The energy density of a light quark jet using AdS/CFT

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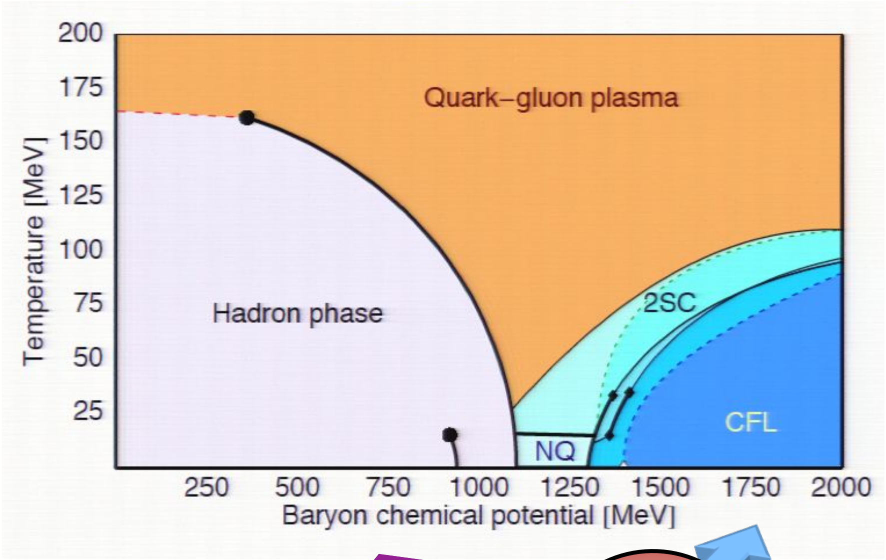
May 24th , 2016

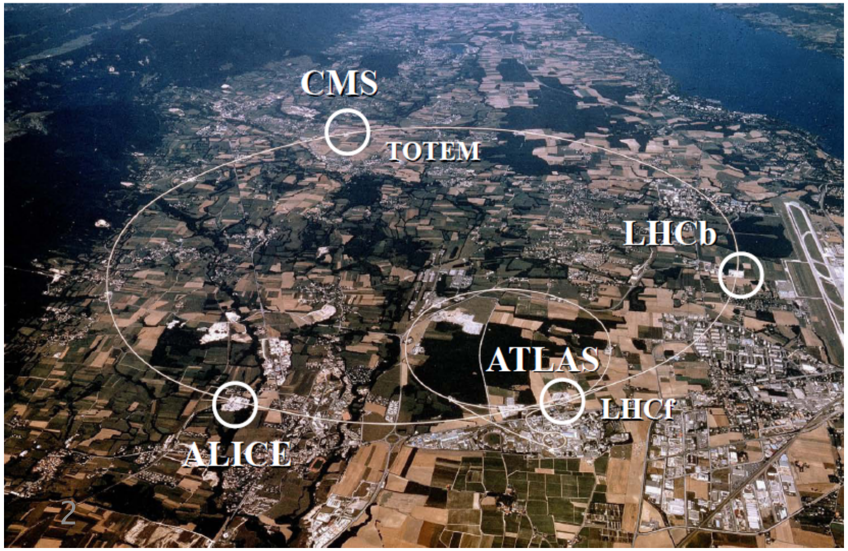
In Collaboration with Dr. W. A. Horowitz

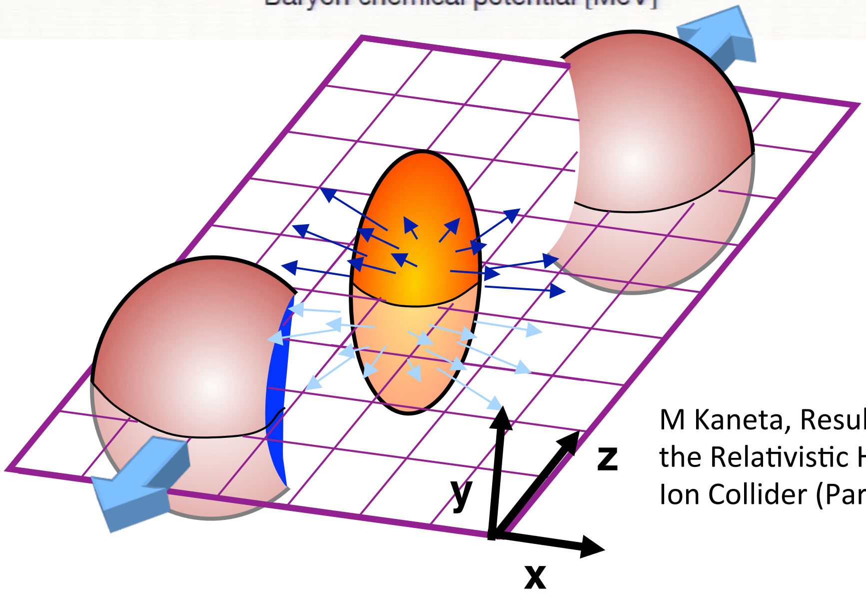
Recent Trends in String Theory and Related Topics,
School of Physics, IPM, Iran

Quark-Gluon Plasma

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



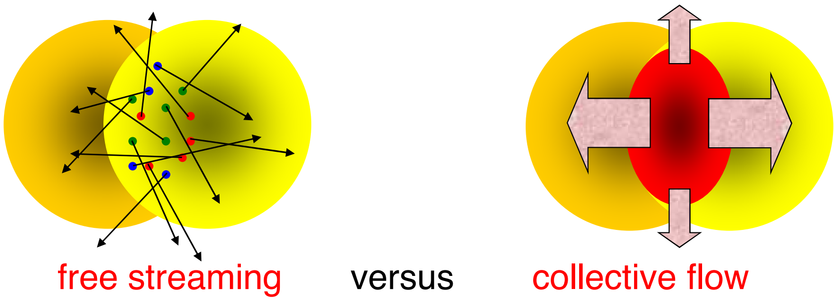


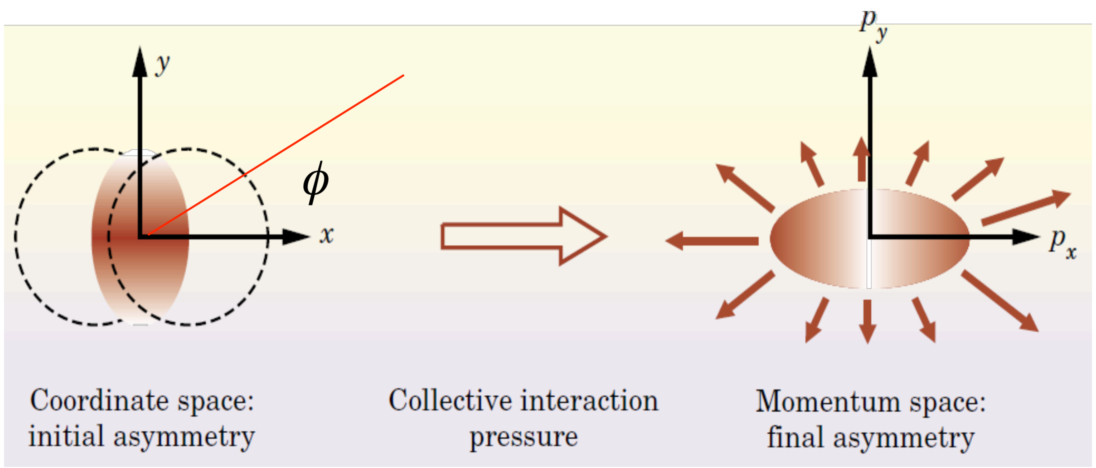


M Kaneta, Results from the Relativistic Heavy Ion Collider (Part II)

Quark-Gluon Plasma

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





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

Anisotropic initial geometry

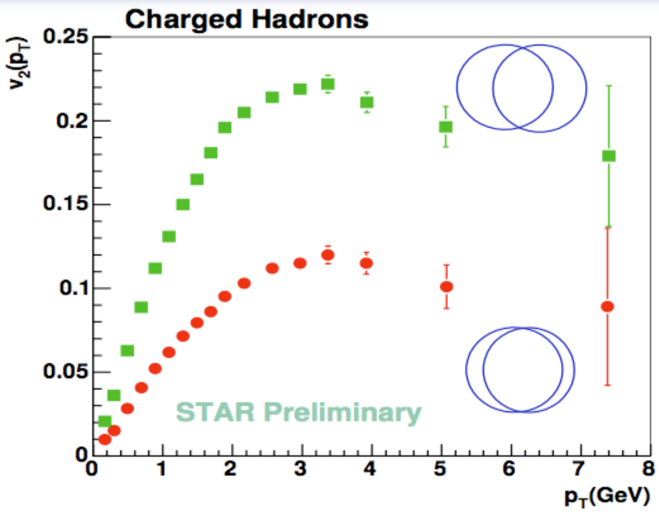
↓

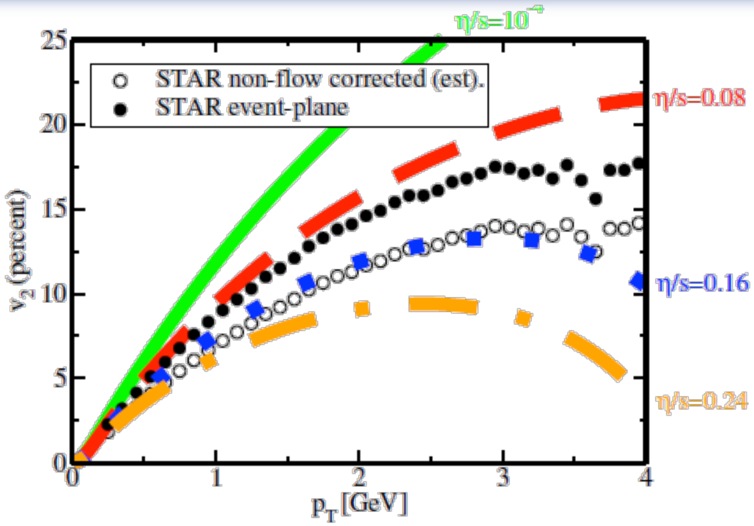
Anisotropic flow

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

Elliptic flow

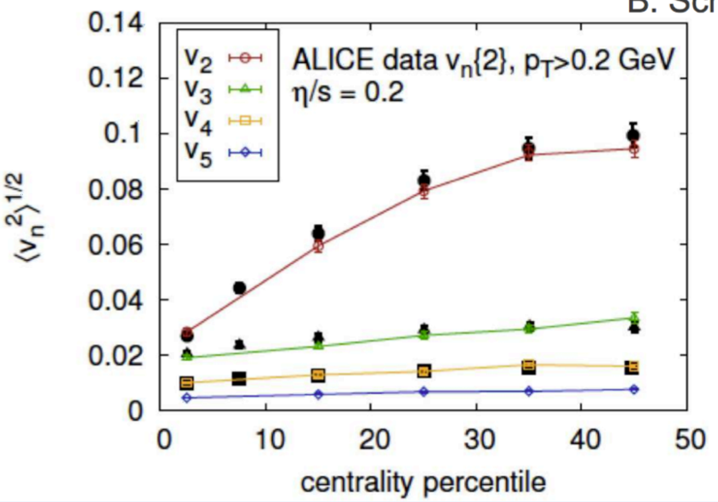
Quark-Gluon Plasma

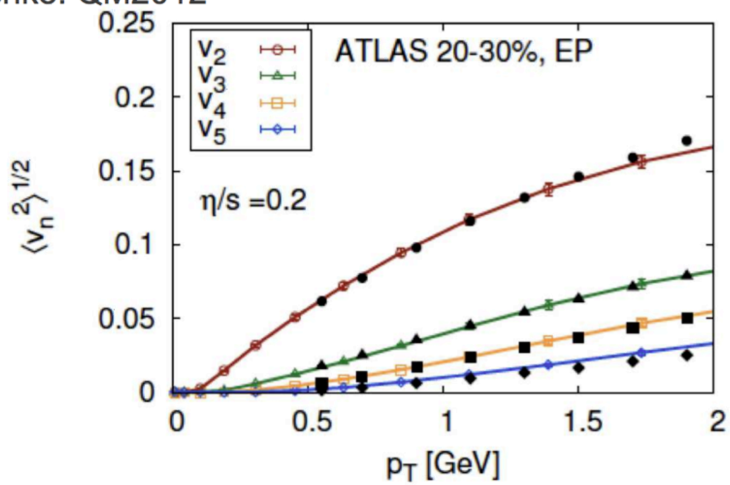




Luzum and Romatschke, Phys.Rev.C78:034915,2008

B. Schenke: QM2012





Schenke, Tribedy, Venugopalan, PRL 108:25231 (2012)

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: $\tau_{therm} \sim 0.35 \quad fm$

Chesler and Yaffe, PRL 106 (2011)
Janik et all (2012),(2014)

Probing the hot matter

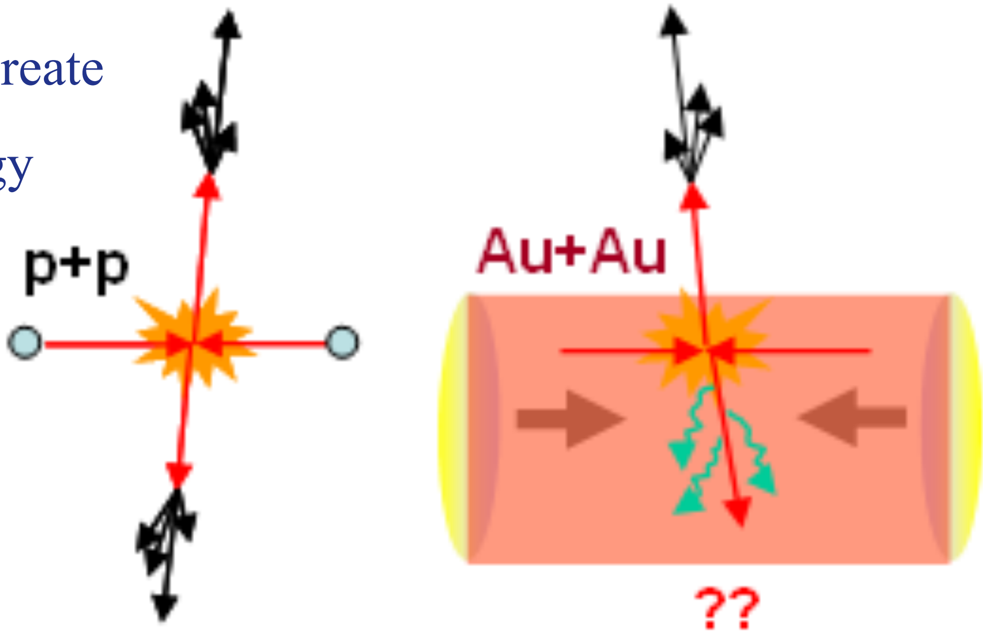
QGP exists for a few fm, making it impossible to study it using any external probes.

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.



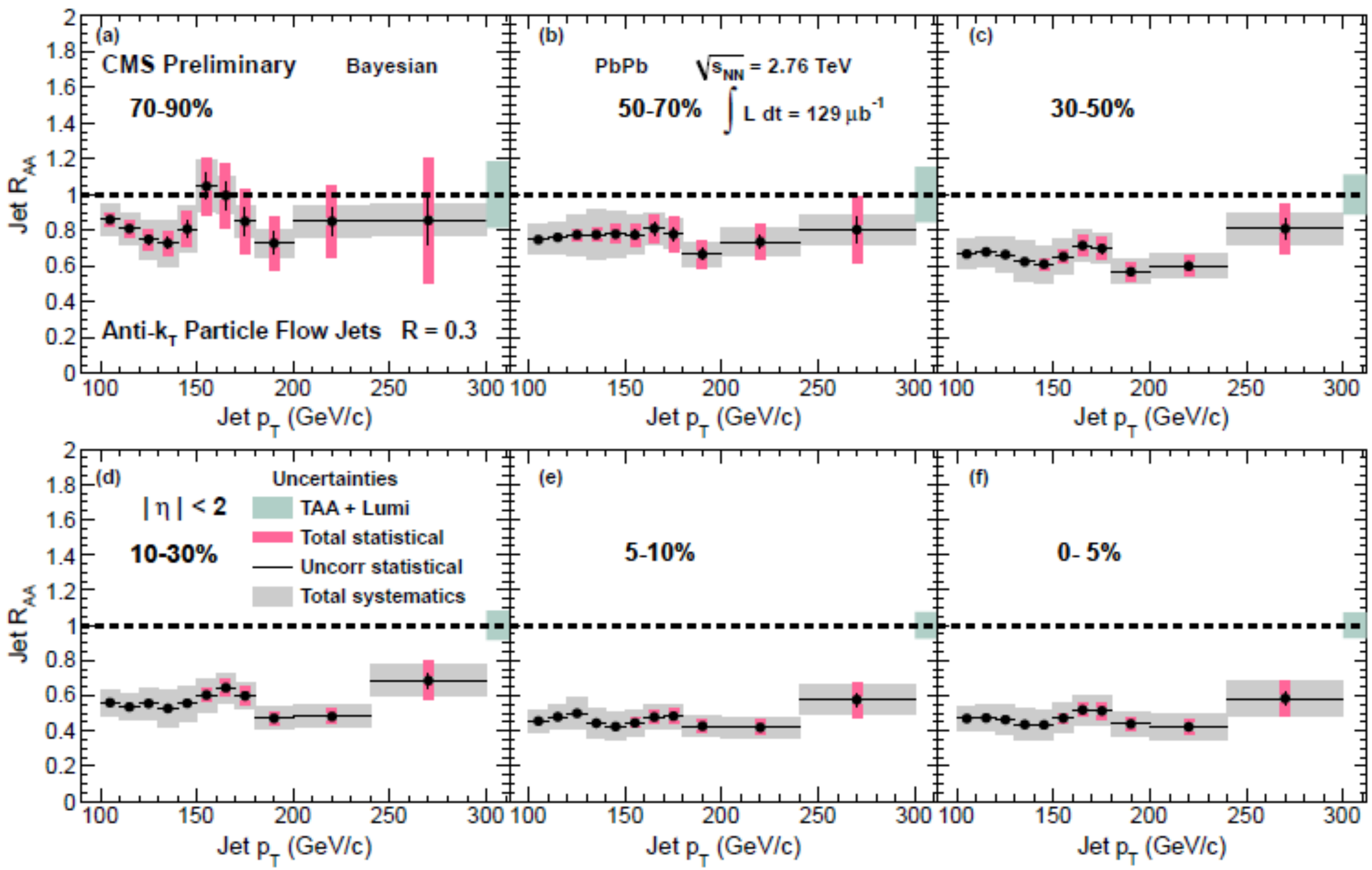
The presence of hot matter modifies the properties of jets.

Jet suppression

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

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

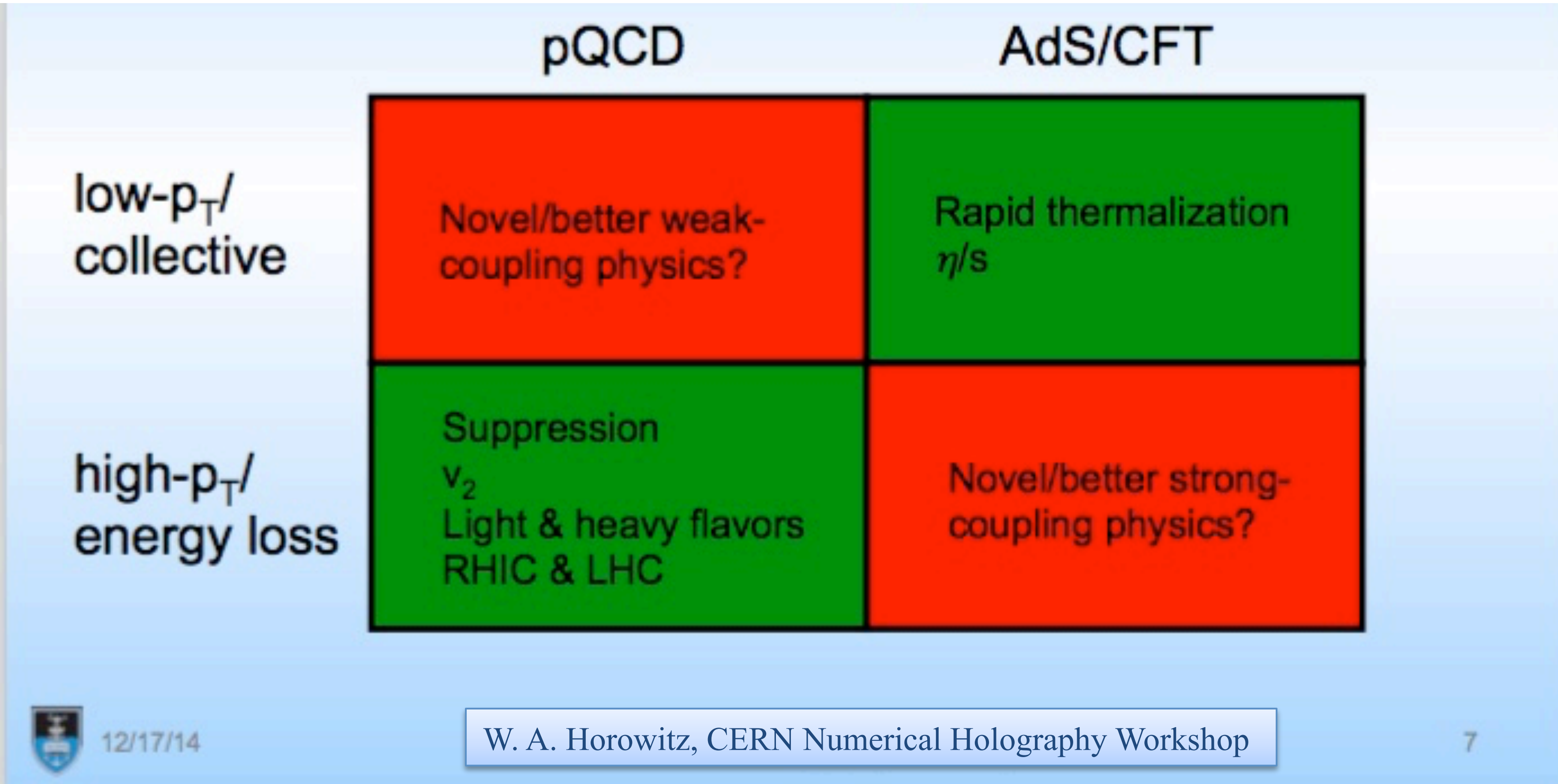
R_{AA}<1 means jet quenching



CMS Preliminary data (2012)

Theoretical Method

Two Common Theoretical Descriptions



We don’t have a consistent theoretical picture that describes all observables.

AdS/CFT Correspondence

Maldacena *Conjecture*

Classical gravity on AdS_{d+1}

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

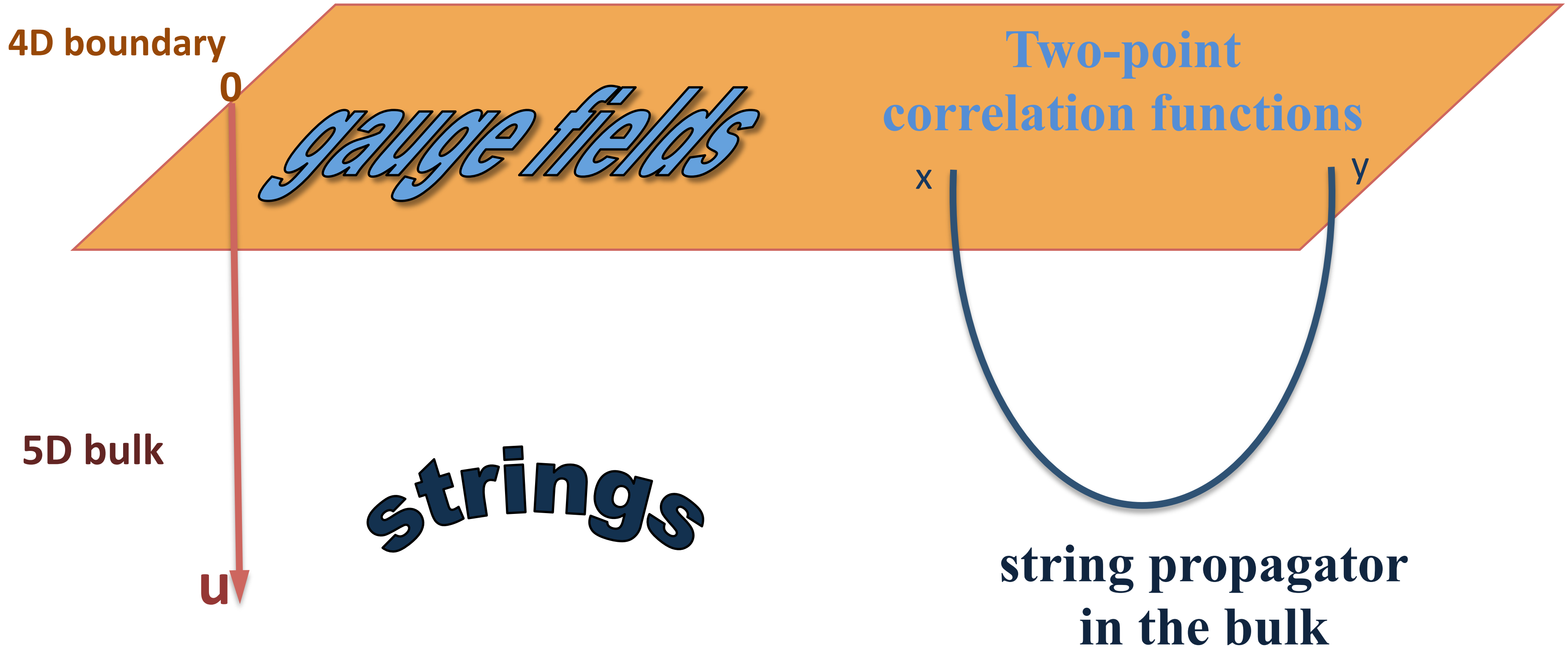
Maldacena 98

Duality unproven, but many consistency checks performed.

AdS/CFT Correspondence

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

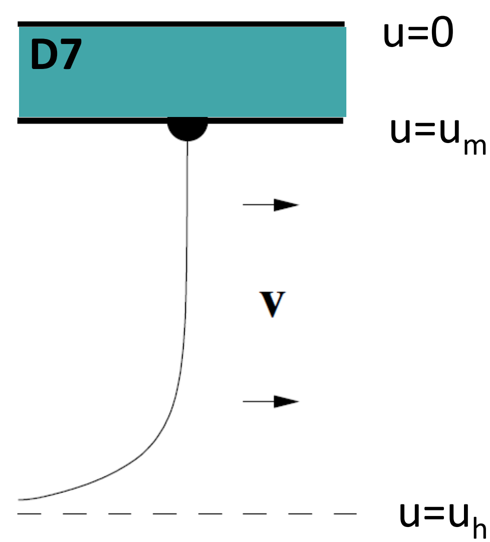
Light-Quark in string Setup

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: $m_Q = T_0 L^2 \left(\frac{1}{u_h} - \frac{1}{u_m}\right)$

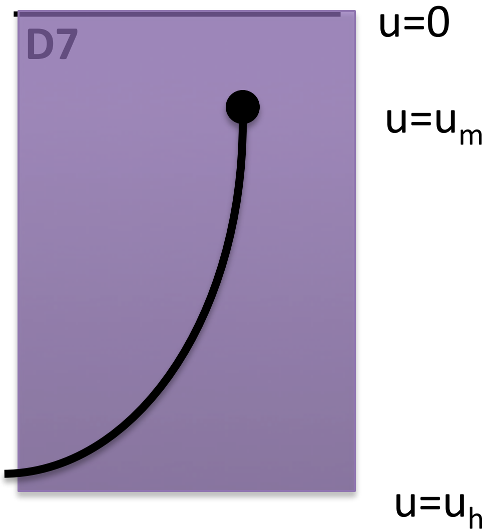
Thermalization distance

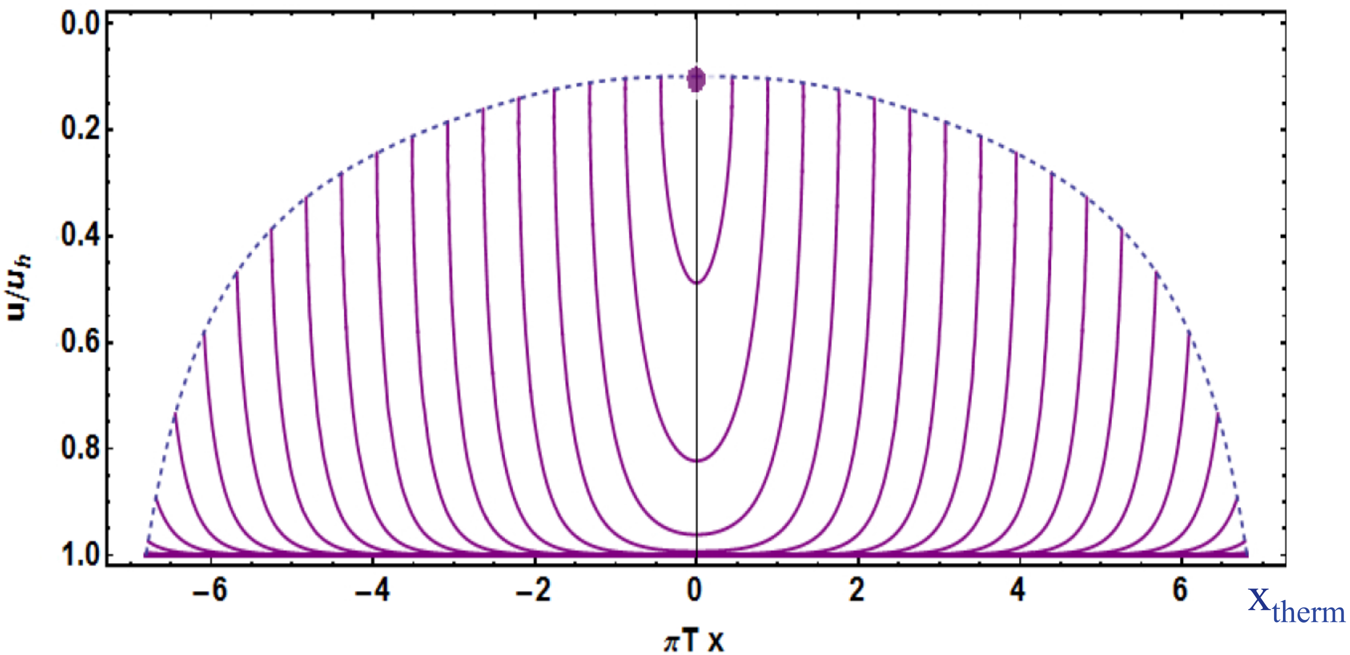
Light Quarks ⟷ **Falling Strings**

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

IC: $$t(0,\sigma) = t_c\,,\;\; x(0,\sigma) = 0\,,\;\; u(0,\sigma) = u_c$$

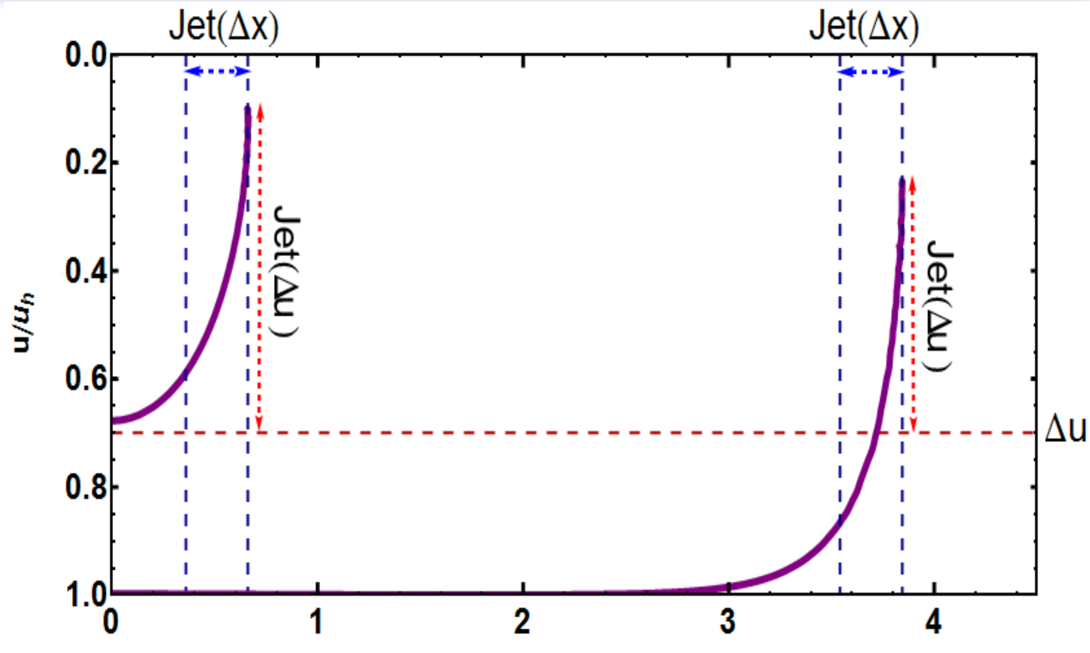
BC: $$X'^\mu(\tau,\sigma^*) = 0$$





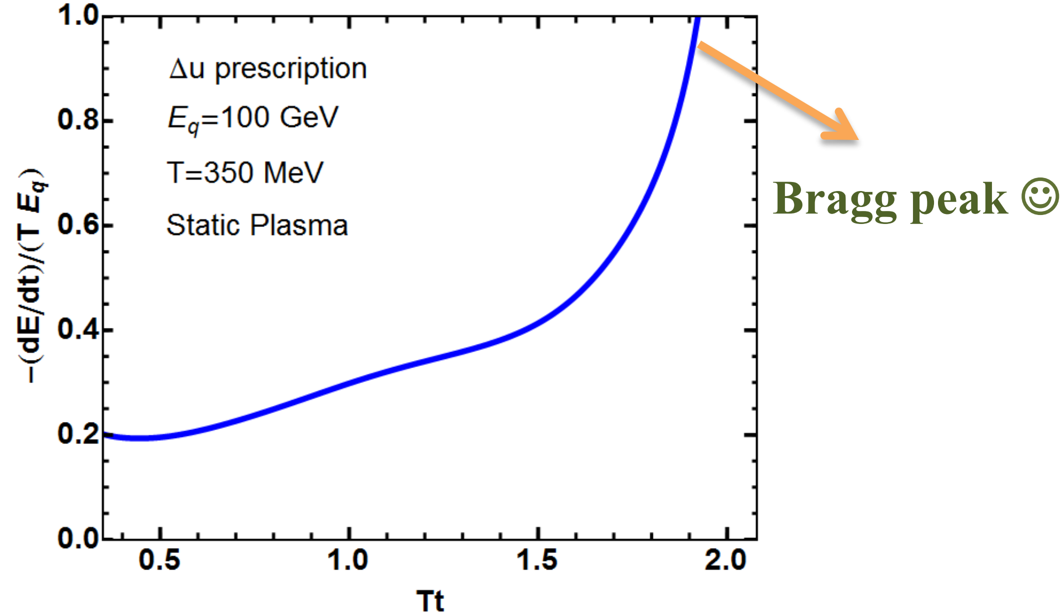
Jet Energy Lost

Prescription of jet in AdS/CFT

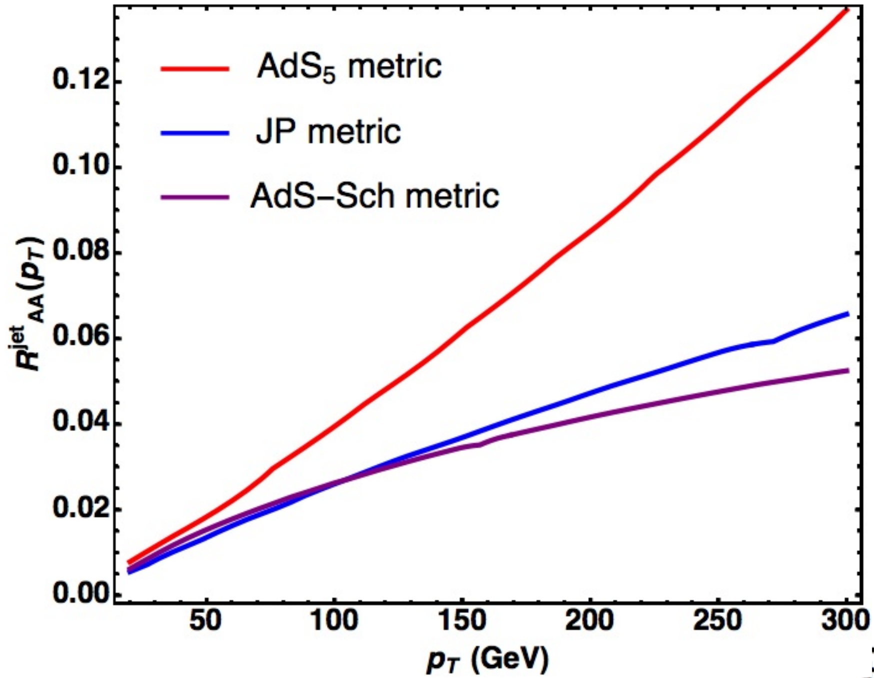


New Jet Prescription based on separation of hard and soft sectors:

Energy Loss:

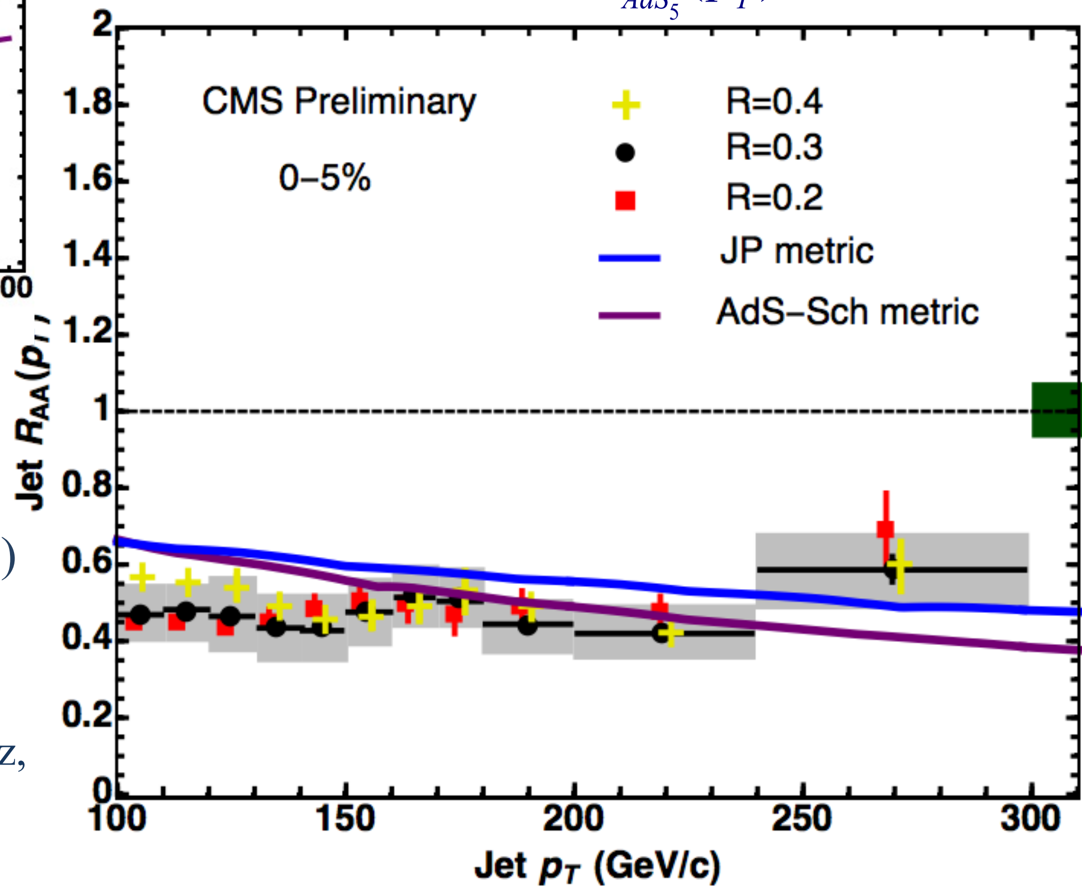


Jet Nuclear Modification Factor



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

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



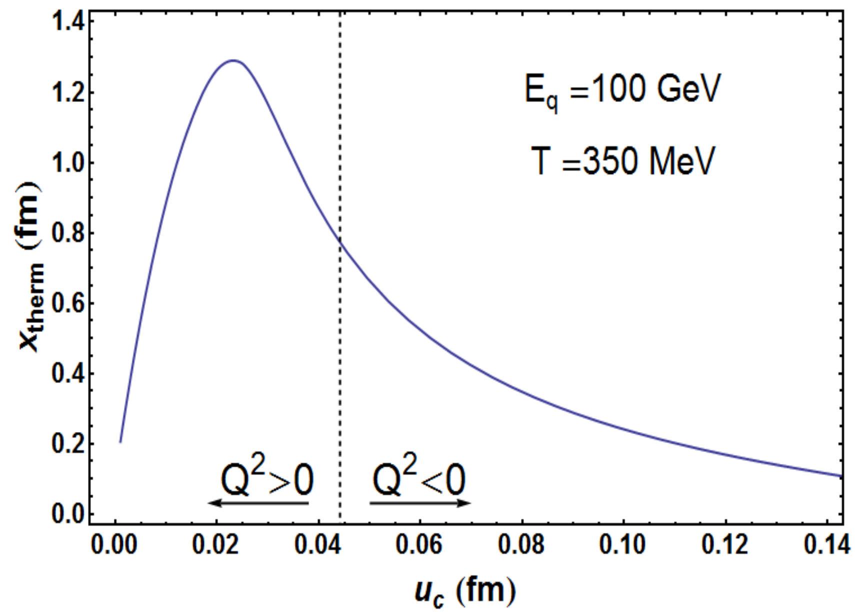
$\Delta E^{sub, ren}(pi , L, T) \equiv$
$\Delta E^{medium}(pi , L, T) - \Delta E^{vacuum}(pi , L, T)$

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

Light-Quark Dynamics

Light quark dynamics highly depends on the initial conditions of the string. Further progress in describing experimental results will require significant advances in the understanding of string initial conditions.

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



That the results of our simple model are in such good agreement with data suggests that we attempt to better define the jet in AdS/CFT and constrain the possible string initial conditions.

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:

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

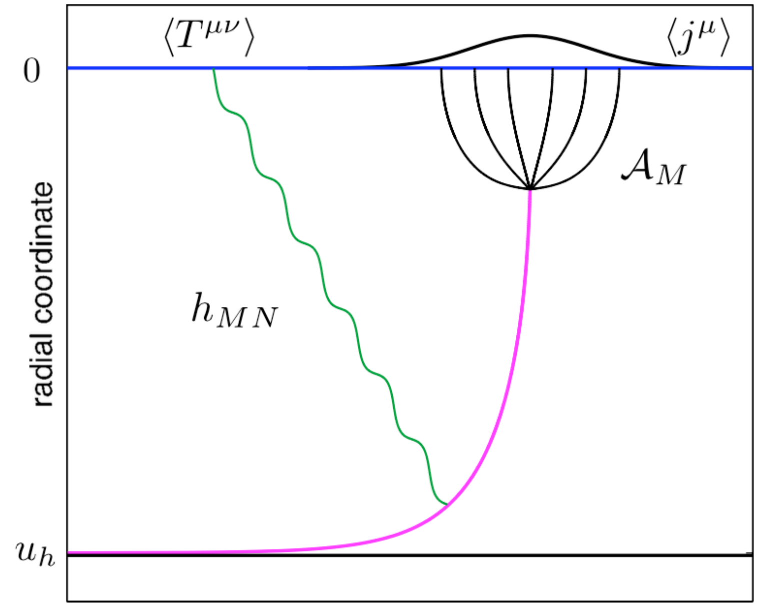
- Metric perturbation h_{MN} : $G_{MN} = G^{(0)}_{MN} + h_{MN}$

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

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



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:

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

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

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

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

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

P. Chesler et al, hep-th/1001.3880

Boundary Energy Density in AdS$_5$

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

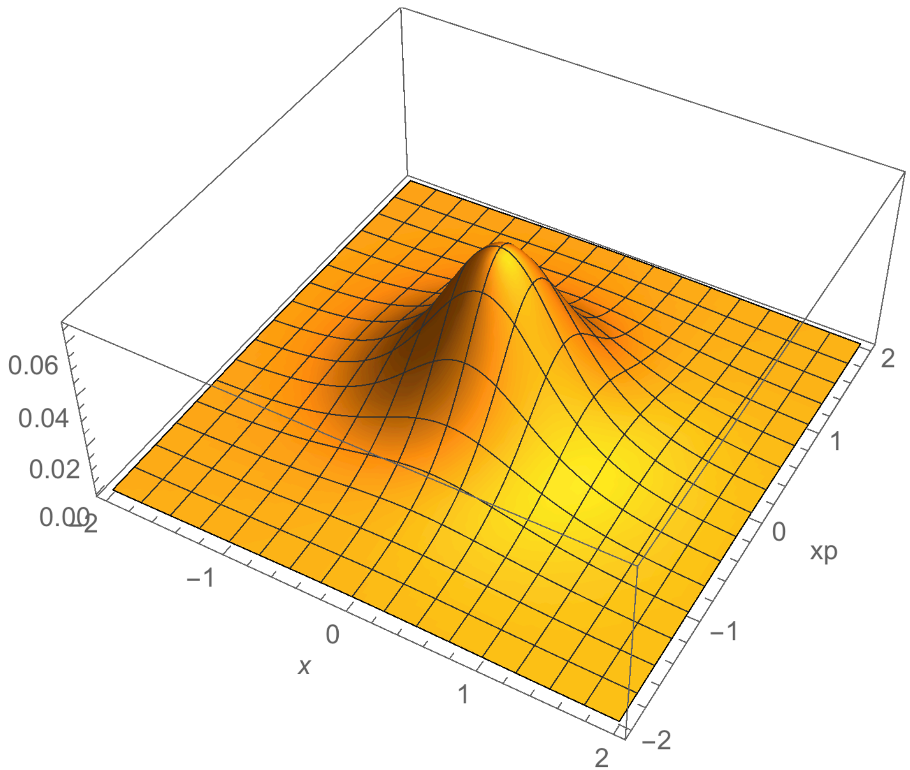
$$\mathcal{E}_\mathcal{A}(t_b, \mathbf{r_b}) = \frac{2L^3}{\pi} \int d^4r \, \frac{du}{u^2} \, \Theta(t_b - t) \, \delta''(W) \left[u(2t_{00} - t_{55}) - (t_b - t)t_{05} + (x_b - x)^i t_{i5}\right]$$

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

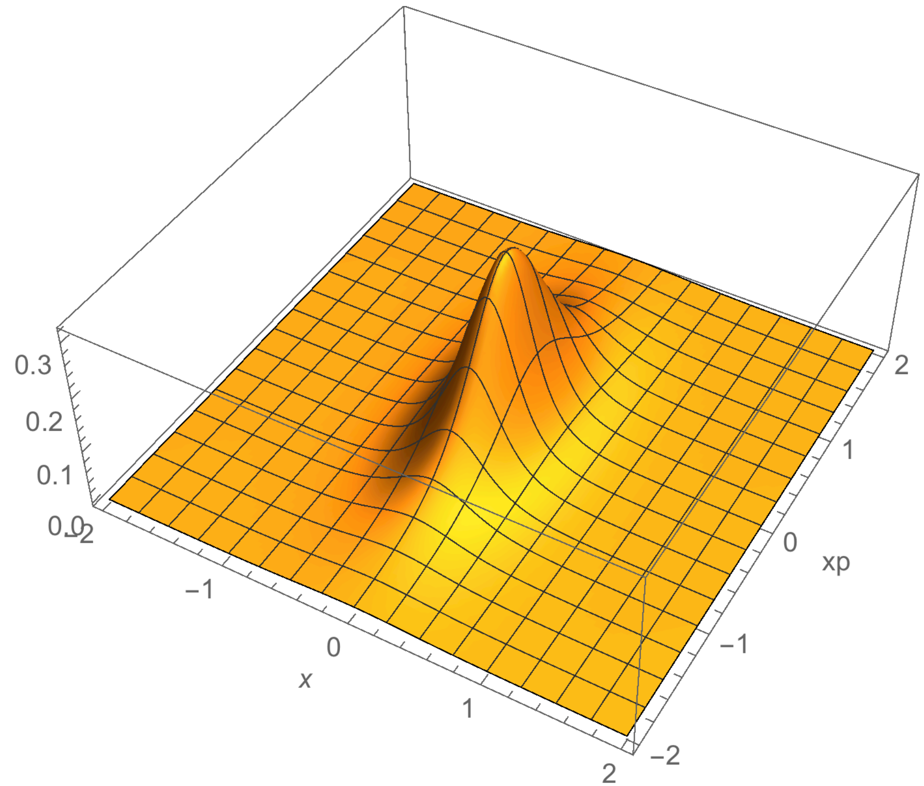
At time t, the bulk excitation localized at (t, r) emits a gravitational wave δG_{MN} which propagates through AdS$_5$ at the respective speed of light up to the measurement point (t_b, x_b, $x_{\perp b}$) on the boundary.

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 excitations and the gravitational waves.

Boundary Energy Density

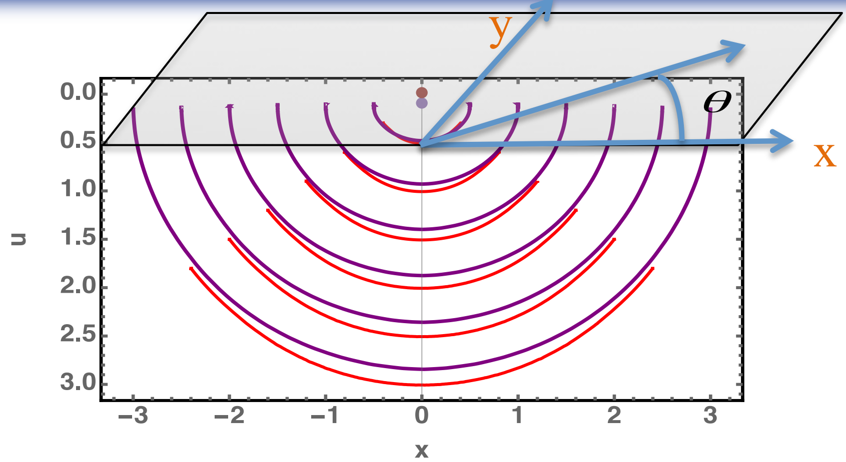


Heavy quark at rest with finite mass in AdS_5



Heavy quark with finite mass and velocity v=0.9 in x direction in AdS_5

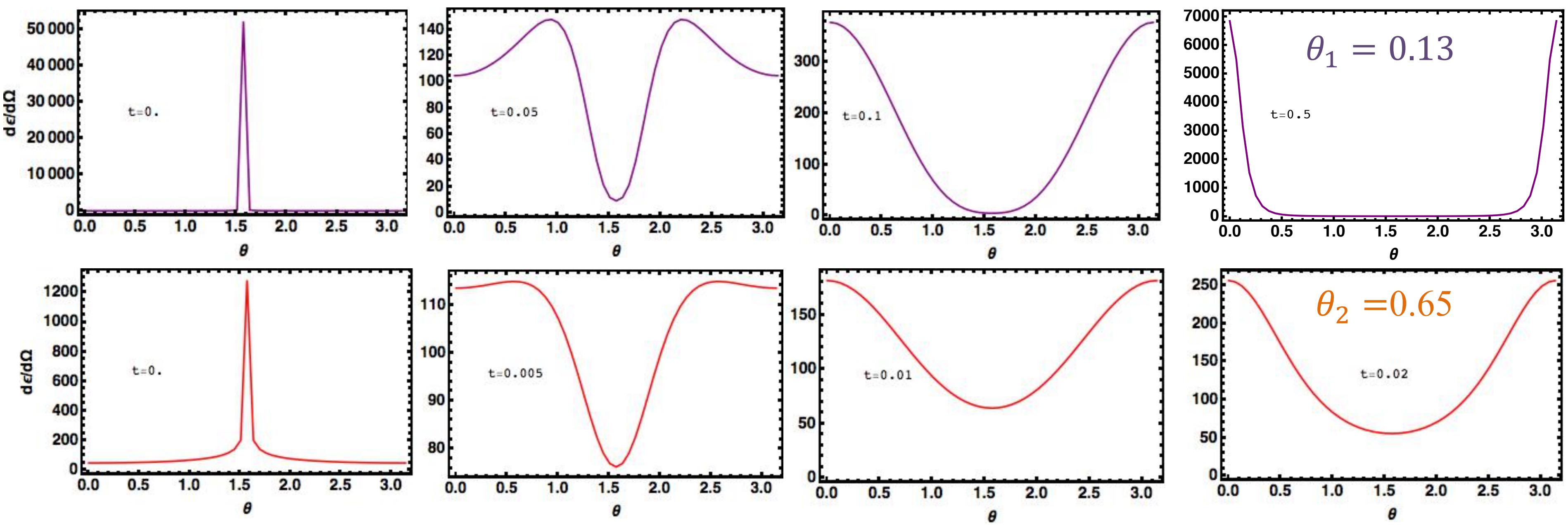
Boundary Jet Energy Density in AdS_5



$Q^2=E^2_q-P^2_q$

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

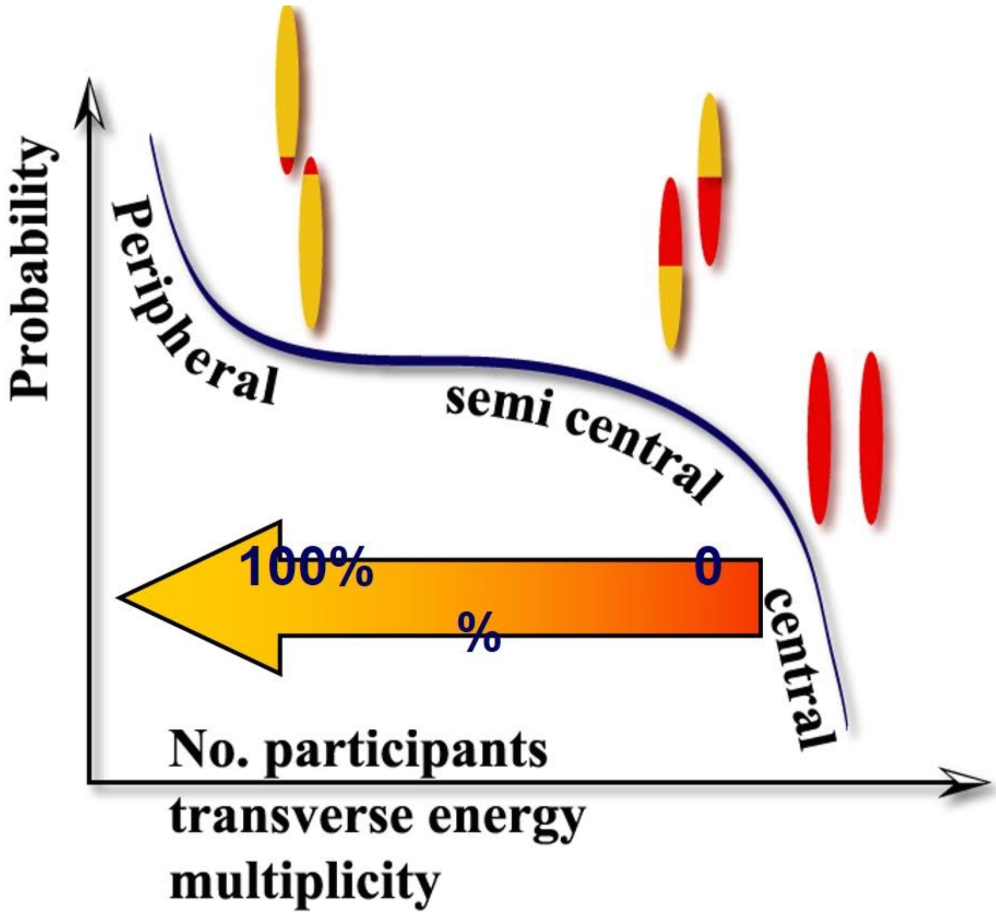


One can define the opening angle of jet: $\theta_j = ArcTan[\frac{\sqrt{Q^2}}{E_q}]$

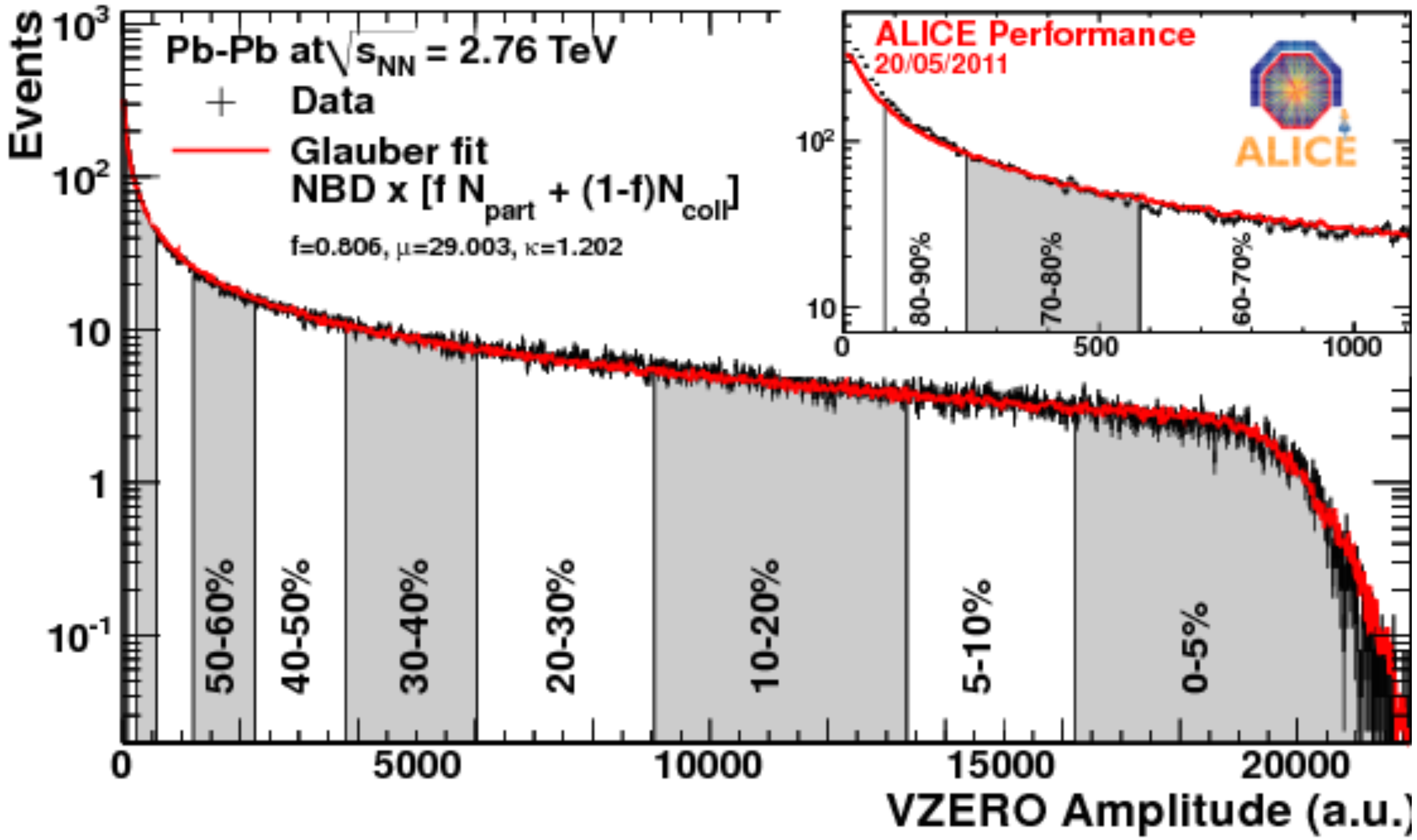
Thank you

Back Up Slides

Centrality


Probability
Peripheral
semi central
central
100%
0
%
No. participants
transverse energy
multiplicity

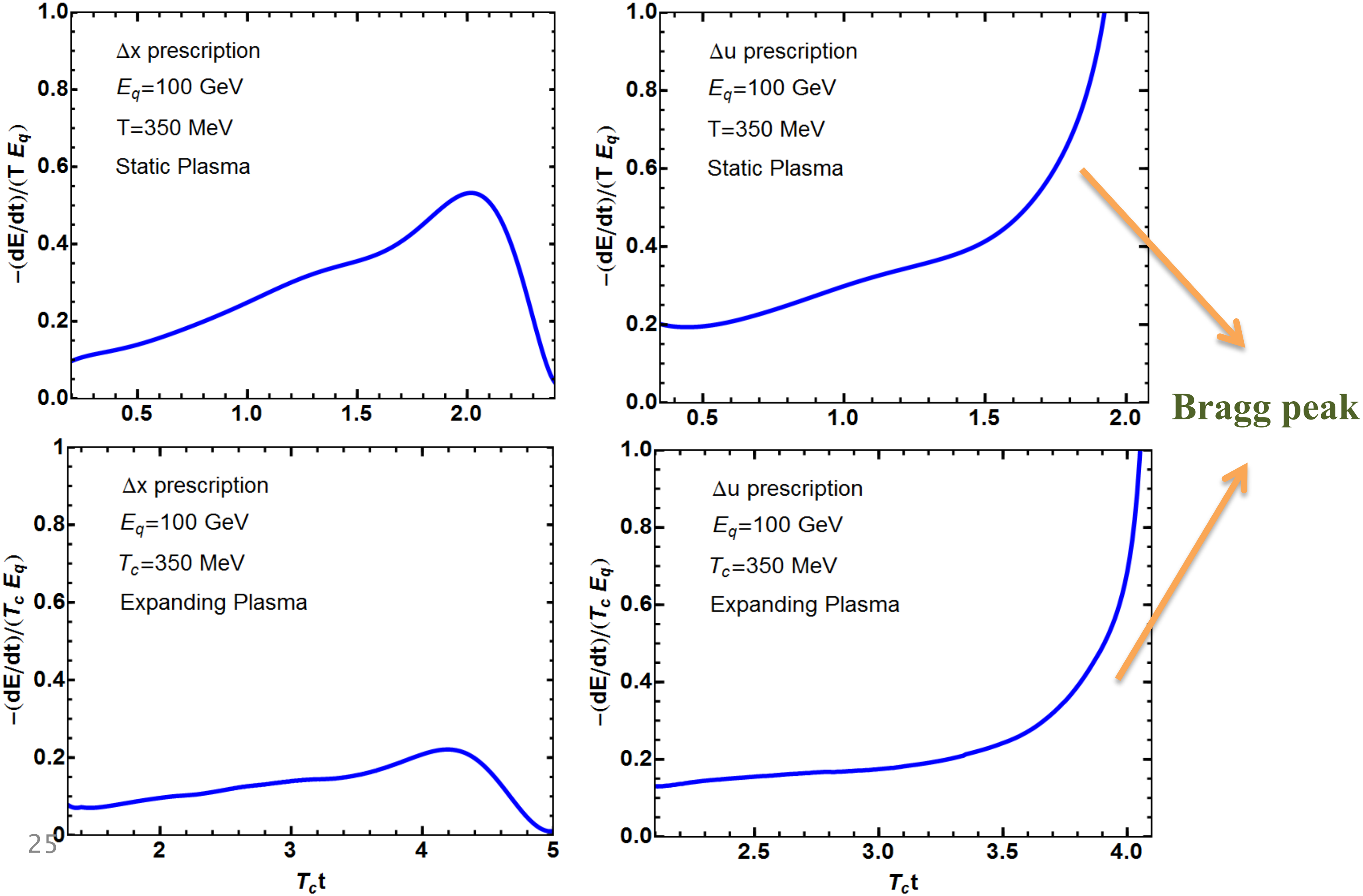
Centrality



Events
Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
Data
Glauber fit
NBD x [f N_{part} + (1-f)N_{coll}]
f=0.806, μ=29.003, κ=1.202
ALICE Performance
20/05/2011
ALICE
80-90%
70-80%
60-70%
50-60%
40-50%
30-40%
20-30%
10-20%
5-10%
0-5%
VZERO Amplitude (a.u.)

Light Quark Jets in AdS/CFT Correspondence

Light Quark Jets Energy Loss



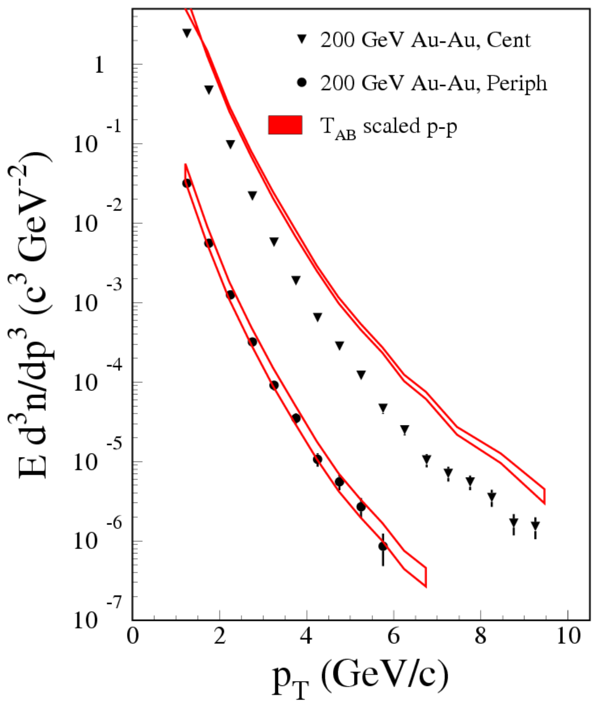
Jet Nuclear Modification Factor

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

$p_T^{\,f}$ Final energy of jet

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

ε Fractional energy loss



$P(\varepsilon\,|\,p_T^i)$ Probability of fractional energy loss of jet with initial momentum $p_T^{\,i}$

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

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