Jet Nuclear Modification Factor from AdS/CFT Correspondence

Razieh Morad

In Collaboration with Dr. W. A. Horowitz

University of Cape Town
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Kruger

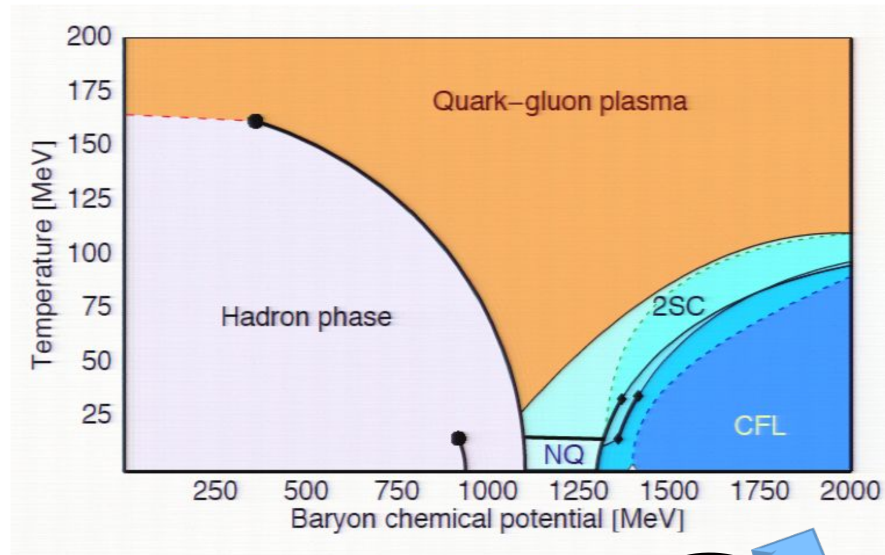
SA-CERN

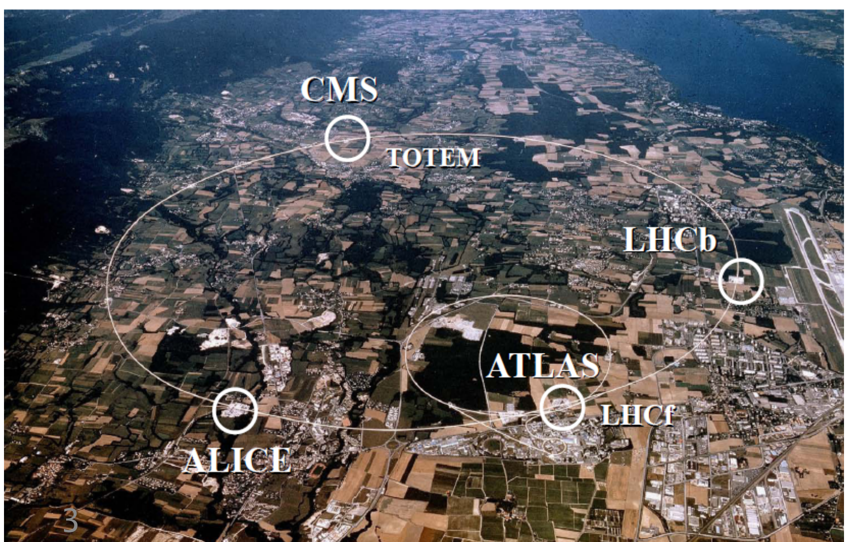
Outline

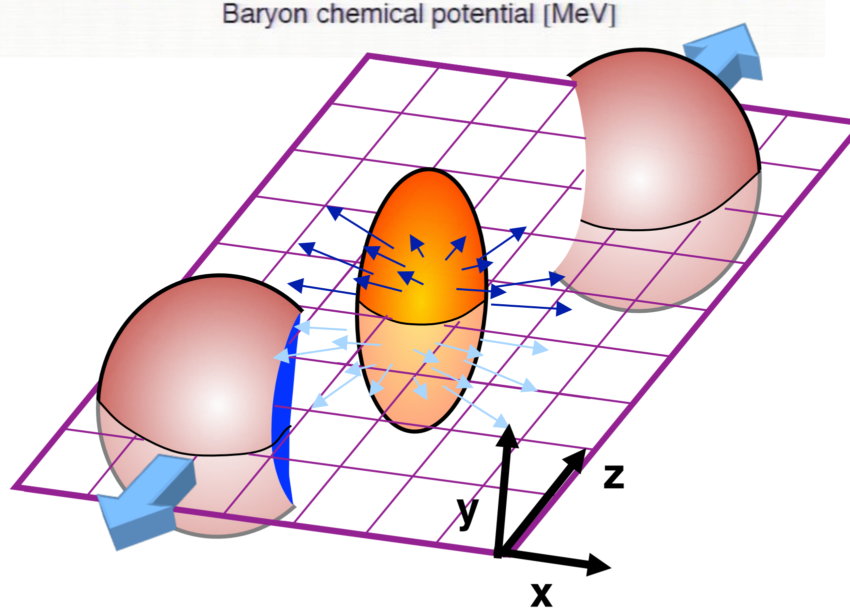
- Quark- Gluon Plasma
- AdS/CFT Correspondence
- Light Quark in AdS_5-Sch Background
- New prescription of Jets in AdS/CFT
- Energy Loss
- Nuclear Modification Factor of Jets
- Conclusion

Quark-Gluon Plasma

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



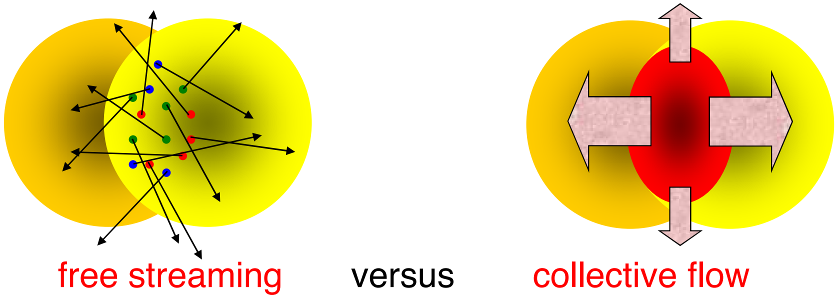




Quark-Gluon Plasma

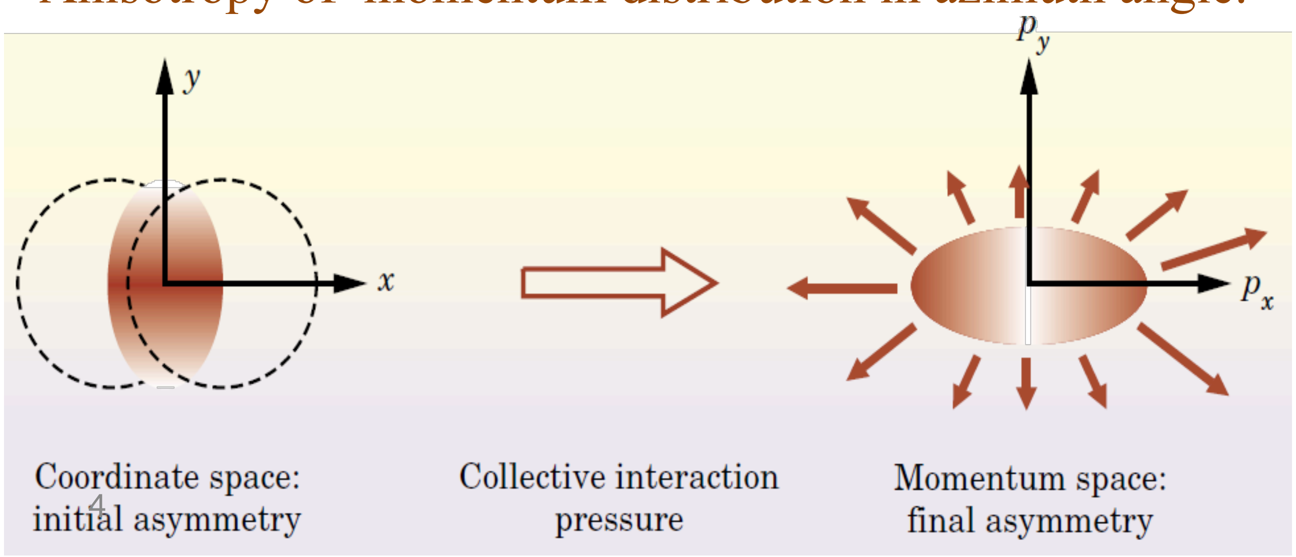
Quark-gluon fluid of RHIC behaves as nearly ideal, strongly coupled fluid (sQGP).

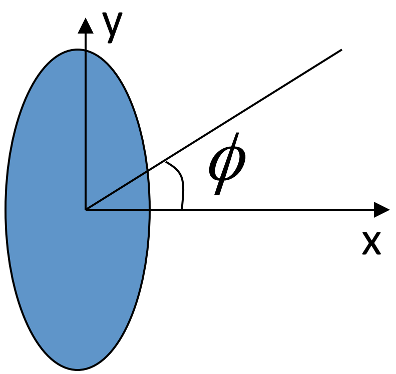
- If lots of p+p collisions plus free streaming: final state momentum uniformly distributed in azimuth angle



- If produced particles interact → Local equilibration → produce some kind of fluid → pressure gradients →collective motion

Anisotropy of momentum distribution in azimuth angle.



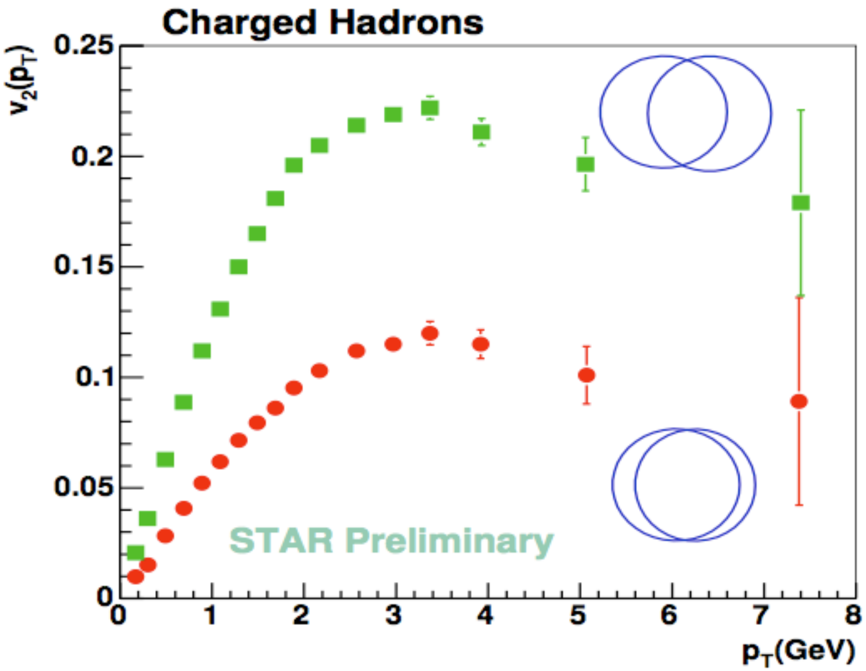


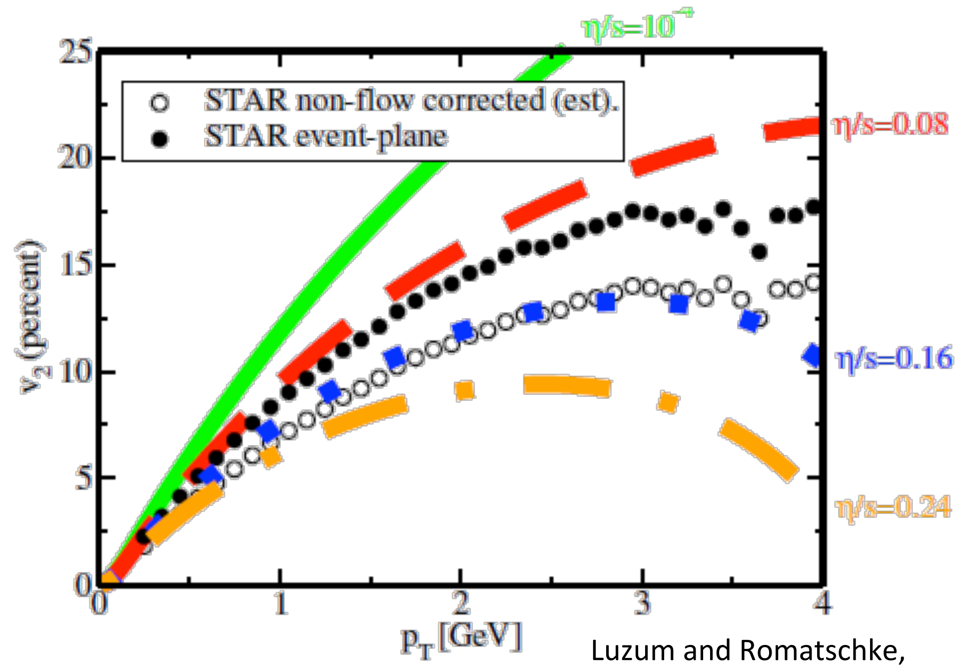
T Ludlum and L McLerran, Phys. Today 56N10 (2003)

Quark-Gluon Plasma

Elliptic flow

$$\frac{dN}{d\phi}(p_T,\phi) \propto \left[1+2\, v_2(p_T)\cos(2\phi)\right]$$





Luzum and Romatschke, Phys.Rev.C78:034915,2008

Rough agreement with hydrodynamic models based on perfect liquid.

- Small shear viscosity → Strongly interacting !
- Short thermalization time, less than 1 fm!

Quark-Gluon Plasma

Shear viscosity

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

Lattice: $\frac{\eta}{s} = 0.13 \pm 0.03, \quad \text{at } T=1.65\ T_C$ 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)

Quark-Gluon Plasma

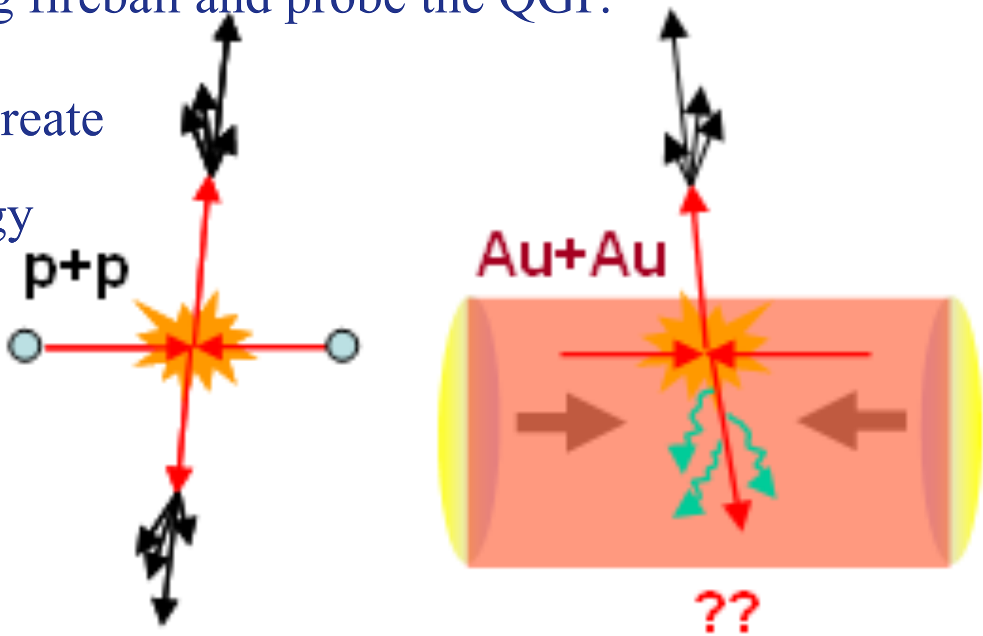
QGP exists for a few fm, making it impossible to study it using any external probes.

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.

Quark-Gluon Plasma

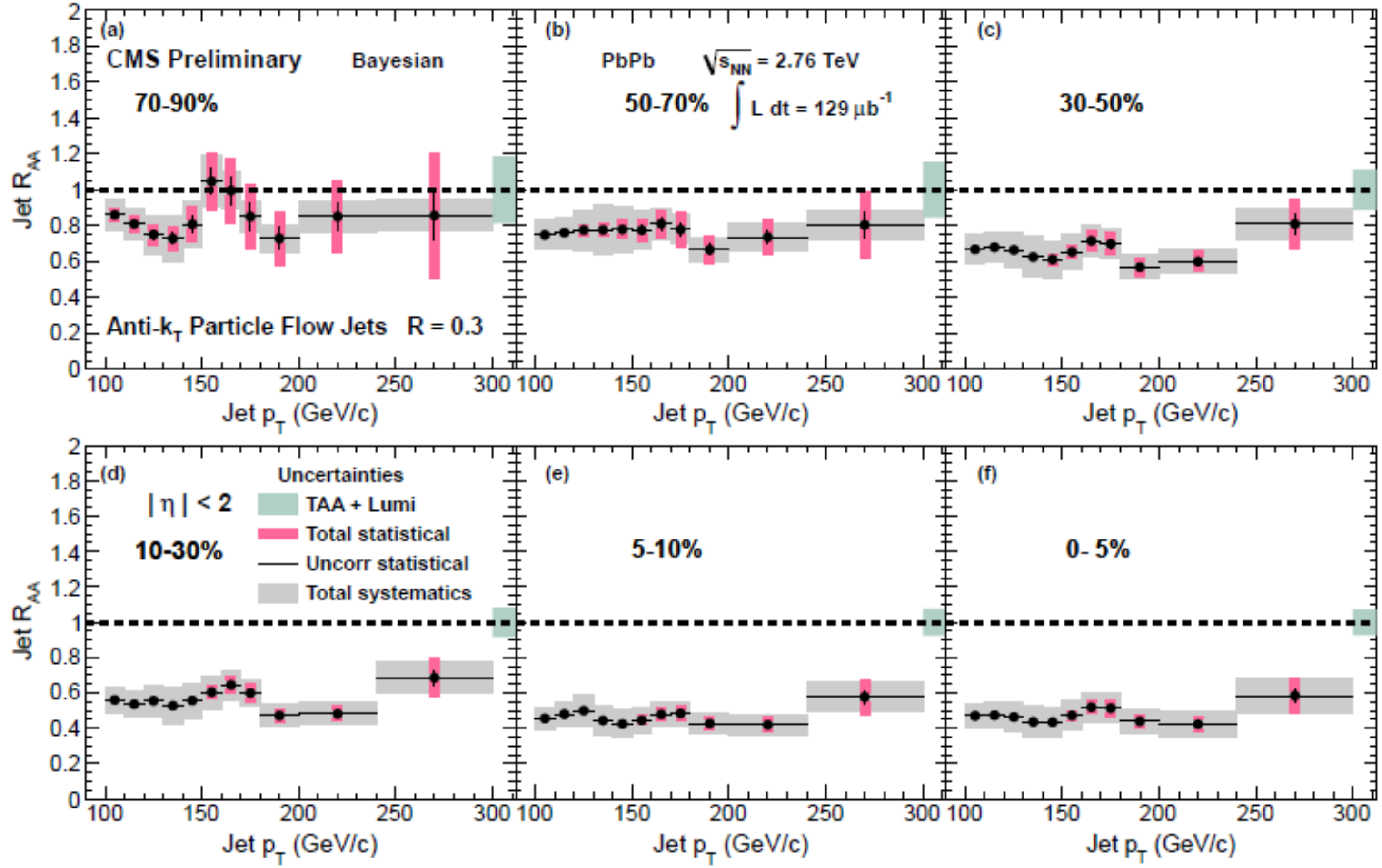
Nuclear Modification Factor:

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

CMS Preliminary data (2012)

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

R_{AA}<1 means jet quenching



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

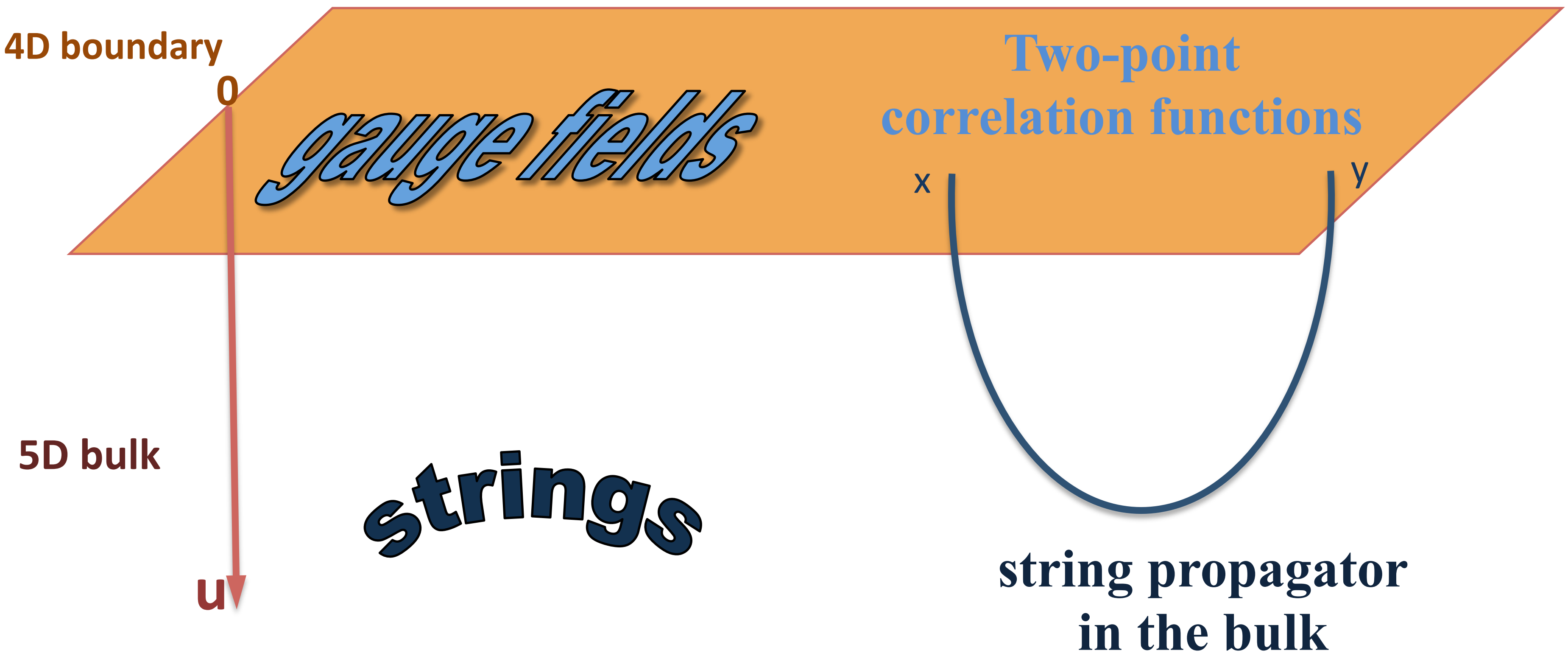
CFT_d	AdS_{d+1}
Conformal symmetry SO(2,d)	Isometry SO(2,d)
Charges	Charges
Global Symmetry “G”	Gauge Symmetry “G”
Local Operators	Quantum Fields
$\left\langle e^{\int d^4x \phi_0(\vec{x}) O(\vec{x})} \right\rangle_{\mathrm{CFT}}$	$Z\left[\phi\left(\vec{x}, z=0\right) \equiv \phi_0\left(\vec{x}\right)\right]$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

Gubser, Klebanov, Polyakov’98, Witten’98

AdS/CFT Correspondence

Anti-de-Sitter space (AdS_5)

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



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

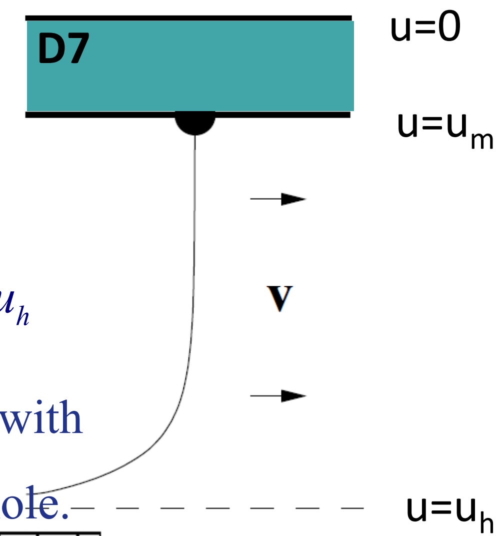
Light Quark Jets in AdS/CFT Correspondence

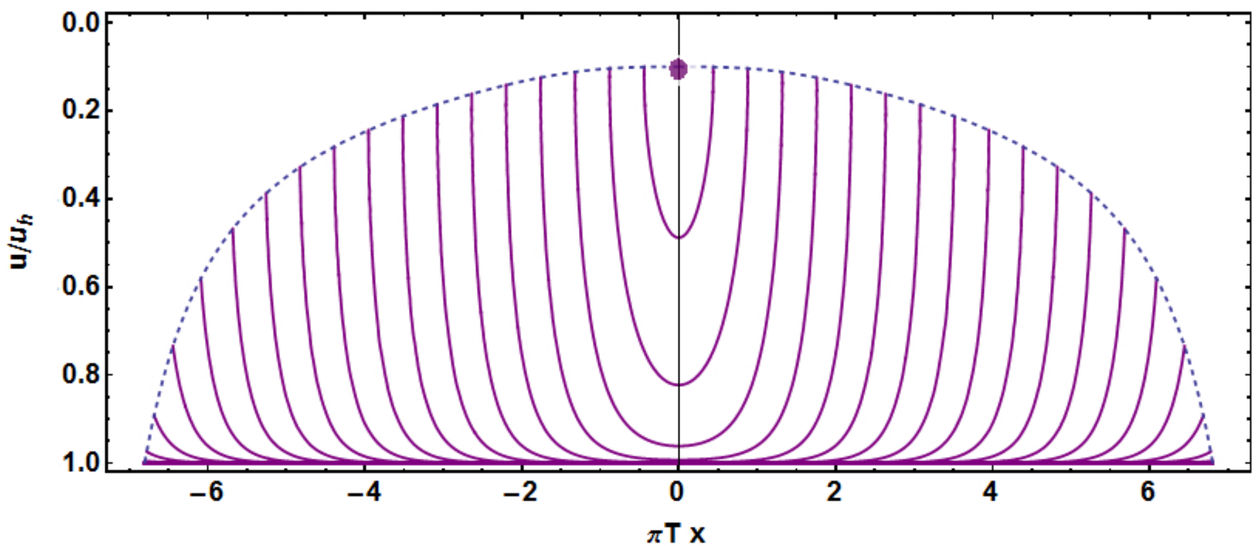
Studying the theory at finite temperature ⟷ Adding black hole to the geometry: AdS-Schwarzchild metric

Quark of mass m_Q is dual to a string in the bulk with an endpoint attached to a D7-brane ending at u_m

For light quarks, D7 brane fills all of the AdS-BH geometry : $u_m \to u_h$

Interactions between the quark and the medium ⟷ Interaction of the string with the horizon of a black hole.





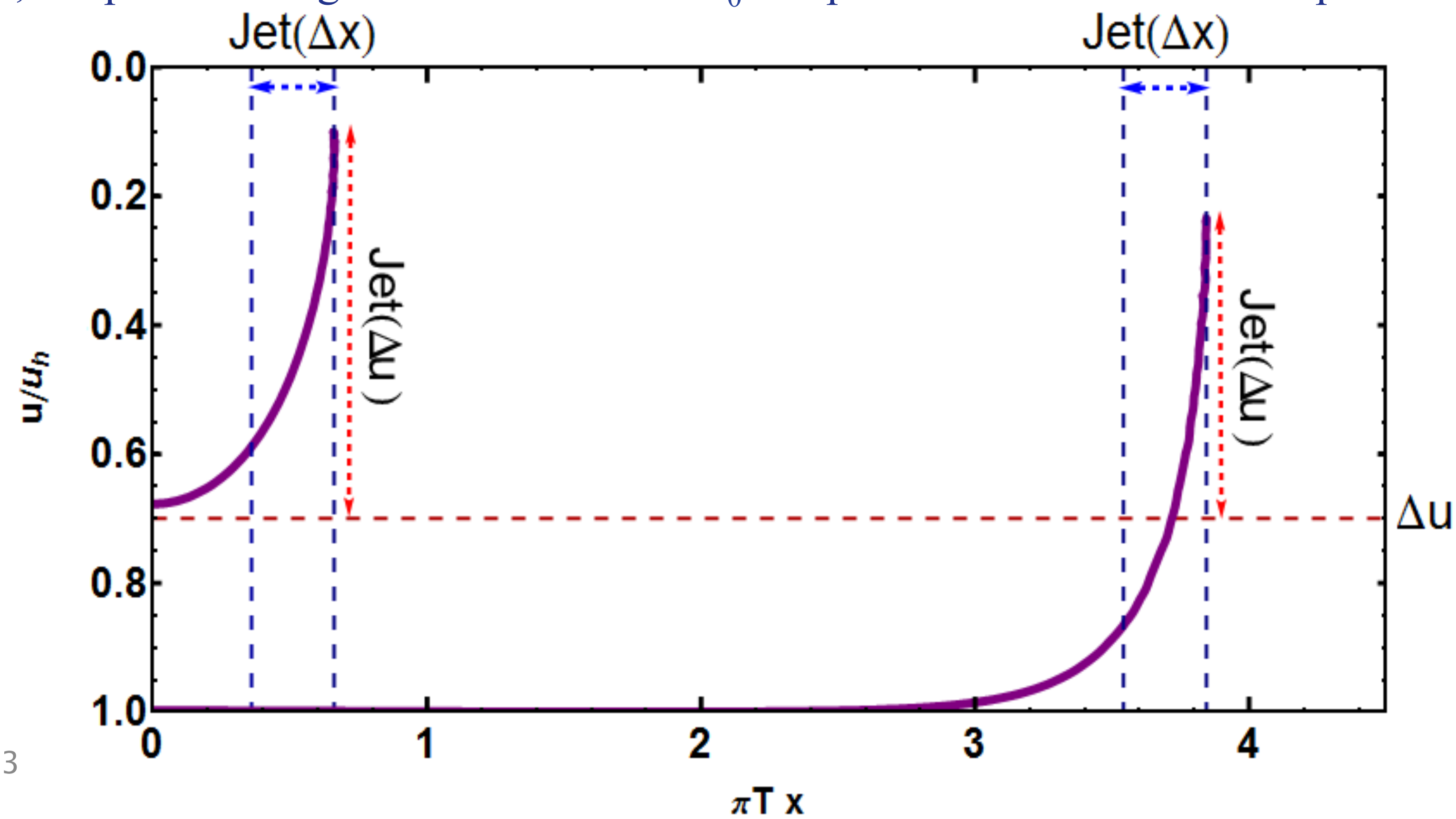
Light Quark Jets in AdS/CFT Correspondence

Prescription of jet in AdS/CFT

New Jet Prescription based on separation of hard and soft sectors:

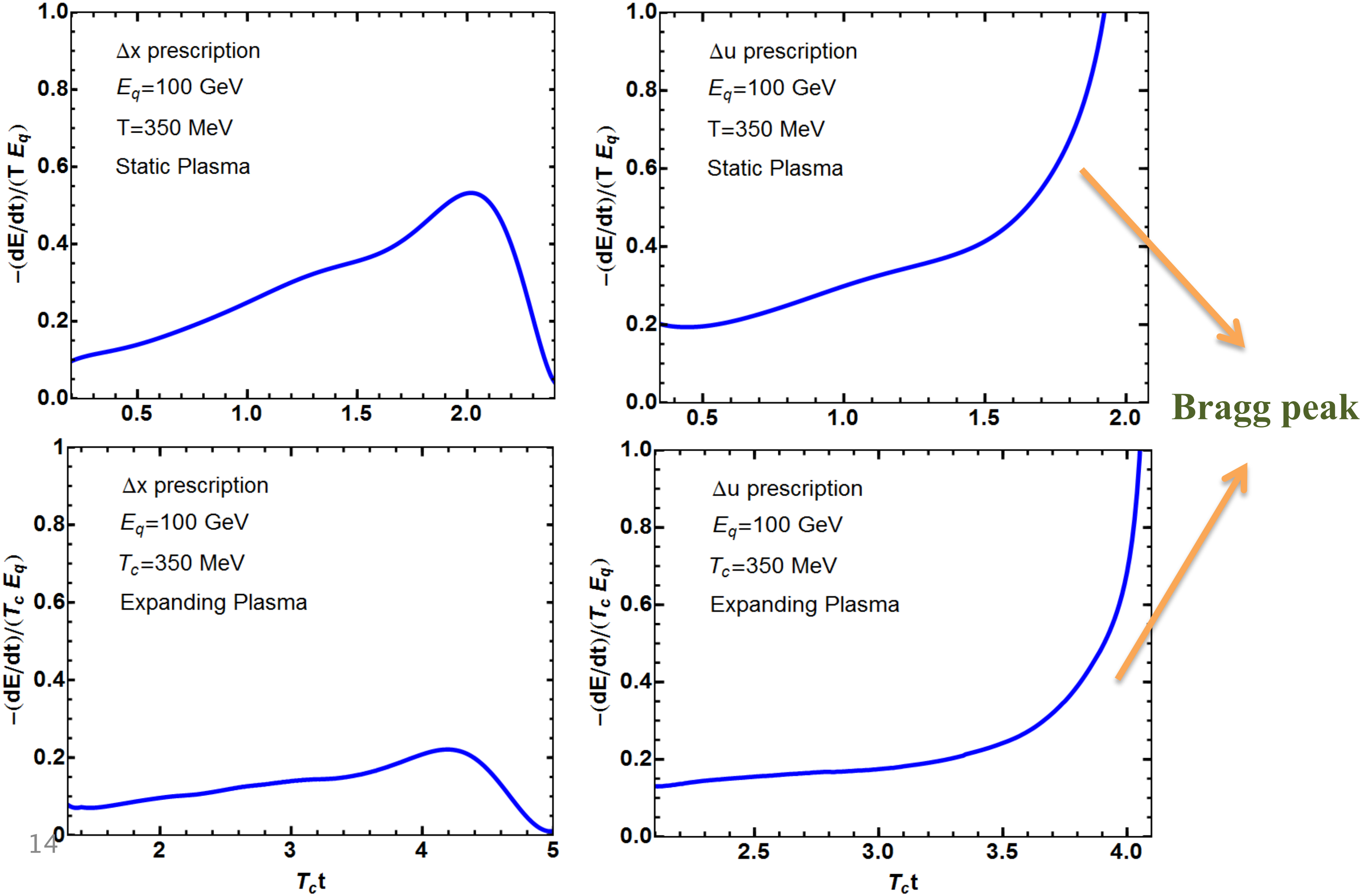
We define jet as a part of string which lies above a critical energy scale ~ 500 MeV.

So, the part of string which is above the u_0 is a part of Jet and the rest is a part of medium.



Light Quark Jets in AdS/CFT Correspondence

Light Quark Jets Energy Loss



Jet Nuclear Modification Factor

$$R_{AA}^{jet}(p_T) \equiv \frac{\frac{dN_{AA\to jet}}{dp_T}(p_T)}{N_{coll}\frac{dN_{pp\to jet}}{dp_T}(p_T)} = \frac{N_{coll}\int \frac{d\varepsilon}{1-\varepsilon}\frac{dN_{pp\to jet}}{dp_T}\left(\frac{p_T^f}{1-\varepsilon}\right) P(\varepsilon \mid p_T^i)}{N_{coll}\frac{dN_{pp\to jet}}{dp_T}(p_T)}$$

p_T^f Final energy of jet

p_T^i Initial energy of quark ; $p_T^f = (1-\varepsilon)\, p_T^i$

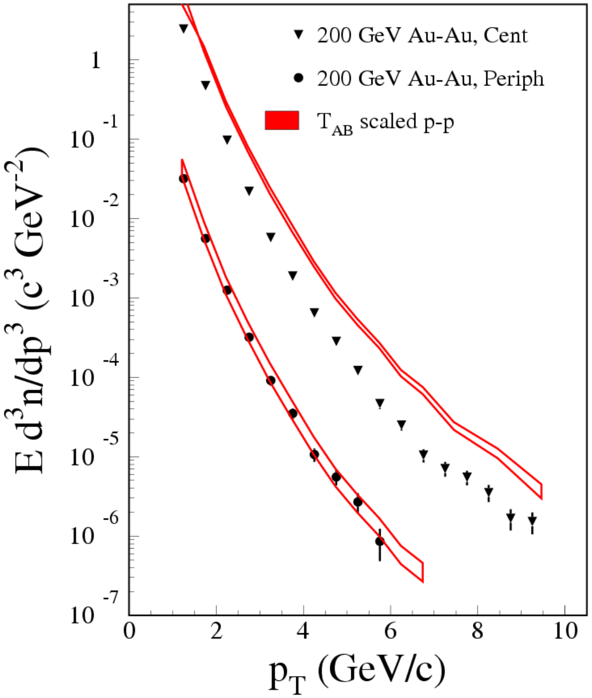
ε Fractional energy loss

$P(\varepsilon \mid p_T^i)$ Probability of fractional energy loss of jet with initial momentum p_T^i

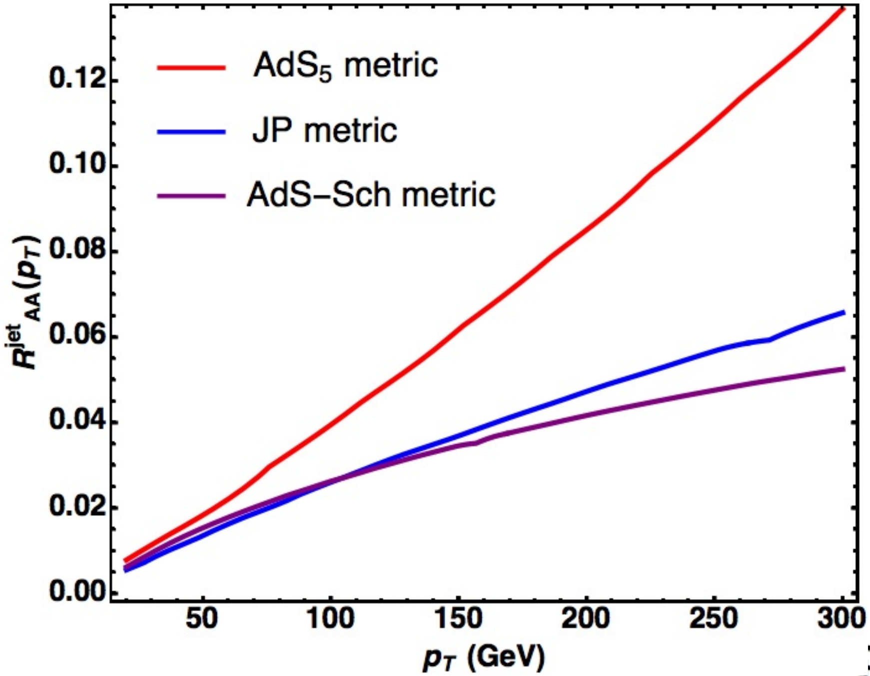
power low production spectrum: $\frac{dN_{pp\to jet}}{dp_T}(p_T) = \frac{A}{p_T^{\,n(p_T)}}$

$$R_{AA}^{jet}(p_T^f) \approx \left\langle \left(\frac{p_T^f}{p_T^i}\right)^{n(p_T^i)-1} \right\rangle$$

geometrical average

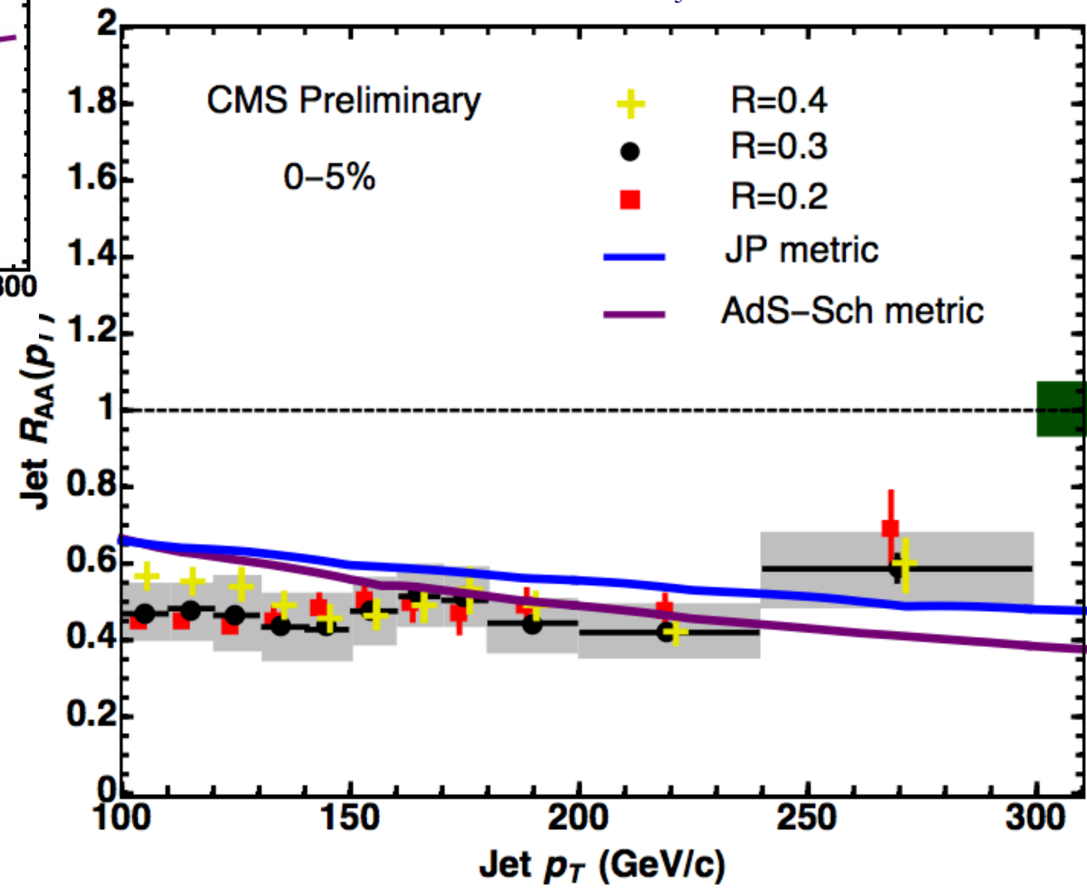


Jet Nuclear Modification Factor



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

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



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

R. Morad and W. A. Horowitz,
JHEP 11 (2014) 017

Conclusion

If we define the jet as a part of string above the energy scale 500 MeV, Bragg peak appeared in light quark energy loss!

The falling string in both AdS-Sch and JP metrics shows over-suppression of hard partons in QGP.

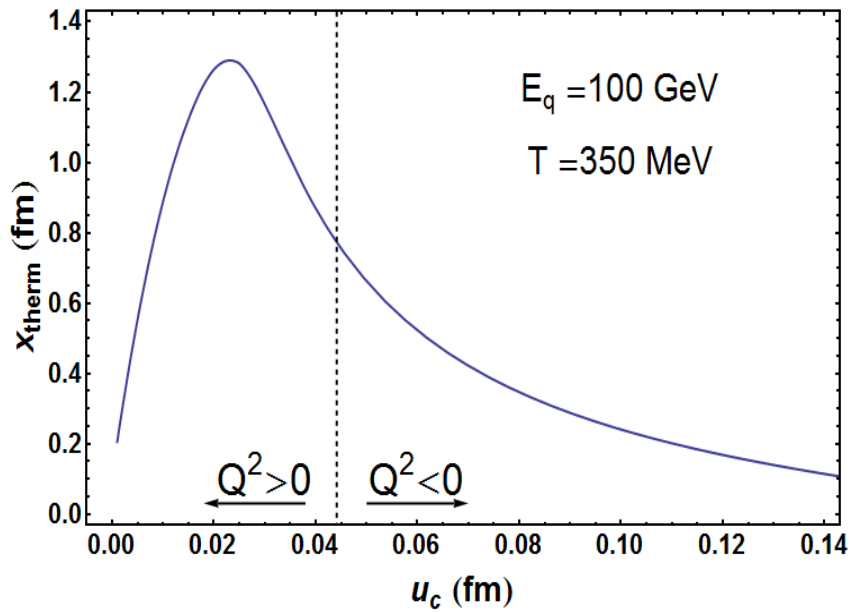
If we define the renormalized R_{AA} by dividing to the $R_{AA}(AdS_5)$, the result are in good agreement with jet data!

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.

Then we will be able to build a hybrid model:
Early, weakly coupled/ late, strongly coupled.



Thank you