Light flavor jets in strongly coupled plasma

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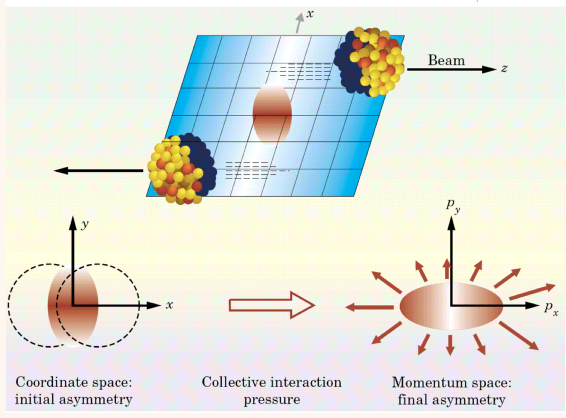
Quark-Gluon Plasma

- There are lots of evidence show that the quark-gluon plasma(QGP) produced in heacy-ion collision behaves as nearly ideal, strongly coupled fluid (sQGP).



- Rough agreement with hydrodynamic models based on perfect liquid.
  - Small shear viscosity → Strongly interacting !
    - Hydrodynamics: $\eta/s = 0.1 \sim 0.2$
    - Naive pQCD: $\eta/s = 1$
    - N=4 SYM: $\eta/s = 1/4\pi$
  - Rapid thermalization: Less than 1 fm!
- Hard Probes:
  - Jets are produced within the expanding fireball and probe the QGP.
  - effect of hot matter on properties of jets → Nuclear Modification Factor

AdS/CFT Correspondence

- N = 4 Super-Yang-Mills theory in 4d in large N_C and strong coupling limit ⇔ A Classical supergravity on the 10d $AdS_5 \times S^5$
- Studying the theory at finite temperature ⇔ Adding black hole to the geometry: AdS-Schwarzchild metric
- Fundamental quarks in theory ⇔ Open strings moving in the 10d geometry

$$ds^2 = \frac{L^2}{u^2}\left[-f(u)\,dt^2 + d\mathbf{x}^2 + \frac{du^2}{f(u)}\right],\; f(u) \equiv 1 - (u/u_h)^4 \tag{1}$$

Hawking temperature: $T \equiv \frac{1}{(\pi u_h)}$, AdS curvature radius: $L^2 T_0 = \frac{\sqrt{\lambda}}{2\pi}$
String attached to a D7-brane ending at um ⇔ Quark of mass m_Q
For light quarks, D7 brane fills all of the AdS-BH geometry ⇔ Falling Strings

Light Quark in AdS-Sch

- Dynamics of classical string : Polyakov action

$$S_P = -\frac{T_0}{2}\int d^2\sigma\sqrt{-\eta}\,\eta^{ab}\,\partial_a X^\mu \partial_b X^\nu\, G_{\mu\nu} \tag{2}$$

- Equations of motion for the embedding functions:

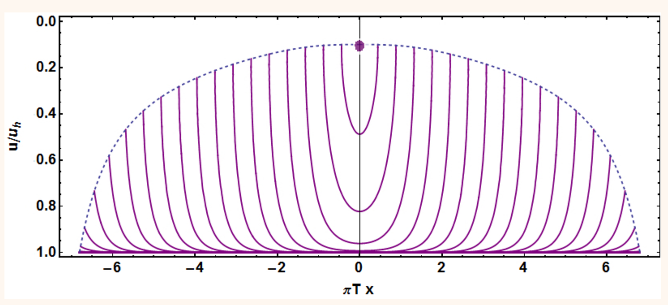
$$\nabla_a \Pi^a_\mu = -\frac{T_0}{2}\eta^{ab}\frac{\partial G_{\nu\rho}}{\partial X^\mu}\partial_a X^\nu \partial_b X^\rho \tag{3}$$

- Point like initial conditions:

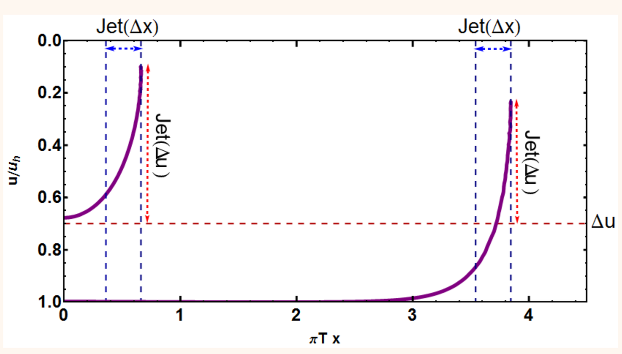
$$x(0,\sigma) = 0\,,\, u(0,\sigma) = u_c\,,\, t(0,\sigma) = t_c \tag{4}$$

- World sheet metric:

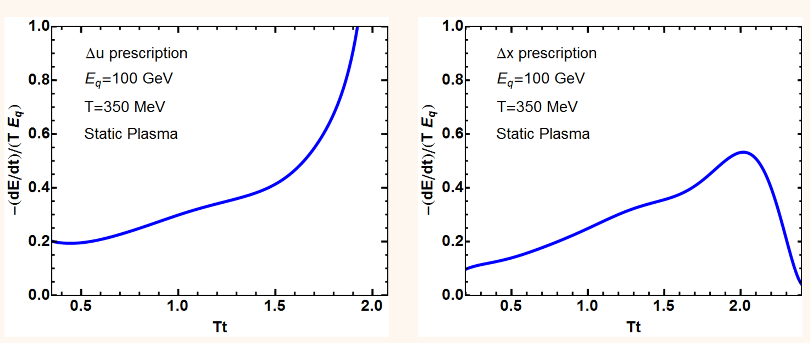
$$\|\eta_{ab}\| = \begin{pmatrix} -\Sigma(x,u) & 0 \\ 0 & \Sigma(x,u)^{-1} \end{pmatrix} \tag{5}$$



- Jet definition[1]:



Energy lost:



Nuclear Modification Factor

- Definition of R_{AA} for a single parton R[1]:

$$R^{R\to jet}_{AA} = \frac{dN^{R\to jet}_{AA}(p_T)/dp_T}{N_{bin}dN^{R\to jet}_{pp}(p_T)/dp_T}. \tag{6}$$

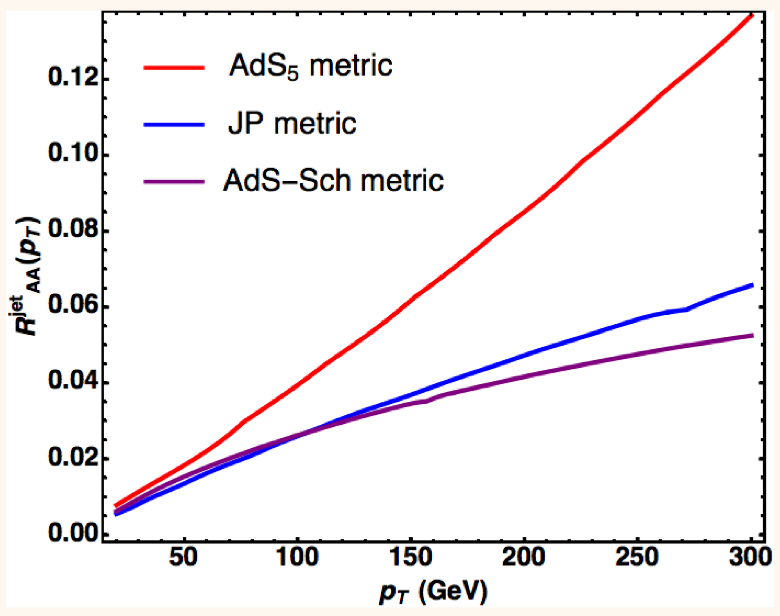
- Considering both quarks and gluons jets and a power low production spectrum comes from pQCD:

$$R^{R\to jet}_{AA}(p_T) = \left\langle\int_0^{L_{max}}\frac{dl}{L_{max}}\left(1 - \epsilon^R(p_T, l, T)\right)^{n_R(p_T)-1}\right\rangle. \tag{7}$$

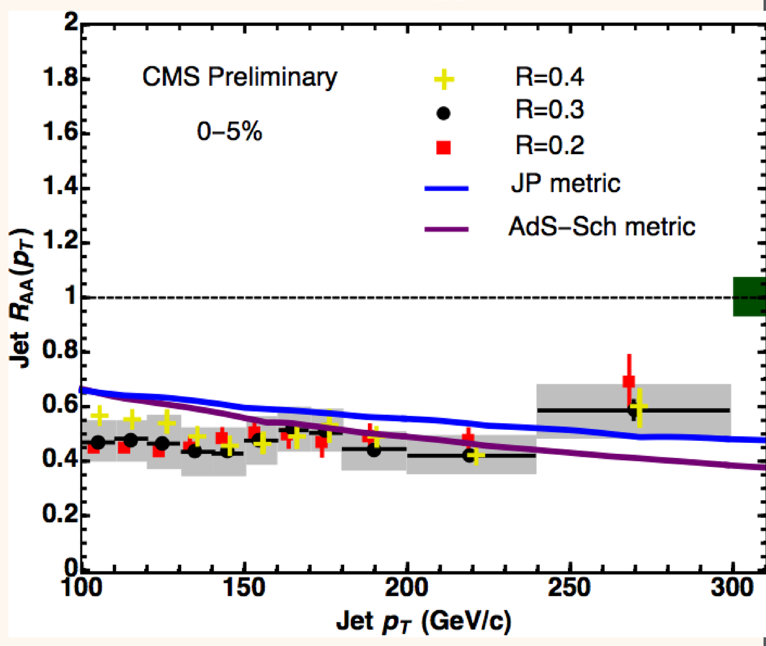
angular brackets denote a geometric average. We use the most simple toy model for the geometry of the nucleus, taking it to be a 1D object of uniform density of total length $L_{max} = 14fm$.

Results: Jet R_{AA}

- R_{AA} using our jet prescription[1]:



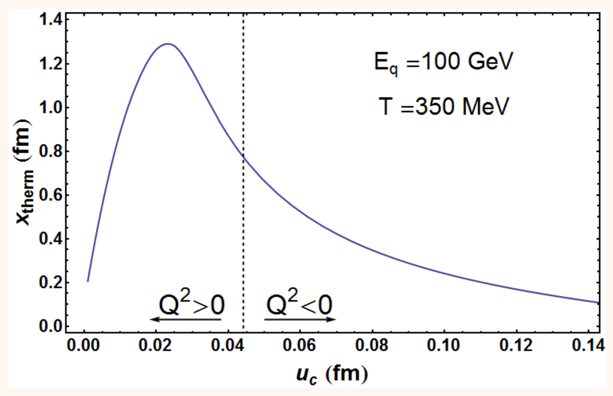
Renormalized R_{AA}:



For such a simple energy loss calculation, our results are in surprisingly good agreement with the preliminary CMS measurement.

Energy-Momentum Tensor

- String dynamics highly depend to the initial conditions[1].
- Further progress in describing experimental results will require significant advances in the understanding of string initial conditions and a better jet definition.



- We can likely accomplish both goals by computing the energy-momentum tensor associated with the propagation of the classical string solution. The energy density on the boundary at a space-time point $(t_b, \mathbf{r_b})$ can be obtained by convolution of the bulk energy-momentum tensor $t^{\mu\nu}$ with the graviton bulk-to-boundary propagator. The final result can be summarized as [2] :

$$\mathcal{E}(t_b, \mathbf{r_b}) = \mathcal{E}_\mathcal{A}(t_b, \mathbf{r_b}) + \mathcal{E}_\mathcal{B}(t_b, \mathbf{r_b}), \tag{8}$$

where

$$\mathcal{E}_\mathcal{A}(t_b, \mathbf{r_b}) = \frac{2L^3}{\pi}\int d^4r\,\frac{du}{u^2}\,\Theta(t_b - t)\,\delta''(W)\times [u(2t_{00} - t_{55}) - (t_b - t)t_{05} + (x_b - x)^i t_{i5}], \tag{9}$$

and

$$\mathcal{E}_\mathcal{B}(t_b, \mathbf{r_b}) = \frac{2L^3}{3\pi}\int d^4r\,\frac{du}{u}\,\Theta(t_b - t)\,\delta'''(W)\times [|\mathbf{r_b} - \mathbf{r}|^2(2t_{00} - 2t_{55} + t_{ii}) - 3(x_b - x)^i(x_b - x)^j t_{ij}]. \tag{10}$$

At time t, the bulk excitation localized at (t, r) emits a gravitational wave δG_{MN} which propagates through AdS_5 at the respective speed of light up to the measurement point $(t_b, \mathbf{r_b})$ on the boundary. The δ function in the integrand represents the support of the retarded bulk-to-boundary propagator for the Einstein equations in AdS_5. Its argument follows from causality together with the condition of propagation at the 5D speed of light, for both the bulk excitation and the gravitational wave.

- Simple example: Energy density on the boundary of a massless point particle falling through a null geodesic inside the bulk[3,4]:

$$\mathcal{E}(t_b, r_b) = \frac{E_0}{2\pi\gamma^4}\frac{(t_b + u_c\gamma)^2}{(t_b + u_c\gamma - v(x_b + u_c v\gamma))^3}\times \delta\left((t_b + u_c\gamma)^2 - x^2_{\perp b} - (x_b + u_c v\gamma)^2\right). \tag{11}$$

- Idea: String can be considered as sum of the point particles falling through null geodesics inside the bulk. Calculations are still in progress!

References

[1] R. Morad and W. Horowitz JHEP 1411 (2014) 017.
[2] C. Athanasiou, P. M. Chesler, H. Liu, D. Nickel, and K. Rajagopal Phys.Rev. D81 126001.
[3] Y. Hatta, E. Iancu, A. Mueller, and D. Triantafyllopoulos JHEP 1212 (2012) 114.
[4] P. M. Chesler and K. Rajagopal Phys.Rev. D90 (2014) 025033.

Acknowledgments

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