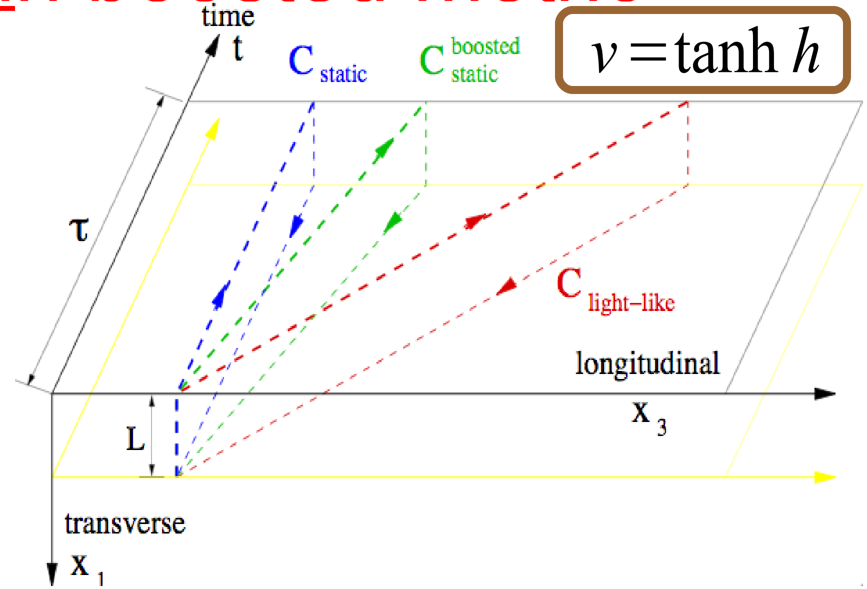
Calculating the loop in boosted metric

- AdS BH metric boosted in x_3-direction:

$$ds^2 = -A\,dt^2 + 2B\,dt\,dx_3 + C\,dx_3^2 + \frac{r^2}{R^2}\left(dx_1^2 + dx_2^2\right) + \frac{1}{f}\,dr^2$$

$$A = \frac{r^2}{R^2}\left(1 - \frac{r_1^2}{r^4}\right),\ B = \frac{r_1^2 r_2^2}{r^2 R^2},\ C = \frac{r^2}{R^2}\left(1 - \frac{r_2^2}{r^4}\right)$$

$$r_1^4 = r_0^4 \cosh^2 h,\ r_2^4 = r_0^4 \sinh^2 h$$



- Parameterization of two-dimensional world-sheet bounded by *C*: $x^m = x^m(s,t)$, $m = t, 1, 2, 3, r$

$$t = t,\ x_1 = s \qquad x_2 = const.,\ x_3 = const. \qquad r = r(s)$$

Nambu-Goto action: $S(C) = \frac{1}{4p\alpha'}\int dsdt\sqrt{\det g_{\alpha\beta}} = \sqrt{\lambda}\,TL_{time}\int_0^{l/2} dsL$

Boundary condition: $y\left(\pm\frac{L}{2}\right) = L,\ r^o r_0\, y$ $\qquad x_1\left(\pm\frac{L}{2}\right) = \pm\frac{L}{2}$

Our task: find catenary