Jet quenching in the strongly-interacting quark-gluon plasma

Cyrille Marquet

Institut de Physique Théorique
CEA/Saclay

based on C. Marquet and T. Renk, arXiv:0908.0880

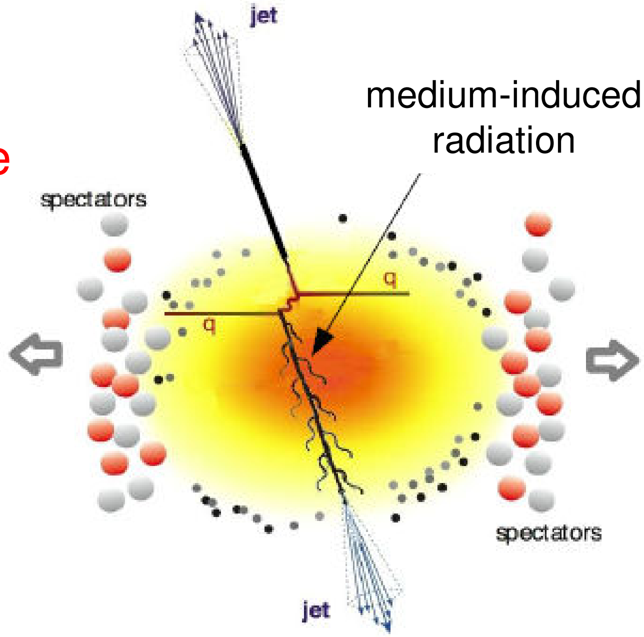
Outline

- Jet quenching in the pQCD picture
  - medium-induced partonic energy-loss
  - the transport coefficient $\widehat{q}$ and the plasma saturation scale Q_s
- Taking into account strong-coupling dynamics
  - high-p_T process $\Rightarrow$ energy is lost via gluon radiation
  - sQGP $\Rightarrow$ the amount of energy lost is bigger than in wQGP
- Comparison with RHIC data
  - good description of R_{AA} for central collisions, with wQGP or sQGP
  - R_{AA} as a function of reaction plane probes the path-length dependence
  - predictions for I_{AA}

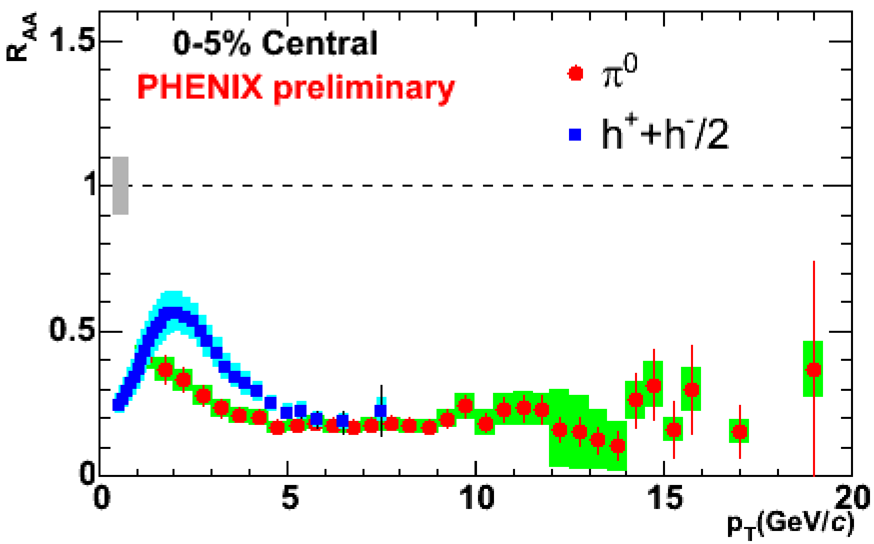
Introduction

- what happens to a quark produced in the early stages of a heavy-ion collision

it loses energy in the plasma and may thermalize



- it is unclear if the pQCD approach can describe the suppression of high-p_T particles in Au+Au collisions:



in the case of light quarks, comparisons between models and data indicate the need for a large jet quenching parameter

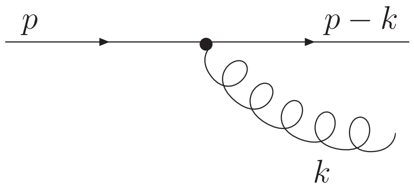
$$\hat{q} = 5 - 10\ \text{GeV}^2/\text{fm}$$

however, for a weakly-coupled QCD plasma we expect $\hat{q} \simeq 1\ \text{GeV}^2/\text{fm}$

Medium induced gluon radiation

- after a bare parton is created in a hard collision, it builds up its wave funcion

the wave function at lowest order



the energy of the parent parton is denoted *E*

the energy of the virtual gluon is denoted ω

the transverse momentum of the gluon is denoted $k_\perp$

the virtuality of the fluctuations is measured by their lifetime or coherence time

$t_c = \omega / k_\perp^2$ short-lived fluctuations are highly virtual

- the presence of the medium prevents the parton to become fully dressed

fluctuations with virtuality less than ~ *T* are screened out of the wave function

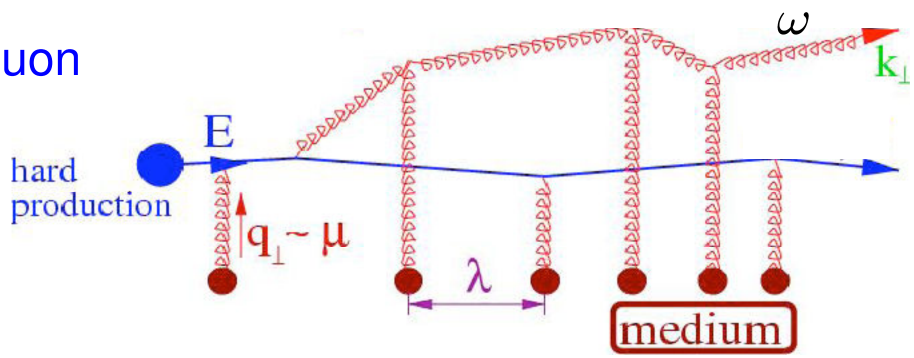
because of the hard process, radiation into the medium comes from the perturbative part of the wave function: gluons are radiated

how much energy is lost depends whether the plasma is weakly or strongly-coupled

Radiative energy loss in pQCD

- multiple scattering of the virtual gluon

in the limit $E \gg \omega \gg |k_\perp|$



the accumulated transverse momentum picked up by a gluon of coherence time t_c

$$p_T^2 = \mu^2 \frac{t_c}{\lambda} \equiv \hat{q}\ t_c$$

$\hat{q} \equiv \mu^2/\lambda \sim T^3$ only property of the medium needed

average p_T^2 picked up in each scattering

mean free path

Baier, Dokshitzer, Muerller, Peigne and Schiff (1997)
Zakharov (1997)

- emission of the radiated gluon

its formation time must be smaller than the path length L : $\omega < L\ k_\perp^2$

it is put on shell and becomes emitted radiation if it picks up enough transverse momentum: $k_\perp^2 < \hat{q}\ L \equiv Q_s^2$ $\qquad \omega_m = L\ Q_s^2$

total energy lost by the quark $\Delta E \propto \alpha_s N_c\ \omega_m = \alpha_s N_c\ \hat{q} L^2$

energy distribution of the radiated gluons $dI/d\omega = f(\omega_m, Q_s^2)$

Realistic calculation of R_{AA}

Renk and Eskola (2007)

- accounting for the medium evolution

for a given position of the hard vertex $\mathbf{r}_0$ and direction of motion ϕ :

$$Q_s^2(\mathbf{r}_0,\phi) = K \int_0^\infty d\xi \, T^3(\xi) \qquad \omega_m(\mathbf{r}_0,\phi) = K \int_0^\infty d\xi \, \xi \, T^3(\xi)$$

only parameter to be adjusted (K)

determined from a 3-d hydro model ($T^3(\xi)$)

- accounting for the medium geometry

$$\frac{dI}{d\omega}(\omega_m, Q_s^2) \Rightarrow P(\Delta E, \mathbf{r}_0, \phi)$$

quenching weight

medium-averaged energy loss probability

$$\langle P(\Delta E)\rangle_{T_{AA}} = \frac{1}{2\pi}\int_0^{2\pi} d\phi \int d^2\mathbf{r}_0 P(\mathbf{r}_0) P(\Delta E, \mathbf{r}_0, \phi)$$

hard vertex probability $P(\mathbf{r}_0) = \dfrac{T_A(\mathbf{r_0}+\mathbf{b}/2)T_A(\mathbf{r_0}-\mathbf{b}/2)}{T_{AA}(\mathbf{b})}$

thickness function from the Woods-Saxon distribution

- computing R_{AA}

$$R_{AA}(P_T,y) = \frac{d\sigma^h_{AA}/dP_T dy}{T_{AA}(\mathbf{b}) d\sigma^{pp}/dP_T dy} \qquad d\sigma_{med}^{AA\to h+X} = \sum_f d\sigma_{vac}^{AA\to f+X} \otimes \langle P(\Delta E)\rangle_{T_{AA}} \otimes D_{f\to h}^{vac}(z,\mu_F^2)$$

Energy loss at strong coupling

- for the *N*=4 SYM theory, the AdS/CFT correspondence allows to investigate the strong coupling regime

Herzog et al (2006), Gubser et al (2006), Liu et al (2006)

the tools to address the QCD dynamics at strong coupling are limited

- the plasma saturation scale at strong coupling

the p_T^2 accumulated by a gluon of coherence time L is $Q_s^2 = T^4 L^2$

Dominguez, C. M., Mueller, Wu and Xiao (2008)

this is consistent with the saturation scale computed in DIS off the plasma

$$Q_s^2 = T^3 L/x$$

Hatta, Iancu and Mueller (2008)

in our energy loss problem where partons are created bare in the plasma, x should be replaced by $1/LT$

- the stronger energy loss at strong coupling

the rate at which the radiated gluons pick up transverse momentum is $\frac{d|p_\perp|}{dt} = \text{cste}$

at strong coupling vs. $\frac{dp_\perp^2}{dt} = \text{cste}(= \hat{q})$ at weak coupling

p_T^2 accumulates faster at strong-coupling, more energetic gluons can be freed

$$\Delta E \propto \omega_m = L Q_s^2 = T^4 L^3$$

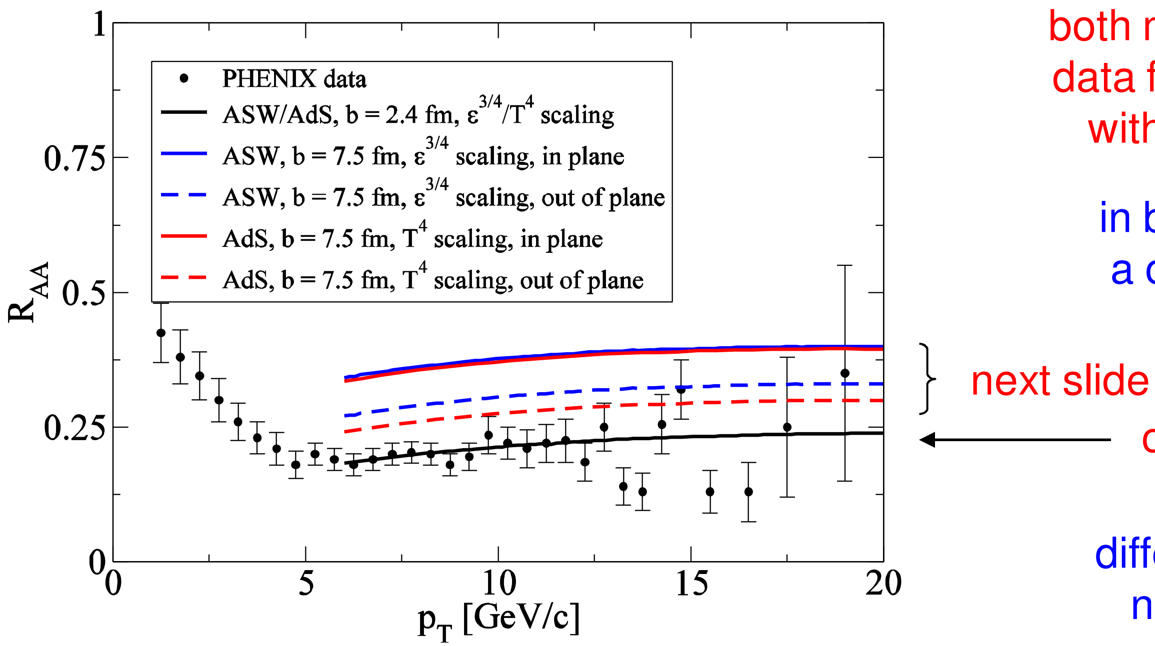
R_{AA} for central collisions

- pQCD model   Armesto, Salgado and Wiedemann

$$Q_s^2(\mathbf{r}_0,\phi) = K\int_0^\infty d\xi\, T^3(\xi) \qquad \omega_m(\mathbf{r}_0,\phi) = K\int_0^\infty d\xi\, \xi\, T^3(\xi)$$

- hybrid model   C.M. and Renk

$$Q_s^2(\mathbf{r}_0,\phi) = K\int_0^\infty d\xi\, \xi T^4(\xi) \qquad \omega_m(\mathbf{r}_0,\phi) = K\int_0^\infty d\xi\, \xi^2\, T^4(\xi)$$



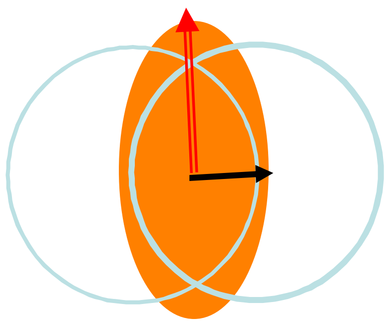
both models describe the data for central collisions with the same quality

in both cases, this is a one-parameter fit

differences are seen for non-central colliions

As a function of reaction plane

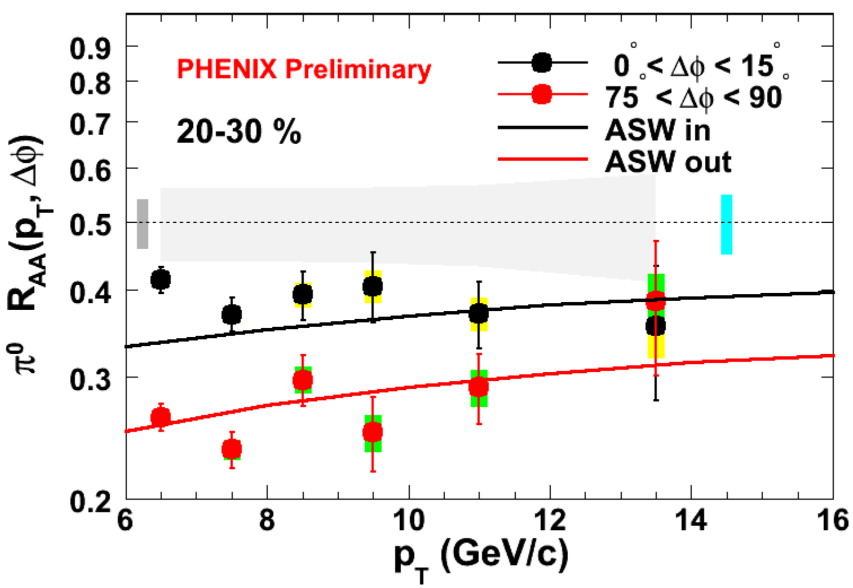
- with non-central collisions, one can probe the path-length dependence



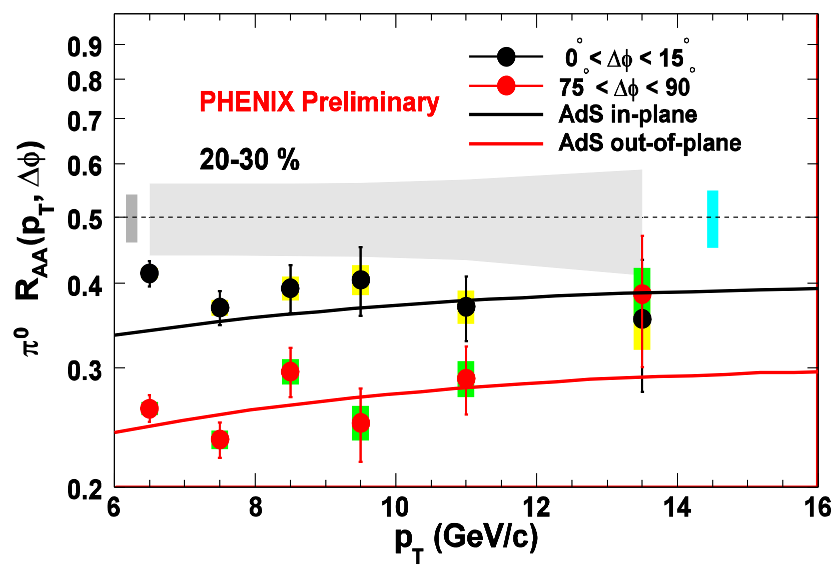
- in-plane
- out-of-plane

the in-plane/out-of-plane difference is larger with strong-coupling dynamics but the net effet is rather small

pQCD model



hybrid model

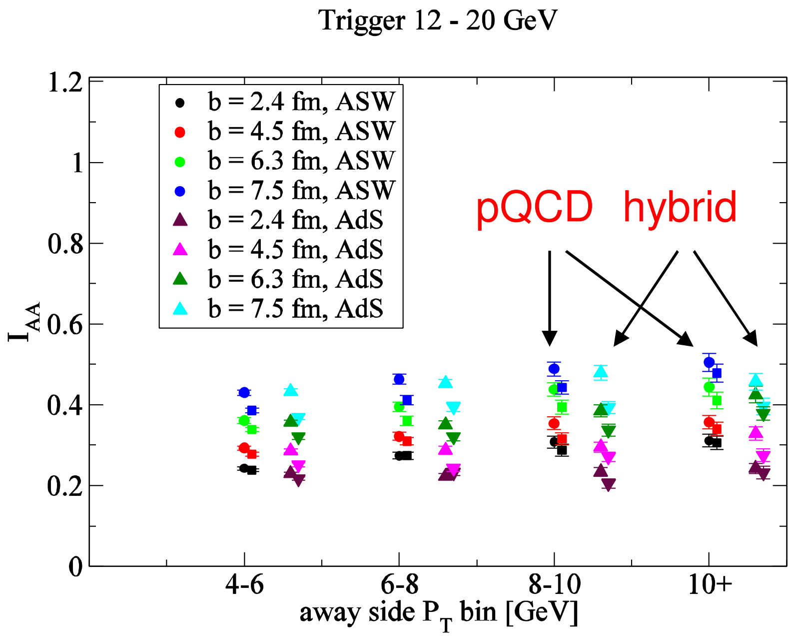


Predictions for I_{AA}

- this is a two-particle correlation measurement

for a trigger particle in a given p_T bin, I_{AA} counts the number of associated particles in a second p_T bin

this measurement is also sensitive to the path-length dependence of the energy loss



again the in-plane/out-of-plane difference is larger with strong-coupling dynamics

→ peripheral collisions, out > in

→ central collisions, in = out

Conclusions

- It is unclear if the pQCD picture can explain jet quenching
  - reproducing R_{AA} for light quarks requires to adjust $\hat{q}$ to a large value
  - heavy quarks and light quarks show a similar suppression
  - however this approach can still be improved

- A hybrid formalism is necessary to address the strong-coupling case
  - a full strong-coupling calculation for high-p_T processes is unrealistic because QCD is asymptotically free
  - the strong-coupling part of the calculation can be modeled by AdS/CFT calculations

- Comparison with the data
  - the one-parameter fit to R_{AA} for central collisions is good with both models
  - differences are clear for path-length dependent observables, even if the effect is small
  - R_{AA} data seem to favor a strong-coupling scenario for the plasma, but I_{AA} measurements are needed to confirm this