JET ENERGY LOSS IN A FLOWING PLASMA

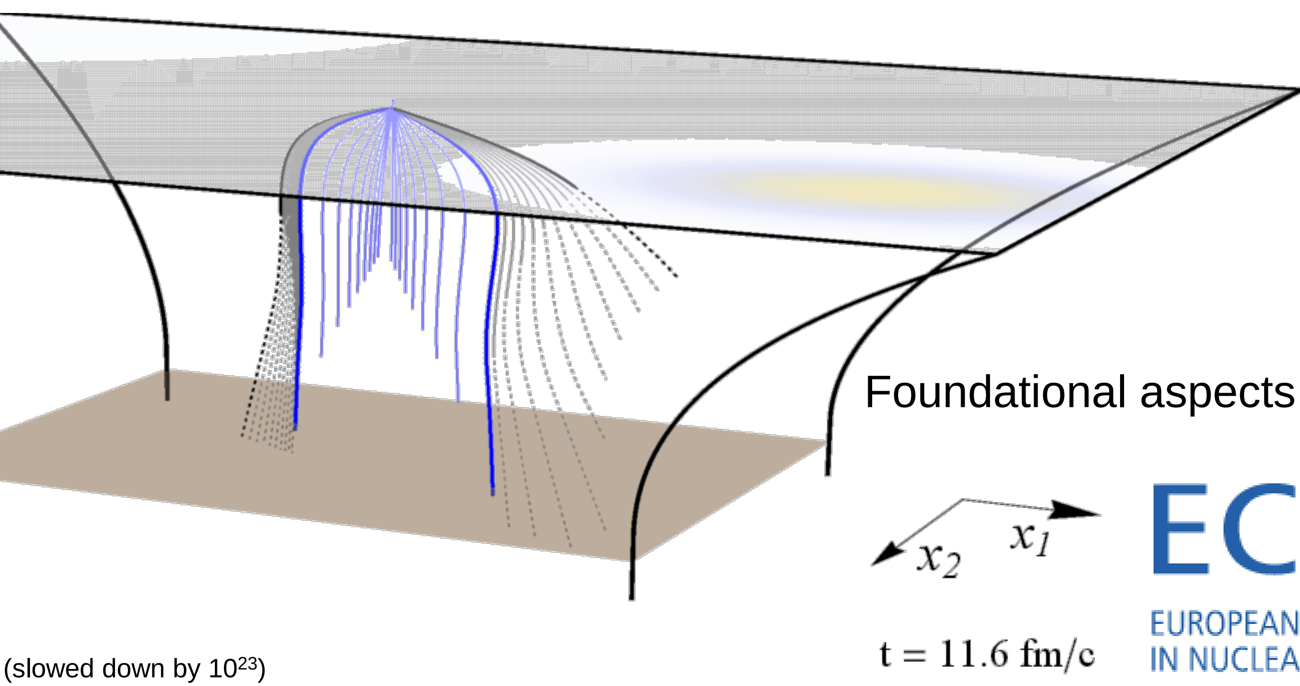
COMBINING QCD, STRINGS, NULL GEODESICS AND VISCOUS HYDRO

With Jasmine Brewer, Krishna Rajagopal and Andrey Sadofyev

1602.04187 (PRL), 1710.03237 and to appear

Wilke van der Schee

Foundational aspects of relativistic hydrodynamics
Trento, 8 May 2018



(slowed down by 10^{23})

Universiteit Utrecht

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

OUTLINE

Motivation, early work and recent progress

- (weakly coupled) jet energy interacts strongly with QGP
- Succesfully matches observations in hybrid model
- From production (pQCD) to strings to null geodesics in AdS

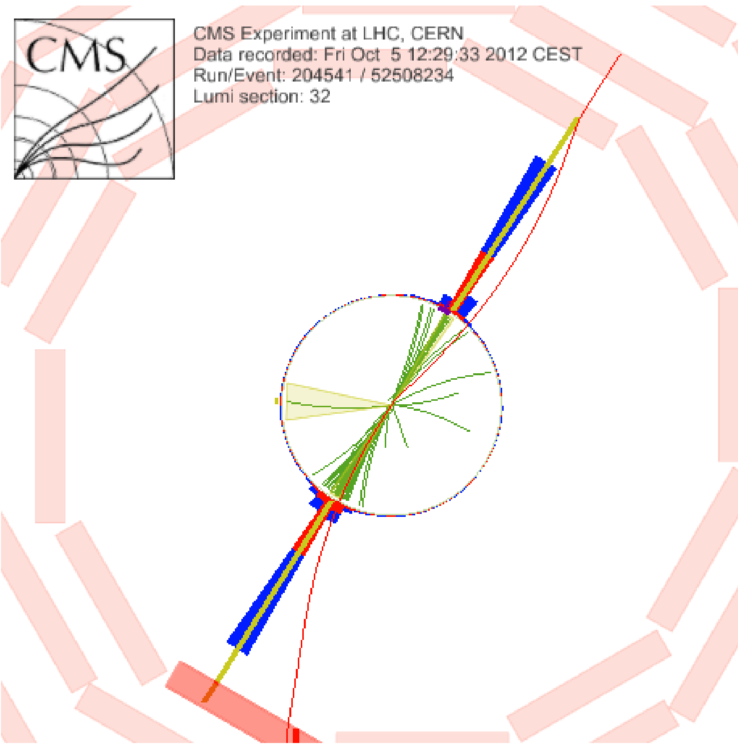
A simple model

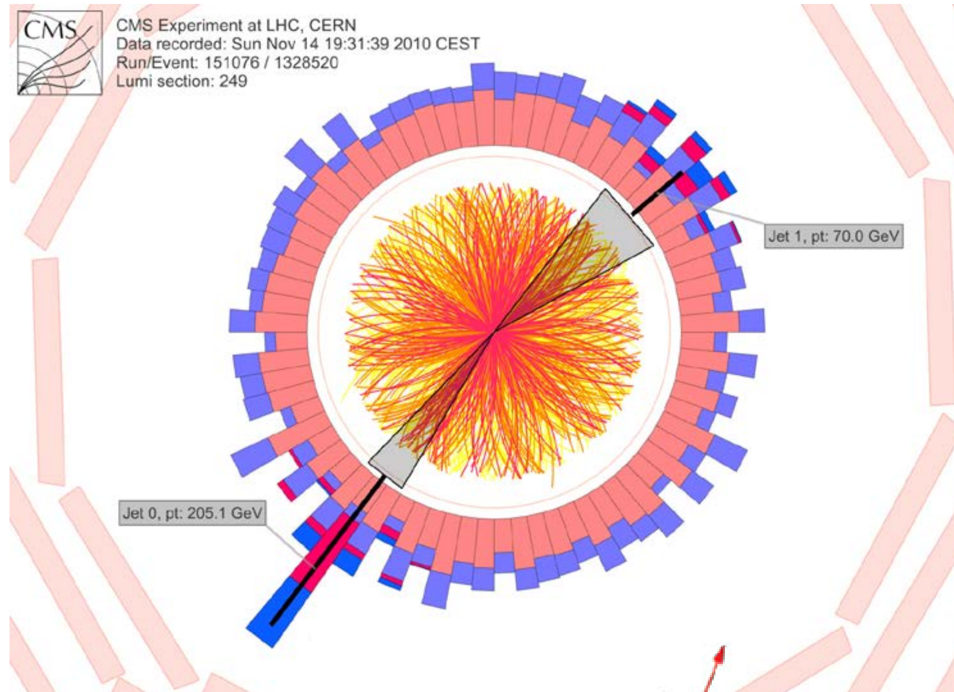
- Four simple examples: energy loss has memory
- Null geodesics in viscous hydrodynamics: formula + subtlety
- Going with or against the flow
- Temperature dependence in Gubser flow

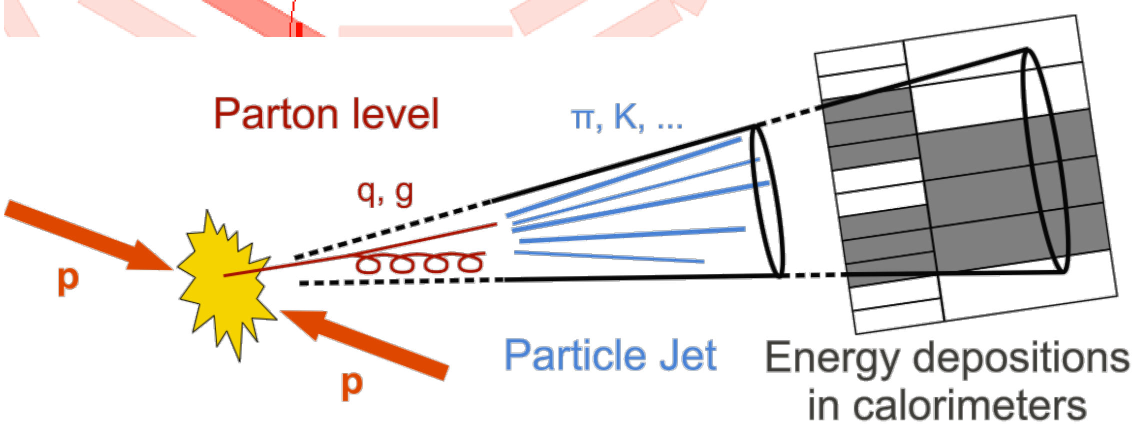
Preliminary results and an easy implementation

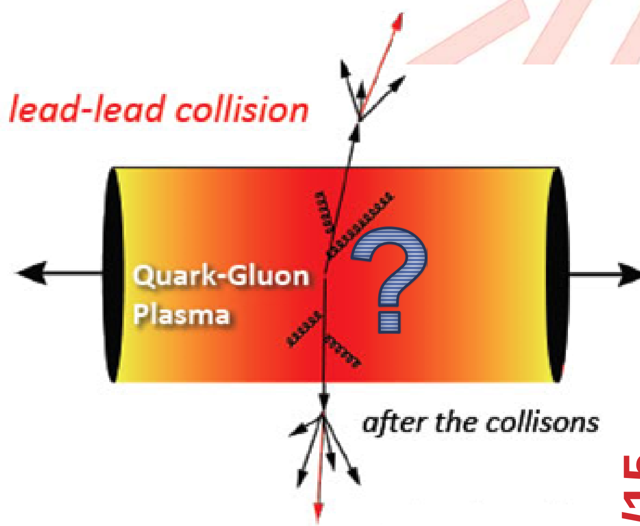
- Goal is to provide energy loss formalism valid for flowing plasma

JETS IN QGP


CMS
CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 12:29:33 2012 CEST
Run/Event: 204541 / 52508234
Lumi section: 32

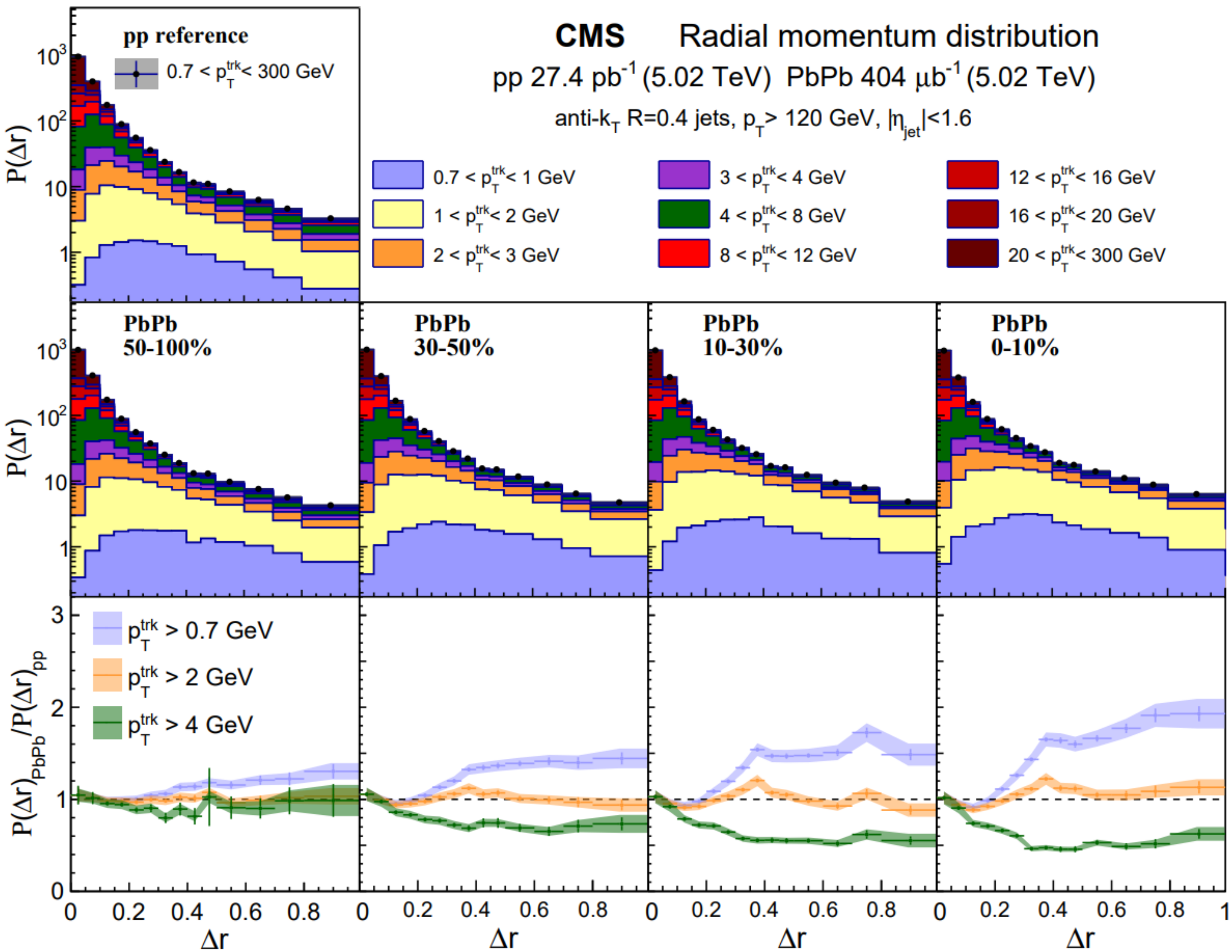

CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

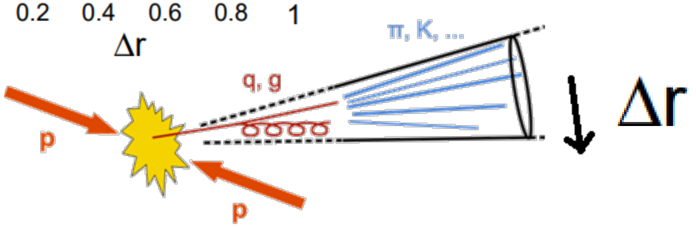

Parton level
π, K, ...
q, g
p
p
Particle Jet
Energy depositions
in calorimeters


lead-lead collision
Quark-Gluon
Plasma
?
after the collisons

Wilke van der Schee, MIT/Utrecht

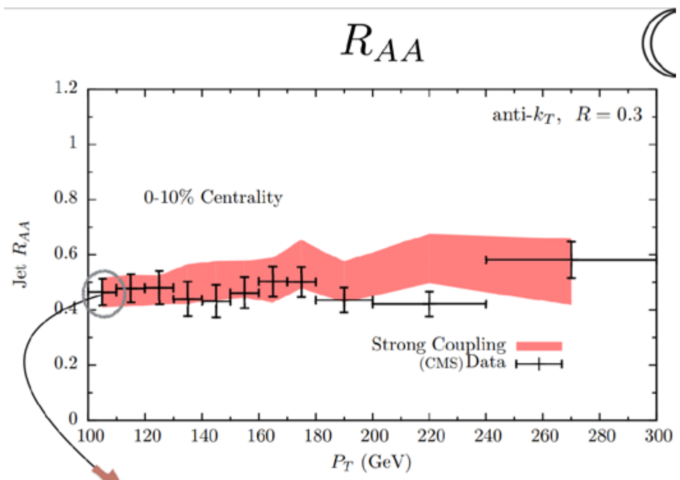
TRENDS IN JET ANALYSIS



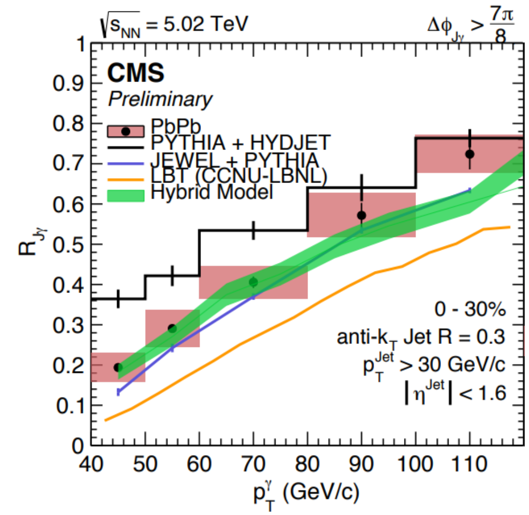


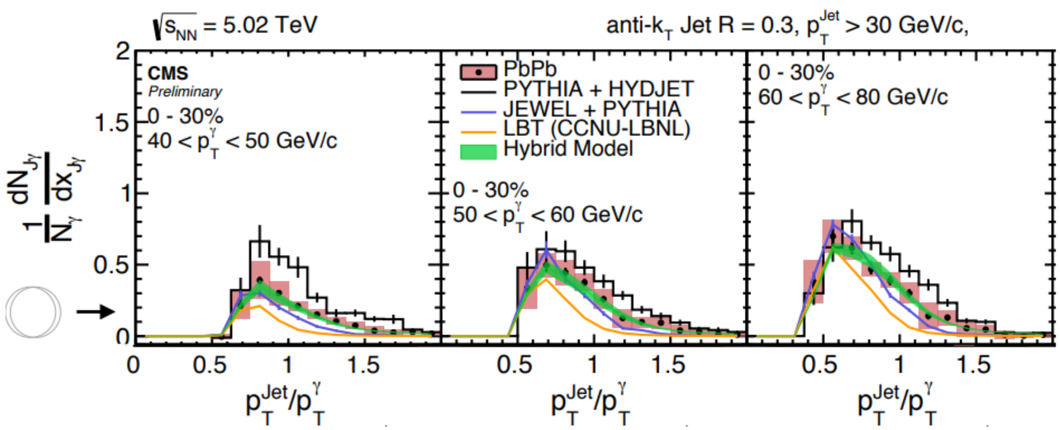
CMS, Jet properties in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV (2018)

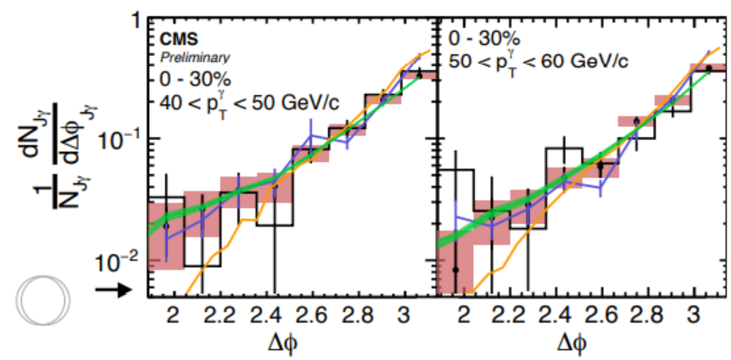
ADS/CFT INSPIRED MODEL WORKS:



One parameter fitted



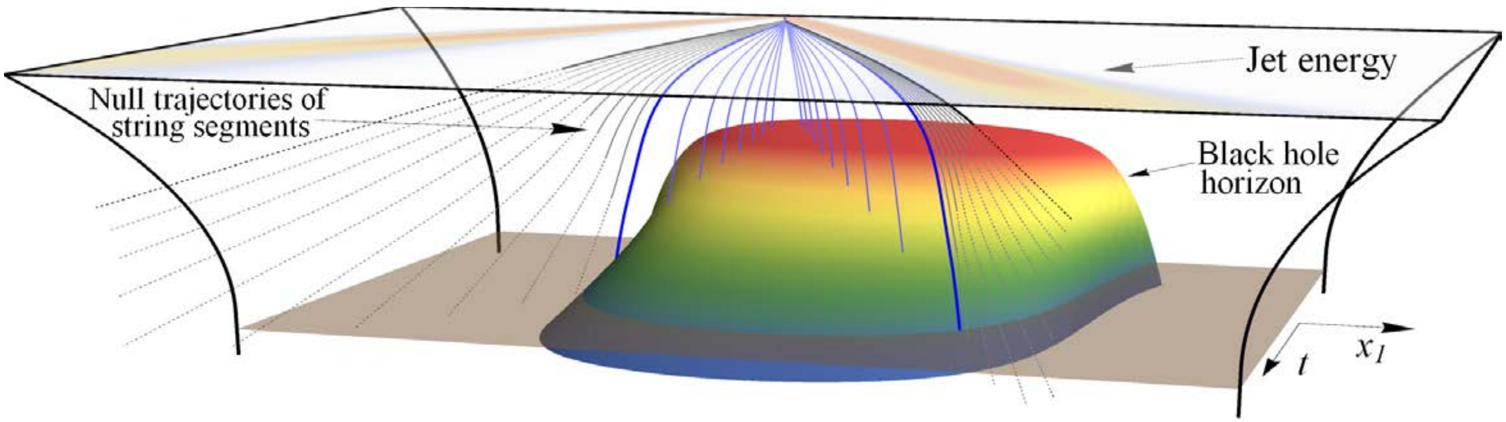




J. Casalderrey, D. Can Gulhan, J. Guilherme Milhano, D. Pablos and K. Rajagopal, A Hybrid Strong/Weak Coupling Approach to Jet Quenching
K. Rajagopal, Presentation Quark Matter 2017

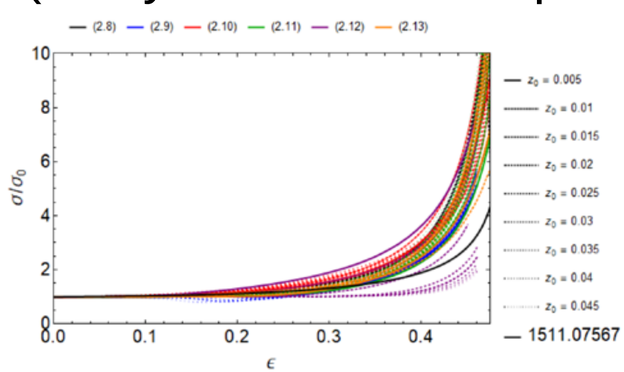
JET ENERGY LOSS IN ADS/CFT

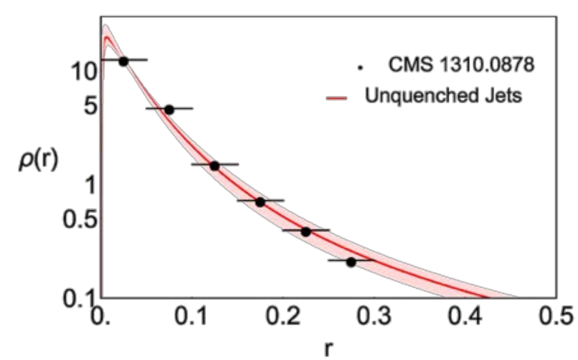
Quark-antiquark pairs ~ strings in AdS geometry



Leads to (simplified) model for jet evolution

- String segments quickly follow null geodesics in semi-universal way
- Possible to track null geodesics falling in: determines energy loss
- (analytic formula for specific case, also assuming constant T)

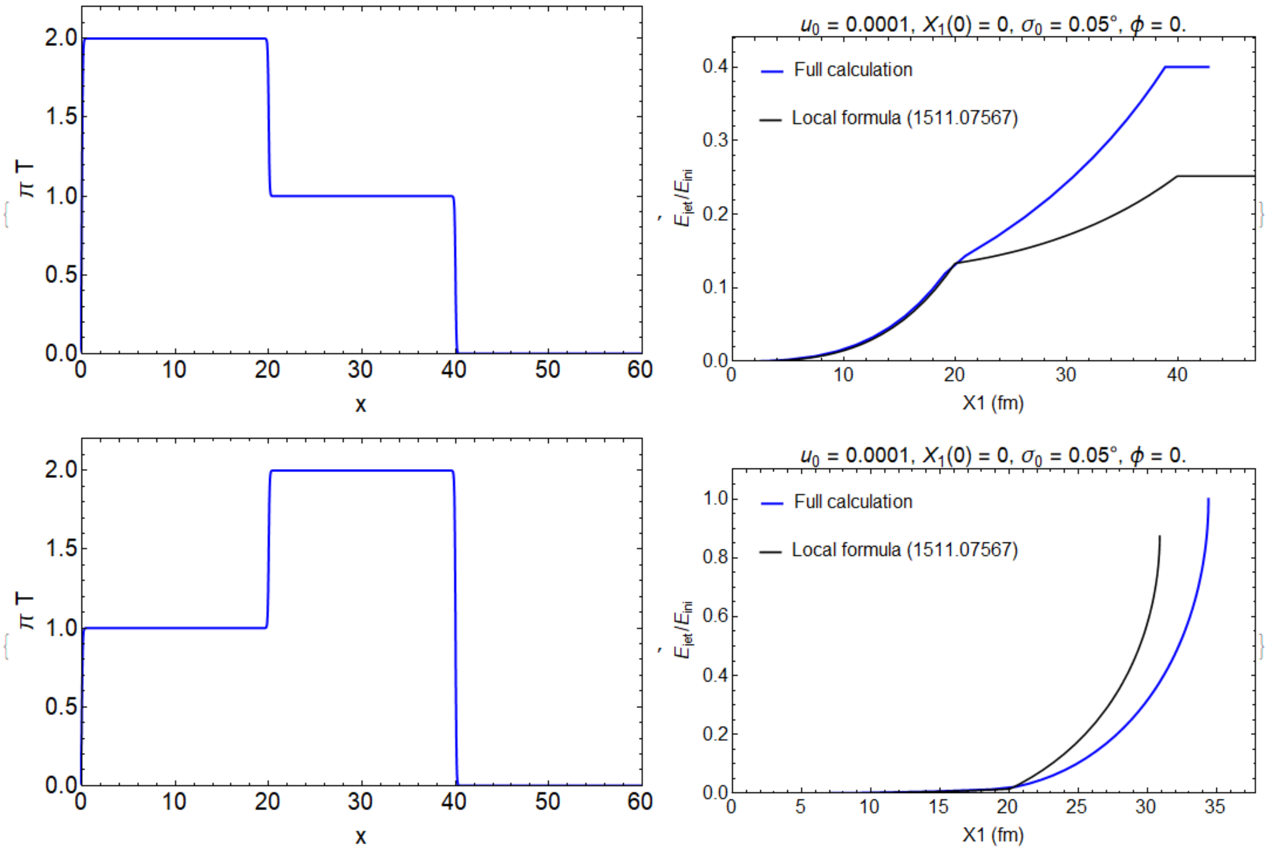




J. Brewer, K. Rajagopal, A. Sadofyev and WS, Jet shape modification in a holographic plasma (2017)

VARYING TEMPERATURE

Energy loss depends on temperature evolution non-linearly:



- First phase agrees with (ultra)local formula (Chesler, Rajagopal)
- Interesting: (final) energy loss much bigger for 2nd profile
- Illustrates `memory-effect': wave function remembers evolution

SECOND EFFECT: FLOW

Flow has not yet been included

- Subtlety in geodesic equation from metric using ideal hydrodynamics:
  - Geodesic equation contains derivatives of metric
  - Includes a term ~ $-\frac{\partial v_x}{\partial x}$, to be compared with Z^3 (typically very small)
- Two solutions: use viscous hydrodynamics (term cancels), or ignore gradients on level of geodesic equation (as opposed to metric, easier)

Final formula for geodesics in ideal hydrodynamics:

$$Z''(t) = -2\pi^4 T^4 \left(1 - v_{||}\right) Z(t)^3 \left(\frac{1 - v_{||}}{v_{||}^2 + v_{\perp}^2 - 1}\right)$$

(full formula including Z' and viscous terms is known but longer)

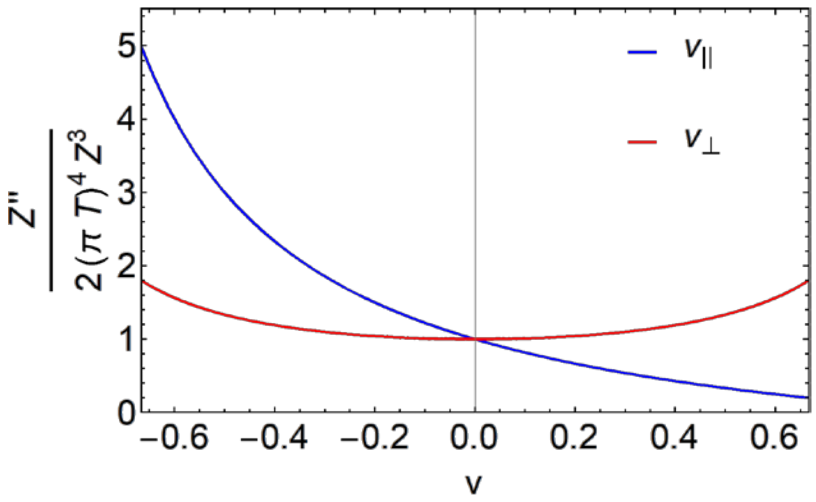
$$ds^2 = -2\, u_\mu\, dx^\mu dr - r^2\, f(b\,r)\, u_\mu u_\nu\, dx^\mu dx^\nu + r^2\, P_{\mu\nu}\, dx^\mu dx^\nu$$
$$+\, 2\, r^2\, b\, F(b\,r)\, \sigma_{\mu\nu}\, dx^\mu dx^\nu + \frac{2}{3}\, r\, u_\mu u_\nu\, \partial_\lambda u^\lambda\, dx^\mu dx^\nu - r\, u^\lambda \partial_\lambda\left(u_\nu u_\mu\right)\, dx^\mu dx^\nu$$

Sayantani Bhattacharyya, Veronika Hubeny, Shiraz Minwalla and Mukund Rangamani, Nonlinear Fluid Dynamics from Gravity (2007)

SECOND EFFECT: FLOW

Final formula for geodesics in ideal hydrodynamics:

$$Z''(t) = -2\pi^4 T^4 \left(1 - v_{||}\right) Z(t)^3 \left(\frac{1 - v_{||}}{v_{||}^2 + v_\perp^2 - 1}\right)$$



(Z'' essential for energy loss, but not proportional to energy loss)

Corrections due to viscosity:

$$\Delta Z''(t) = -2\pi^4 T^3 \left(\frac{2}{3}\frac{\partial v_x}{\partial x} + 2\left(\frac{\partial v_x}{\partial x} + 2\frac{\partial v_x}{\partial t}\right) T\, Z(t)\right) Z(t)^3$$

A SIMPLE ALGORITHM

Energy loss from AdS/CFT in a dynamic setting

- Start with several string segments at boundary (~20), with different *Z'*
    - *Z'* of endpoint is determined by pQCD opening angle of q/g
    - *Z'* of other segments is taken from semi-universal curve (slide 6)
- Evolve *Z(t)* according to simple differential equation
- Straightforward to determine energy outside horizon

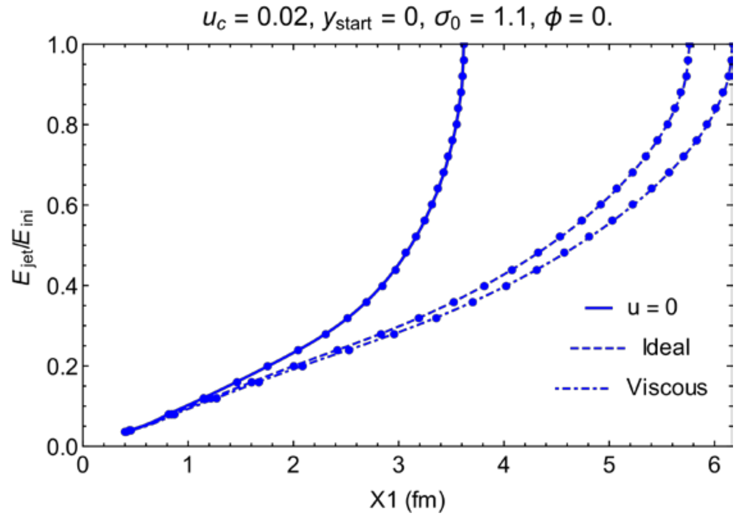
Main difference with current dE/dx approaches:

- Need to keep track of ~20 variables per parton, i.e. parton wave function more complicated than just energy
- 2nd order equation: memory effect
    - Perhaps similar to L^2 or L^3 scaling of current approaches
- Relatively non-linear interplay of E(x) versus T(t) and v(t)

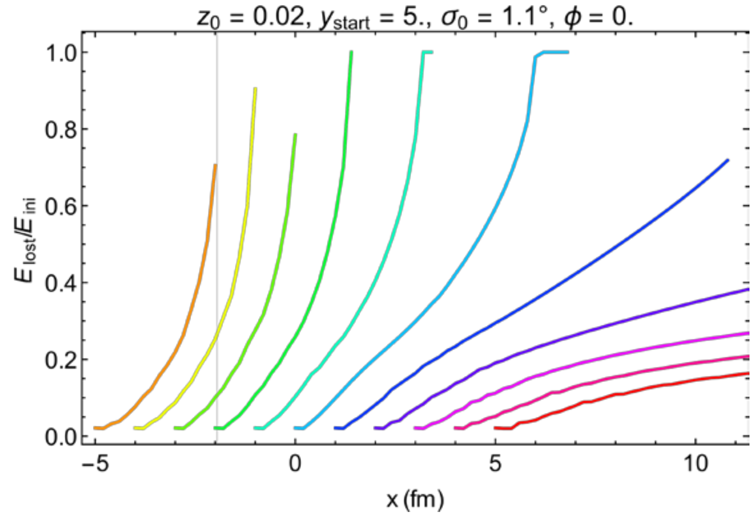
RESULTS IN GUBSER FLOW

Resulting energy loss in (analytic) simple model for central collision

Compare no flow, ideal and viscous



different starting points



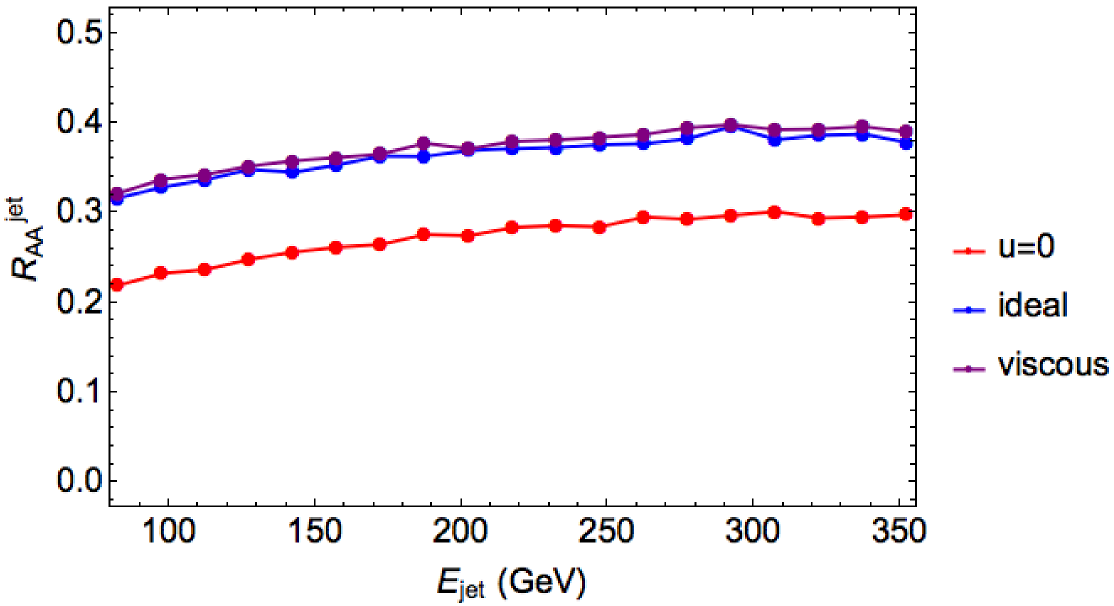
- Flow has extremely important effect, doubling stopping distance
  - Recall old result: $\Delta x_{\text{stop}} = \left[\frac{2^{1/3}}{\sqrt{\pi}}\frac{\Gamma\left(\frac{5}{4}\right)}{\Gamma\left(\frac{3}{4}\right)}\right]\frac{1}{T}\left(\frac{E_*}{\sqrt{\lambda}T}\right)^{1/3}$
- Corrections due to gradients significant, but small

P.M. Chesler, K. Jensen, A. Karch and L.G. Yaffe, Light quark energy loss in strongly-coupled N = 4 supersymmetric Yang-Mills plasma (2008)
Andrej Ficnar and Steven Gubser, Finite momentum at string endpoints (2013)

R^{JET}_{AA} COMING FROM NEW FORMULA

Result on nuclear modification factor

- Overall scaling somewhat arbitrary, determined by free parameter
- Effect of including flow significant, viscous contribution smaller
- Result quite similar to hybrid model, but different physics input: dynamic temperature + varying string initial conditions from pQCD

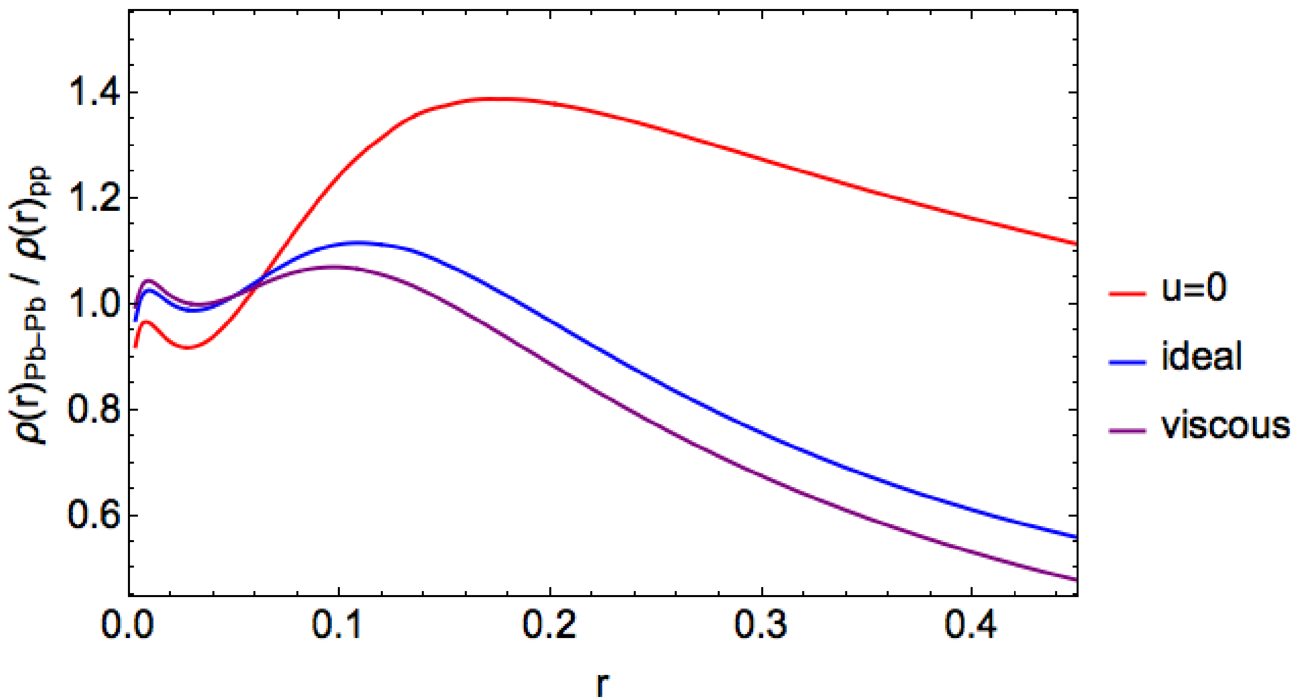


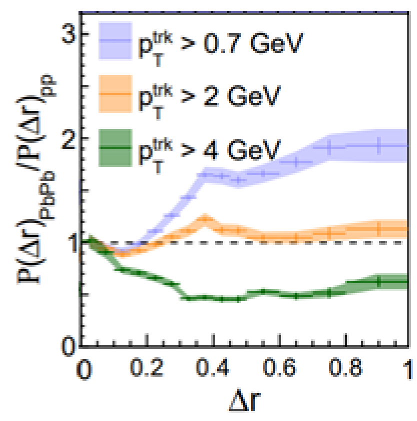
MODIFIED JET SHAPES

Jet shapes have interesting interplay:

- All jets get wider due to black hole
- Selection effect: narrower jets more likely to survive

- Now new effect: *jets in flow tend to stay narrower*

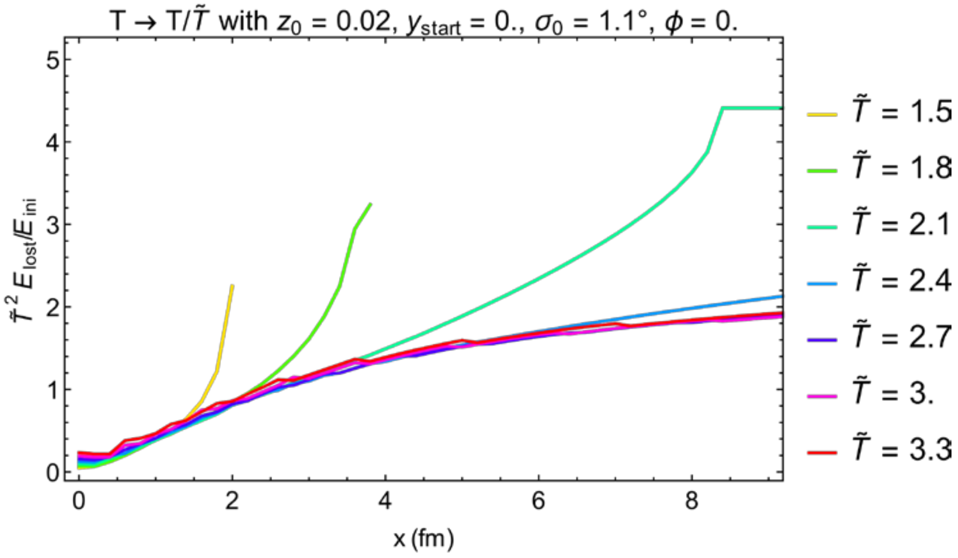




ENERGY LOSS VERSUS TEMPERATURE

Are there semi-general lessons for this energy loss?

- Try extracting dependence dE/dx on temperature: rescale T by $\tilde{T}$
- Numerical finding: different curves collapse when scaling by T^2
    - Up to point where particular jet loses all energy: early time scaling



- (fairly robust, but scaling somewhat dependent on semi-universal curve, e.g. result from different black line gives T^3)

DISCUSSION

Strong versus weak coupling

- Strings provide well-defined first-principle computation at strong coupling
  - Interaction with medium may well be strongly coupled
- Limitations are clear: q/g production is described by pQCD
  - Can give us insights into *initial conditions of strings*, i.e. energy + opening angle/jet width
  - Holography misses hard splittings: all radiation is soft, no 3rd jets
  - Likewise extra care is needed for jet radius (R) dependence of results
- A combination likely possible: treat all hard splittings (>10 GeV?) in pQCD, then switch to strings

Provided a simple algorithm for energy loss in a dynamic flowing medium

- Relatively straightforward implementation in e.g. Monte Carlos
- Interesting illustration of memory-effect: *temperature evolution matters*
- Very strong effects of flow, mild effects of gradient corrections (modulo subtlety)
- Interesting scaling $dE/dx \sim T^2$ in specific (realistic) model?

Outlook

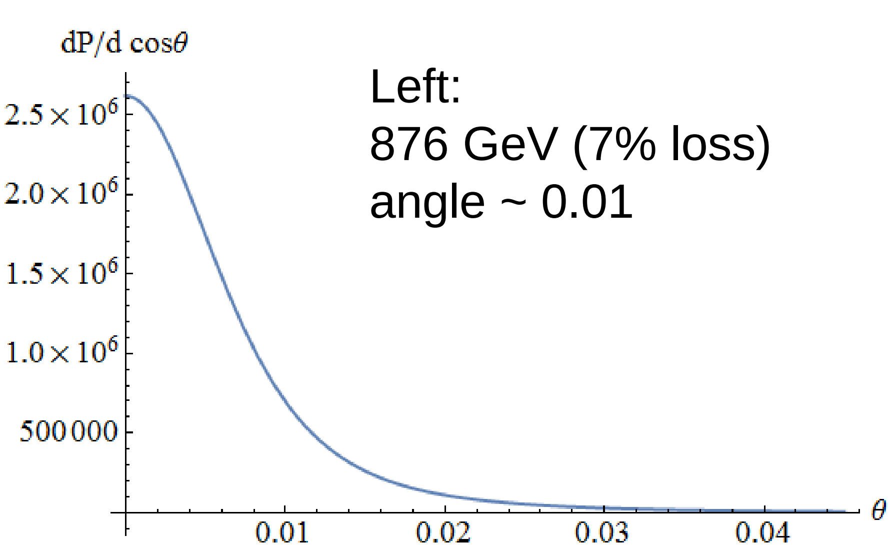
- Implementation in Monte Carlo?
- Full understanding initial string condition still somewhat unsatisfactory: 3-jets etc
- Not quite related: back-reaction lost energy on medium: where does E/p go?

JET ANGULAR SPECTRUM

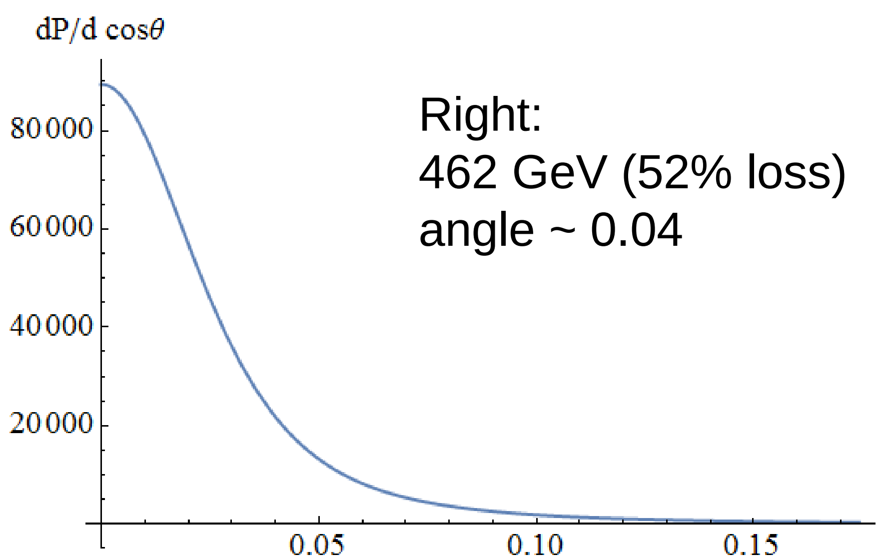
At late times string falls into AdS, straight lines for each σ.

- Stress-energy on boundary due to `collection of AdS point particles':
  energy e,
  angle to center θ,
  AdS angle α

$$\frac{dP}{d\cos\theta} = \frac{e}{4\pi}\frac{\sin^4(\alpha)}{(1-\cos(\theta)\cos(\alpha))^3}$$



Left:
876 GeV (7% loss)
angle ~ 0.01



Right:
462 GeV (52% loss)
angle ~ 0.04

Y. Hatta, E. Iancu, A. Mueller and D. Triantafyllopoulos, Aspects of the UV/IR correspondence: energy broadening and string fluctuations (2010)