QGP vs. AdS/CFT

Summer School on

AdS/CFT Correspondence and its Applications

Tihany, 24-28th August 2009

Gergely Gábor Barnaföldi

MTA KFKI RMKI

Summer School on AdS/CFT and its Applications

24-28 August 2009, Tihany

Organizers:

Z. Bajnok
G. Cynolter
L. Fehér

This talk summarise several works...

CAST

Heavy quark

B Betz, W Horowitz, M Gyulassy, P Lévai, J Norongha, G Torrieri (arXiv: 0807.1038) S Gubsen, H Liu, CP Herzog (arXiv: 0803.1470) Casalderrey-Solana, D Tenley, EV Shuryak, G Yaffe, F Dominguez, CM Mueller, B Wu, B-W Xiao (NP A811, 197, 2007), G. Beuf, CM Xiao BW Xiao (arXiv:08121051)

AdS/CFT

JM Maldacena, M Natsuume (hep-ph/0701201), E Witten

Jet quenching

A Bucher (hep-th/0605178), H Liu, K Rajagopal, UA Wiedemann (hep-ph/0605178)

More

RHIC experiments, hydro and bulk physics see: T. Csörgő's talk

OUTLINE

- Introduction to Heavy Ion Physics

    QGP and its signatures (Gral vs. swamp)

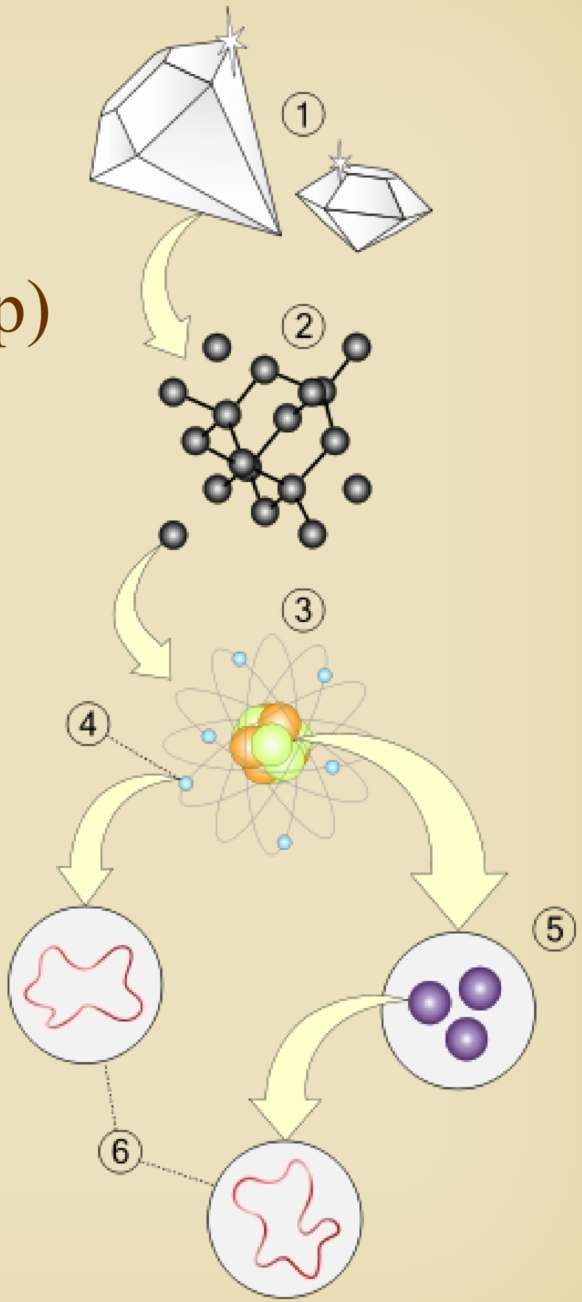
    Success of hard probes

    sQGP vs. wQGP

- Hard Probes with AdS/CFT

    Jet quenching (g/q energy loss)

    Heavy quarks energy loss

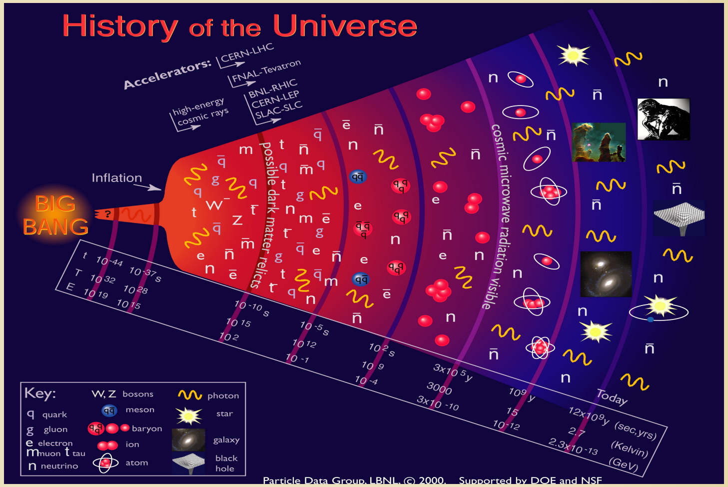


QGP signatures on the usual way...

- Introduction to Heavy Ion Physics

  Goal: create/analyze properties of primordial matter in laboratories.

  De-confinement: no direct observation

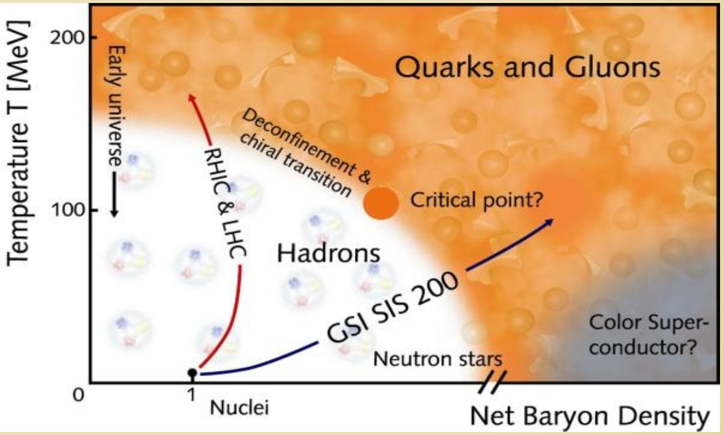


- Phases of strongly interacting matter

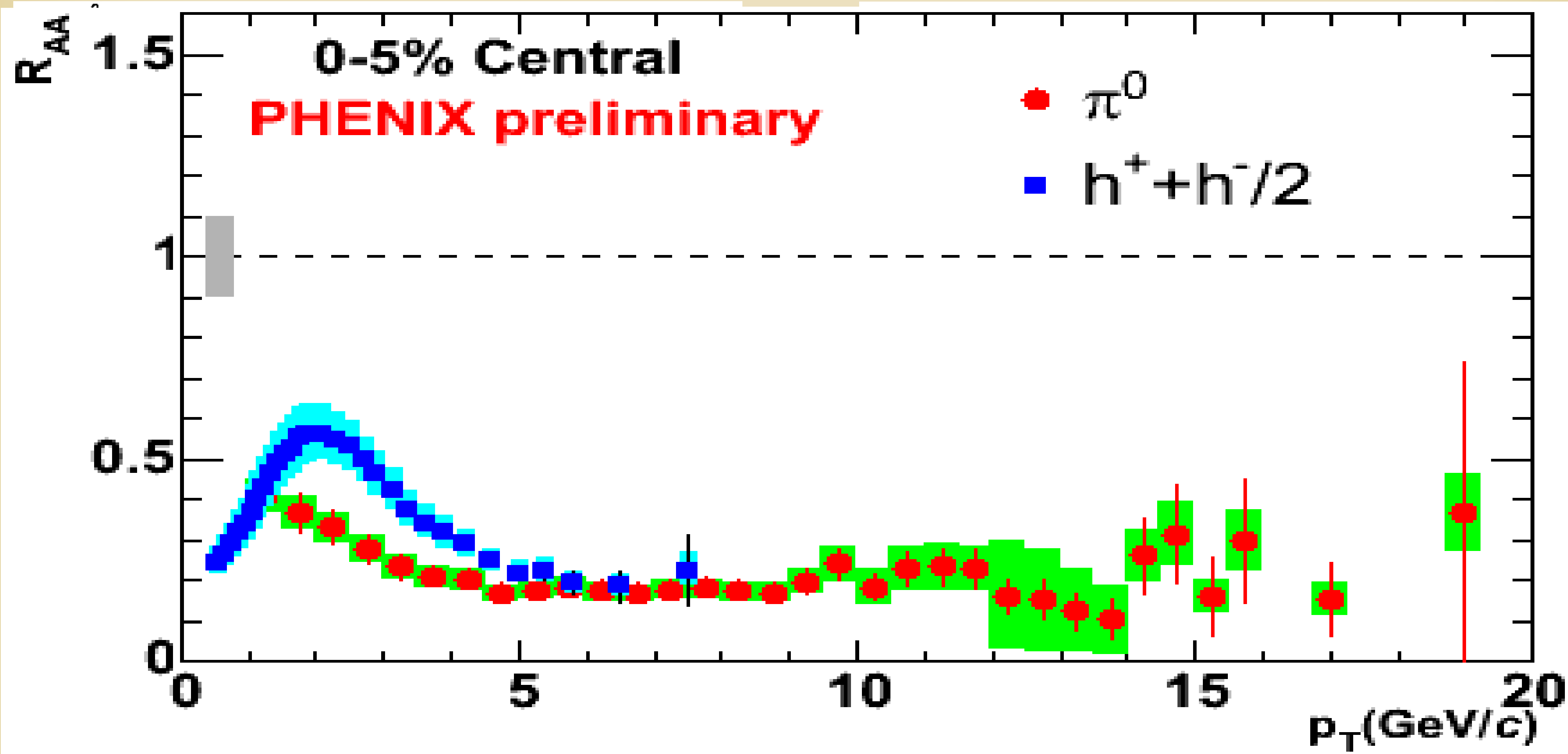
  Jet suppression (quark/gluon)

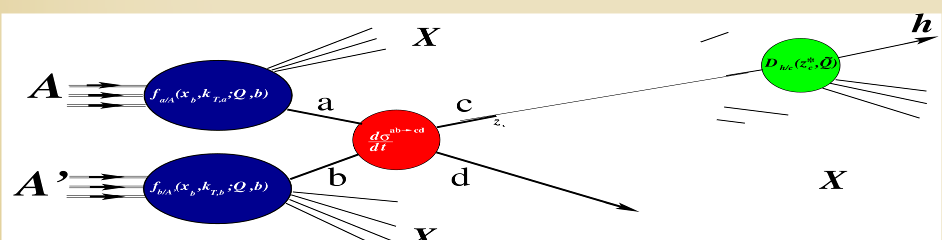
  Heavy quarks (quarkonia, R^{e}_{AA})

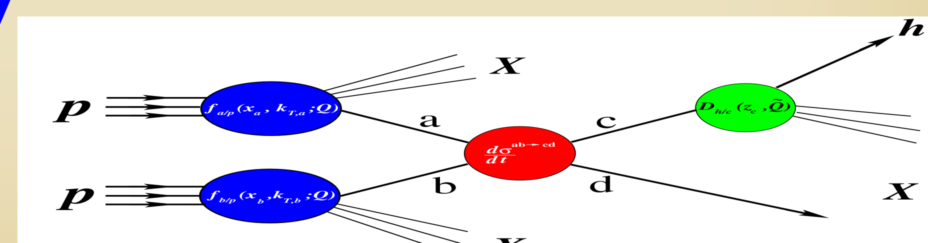
  Superfluidity, flow (collective)



$$R^h_{AA}(p_T) = \frac{1}{\langle N_{bin} \rangle} \cdot \frac{E_h \mathrm{d}\sigma_h^{AA} / \mathrm{d}^3 p_h}{E_h \mathrm{d}\sigma_h^{pp} / \mathrm{d}^3 p_h}$$



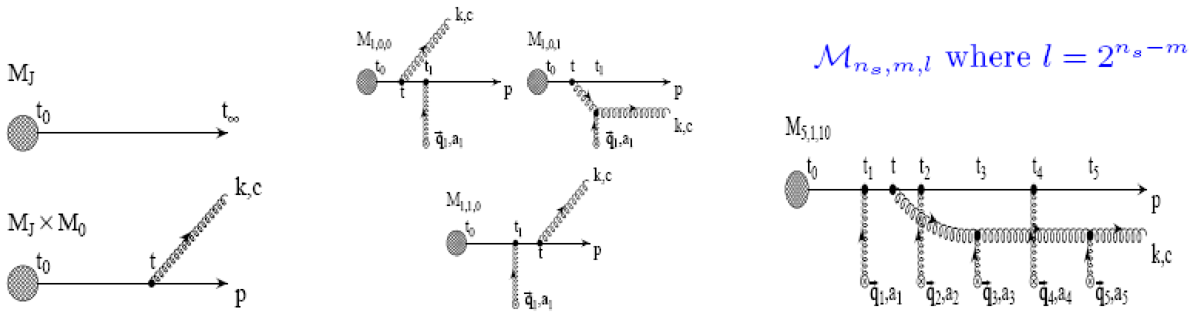




Jet Tomography (GLV)

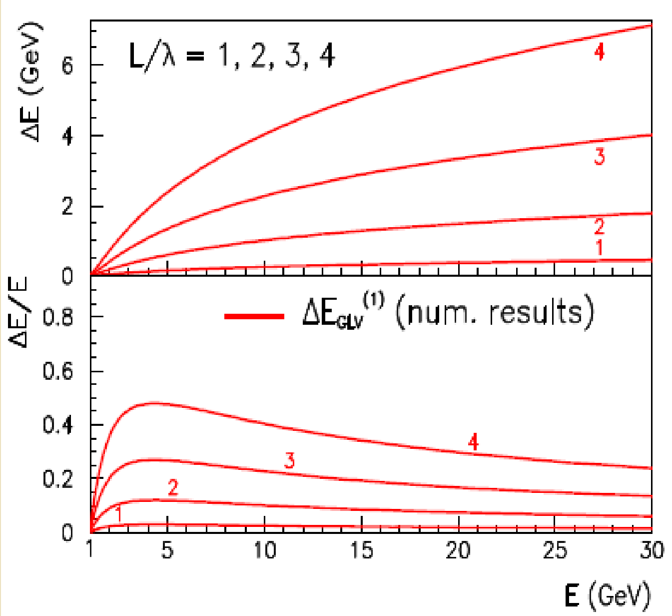
GLV: time-ordered pQCD (Feynman diagramms)
$+$ OPACITY expansion ($N = 1, 2, 3, \ldots$)
$+$ kinematical cuts

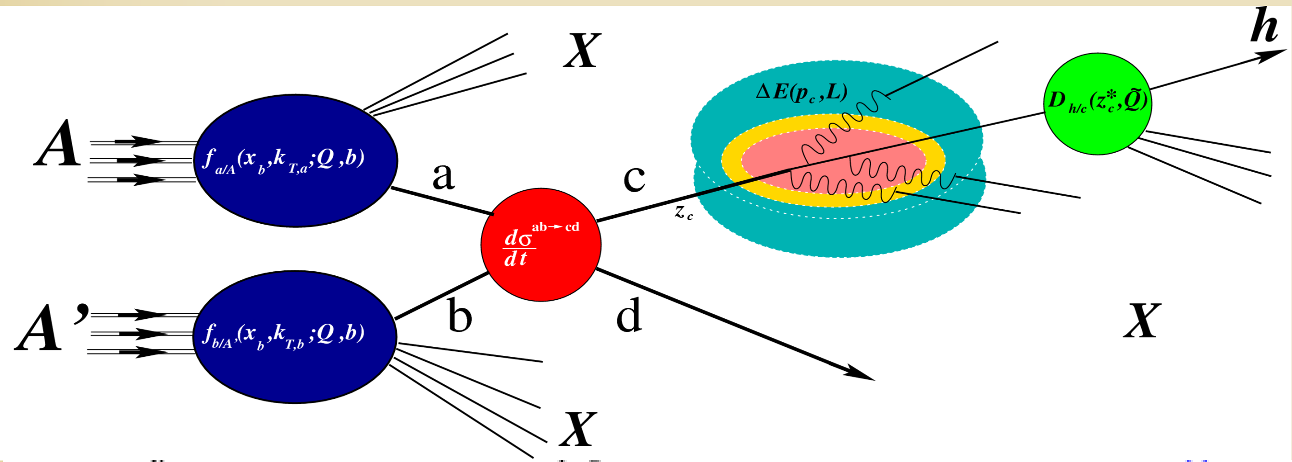
thin plasma: $L \sim \lambda_g$



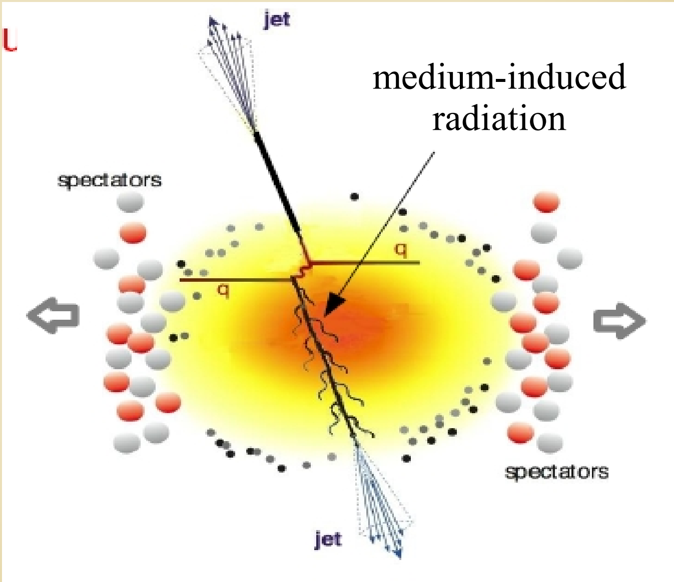
$\mathcal{M}_{n_s,m,l}$ where $l = 2^{n_s - m} - 1$

$$\Delta E_{GLV} \approx \frac{C_R \alpha_s}{N(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu} = \frac{C_R \alpha_s}{N(E)} \frac{1}{A_\perp} \frac{dN}{dy} \langle L \rangle \log \frac{E}{\langle \mu \rangle}$$





$$\frac{D_{\pi/c}(z_c, Q'^2)}{\pi z_c^2} \rightarrow \frac{z_c^*}{z_c} \frac{D_{\pi/c}(z_c^*, Q'^2)}{\pi z_c^2}, \quad \text{where} \quad z_c^* = \frac{z_c}{1 - \Delta E / p_c}$$



Discovery of Jet Quenching at RHIC and the Opacity of the Produced Gluon Plasma **(Quark Matter 2001)**

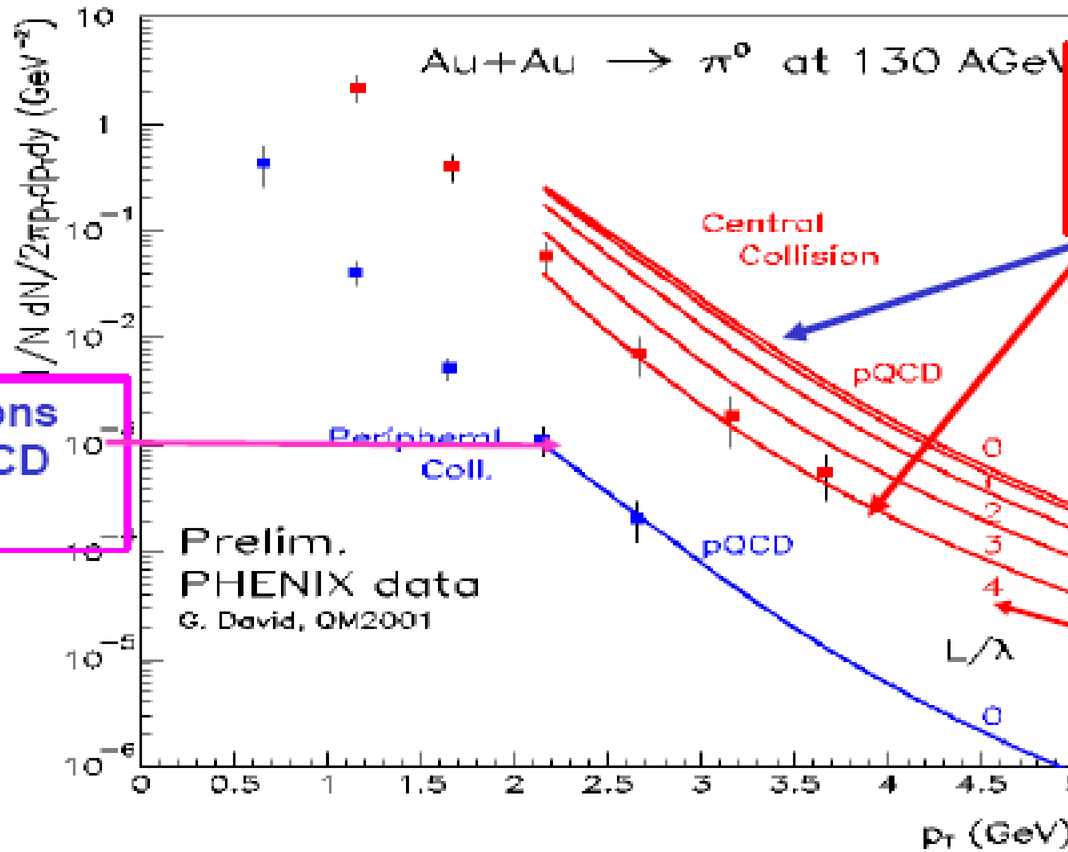
P. Lévai[a], G. Papp[b], G. Fai[c], M. Gyulassy[d], G.G. Barnaföldi[a], I. Vitev[d] and Y. Zhang[c a]

Jet quenching on hadron yields - 3

PHENIX prel. results at $\sqrt{s} = 130$ GeV G. David's talk

Periferial collisions (75-92 %; $< N_{coll} >= 5.5$)

Central collisions (10 %; $< N_{coll} >= 857$)



Central Collisions are Medium Modified (quenched high pT)

Peripheral Collisions Follow simple pQCD Binary T_{AA} scaling

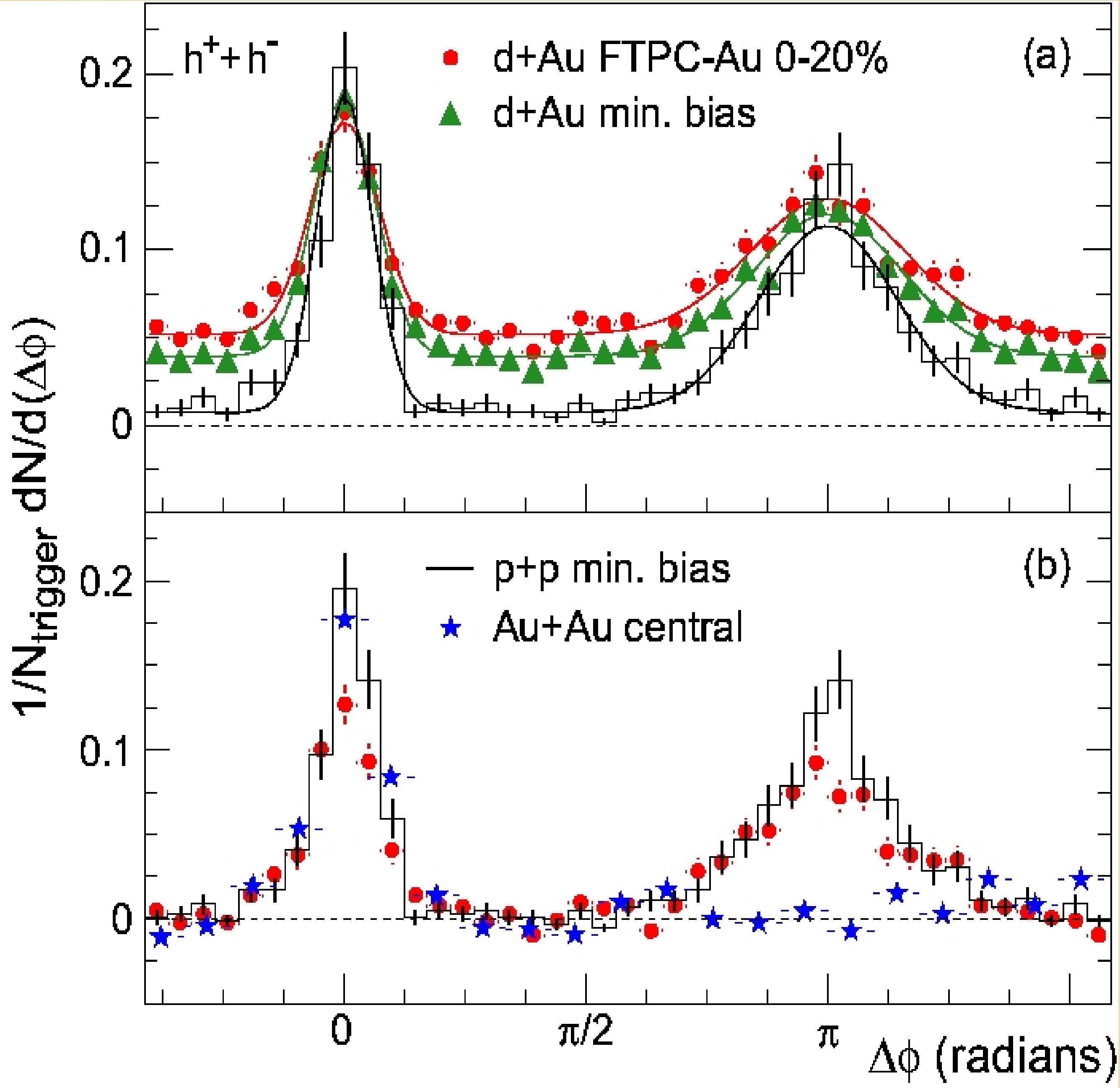
Data =>Moderate QGP Opacity

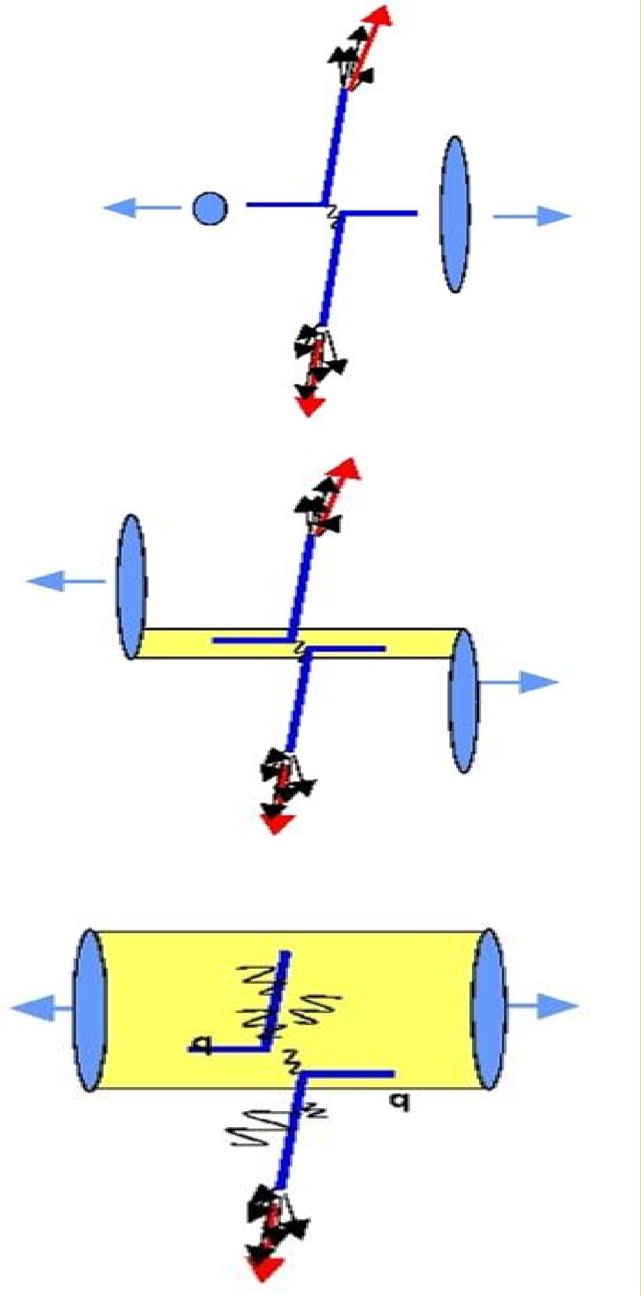
$n_{scat} = L/\lambda \approx 4$

$\Delta E_{GLV}/E_{jet} \approx 0.4$

via GLV/pQCD theory

QGP Signatures: Di-jet correlation





QGP – what have we found at RHIC?

Properties:

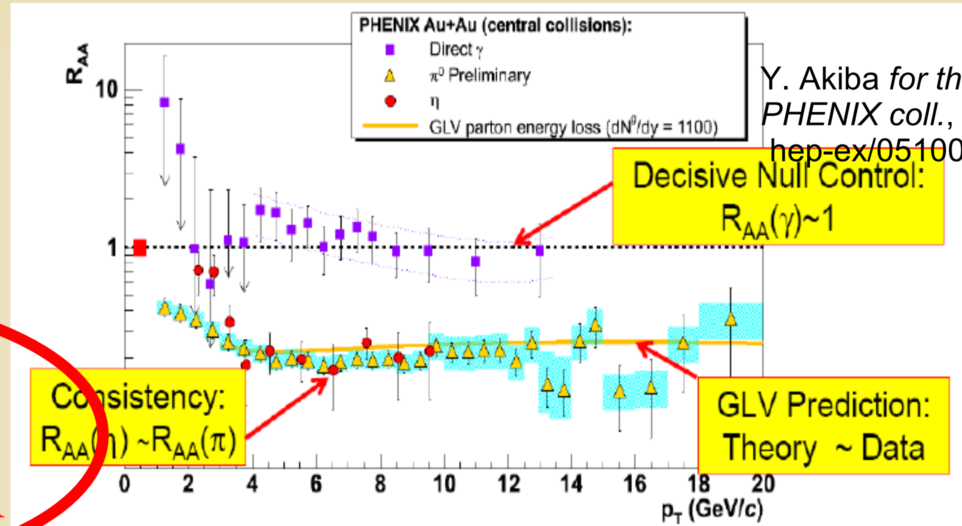
$dN/dy > 1000$

$\varepsilon = 1\text{-}10\,GeV/fm^3$

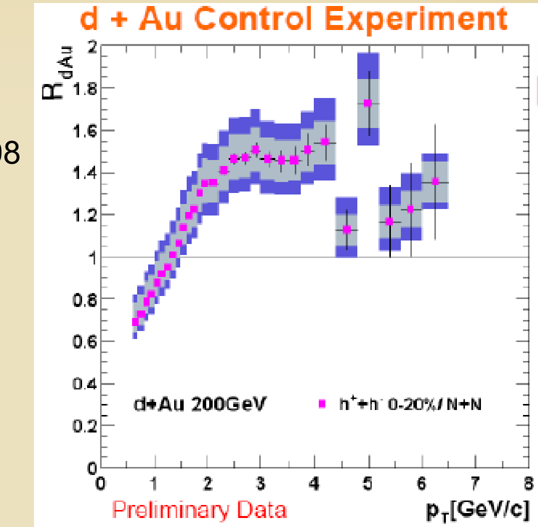
$L / \lambda = 3 - 4$

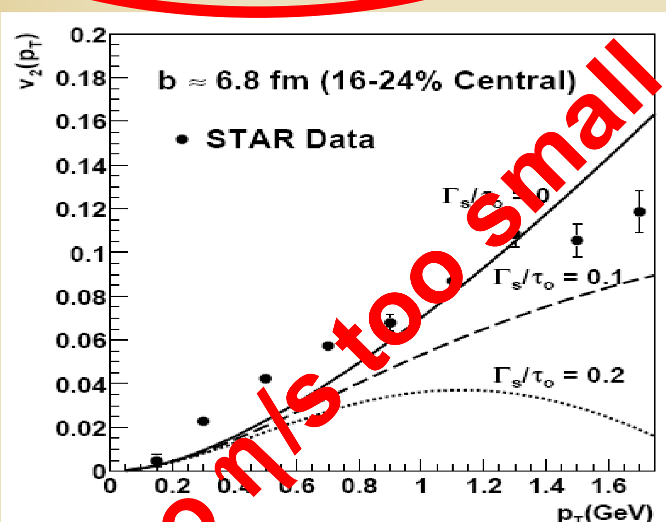
$L \approx 5$ fm

$q = 5\text{-}10\ GeV^2/fm$



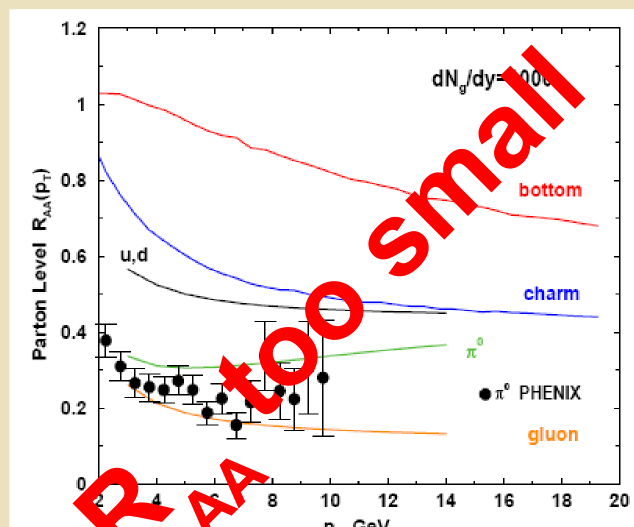
Y. Akiba *for the PHENIX coll.*, hep-ex/0510008





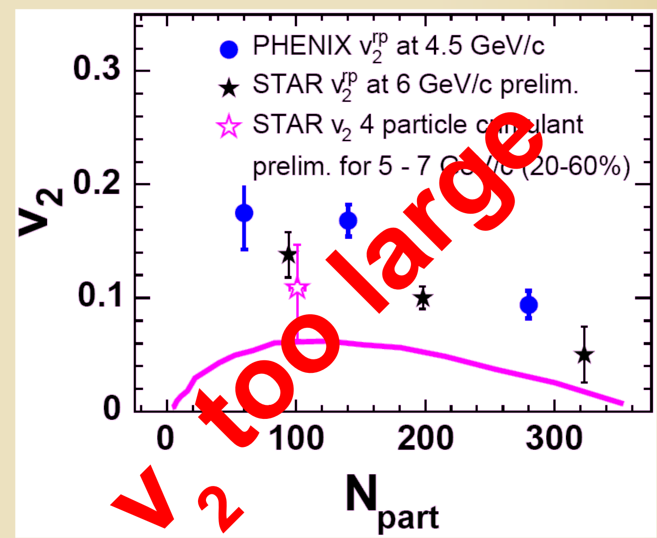
Hydro η/s too small

D. Teaney, Phys. Rev. **C68**, 034913 (2003)



e^- R_{AA} too small

M. Djorjevic, M. Gyulassy, R. Vogt, S. Wicks, Phys. Lett. **B632**:81-86 (2006)



v_2 too large

A. Drees, H. Feng, and J. Jia, Phys. Rev. **C71**:034909 (2005) (first by E. Shuryak, Phys. Rev. **C66**:027902 (2002))

Heavy Quarks in QGP

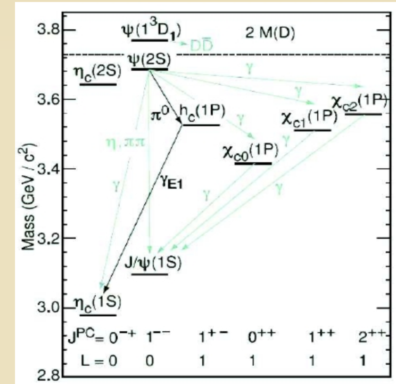
Quarkonium states, J/Ψ suppression

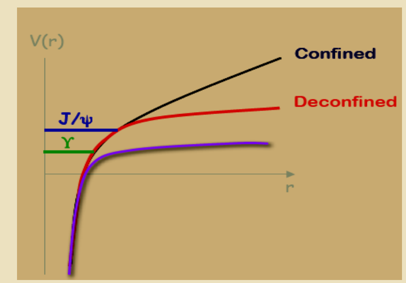
J/Ψ is a heavy cc pair, can be created in the early stage of the QGP formation.

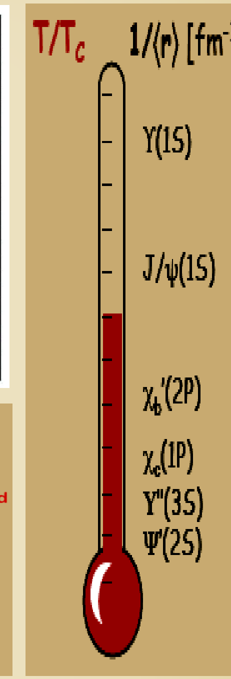
Suppression takes place in QGP

Some charmonia may survive beyond T_c

quarkonia melting

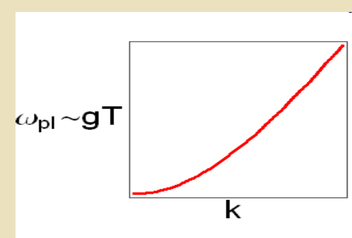


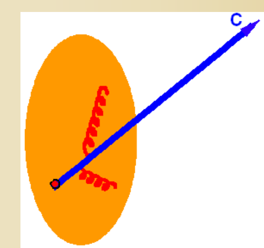


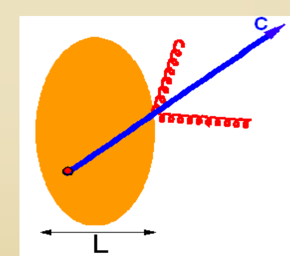


Open charm

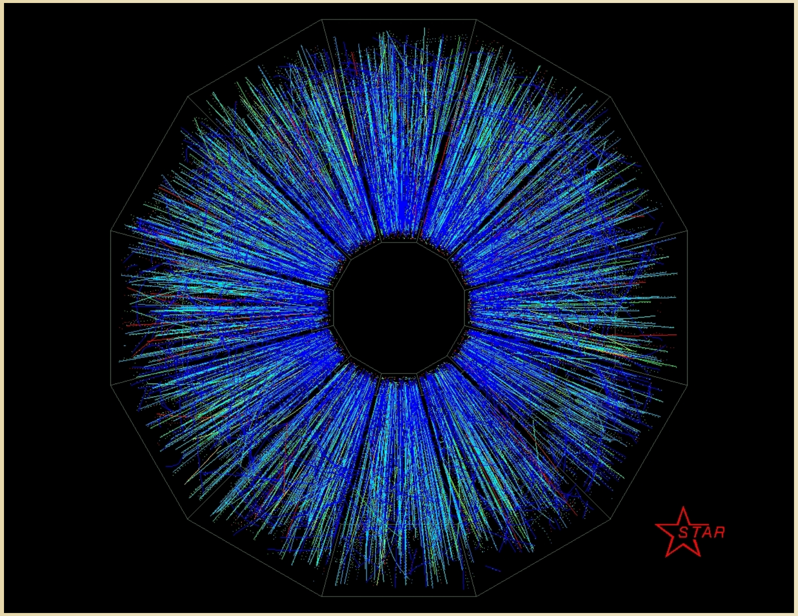
D meson (electron pair) production is suppressed by the Ter-Mikayelian, transition radiation and jet energy loss.



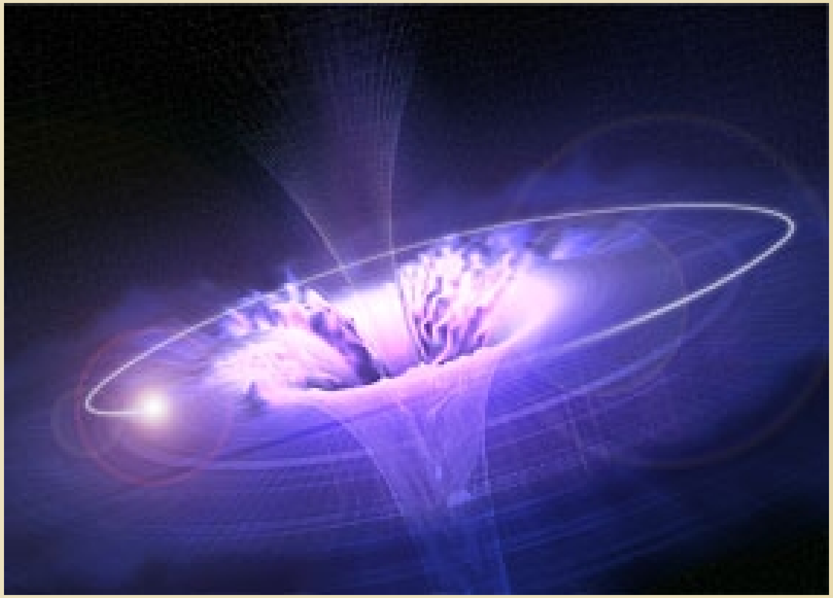




Hard Probes with AdS/CFT...



?



… why do we need this?

Need for AdS/CFT in Heavy Ion Physics

- Models in HI are mostly based on QCD
- Running LHC, we will reach a new energy regime (10 TeV)
- Even at highest energies we still have soft/bulk part
- Thermal (p)QCD is even more complicated

- Most models are phenomenological, no general 'ToE'
- Chance for a 'Golden Way' between soft and hard
- New solution or bounds appears for 'old problems'
- BUT, interpretations in AdS/CFT are quite fragile

Why AdS/CFT in Heavy Ion Physics

Modelling Strongly Interacting Quark Gluon Plasmas

On the Fragile Boundary

between g=0 (wQGP) and g= ∞ (sQGP ~ AdS/CFT)

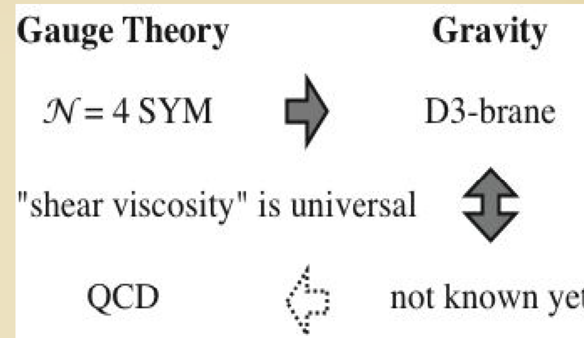
$$0 \ll \Gamma = \alpha\, \rho^{1/3} / T \sim 1 \ll \infty$$

Perturbative Gauge Field Theory QCD → ??? ← **Dual Geometry (Gravity) AdS/CFT**

Heavy Ions in AdS/CFT framework

The supergravity dual conjecture:

QCD ↔ SYM ↔ IIB



PROGRAM:

IF

super Yang-Mills (SYM) is not too different from QCD,

AND

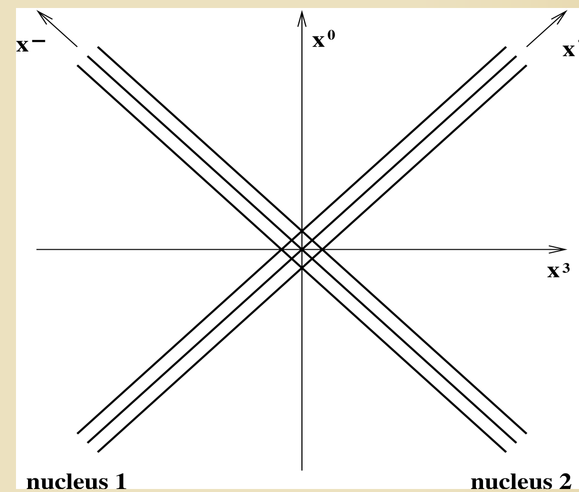
IF

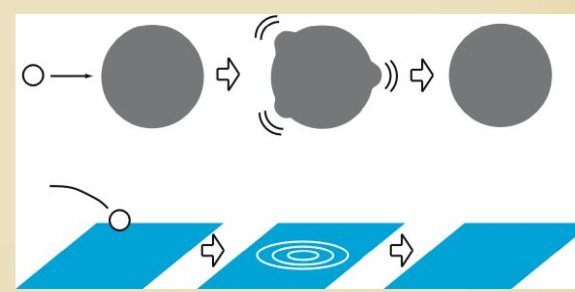
Maldacena conjecture is true

THEN

a tool exists to calculate strongly-coupled QCD in classical SUGRA

ELSE ????





Gluon energy loss in AdS/CFT

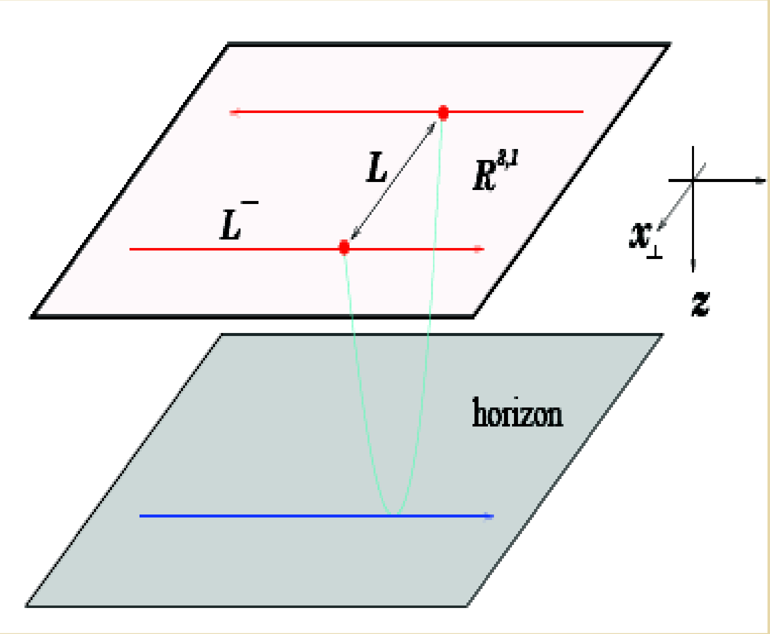
- Non-Abelian energy loss

  BDMPS can be described by the transport parameter, $\hat{q}$

  Two competing ways are exist:

- Partially lightlike Wilson loop

  For small L: $\langle W^A(\mathcal{C})\rangle \approx \exp\left\{-\frac{1}{4\sqrt{2}}\hat{q}L^-L^2\right\}$



Liu, Rajagopal, Wiedemann

Then, $$\hat{q}_{\rm LRW} = \frac{\pi^{3/2}\Gamma(3/4)}{\Gamma(5/4)}\sqrt{\lambda}\,T^3 \approx 3.6\,\frac{\rm GeV^2}{\rm fm}\left(\frac{T_{SYM}}{280\ \rm MeV}\right)^3$$

where $\lambda = 6\pi$.

Gluon energy loss in AdS/CFT

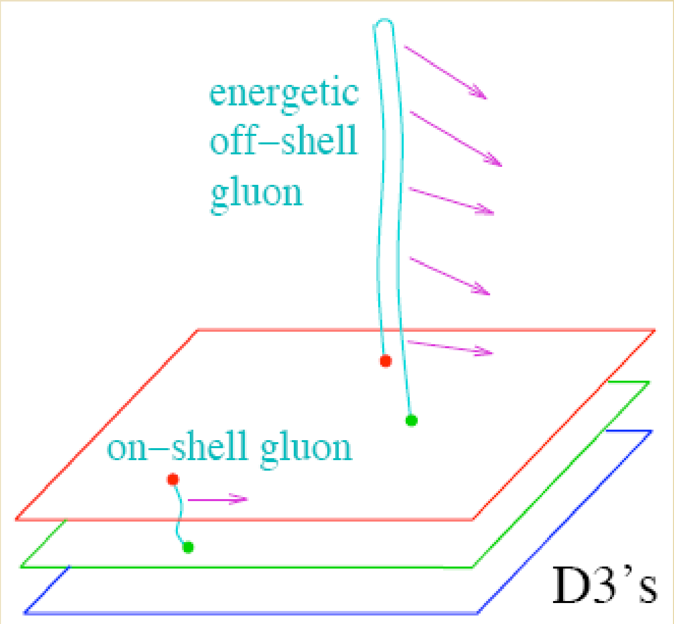
- Off shell gluon as a falling string

Rel. energy loss for large E, $\Delta E \propto L^3$

String quickly settles down into a segment of a trailing string.

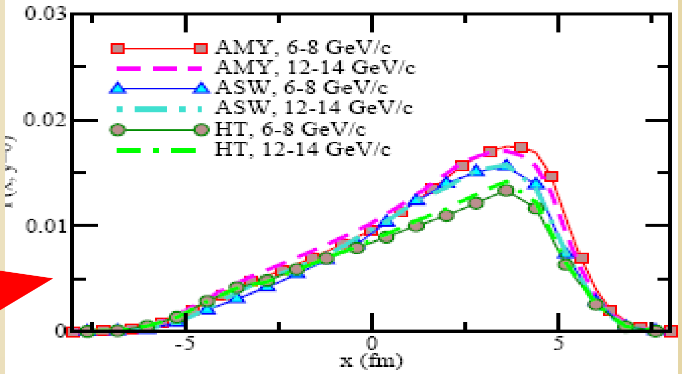
Taking the $E \gg \sqrt{\lambda} T_{SYM}$, then stopping:

$$x_{\text{stop}} \lesssim \frac{1}{\pi T_{SYM}} \left(\frac{1}{\sqrt{\lambda}} \frac{E}{T_{SYM}} \right)^{1/3}$$



Gubser, Hatta, Chesler

Stopping is really strong taking $\lambda = 5.5$, $T_{QCD} = 280$ MeV, a E = 10 GeV gluon stops in L = 0.5 fm. Too strong!!!



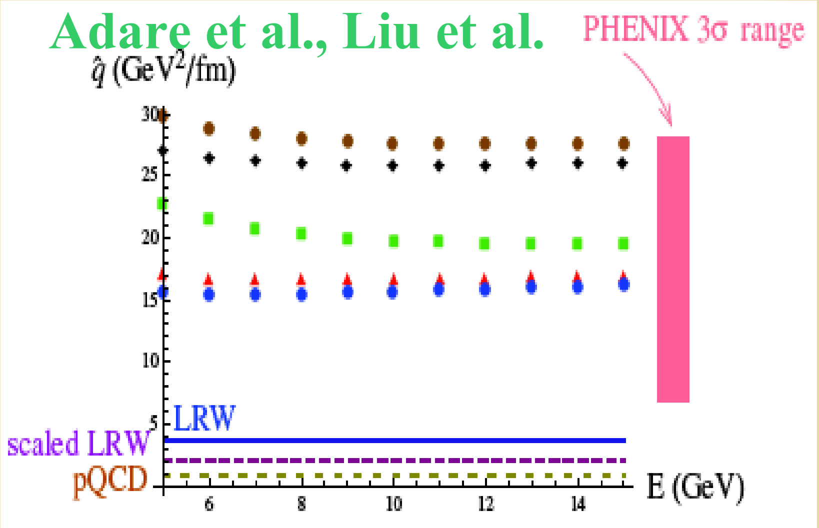
T. Renk et al. 2008

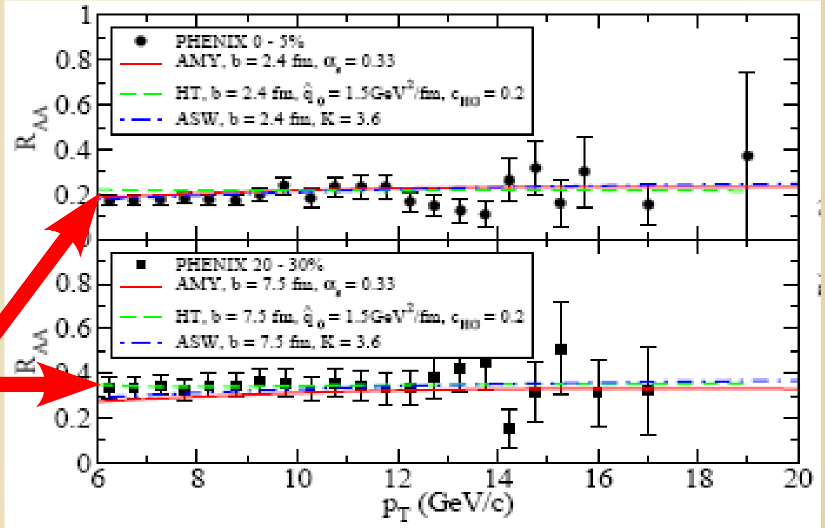
Test of the gluon energy loss

- Gubser said: $\Delta E \propto L^3$ vs. $\Delta E \propto L^2$ „,... is NOT too different...“
- A rough estimate: $\hat{q}_{\rm rough} \equiv \frac{4E}{3\alpha_s x_{\rm stop}^2}$

  $\lambda = 5.5$, $\alpha_S = 0.5$, $T_{SYM} = 280$MeV
- PHENIX 3σ range vs. LRW or pQCD based on: $\hat{q} = \frac{8\zeta(3)}{\pi}\alpha_s^2 N^2 T^3$.
- Energy loss is too strong, but comparision is hard: 'models' of g are quite different from pQCD

$0.5 \cdot \hat{q}_{ASW} \sim \hat{q}_{AMY} \sim 2\hat{q}_{HT}$, $\hat{q}_{AMY} \sim$ ideal QGP

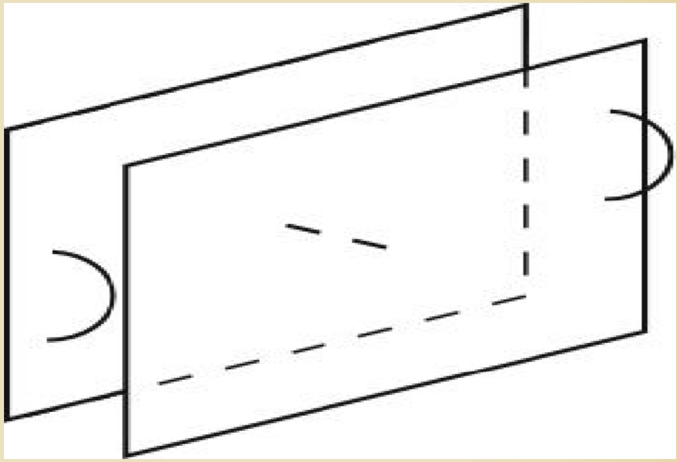




T. Renk et al. 2008

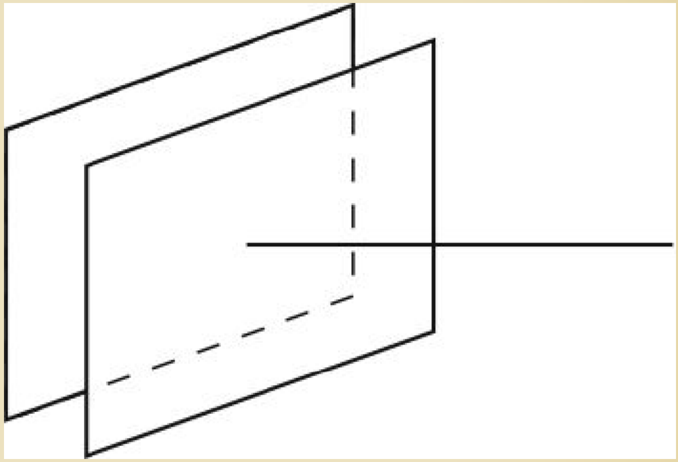
How to make heavy quarks in AdS/CFT?

Open or closed strings on branes?



- Open strings can have endpoints on branes in N^2 ways.
- String transforms as the adjoint representation of SU(N) gauge theory.

Let's take an infinitely long string



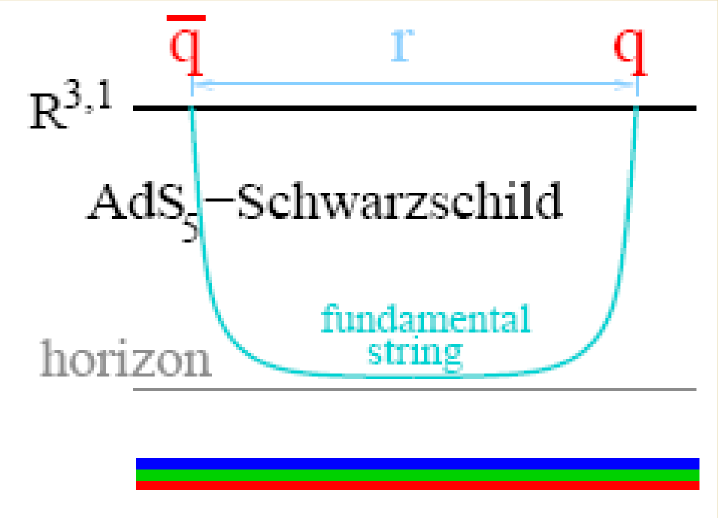
- String transforms as representation of the fundamental SU(N) theory.
- In this picture for quark $m \to \infty$:

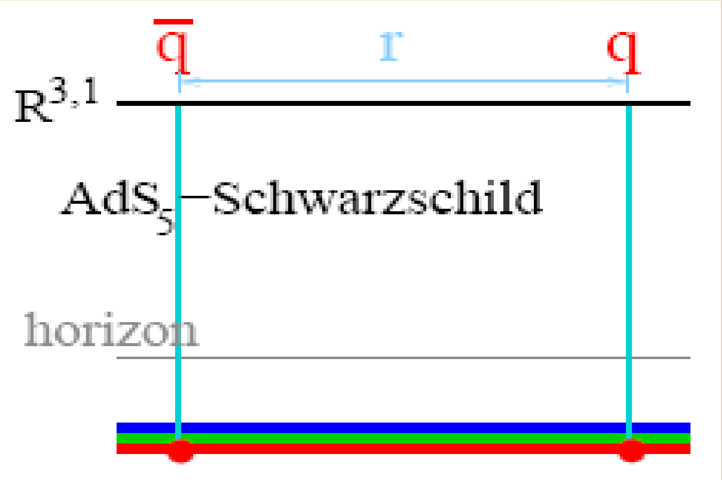
$$\infty \text{ STRING} = \text{QUARK}$$

Heavy Quarks in AdS/CFT

Long string represents a heavy quark

- String has extension and tension, thus has large mass like a heavy qq.
- Min. energy configuration: one string connects qq pair better than 2 strings.
- Energy difference between 2 strings and 1 string states of qq, is a Coulomb-like potential in $N = 4$ case.
- These are true in case $T = 0$





hep-th/9803001v3

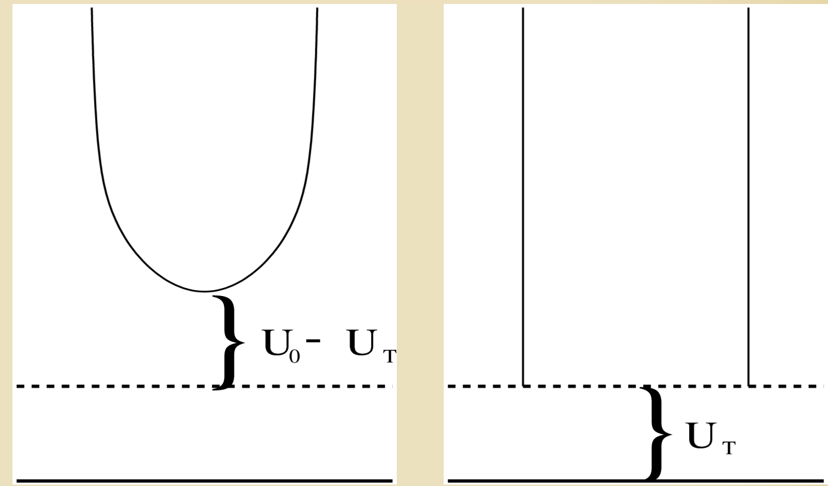
Heavy Quarks in AdS/CFT

Finite temperature case

- At finite T, isolated strings have the lowest energy.

  Isolated strings with $L_s > L_C$: distance L_s is the AdS/CFT version of Debye screening.

- If $L_s << 1/T$, then Coulomb-like.
- If $L_s >> 1/T$, free-like quarks due to the screening by the thermal bath.



hep-th/9803137

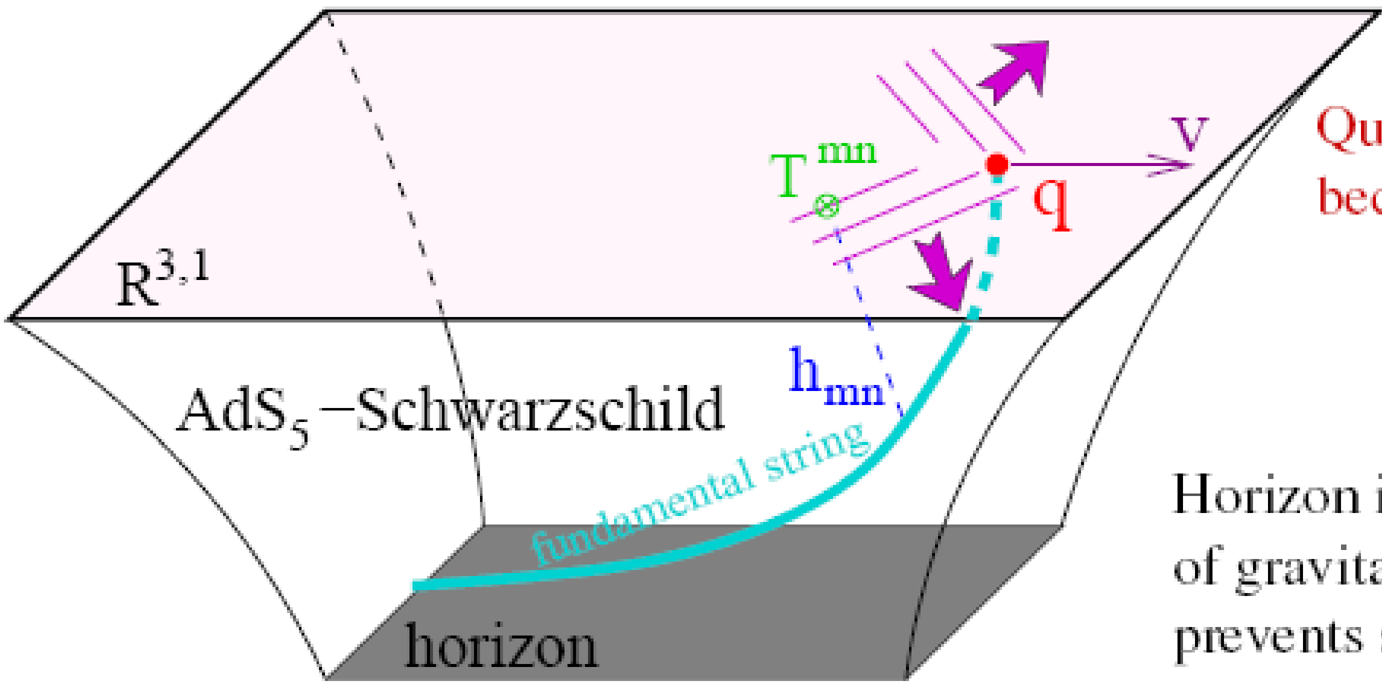
$$\text{QCD:} \quad V_{q\bar{q}}(r) = \left(-\frac{4\alpha/3}{r} + \sigma r\right) \times \left[1 - (\text{Debye screening})\right]$$

$$\text{SYM:} \quad V_{q\bar{q}}(r) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{r} \times \left[1 - (\text{Debye screening})\right]$$

AdS/CFT for Heavy Quark Energy Loss

- Langevin model
  - Collisional energy loss for heavy quarks
  - Restricted to low p_T
  - pQCD vs. AdS/CFT computation of *D*, the diffusion coefficient
- ASW – Arnesto Salgado Wiedermann model
  - Radiative energy loss model for all parton species
  - pQCD vs. AdS/CFT computation of $\hat{q}$
  - Debate over its predicted magnitude
- ST – Casalderrey-Solana Teaney calculation
  - Drag coefficient for a massive quark moving through a strongly coupled SYM plasma at uniform T
  - not yet used to calculate observables: let's do it!

Heavy Quark Energy Loss



Quark can't slow down because $m = \infty$

Horizon is "sticky" because of gravitational redshift: prevents string from moving.

$$\frac{dp}{dt} = -\frac{p}{\tau_Q} + \textbf{stochastic} \;\rightarrow\; \frac{dp}{dt} = -\frac{\pi\sqrt{\lambda}}{2} T_{SYM}^2 \frac{v}{\sqrt{1-v^2}} = -\frac{p}{\tau_Q} \qquad \tau_Q = \frac{2m_Q}{\pi T_{SYM}^2 \sqrt{\lambda}}$$

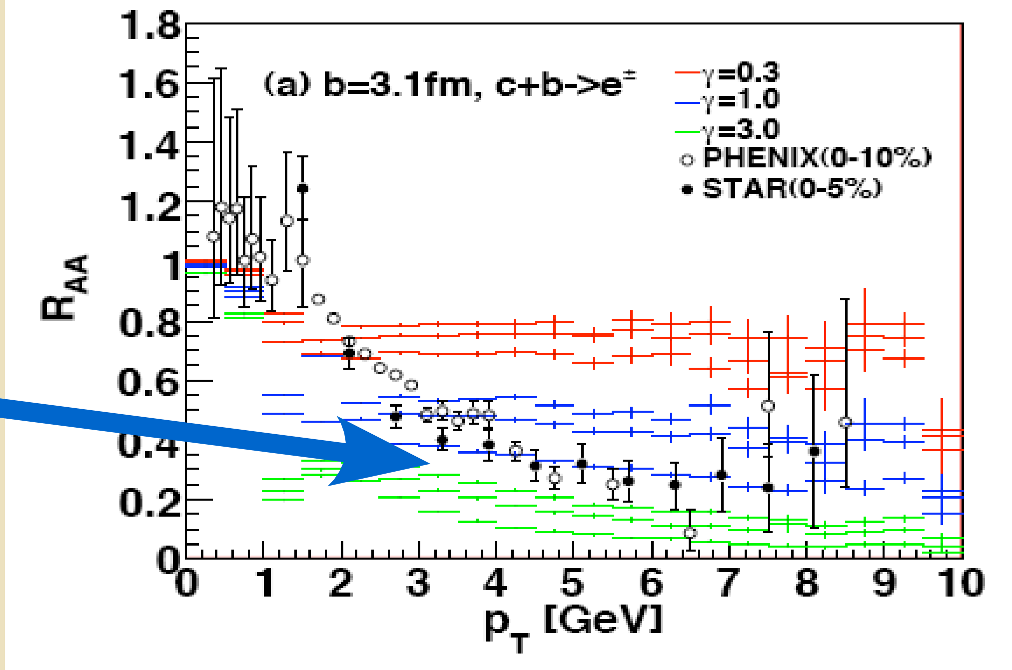
Calculated values: $\tau_{\text{charm}} \approx 2\,\text{fm} \qquad \tau_{\text{bottom}} \approx 6\,\text{fm} \qquad \text{if } T_{QCD} = 250\,\text{MeV}$

Heavy Quark Energy Loss – Comparision

R_{AA} for non-photonic e^-

Calculations based on the drag force: $\vec{F}_{\rm drag} = -\gamma \frac{T^2}{m_Q}\vec{p}$

seems to have $\gamma \approx 2$ in AdS/CFT for $p_T \geq 3$ GeV/c



Langevin eq. for heavyquarks:

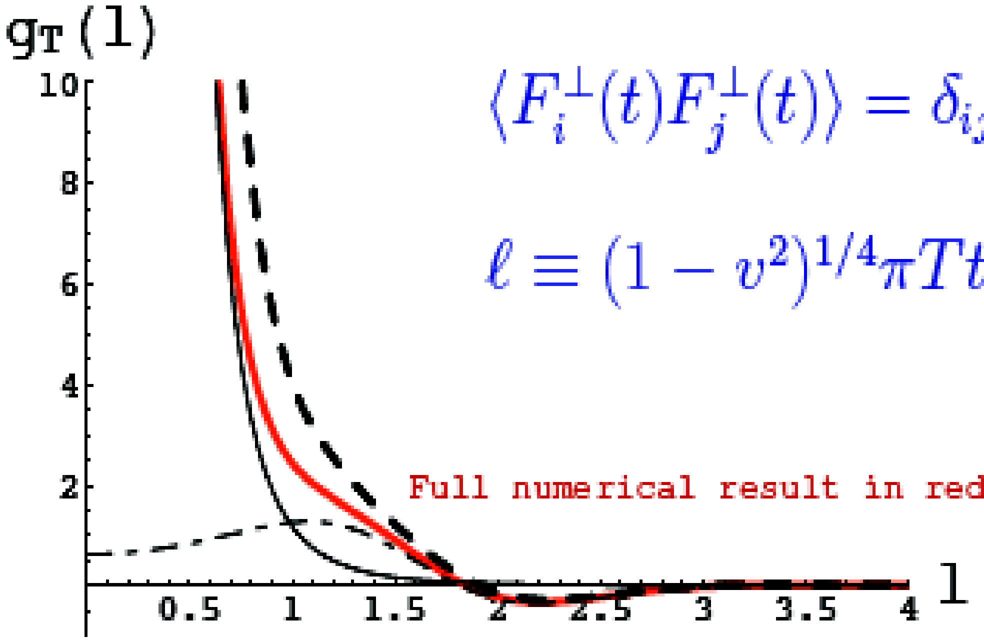
$$\frac{d\vec{p}}{dt} = -\Gamma\vec{p} + \vec{F}(t) \qquad \langle F_i(t)F_j(0)\rangle = D(p)\delta_{ij}\delta(t) \qquad \Gamma = \frac{D(p)}{2ET} - \frac{1}{2p}\frac{dD(p)}{dp}$$

Direct cal. of stochastic term:

$$\langle F^{||}(t)F^{||}(0)\rangle \approx \frac{\pi\sqrt{\lambda}}{(1-v^2)^{5/4}}T^3\delta(t) \qquad \langle F_i^{\perp}(t)F_j^{\perp}(0)\rangle \approx \frac{\pi\sqrt{\lambda}}{(1-v^2)^{1/4}}T^3\delta_{ij}\delta(t)$$

Heavy Quark Energy Loss – Comparision

$$\langle F^{\parallel}(t)F^{\parallel}(0)\rangle \approx \frac{\pi\sqrt{\lambda}}{(1-v^2)^{5/4}}T^3\delta(t) \qquad \langle F_i^{\perp}(t)F_j^{\perp}(0)\rangle \approx \frac{\pi\sqrt{\lambda}}{(1-v^2)^{1/4}}T^3\delta_{ij}\delta(t)$$



$$\langle F_i^{\perp}(t)F_j^{\perp}(t)\rangle = \delta_{ij}\pi T^3\frac{\sqrt{\lambda}}{(1-v^2)^{1/4}}g_T(\ell)$$

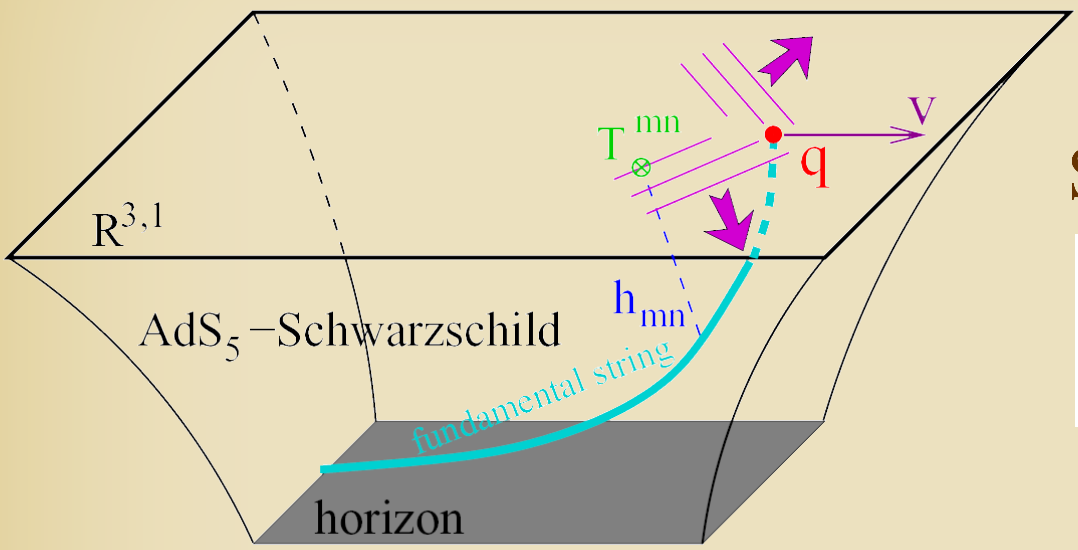
$\ell \equiv (1-v^2)^{1/4}\pi T t,$ so $t_{\mathrm{correlation}} \to \infty$ as $v \to 1$

[Gubser 2006b]

$$\frac{1}{\sqrt{1-v^2}} \lesssim \frac{4}{\lambda}\frac{m_Q^2}{T^2}$$

Langevin case: $t_{\mathrm{correlation}} < t_Q$ then $p_T < 20$ GeV

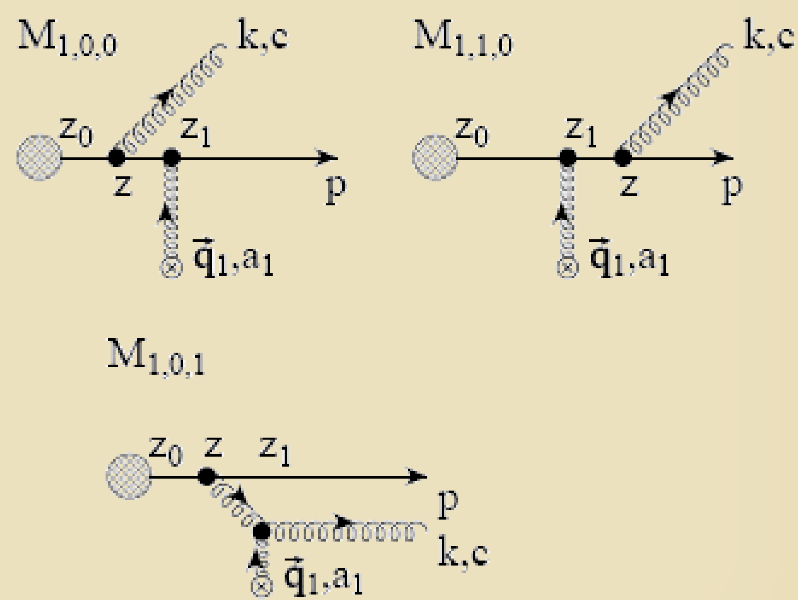
Drag Calculation for Heavy Quarks



$$\lambda = \sqrt{g^2_{SYM} N_c} \gg 1,\ N_c \gg 1,\ M_Q \gg T^{SYM}$$

ST Drag calculation:

$$\frac{dp_T}{dt} = -\mu_Q p_T = \frac{\pi\sqrt{\lambda}(T^{SYM})^2}{2M_Q} p_T$$



– Compare to Bethe-Heitler

$dp_T/dt \sim -(T^3/M_q^2)\, p_T$

– Compare to LPM

$dp_T/dt \sim -LT^3 \log(p_T/M_q)$

Calculation method for prediction

Estimate for the spectrum, is a parameterization: $dN_Q/dp_T \sim 1/p_T^{n_Q(p_T)}$

Nuclear modification factor: $R^Q_{AA}(p_T) = \left\langle \left(1-\epsilon(\vec{x},\phi)\right)^{n_Q(p_T)-1} \right\rangle_{geom}$

Fractional energy loss in AdS/CFT: $\bar{\epsilon}_{AdS} = 1-\exp(-\mu_Q L)$ and $p_f = (1-\epsilon)p_i$

Comparision for pQCD and AdS/CFT :

$$R^{cb}_{AdS}(p_T) \simeq \frac{n_b \mu_b}{n_c \mu_c} \simeq \frac{M_c}{M_b},$$

$$R^{cb}_{pQCD}(p_T) \simeq 1-\kappa \alpha_s n(p_T) L^2 \log(M_b/M_c) \frac{\hat{q}}{p_T},$$

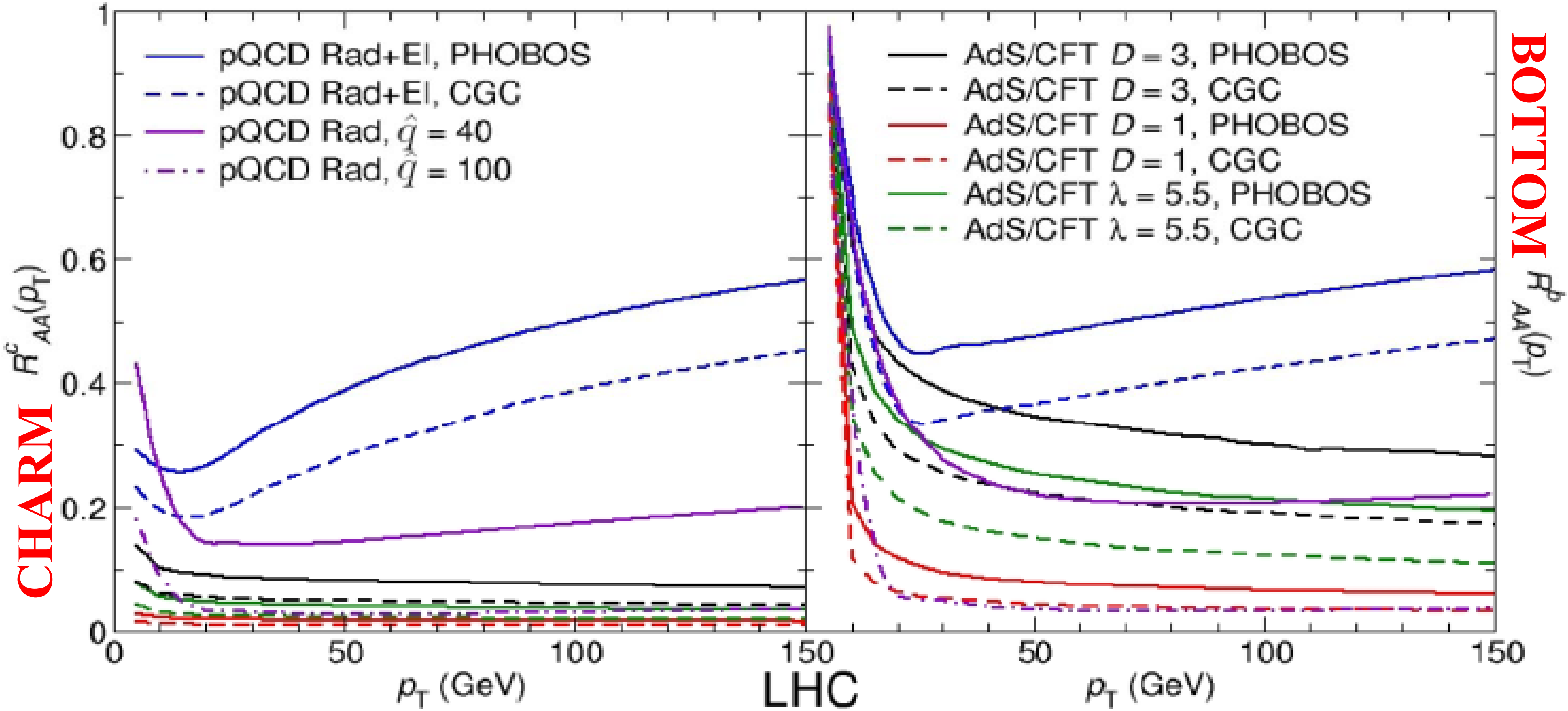
More speed limit for the string:

$$\gamma_c = \left(1+\frac{2M}{\sqrt{\lambda} T^{SYM}}\right)^2 \approx \frac{4M^2}{\lambda (T^{SYM})^2}$$

Inputs: $n_b(p_T) \simeq n_c(p_T) \simeq n(p_T)$, $T^{SYM} = T^{QCD}/3^{1/4}$, $D \simeq 3/2\pi T$, $\lambda_{SYM} \simeq 5.5$, $\alpha_{SYM} = .05$

W.Horowitz, MG: Phys.Lett.B666 (2008)

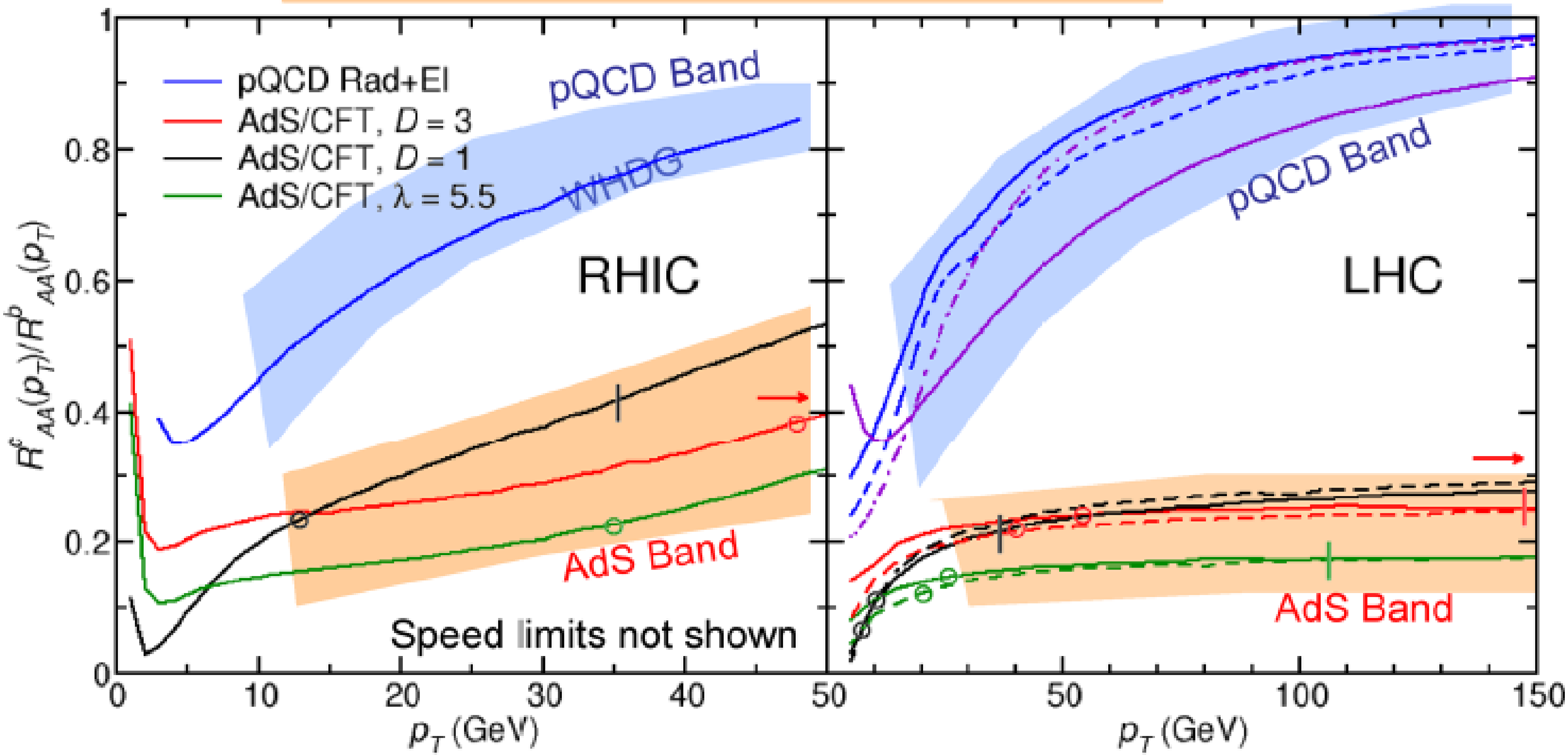
LHC *charm*, *bottom* R_{AA} (p_T, M_Q) : pQCD vs AdS/CFT



- Absolute R^Q Predictions for LHC vary strongly with opacity and coupling parameters in both models. The is no Fragility as Eskola+ASW claimed.
- With freedom to adjust transport params makes differentiating pQCD vs AdS hard

RHIC and LHC $R^{cb} = R^{c}_{AA}(p_T)/R^{b}_{AA}(p_T)$

Robust Way to differentiate pQCD vs AdS, $\lambda_{GB}=0$



Bunching into a "pQCD band" vs a "AdS/CFT band" make this *Double* ratio of charm and bottom jet nuclear modification factors the ideal test of pQCD vs AdS/CFT gravity models of sQGP

SUMMARY


HEAVY ION PHISICS
QCD
PHENOMENOLOGY
AVP
ALIEN VS. PREDATOR
AdS/CFT
WHOEVER WINS... WE LOSE
WE SURVIVE

Backdoor from our room at CERN