# Jets of light hadrons via AdS/CFT correspondence

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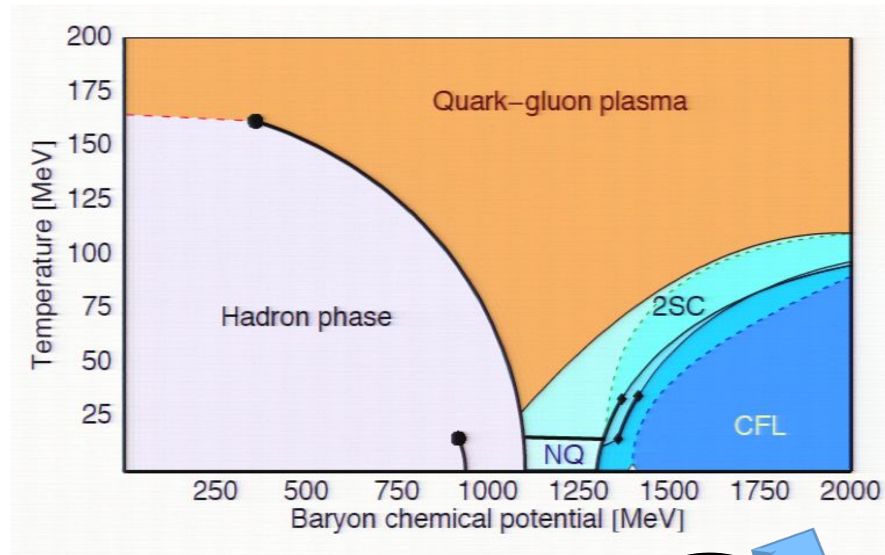
R. Morad and W. A. Horowitz, JHEP 11 (2014) 017

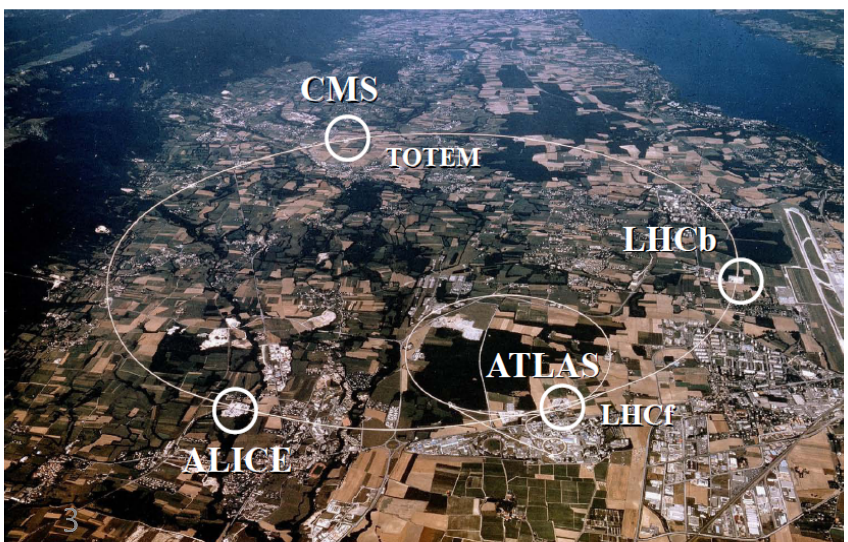
# Outline

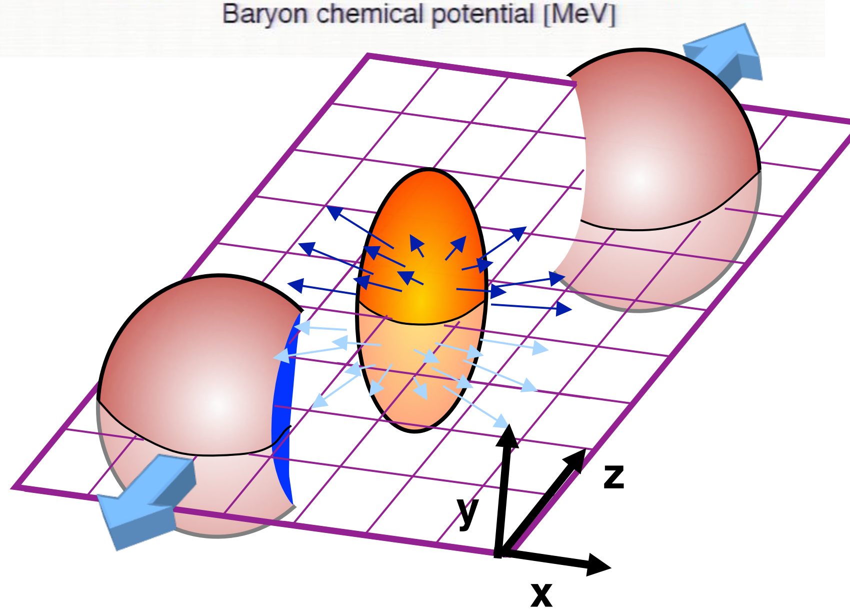
- Quark- Gluon Plasma
- AdS/CFT Correspondence
- Light Quark in $AdS_5$-Sch Background
  - New prescription of Jets in AdS/CFT
  - Energy Loss
- Nuclear Modification Factor of Jets
- Conclusion

# Quark-Gluon Plasma

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

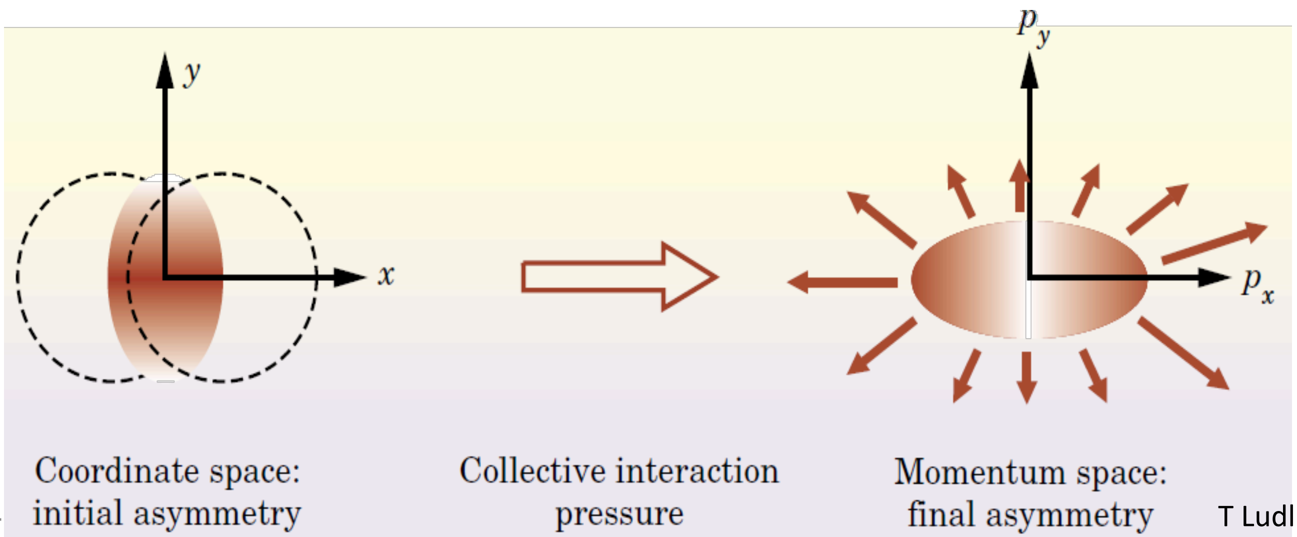
# Quark-Gluon Plasma

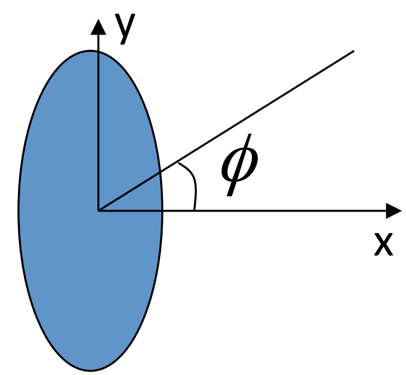
**Quark-gluon fluid of RHIC behaves as nearly ideal, strongly coupled fluid (sQGP).**

- 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.

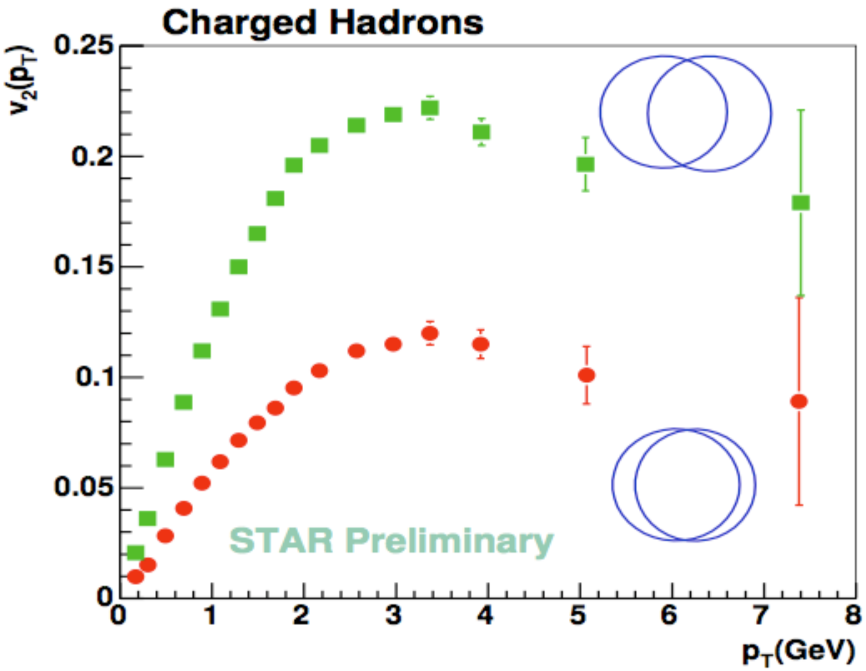


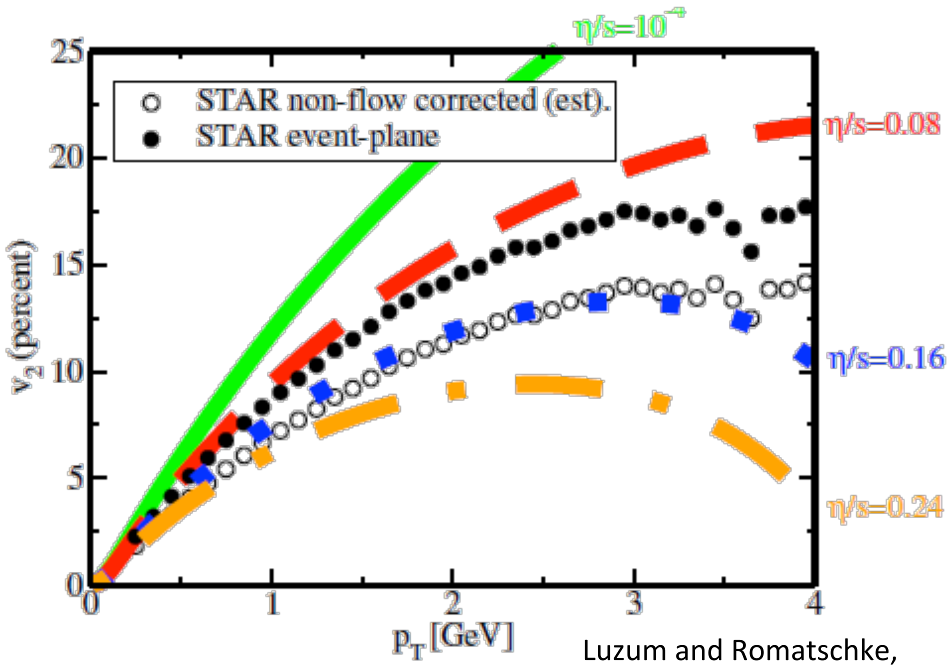




T Ludlum and L McLerran, Phys. Today 56N10 (2003)

# Quark-Gluon Plasma

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




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: $\frac{\eta}{s} = 0.13 \pm 0.03$, 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

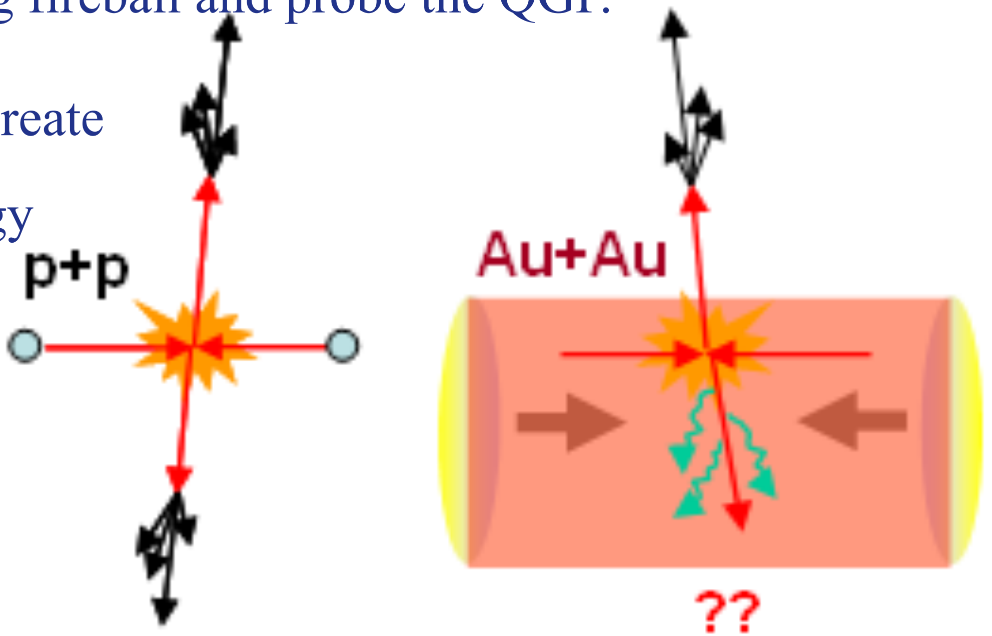
QGP exists for a few fm, making it impossible to study it using any external probes.

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

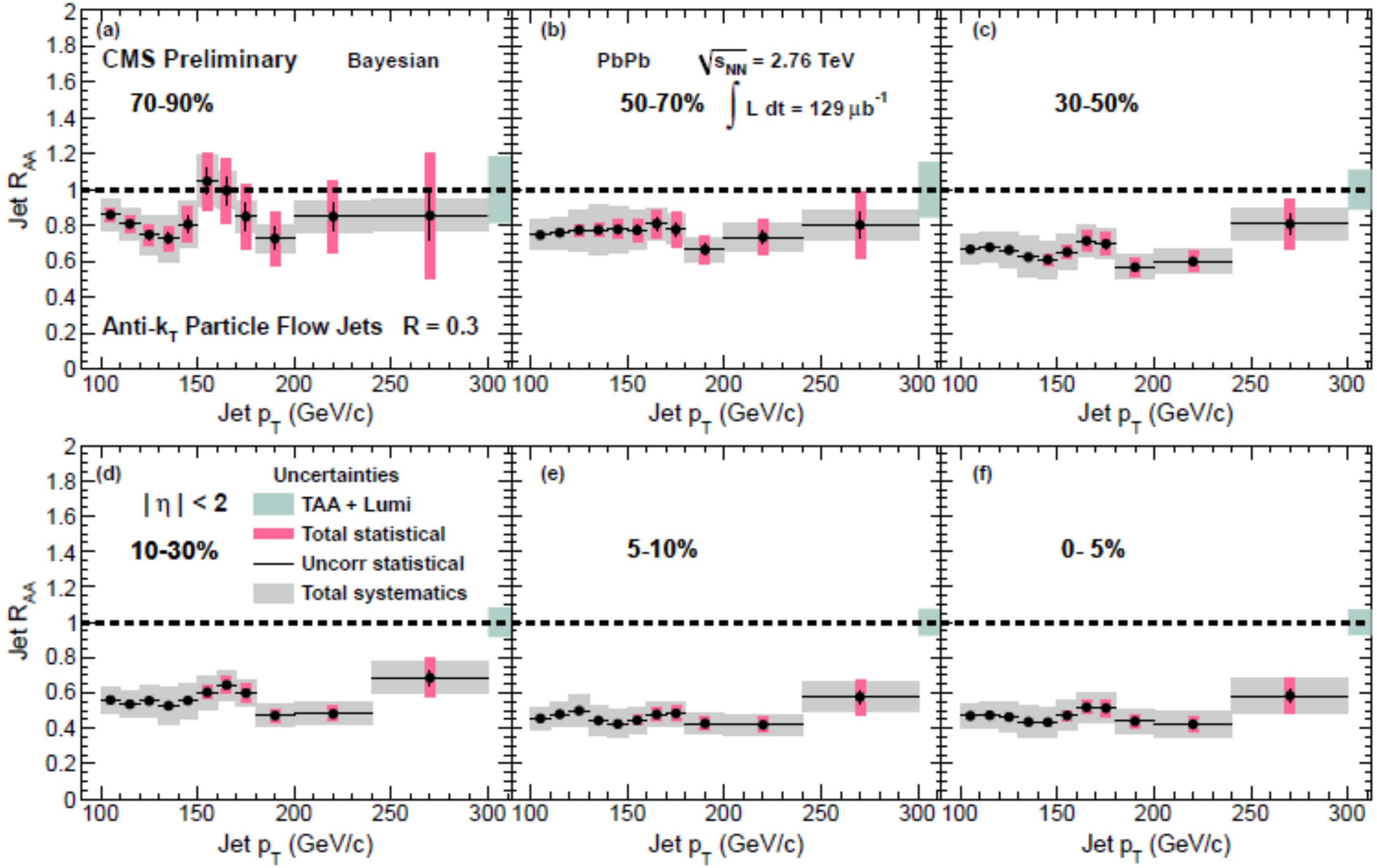
## Nuclear Modification Factor:

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

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 $\text{AdS}_{d+1}$**

**Strongly coupled d - dimensional CFT which lives on boundary of $\text{AdS}_{d+1}$**

Maldacena 98

**Duality unproven, but many consistency checks performed.**

# AdS/CFT Correspondence

## *AdS/CFT Dictionary*

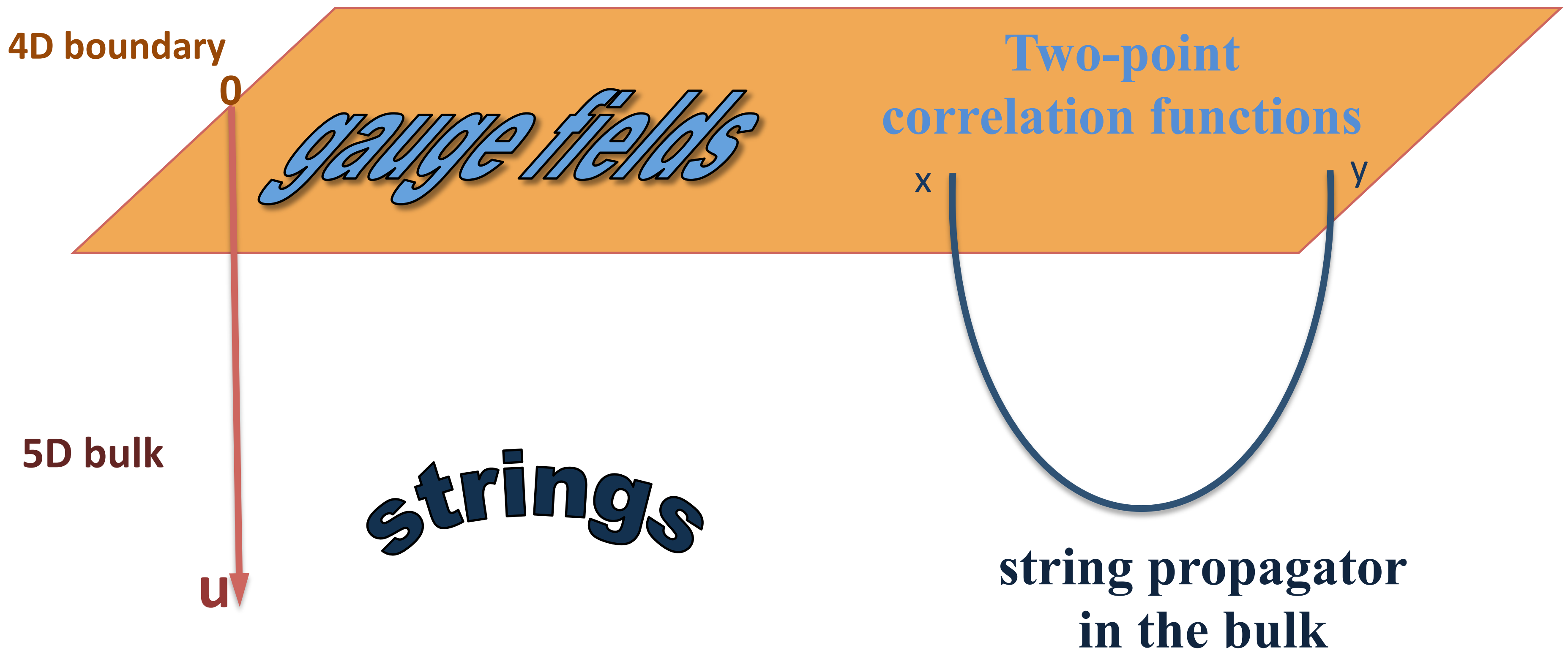
| $\mathrm{CFT}_d$ | $AdS_{d+1}$ |
|---|---|
| Conformal symmetry SO(2,d) | Isometry SO(2,d) |
| Charges | Charges |
| Global Symmetry "G" | Gauge Symmetry "G" |
| Local Operators | Quantum Fields |
| $\left\langle e^{\int d^4x \phi_0(\vec{x}) O(\vec{x})} \right\rangle_{CFT}$ | $Z\left[\phi\left(\vec{x},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

Gubser, Klebanov, Polyakov'98, Witten'98

# AdS/CFT Correspondence

## Anti-de-Sitter space ($AdS_5$)

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

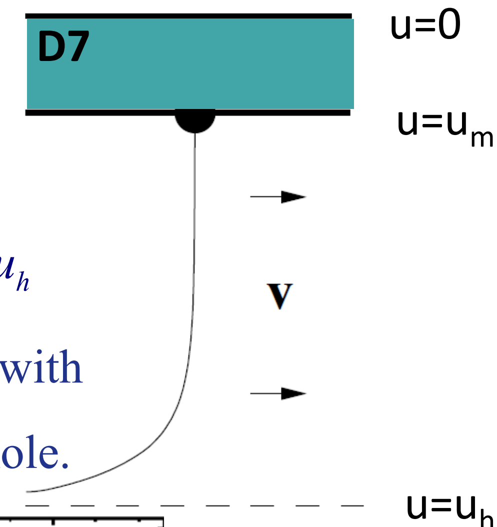



u plays a role of inverse energy scale in 4D theory

# Light Quark Jets in AdS/CFT Correspondence

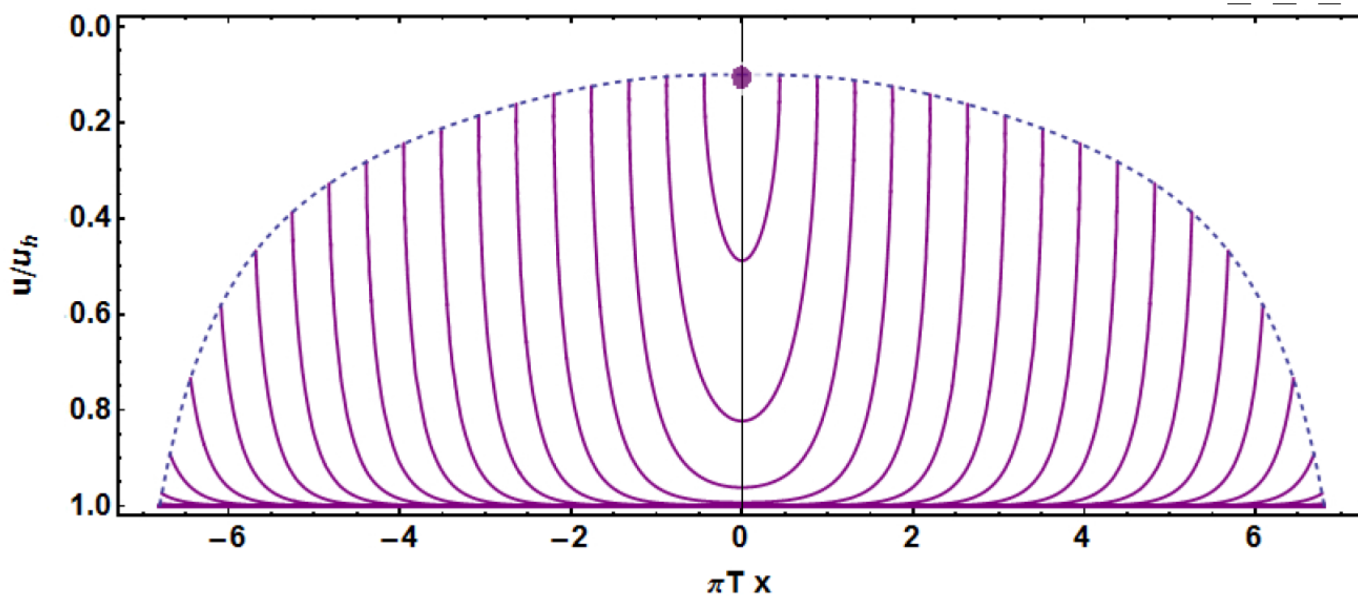
Studying the theory at finite temperature ⟷ Adding black hole to the geometry: AdS-Schwarzchild metric

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



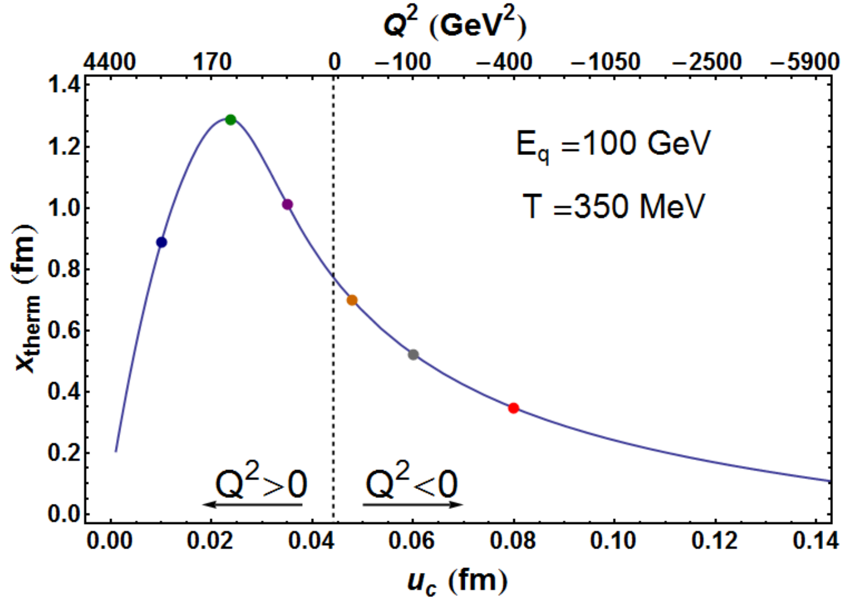

For light quarks, D7 brane fills all of the AdS-BH geometry : $u_m \to u_h$

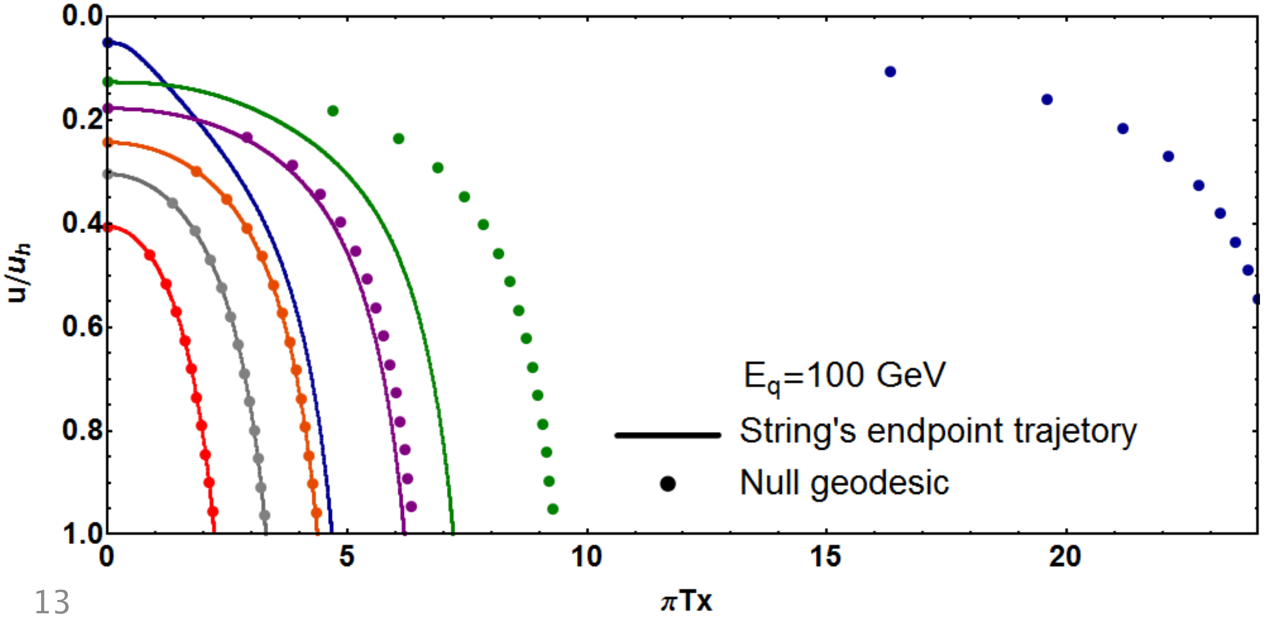
Interactions between the quark and the medium ⟷ Interaction of the string with the horizon of a black hole.



# Light Quark in $AdS_5$-BH Background

**Maximum stopping distance:**



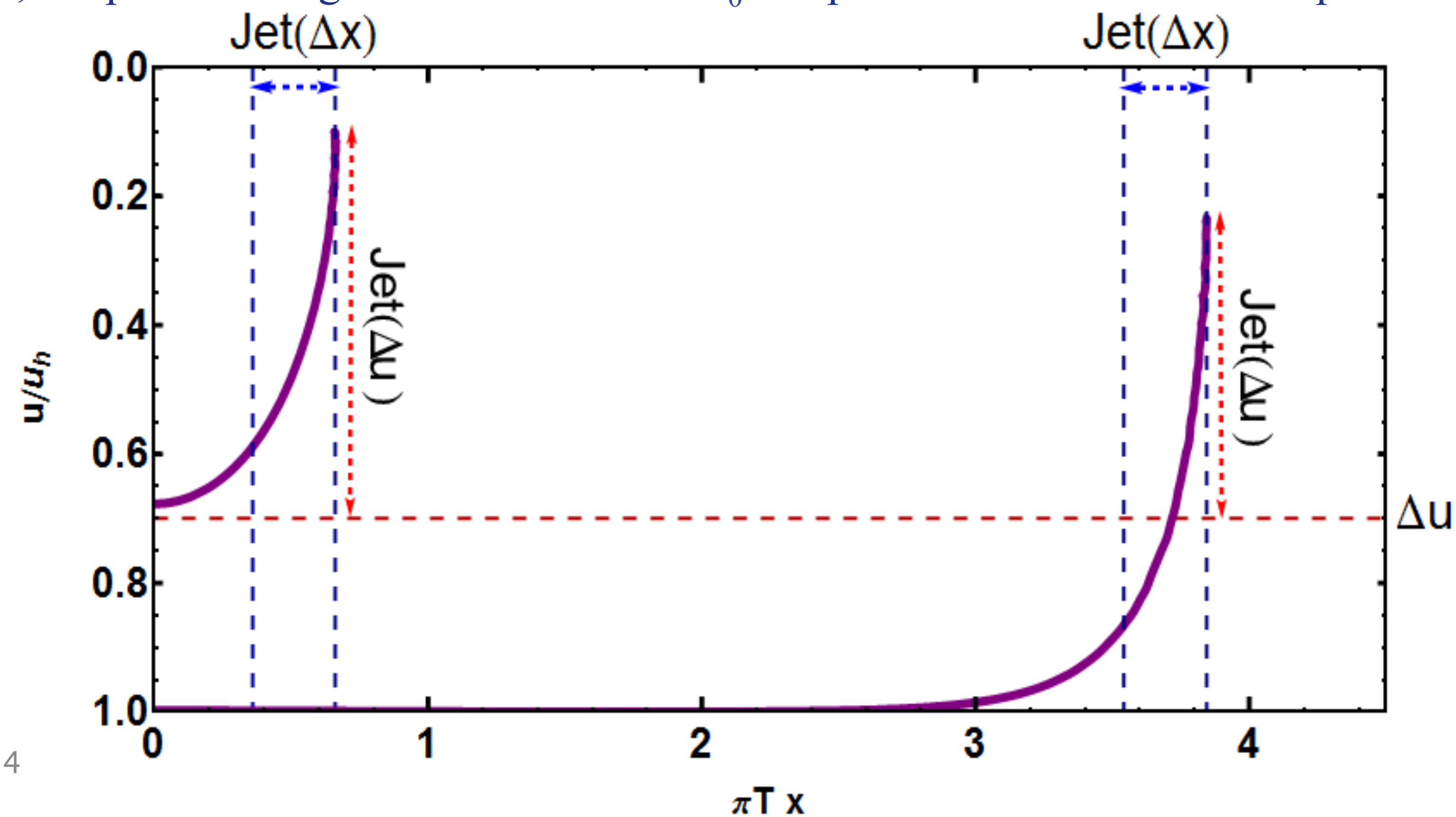
# Light Quark in $AdS_5$-BH Background

**Prescription of jet in AdS/CFT**

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

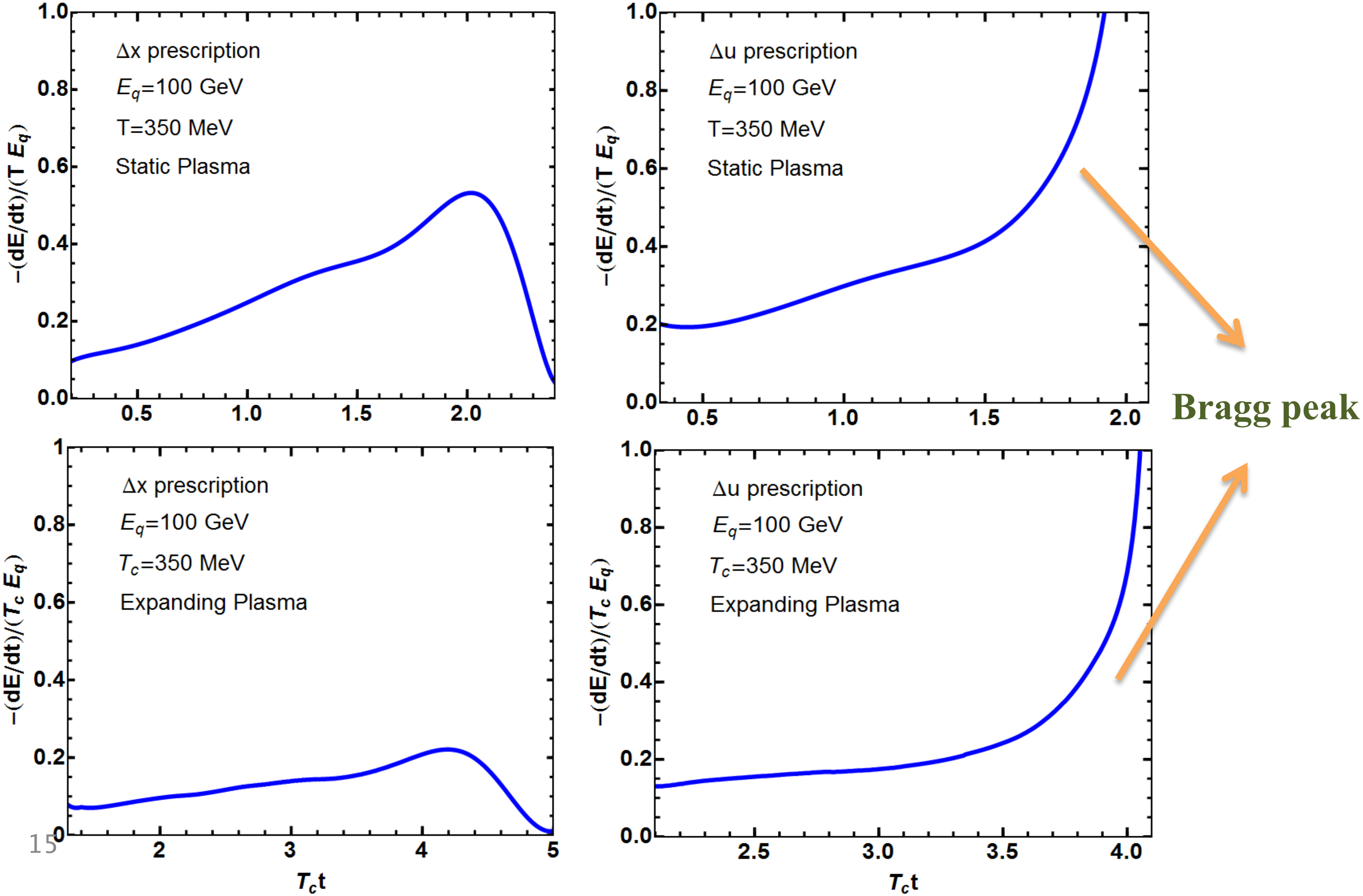
We define jet as a part of string which lies above a critical energy scale ~ 500 MeV.

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

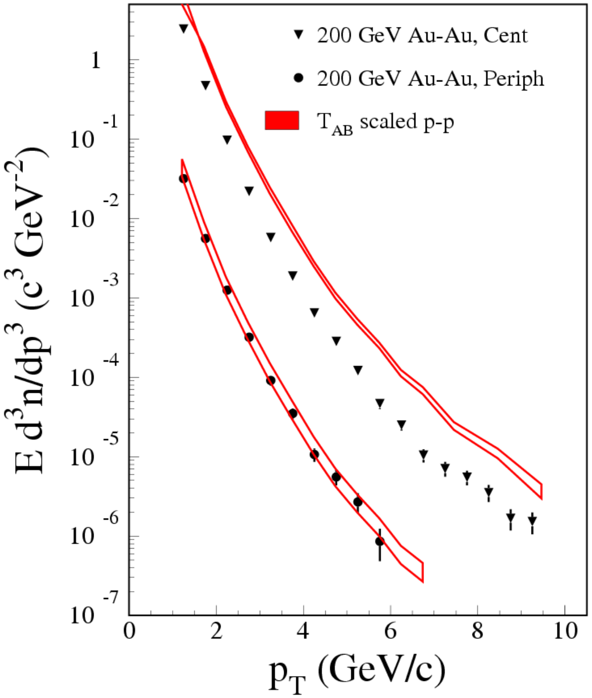
$p_T^i$ Initial energy of quark ; $p_T^f = (1-\varepsilon)\, p_T^i$

$\varepsilon$ Fractional energy loss

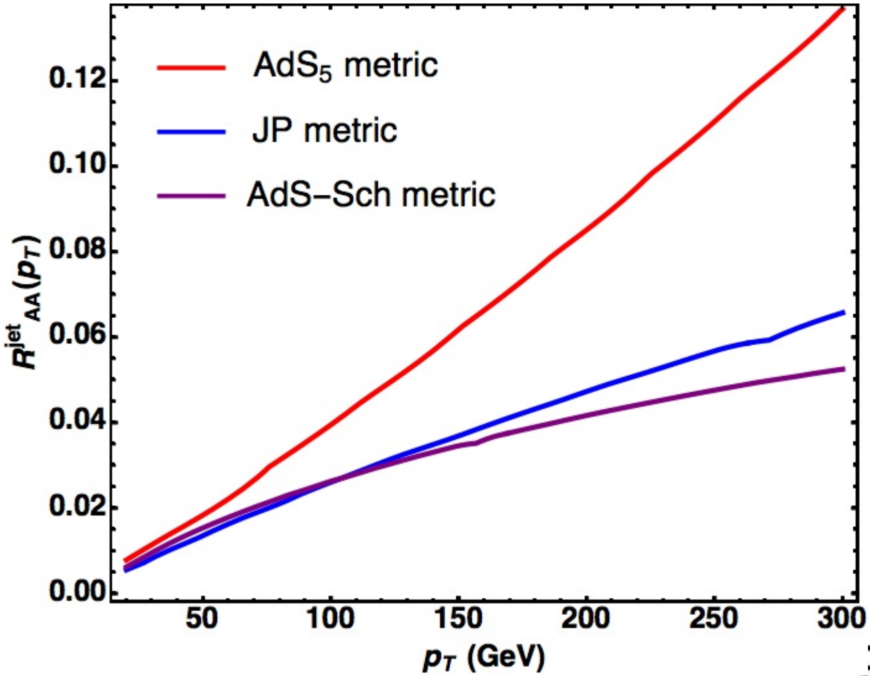
$P(\varepsilon \mid p_T^i)$ Probability of fractional energy loss of jet with initial momentum $p_T^i$

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

$$R_{AA}^{R\to jet}(p_T) = \int_0^{L_{\max}} \frac{dl}{L_{\max}} \left(1 - \epsilon^R(p_T,\, l,\, T)\right)^{n_R(p_T)-1}$$

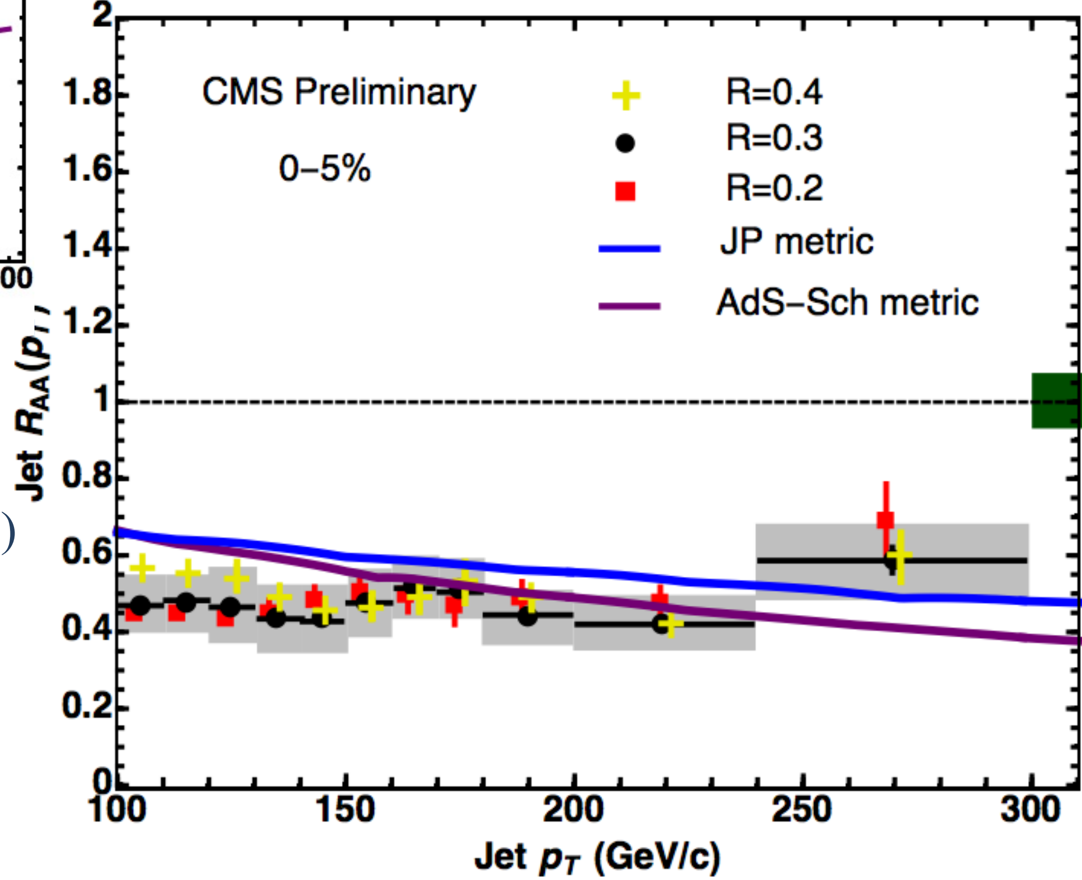


# Jet Nuclear Modification Factor




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

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




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

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.

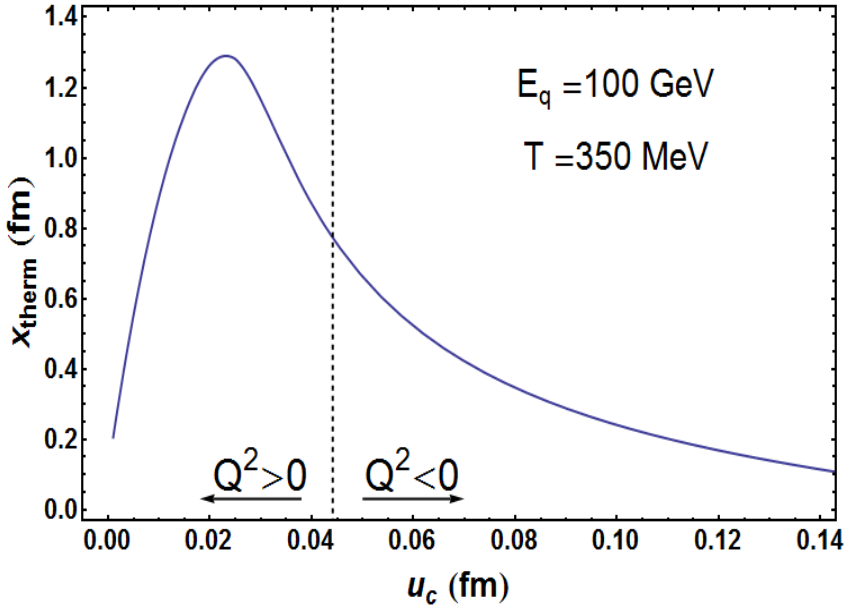
If we define the renormalized $R_{AA}$ by dividing to the $R_{AA}(AdS_5)$, the result are in good agreement with jet data!

**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