Jet quenching in the strongly-interacting quark-gluon plasma

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based on

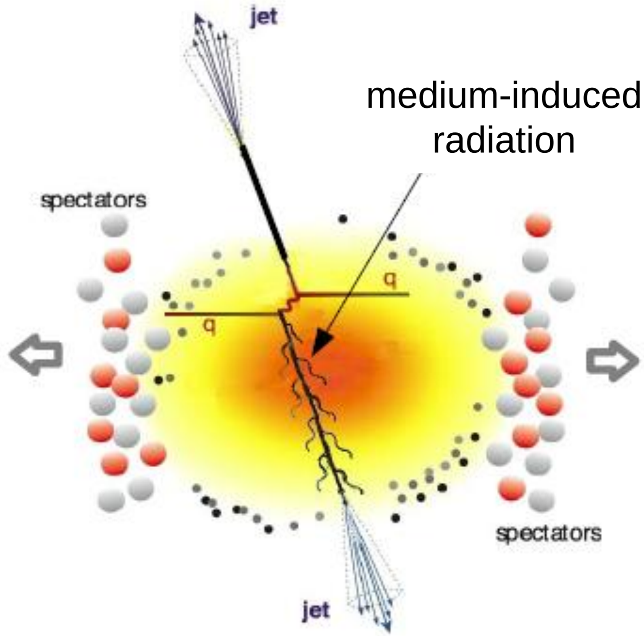
F. Dominguez, CM, A. Mueller, B. Xiao and B. Wu, arXiv:0803.3234

CM and T. Renk, arXiv:0908.0880

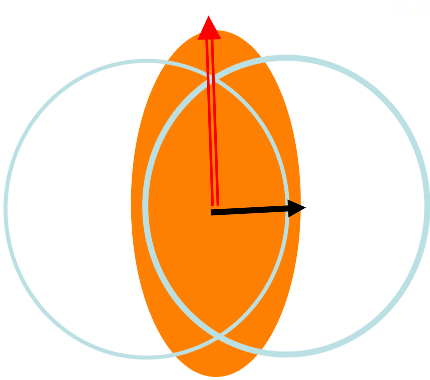
Outline

- High-p_T observables in heavy-ion collisions
  - R_{AA} and v_2
  - comparison with pQCD calculations
- Jet quenching in the pQCD picture
  - medium-induced partonic energy-loss
  - the transport coefficient $\widehat{q}$ and the energy loss $\Delta E \propto \hat{q} L^2$
- Taking into account the 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 $\Delta E \propto T^4 L^3$
- 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 v_2

High-p_T observables in HIC



$$R_{AA}(p_T, b) = \frac{d\sigma_{AA}/dp_T d^2 b}{T_{AA}(b) d\sigma_{pp}/dp_T}$$



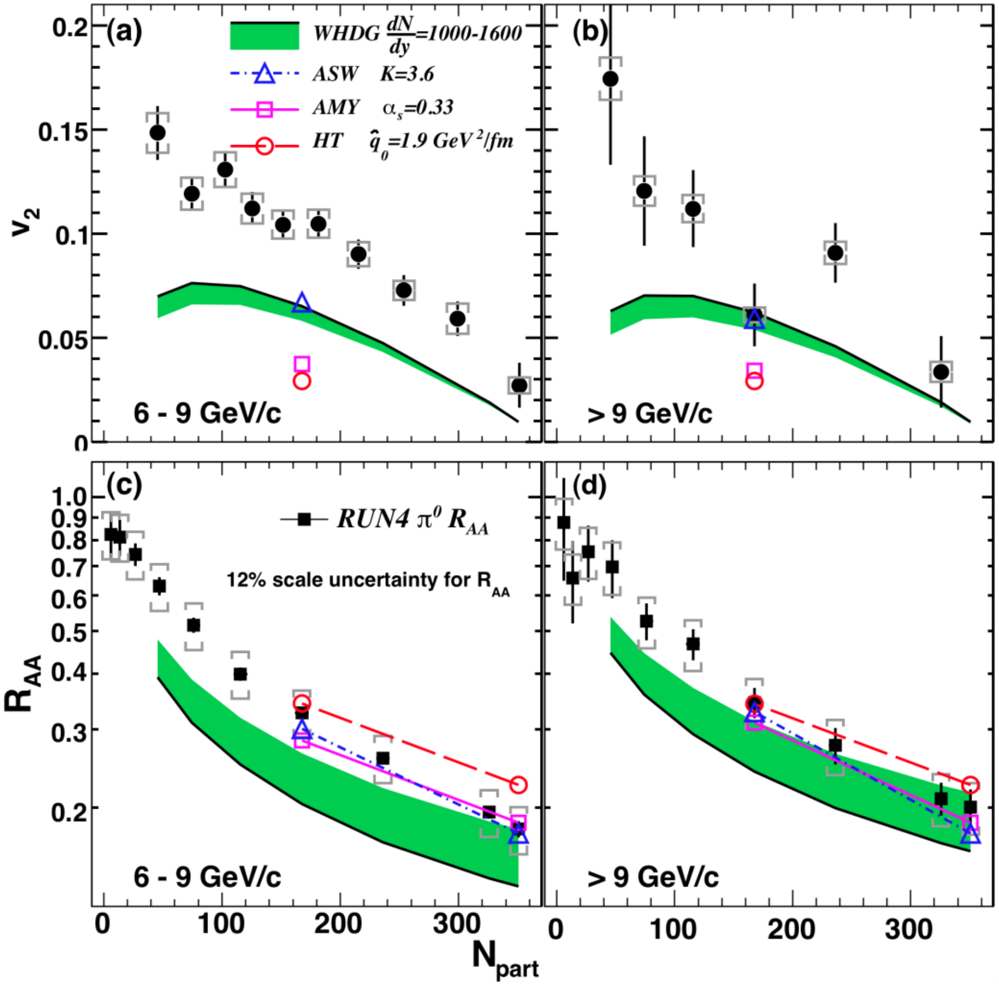
● **in-plane** ● **out-of-plane**

$$v_2(p_T, b) = \frac{\int d\phi \cos(2\phi)\; d\sigma_{AA}/d^2 p_T d^2 b}{\int d\phi\; d\sigma_{AA}/d^2 p_T d^2 b}$$

Failure of pQCD calculations

WHDG, ASW, AM, HT : pQCD results obtained with different assumptions

once parameters are adjusted to describe R_{AA}, v_2 cannot be reproduced



PHENIX collaboration, 2010

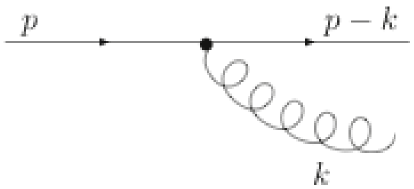
Medium-induced energy loss in pQCD

(the BDMPS-Z / ASW version)

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

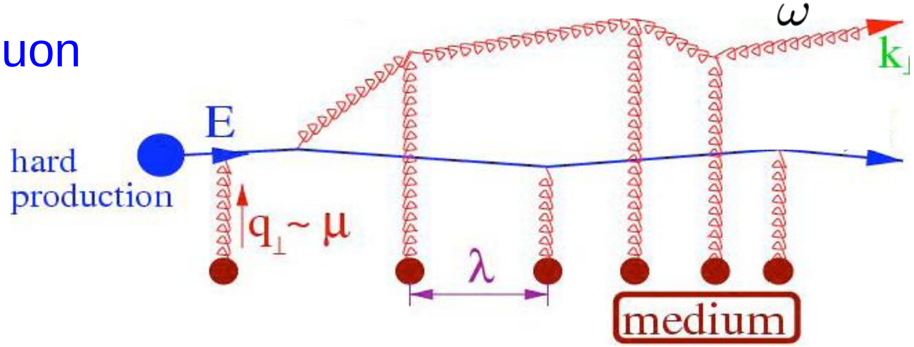
- the presence of the medium prevents the parton to become fully dressed

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 on medium properties,
for instance 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, Mueller, 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: $k_\perp^2 < \hat{q} \; L \equiv Q_s^2$ $\omega_m = L \; Q_s^2$

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 $dI/d\omega = f(\omega_m, Q_s^2)$

How to account for strong-coupling dynamics ? AdS/CFT ?

The LRW approach

- a full AdS/CFT calculation for high-p_T processes is unrealistic because QCD is asymptotically free

instead, let's assume that energy is still lost via gluon radiation, but the amount of energy lost is enhanced by the strongly-coupled nature of the QGP

Liu, Rajagopal and Wiedemann (2006)

- however, one cannot just say that everything is the same than at weak coupling except for a larger $\widehat{q}$

$$\xcancel{\Delta E \propto \hat{q}_{\mathrm{SC}} L^2}$$

$\widehat{q}$ is defined via transverse momentum broadening (i.e. via local elastic scatterings), not via gluon radiation

even though gluon radiation is not local, at weak-coupling it happens that $\widehat{q}$ also determines radiative energy loss (because the radiated gluons undergo multiple scatterings)

this does not happen at strong-coupling, as $\Delta E \propto T^4 L^3$

Energy loss at strong coupling

- the accumulated p_T^2 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

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

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

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

- from actual AdS/CFT calculations, one also obtains $\Delta E \propto L^3$

Gubser et al (2008), Chesler et al (2009)

Comparisons with RHIC data

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

determined from a 3-d hydro model

- accounting for the medium geometry

medium-averaged energy loss probability

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

quenching weight

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

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}

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

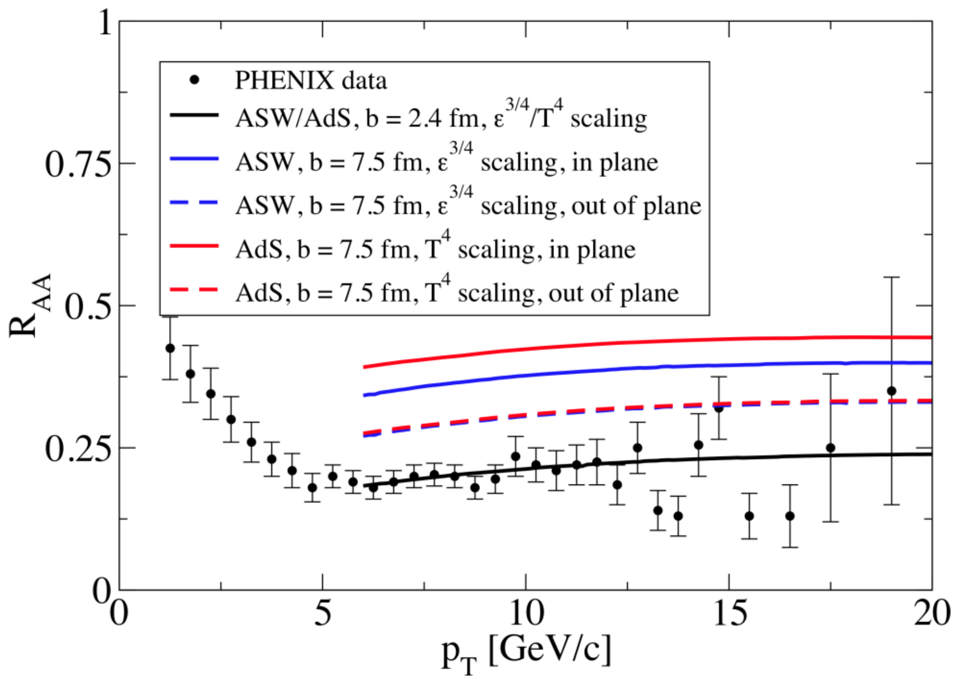
R_{AA} for central collisions

- 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, arXiv:0908.0880

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



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

in both cases, this is a one-parameter fit

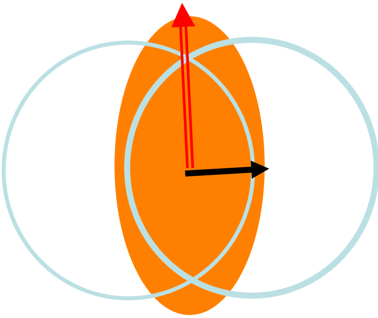
next slide

central collisions

differences are seen for non-central colliions

As a function of reaction plane

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

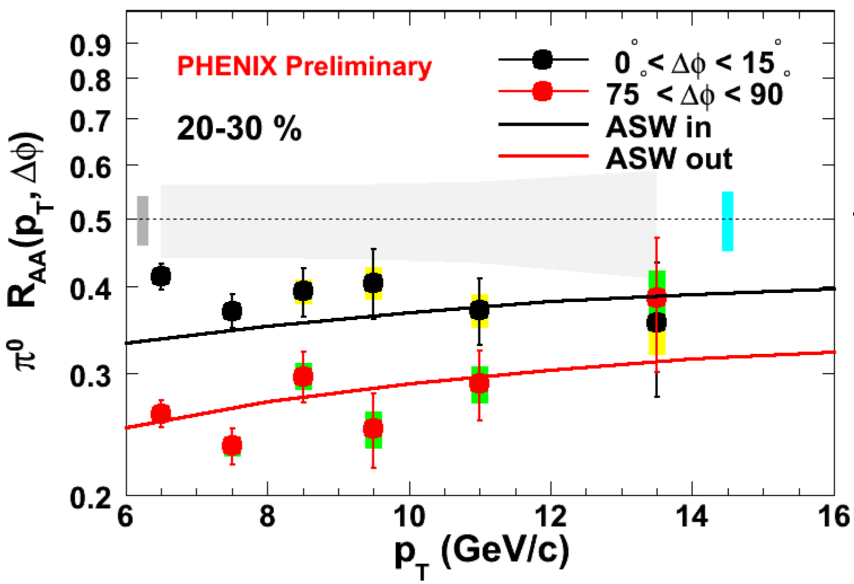


● in-plane

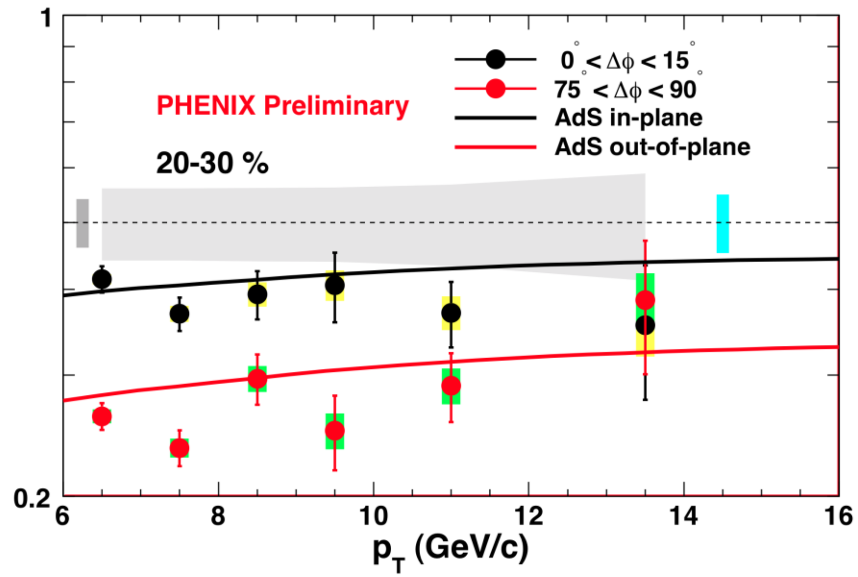
● out-of-plane

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

pQCD model

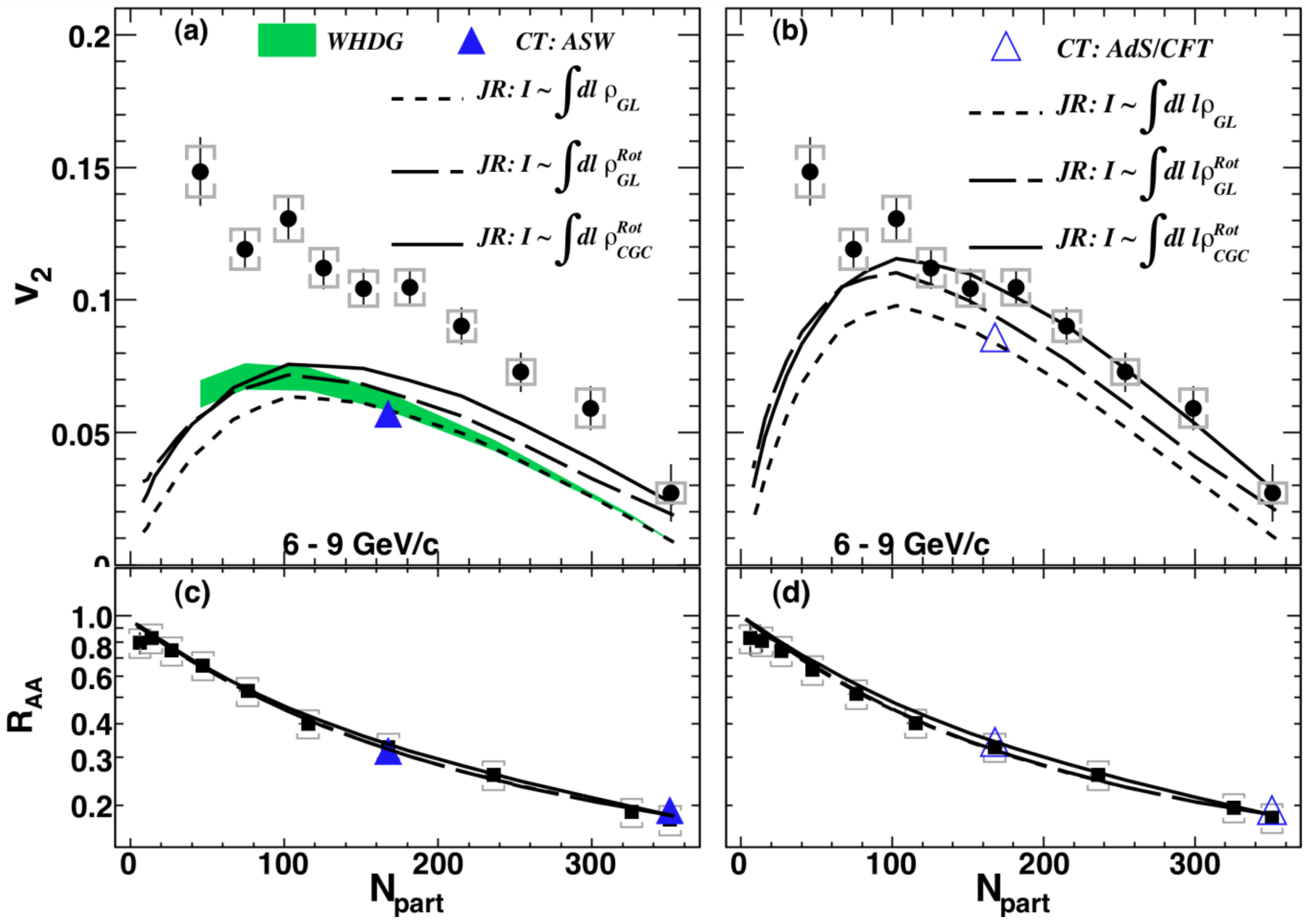


hybrid model



Predictions for v_2

pQCD model | hybrid model



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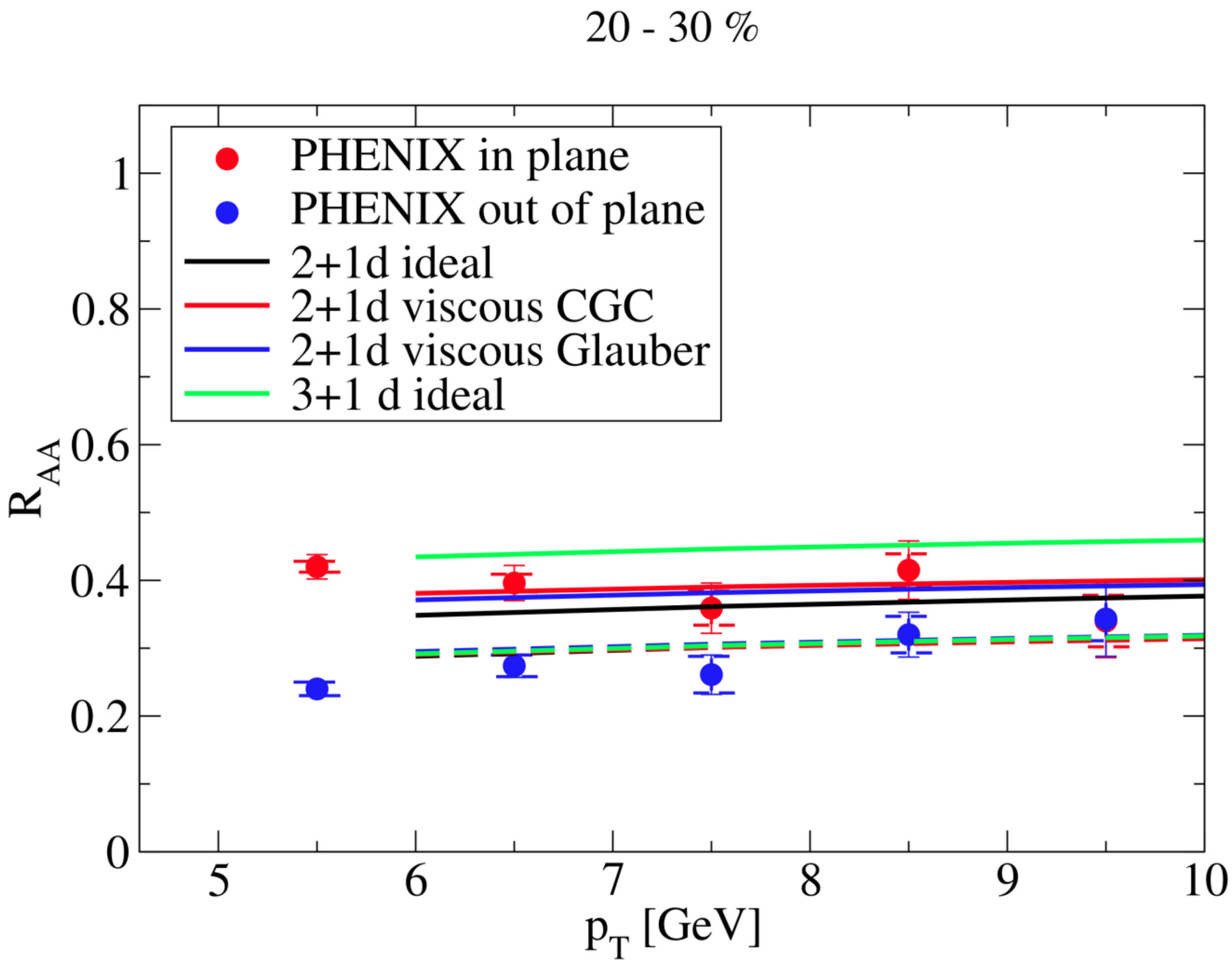
Dependence on hydro model



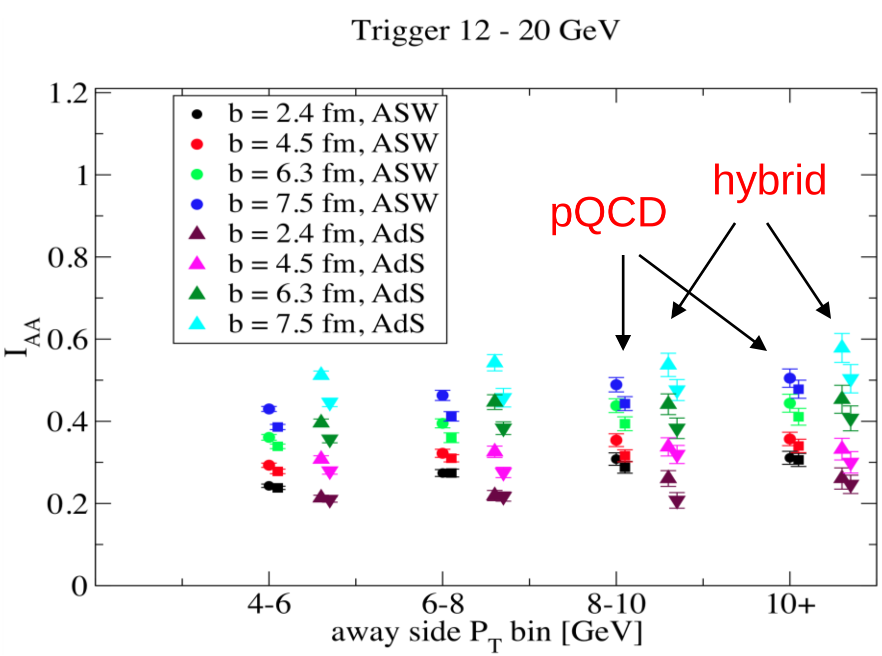
Heinz, Holopainen, Renk and Shen, work in progress

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 $\hat{q}$
  - then the strong v_2 (and heavy-quark suppression) are not natural
  - however this approach can still be improved

- A hybrid formalism 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 according to AdS/CFT results

- Comparison with the data
  - one-parameter fit to R_{AA} for central collisions good with both models
  - differences seen for path-length dependent observables
  - $R_{AA}(\Delta\Phi)$ and v_2 data seem to favor a strong-coupling scenario for the plasma, but I_{AA} measurements are needed to confirm this