Energy density of light quark jet using AdS/CFT

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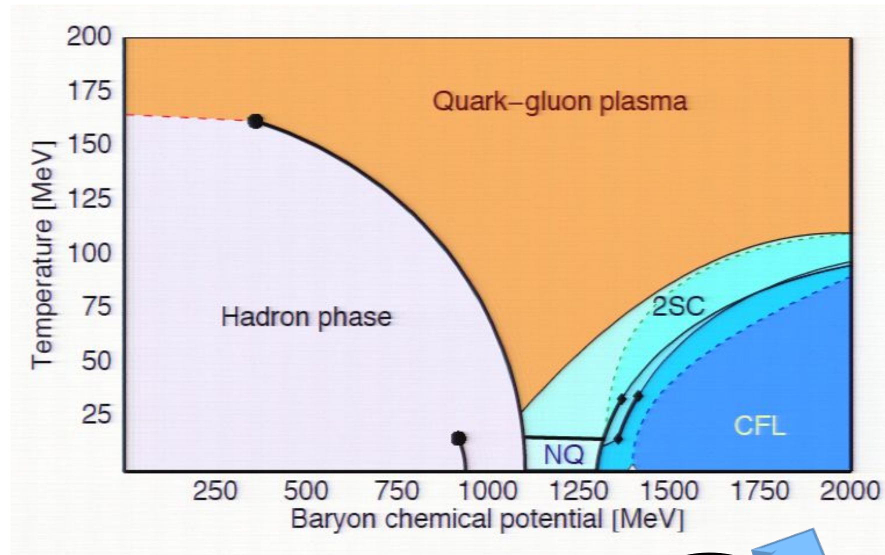
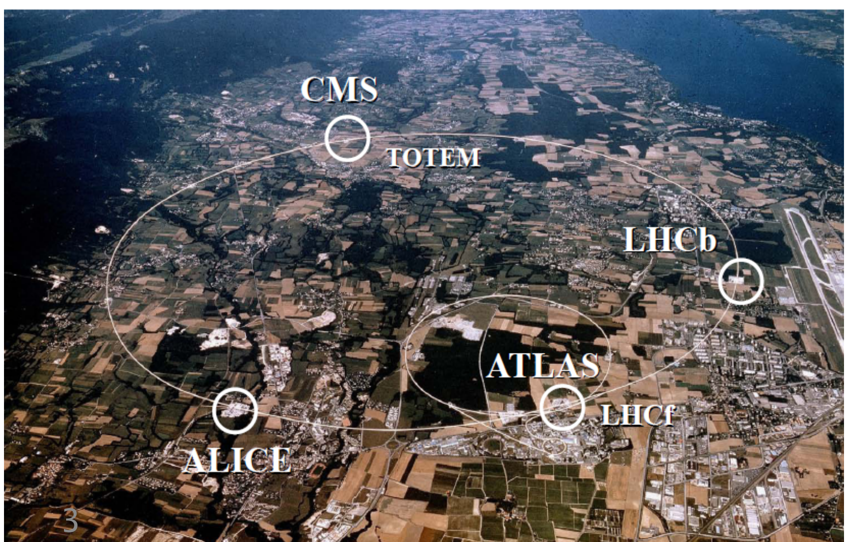
Outline

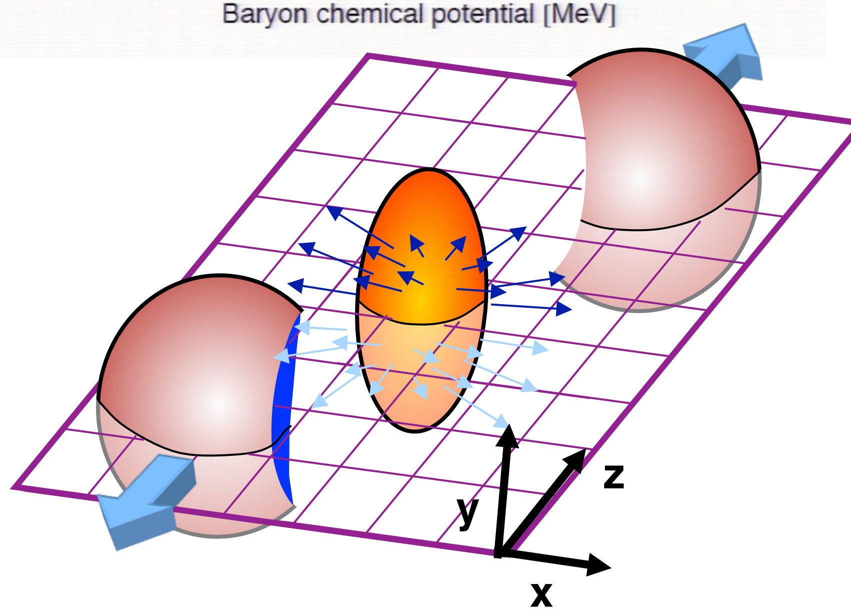
- Quark-Gluon Plasma
- AdS/CFT Correspondence
- Jets
- Light Quark Jet in String Setup
- N=4 SYM Stress Tensor

Quark-Gluon Plasma

Quark-Gluon Plasma is formed in Heavy Ion Collision at RHIC and LHC.







Quark-Gluon Plasma

Shear viscosity

Hydrodynamics prediction: $\frac{\eta}{s} < 0.1 - 0.2$ Teaney (2003)

Lattice: $\frac{\eta}{s} = 0.13 \pm 0.03$, at $T=1.65\ T_C$ Meyer (2007)

Naive pQCD: $\frac{\eta}{s} \sim 1$

N=4 SYM: $\frac{\eta}{s} = \frac{1}{4\pi} \approx 0.08$ Policastro, Son, and Starinets (2001)

AdS/CFT predicts a universal lower bound for the ratio of shear viscosity to entropy.

Kovton, Son and Starinets (2003)

Rapid thermalization

Chesler and Yaffe (2010)
Janik et all (2012),(2014)

AdS/CFT Correspondence

Maldacena *Conjecture*

Classical gravity on AdS_{d+1}

Strongly coupled d - dimensional CFT which lives on boundary of AdS_{d+1}

Maldacena 98

Duality unproven, but many consistency checks performed.

AdS/CFT Correspondence

AdS/CFT Dictionary

CFT_d	AdS_{d+1}
Conformal symmetry SO(2,d)	Isometry SO(2,d)
Charges	Charges
Global Symmetry "G"	Gauge Symmetry "G"
Local Operators	Quantum Fields
$\left\langle e^{\int d^4x \phi_0(\vec{x}) O(\vec{x})} \right\rangle_{\text{CFT}}$	$Z\left[\phi(\vec{x}, z=0) \equiv \phi_0(\vec{x})\right]$
Partition Function of operator	Classical Action

Gubser, Klebanov, Polyakov'98, Witten'98

AdS/CFT Correspondence

Anti-de-Sitter space (AdS_5)

$$ds^2 = \frac{dx^\mu d\, x_\mu + du^2}{u^2}$$

string propagator in the bulk

u plays a role of inverse energy scale in 4D theory

Probing the hot matter

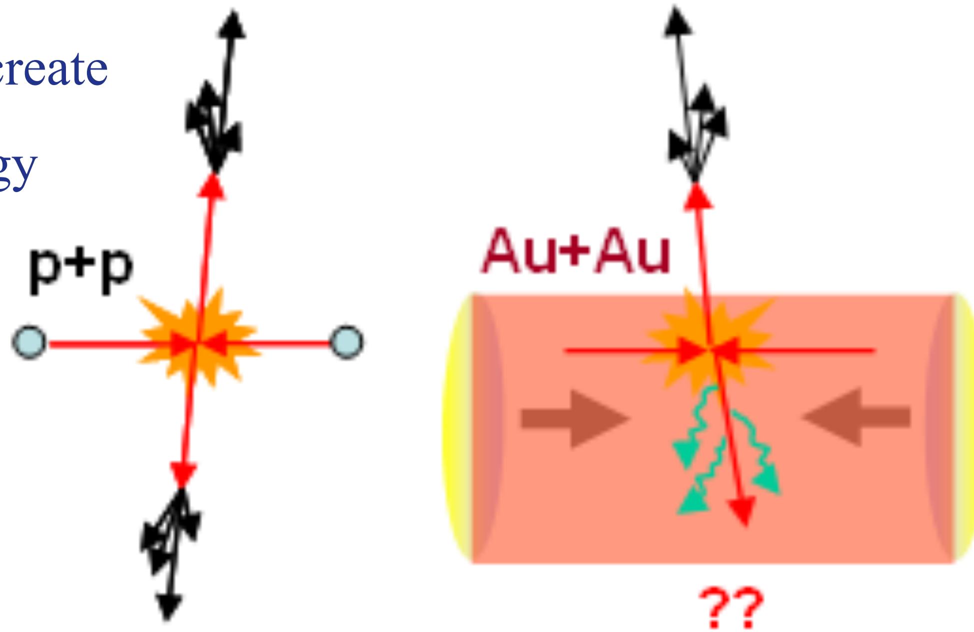
QGP exists for a few fm, making it impossible to study it using any external probes.

Use self-generated quarks/gluons/photons as probes of the medium

Hard Probes:

Jets are produced within the expanding fireball and probe the QGP.

Before they become hadronized and create jets, the scattered quarks radiate energy (~ GeV/fm) in the colored medium.



The presence of hot matter modifies the properties of jets.

Jet suppression

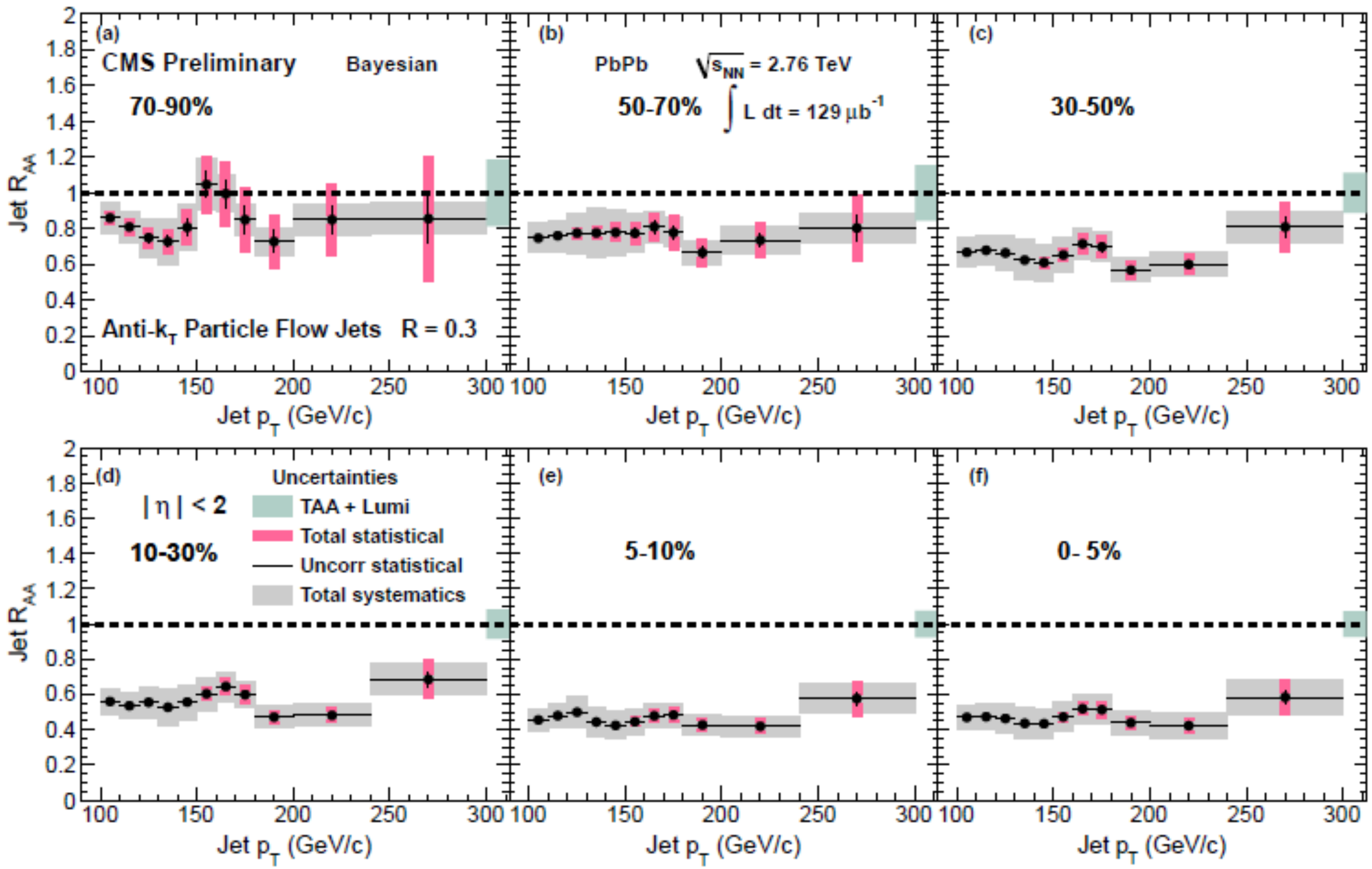
Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{\#\ \text{of particles observed at}\ p_T}{\#\ \text{of particles expected from pp collisions}}$$

CMS Preliminary data (2012)

Naively, if medium has no effect, then R_{AA} =1.

R_{AA}<1 means jet quenching



Light-Quark in string Setup

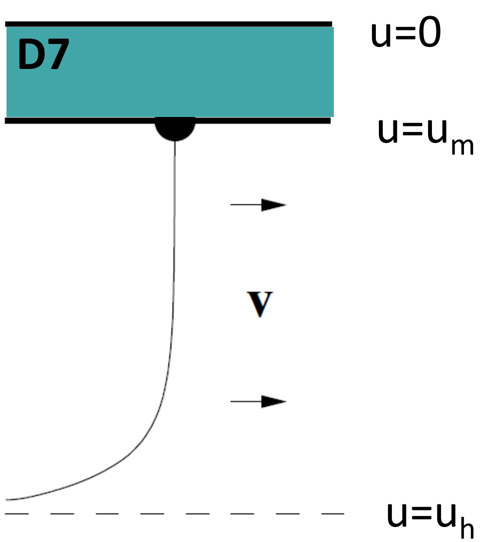
N = 4 Super-Yang-Mills theory in 4d in large N_C and strong coupling limit λ ⟷ A Classical supergravity on the 10d $AdS_5 \times S^5$

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

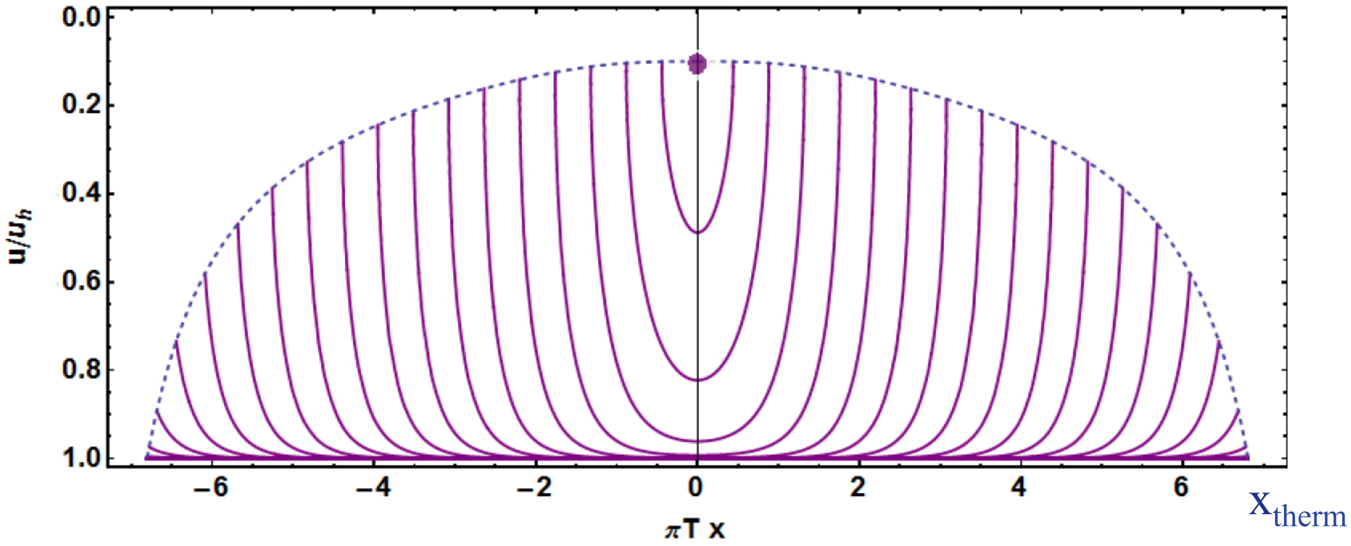
Fundamental quark is dual to a string in the bulk with an endpoint attached to a D7-brane ending at u_m.

For a massive quark at rest: $m_Q = T_0 L^2 \left(\frac{1}{u_h} - \frac{1}{u_m}\right)$



Light Quarks ⟷ **Falling Strings**

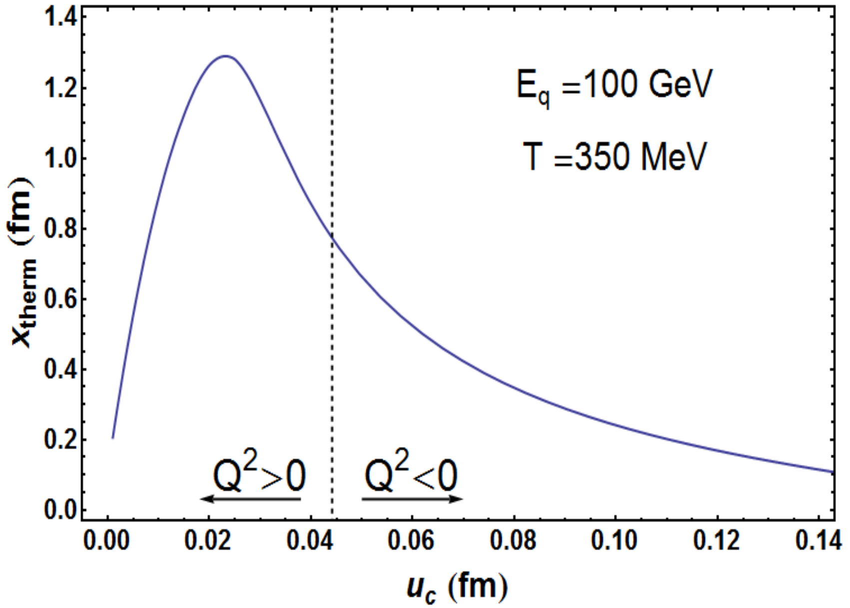
Thermalization distance



Light quark dynamics highly depends on the initial conditions of the string:

There is no known map between the string initial profiles and states in dual field theory.

The only way, is calculating the **energy-momentum tensor of the string** on the boundary and compare with the QCD results.



SYM Stress-Tensor

- Presence of string source with the following energy-momentum profile in the bulk perturb the metric:

$$t^{MN} = -\frac{T_0}{\sqrt{-G}}\sqrt{-g}g^{ab}\partial_a X^M \partial_b X^N \delta^3(\boldsymbol{r}-\boldsymbol{r}_s)$$

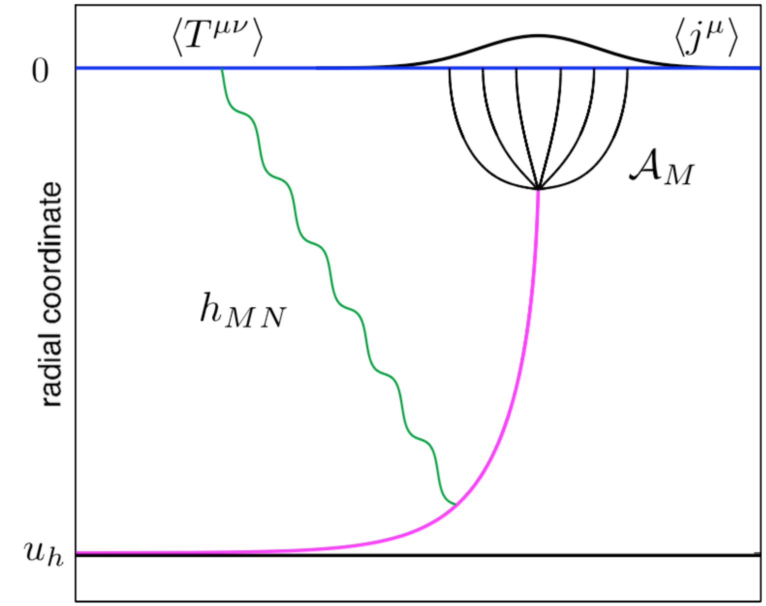
- Metric perturbation h_{MN} : $G_{MN} = G^{(0)}_{MN} + h_{MN}$

- Linearized Einstein equation for h_{MN}:

$$-D^2 h_{MN} + 2D^P D_{(M} h_{N)P} - D_M D_N h + \tfrac{8}{L^2} h_{MN}$$
$$+ \left(D^2 h - D^P D^Q h_{PQ} - \tfrac{4}{L^2} h\right) G^{(0)}_{MN} = 2\kappa_5^2\, t_{MN}\,,$$

- On-shell gravitational action: $S_G = \dfrac{1}{2\kappa_5^2}\displaystyle\int d^5x\sqrt{-G}\left(\mathcal{R} + \frac{12}{L^2}\right) + S_{GH}$

- SYM energy-momentum tensor: $T^{\mu\nu}(x) = \dfrac{2}{\sqrt{-g}}\dfrac{\delta S_G}{\delta g_{\mu\nu}(x)}$



h_{MN} has 15 degrees of freedom ⟷ **$T_{\mu\nu}$ has 5 degrees of freedom**

?

Gauge-Invariants

It is possible to construct gauge invariant quantities out of linear combinations of h_{MN} and its derivatives.

✓ **There are just 5 of them.**
✓ **Their equation of motions are completely decoupled.**

The gauge invariant which is transformed as scalar under rotation Z, can give us the energy density of the SYM stress tensor on the boundary:

$$Z'' + AZ' + BZ = S$$

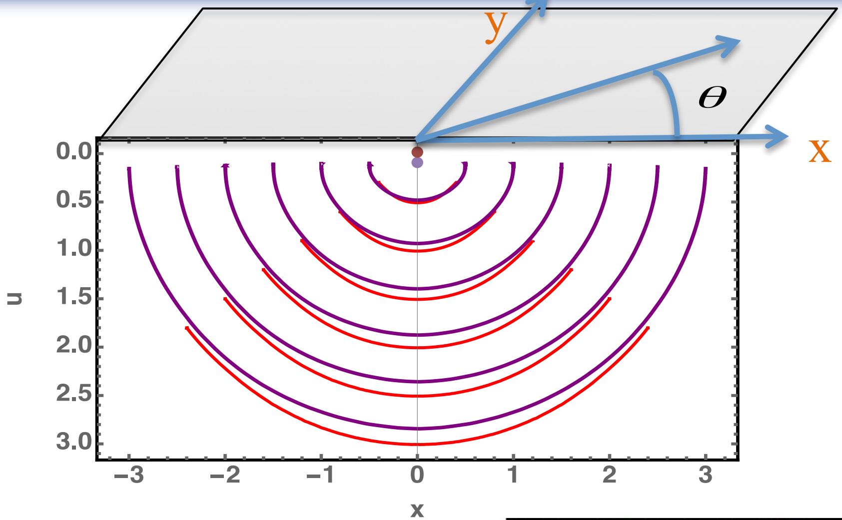
$$A \equiv -\frac{24 + 4q^2u^2 + 6f + q^2u^2 f - 30f^2}{uf\,(u^2q^2 + 6 - 6f)}, \qquad B \equiv \frac{\omega^2}{f^2} + \frac{q^2u^2(14 - 5f - q^2u^2) + 18(4 - f - 3f^2)}{u^2 f\,(q^2u^2 + 6 - 6f)}$$

$$\frac{S}{\kappa_5^2} \equiv \frac{8}{f}t'_{00} + \frac{4\,(q^2u^2 + 6 - 6f)}{3uq^2 f}(q^2\delta^{ij} - 3q^iq^j)t_{ij} + \frac{8i\omega}{f}t_{05} + \frac{8u\left[q^2\left(q^2u^2 + 6\right) - f\left(12q^2 - 9f''\right)\right]}{3f^2\left(q^2u^2 - 6f + 6\right)}t_{00} - \frac{8q^2u}{3}t_{55} - 8iq^it_{i5}$$

Asymptotic behavior of Z: $Z(u) = Z_{(2)}\,u^2 + Z_{(3)}\,u^3 + \cdots$

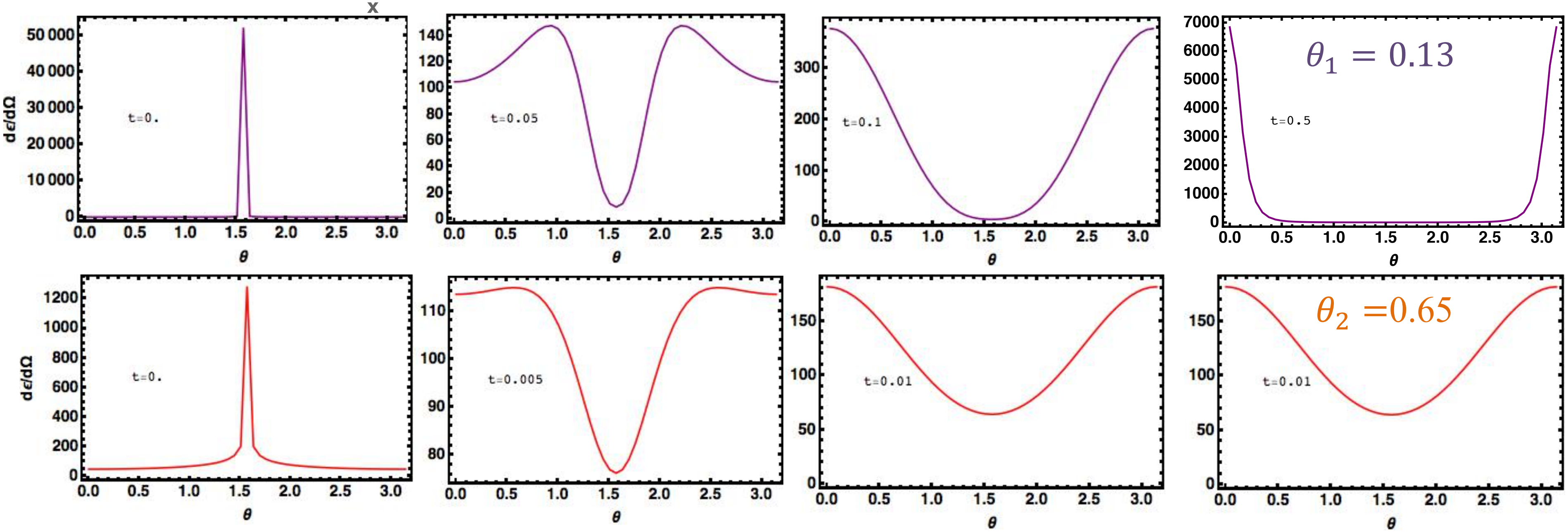
Energy density: $\mathcal{E} = -\frac{L^3}{8\kappa_5^2}Z_{(3)}$

Boundary Jet Energy Density in AdS_5



String 1 created at u_c=0.1 :
E_q=100 GeV, Q^2=176 GeV^2

String 2 created at u_c=0.01 :
E_q=100 GeV, Q^2=6000 GeV^2



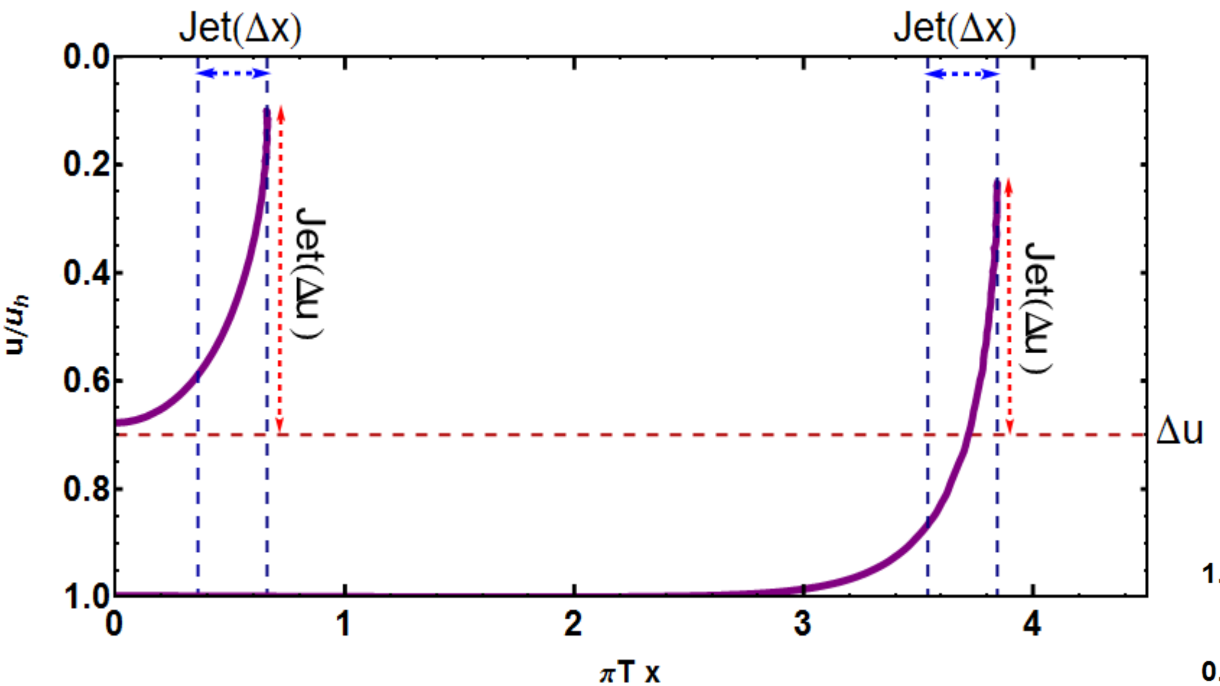
One can define the opening angle of jet: $\theta_j = ArcTan[\frac{\sqrt{Q^2}}{E_q}]$

Thank you

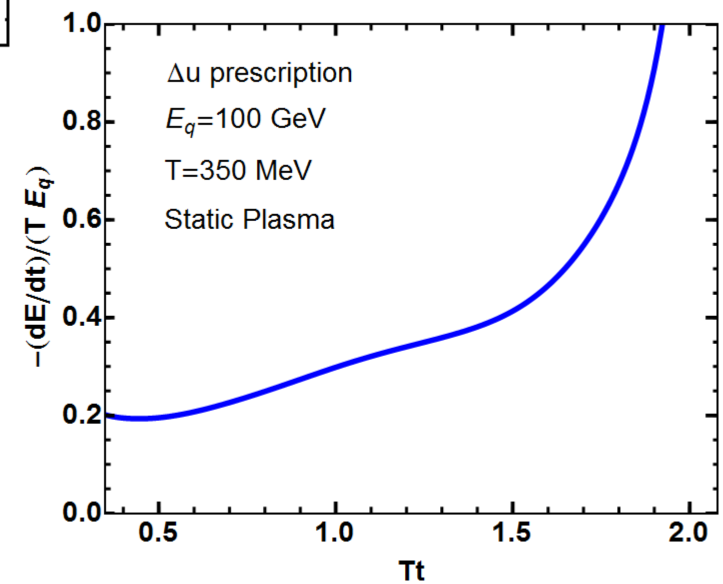
Back up slides

Jet Prescription in AdS/CFT

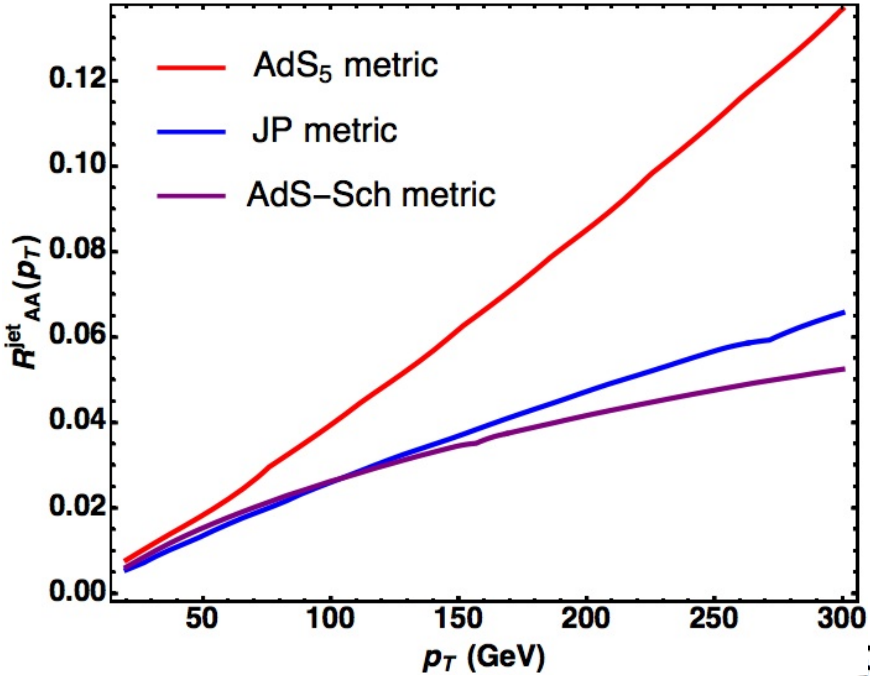
Our prescription of jet in AdS/CFT: based on separation of hard and soft sectors



Jet energy lose rate:

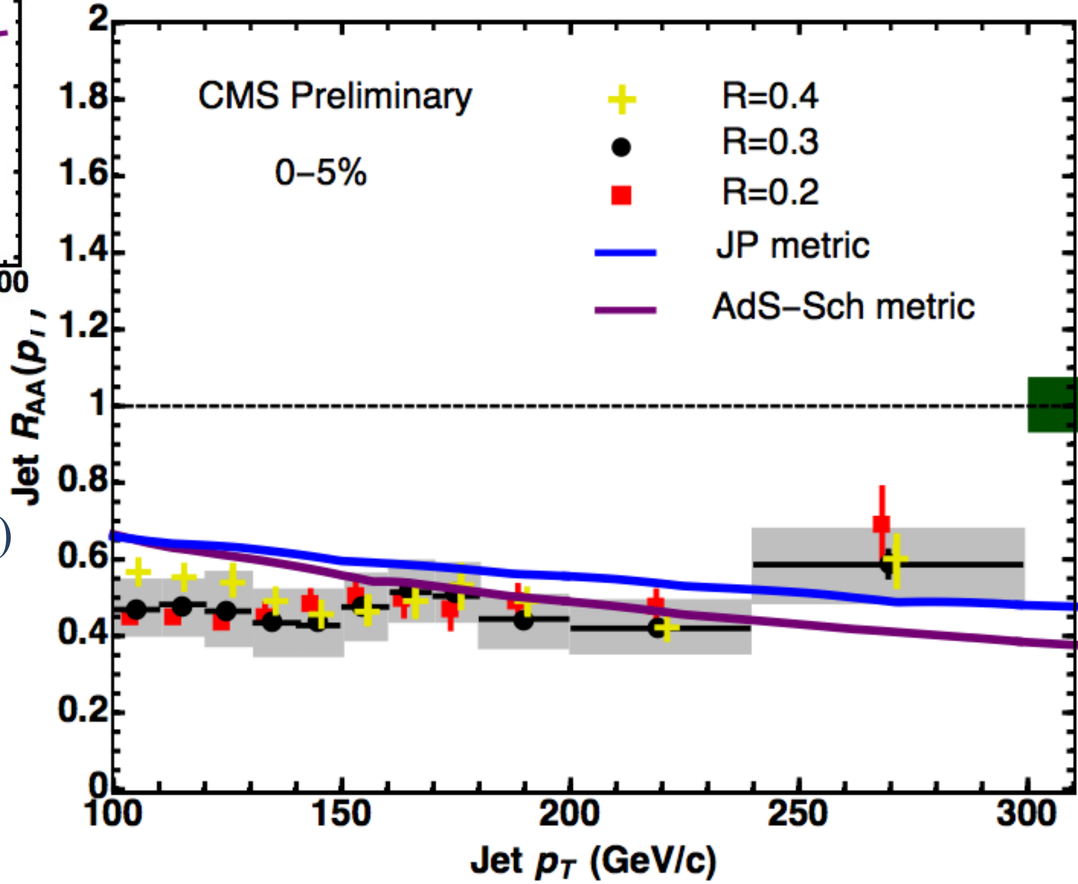


Jet Nuclear Modification Factor



We define a renormalized R_{AA} in AdS/CFT:

$$R^{jet}_{AA}(p_T)_{AdS/CFT} \equiv \frac{R^{jet}_{medium}(p_T)}{R^{jet}_{AdS_5}(p_T)}$$



$\Delta E^{sub,\,ren}(p_i, L, T) \equiv$
$\Delta E^{medium}(p_i, L, T) - \Delta E^{vacuum}(p_i, L, T)$

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