Jet shape modifications in holographic dijet systems

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based on J. Brewer, AS, W. van der Schee, 1809.10695

- QGP is a novel state of matter prodcued in HIC and successfully described by the equations of relativistic hydrodynamics;
- QGP is strongly interacting, e.g. η/s tends to the limiting value as is expected for *a strongly interacting* system;
- Jets are main available probes of the plasma;
- A jet could be treated perturbatively (ingnoring the first point);
- One could use holographic duals turning to the strongly coupled regime (ignoring everything else);

and I will present recent result in our model incorporating insights from both perspectives.

AdS/CFT is a beautiful tool to deal with $N = 4$ SYM in the strong coupling limit which shares some properties with QCD in the same regime.

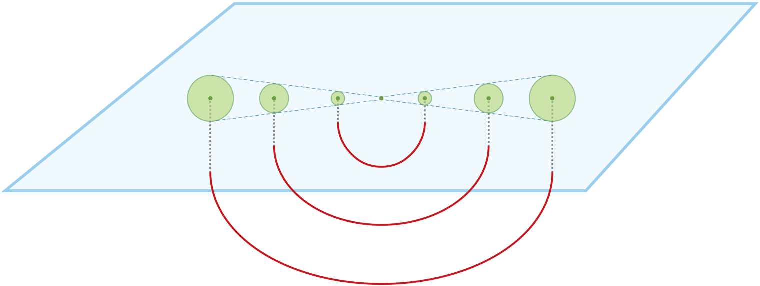
Using holography involves some caveats:

- Infinite coupling limit (while QCD is at an intermediate regime);
- No confinement in SYM (not a problem with plasma);

However it is useful in other aspects:

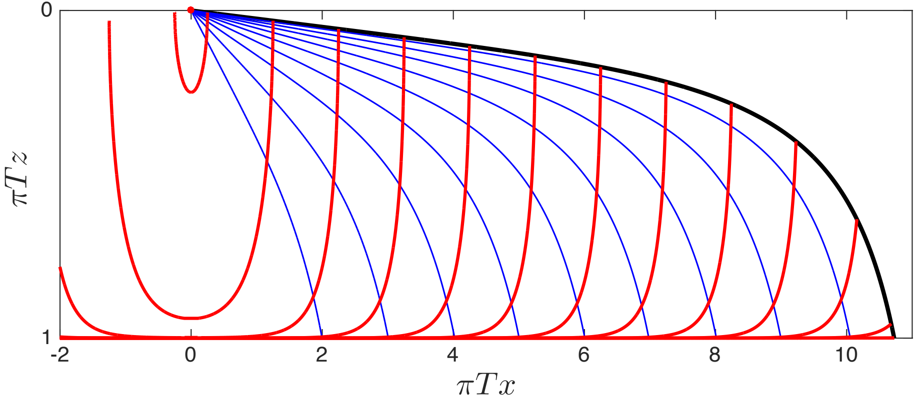
- A method to treat strongly interacting media;
- Allow improved models involving some aspects of pQCD;

What is the jet proxy in the dual theory?



A quark is dual to the end point of a string in the bulk[2] and the depth in the bulk corresponds to *the size of the energy cloud* surrounding the quark in the boundary theory.

[2] see e.g. K. Jensen et al., 2008; L. Yaffe et al., 2008.



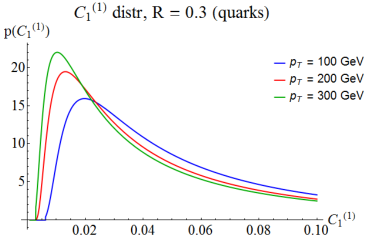
With this jet model energy approximately propagates along null geodesics. Notice that a jet *with a wider opening angle*, corresponding to a greater initial downward angle of the end point trajectory σ_0, loses more energy.

P. Chesler, K. Rajagopal, 2015

To mimic *pp* collisions we choose the energy distribution E^{-6} and take the result from pQCD for the angle distribution[3]:

$$C_1^{(\alpha)} = \sum_{i,j} z_i z_j \left(\frac{|\theta_{ij}|}{R} \right)^{\alpha}$$

z_i-fraction of jet energy,
θ_{ij} - angle between particles,
R - jet radius parameter.



Some free parameters:

$$\boldsymbol{C_1^{(1)} = a\sigma_0 \quad , \quad T_{SYM} = bT_{QCD}}$$

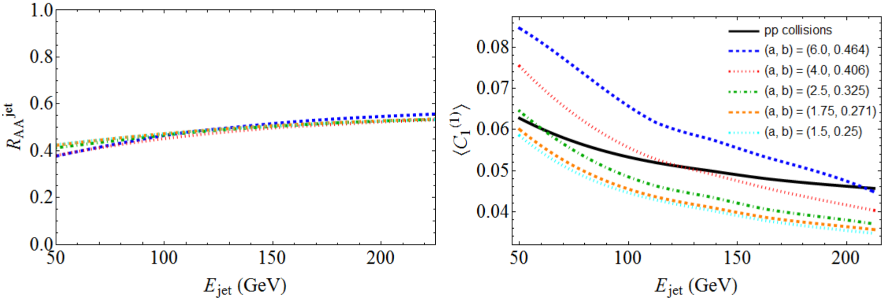
[3] A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, 2014.

For $T(x_\mu)$ we assume boost invariant longitudinal expansion and use a simplified blast-wave expression for the transverse expansion[4]. Thus we need to analyze only jets with zero rapidity.

The procedure:

- Generate an initial set of opening angles and energies;
- Generate an initial set of transverse positions;
- Let each jet to propagate through the prepared plasma droplet;
- Find the energy and the opening angle for each jet at the moment of freeze-out (region with $T = 175\text{MeV}$);
- Scan the parameter space sorting energies/angles;
- Compare initial and final distribution;

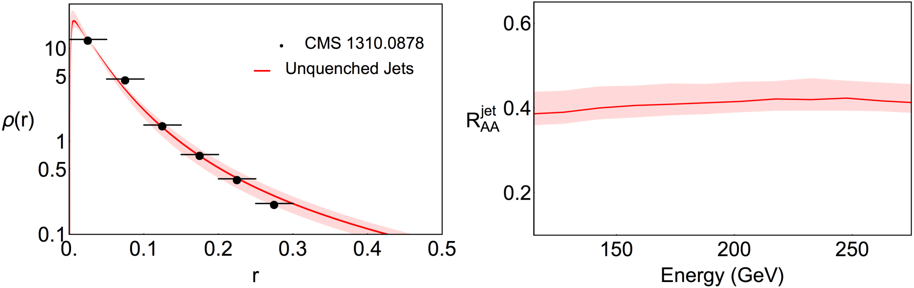
[4] A. Ficnar, S. Gubser, M. Gyulassy, 2014.



- Here R_{AA}^{jet} is the ratio of the number of jets with a given energy after propagation through the plasma to that in the initial ensemble.
- The combinations of (a, b) are chosen to keep R_{AA}^{jet} the same.

K. Rajagopal, AS, W. van der Schee, PRL, 2016

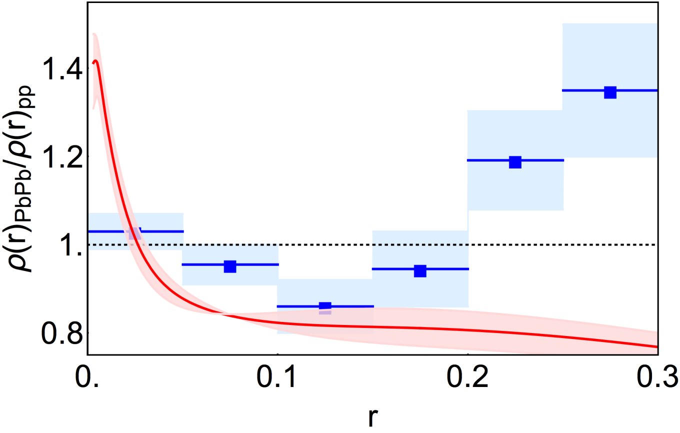
Fitting pp-shape and R_{AA} by the free parameters



$$p_T > 100\text{GeV} \quad , \quad 0.3 < |\eta| < 2 \quad , \quad R = 0.3$$
$$a = 2 \quad , \quad b = 0.21$$

J. Brewer, K. Rajagopal, AS, W. van der Schee, JHEP, 2018

The jet shape modification

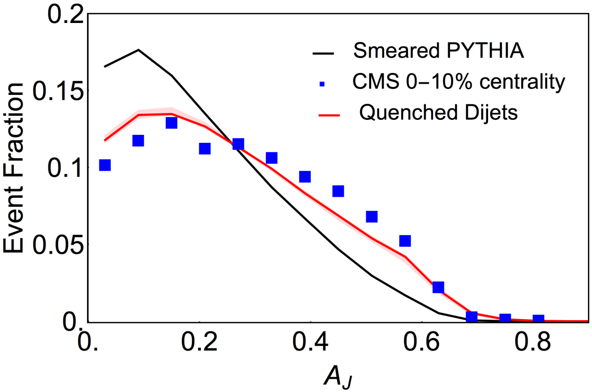


Large r behavior requires study of the medium backreaction.

J. Brewer, K. Rajagopal, AS, W. van der Schee, JHEP, 2018

- One of the most famous observables showing the strongly interacting nature of QGP is the increased imbalance of energies in a dijet system;
- This is characterized by the modification of the dijet asymmetry defined as $A_J = \frac{p_1 - p_2}{p_1 + p_2}$ where $p_{1,2}$ are transverse momenta of the jets;
- The energy loss clearly depends on the path length of a jet through the medium;
- The energy loss also fluctuates from jet to jet, say due to variation of opening angles in our model;

The dijet asymmetry modification in the hybrid holographic model

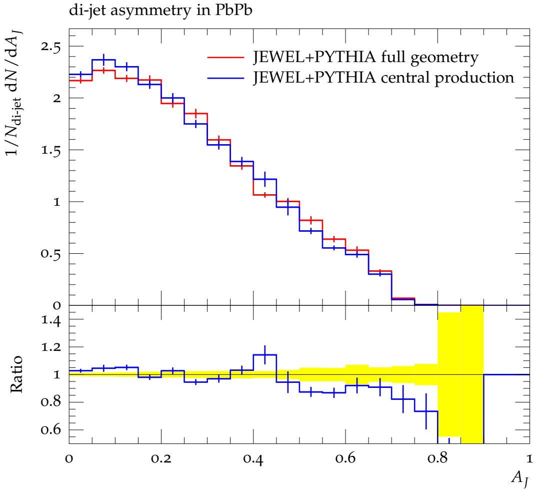


with transverse momentum cuts $(p_1, p_2) > (120, 30) GeV$.

Data points and PYTHIA+HYDJET: CMS 1202.5022

J. Brewer, K. Rajagopal, AS, W. van der Schee, JHEP, 2018

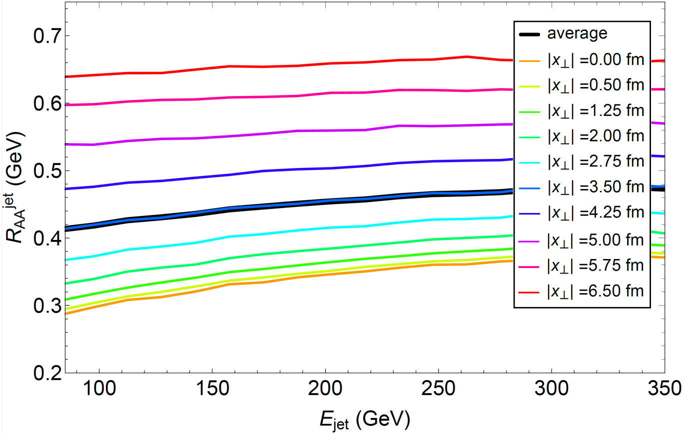
Strikingly, it was shown[5] that the energy loss fluctuations *can explain the dijet asymmetry* observed in HIC even if all dijets are centrally produced.



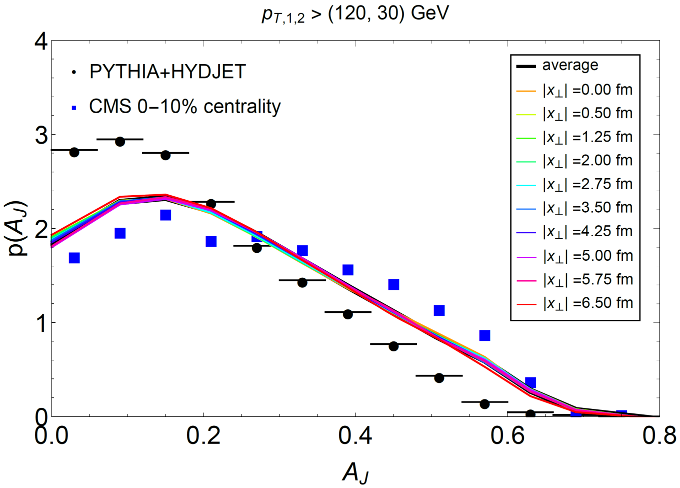
[5] J.G. Milhano, K.C. Zapp, EPJC, 2016

Can we see that in the holographic model?

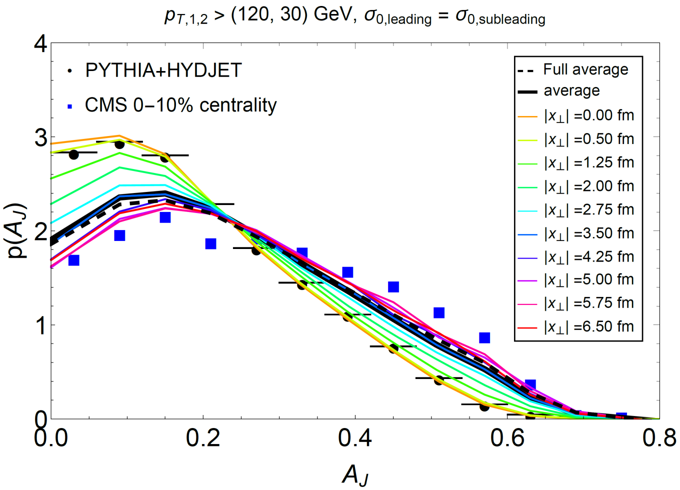
J. Brewer, AS, W. van der Schee, 1809.10695



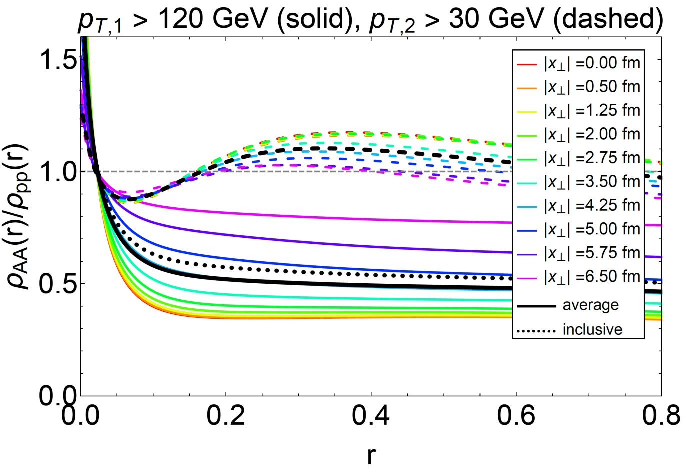
R_{AA} for different starting points of dijets in the transverse plane.



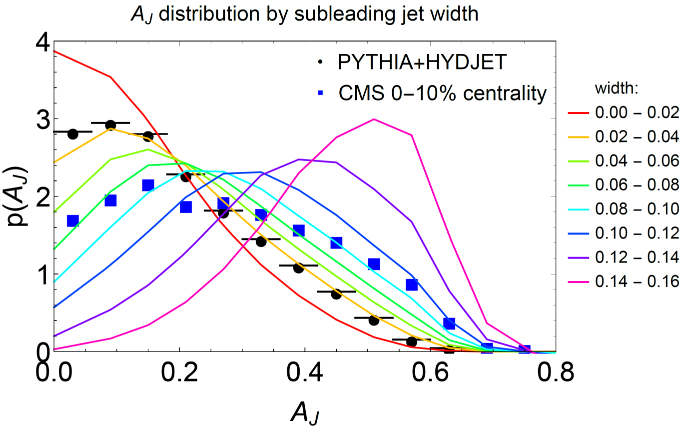
The dijet asymmetry distribution is surprisingly insensitive to the starting position, even for $|x_\perp| = 0$ with balanced path lengths.



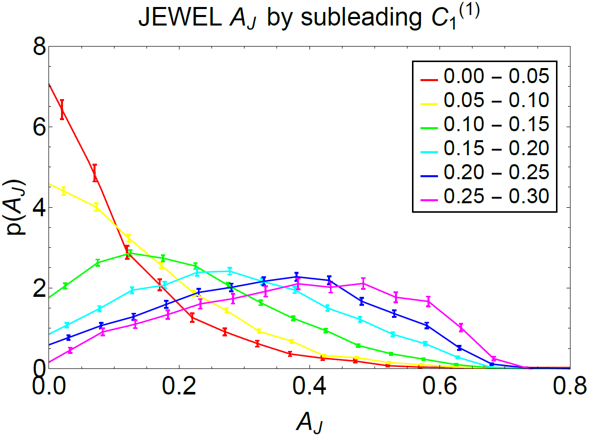
When (artificially) demanding that both jets in a dijet system have the same jet width the dijet distribution does depend on the path length.



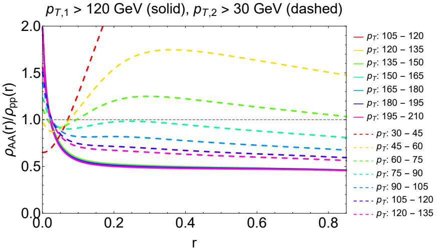
Leading/subleading jet shapes (solid/dashed) are more modified for centrally produced jets, $|x_\perp| = 0$.

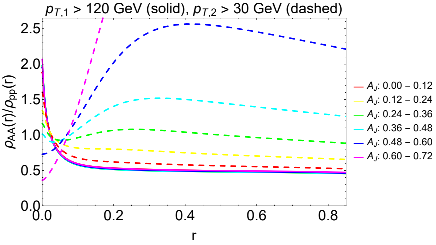


A_J binned for different widths of the subleading jets shows a strong qualitative difference for wide and narrow subleading jets.



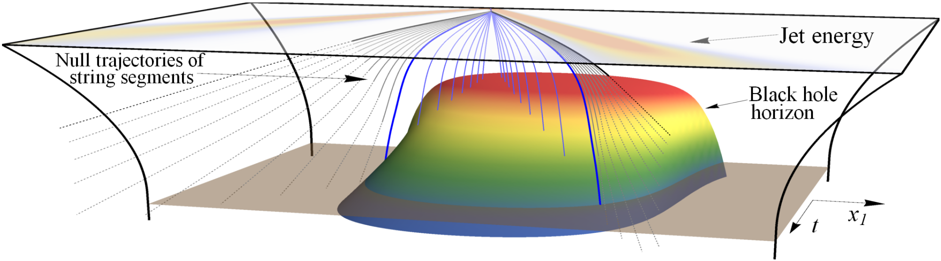
In JEWEL dijets with a wider subleading jet also have a more imbalanced A_J distribution, but for wide subleading jets the distribution is broader and for narrow subleading jets it is narrower.





Binning with the starting points is ‘theoretical’ but it is possible experimentally to select dijets according to their p_T or A_J. The leading jet shape does not depend strongly on either p_T or A_J. However, the subleading jet shapes strongly depend on both p_T and A_J, with more unbalanced dijets having wider subleading jets.

- In our model we take input from pQCD to model dijet evolution through a holographic plasma.
- We suggest two new observables: the A_J distribution binned for different subleading jet widths and the jet shape modifications of leading/subleading jets binned for different A_J.
- Both experimental measurements and different model results of these observables will shed light on the interplay of path lengths, energy loss fluctuations, jet structure and substructure.
- Our model requires future improvements and the results should be seen as qualitative: no third jets, no back reaction on the medium, no hadronization procedure, etc.



K. Rajagopal, AS, W. van der Schee, PRL, 2016

The dual of the QGP droplet:

- To the ideal hydrodynamic order the dual metric is given by

$$ds^2 = 2u_\mu dx^\mu dr + r^2(\eta_{\mu\nu} + (1 - f(r))u_\mu u_\nu)dx^\mu dx^\nu,$$

where $f(r) = 1 - (\pi T)^4/r^4$;

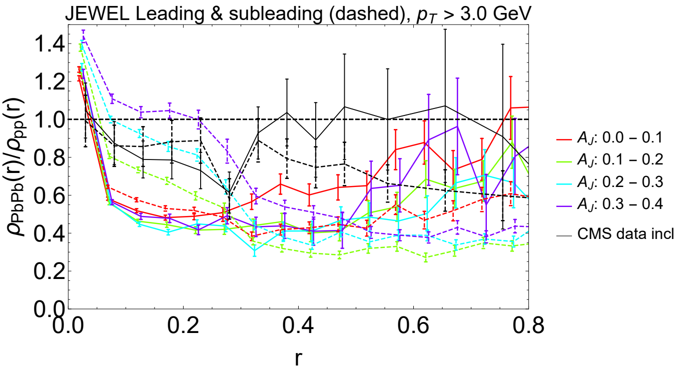
- The temperature is modeled with a simple blast-wave profile

$$T = b\left[\frac{dN_{\rm ch}}{dy}\frac{\rho_{\sf part}(\vec{x_\perp}/r_{\sf bl}(t))}{N_{\sf part}(t+t_i)\,r_{\sf bl}(t)^2}\right]^{1/3},$$

where $\rho_{\sf part}(\vec{x_\perp})$ is given by an optical Glauber model, parameters are estimated at mid-rapidity at the LHC and $r_{\sf bl}(t) = \sqrt{1 + (v_T t/R)^2}$;

- For the transverse velocity we take $u_i = -\tanh\left(\frac{4\tau}{3T}\nabla_i T\right)$;

J. Brewer, AS, W. van der Schee, 1809.10695



The JEWEL analysis confirms the dependence on A_J qualitatively, except at large r. JEWEL contains a full Monte Carlo and incorporates 3rd jets and other effects not included in our oversimplified model.

J. Brewer, AS, W. van der Schee, 1809.10695