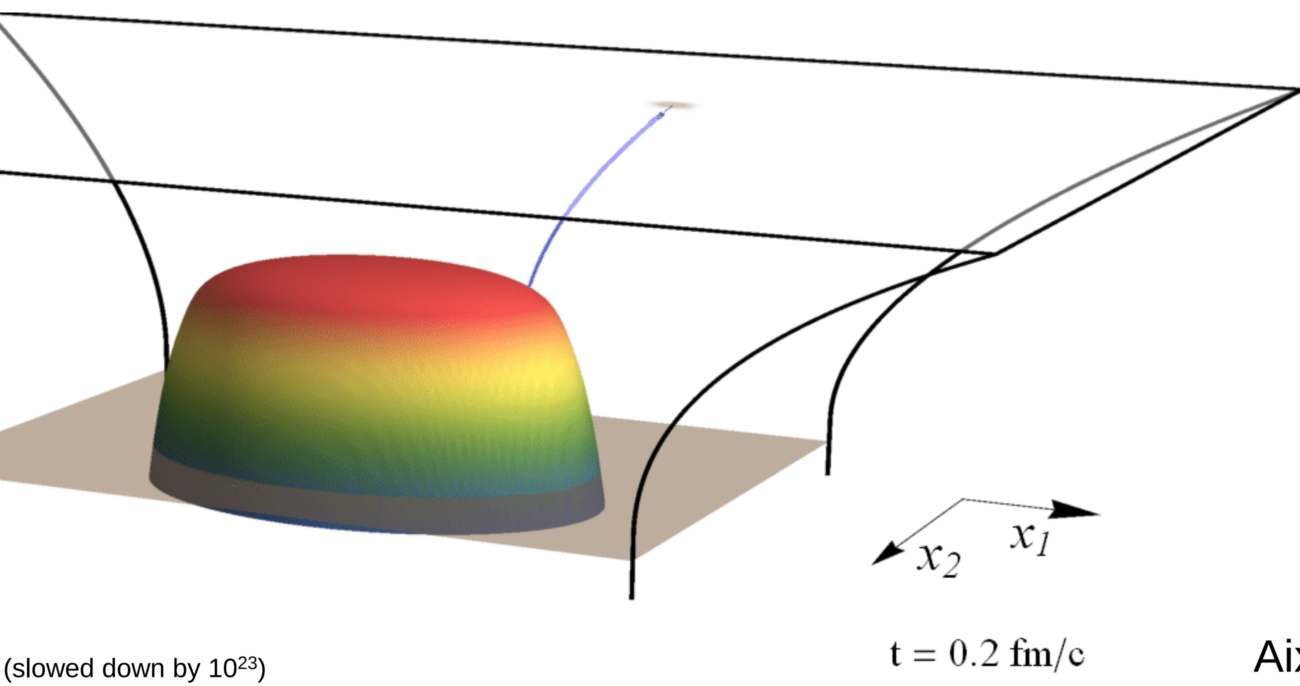
# JET ENERGY LOSS IN A FLOWING PLASMA

## JET SHAPE MODIFICATIONS IN HOLOGRAPHIC DIJET SYSTEMS

With Jasmine Brewer, Krishna Rajagopal and Andrey Sadofyev
1602.04187 (PRL), 1710.03237 (JHEP) and 1809.10695




(slowed down by $10^{23}$)

**Wilke van der Schee**

Hard Probes 2018
Aix-Les-Bains, 2 October 2018

# OUTLINE

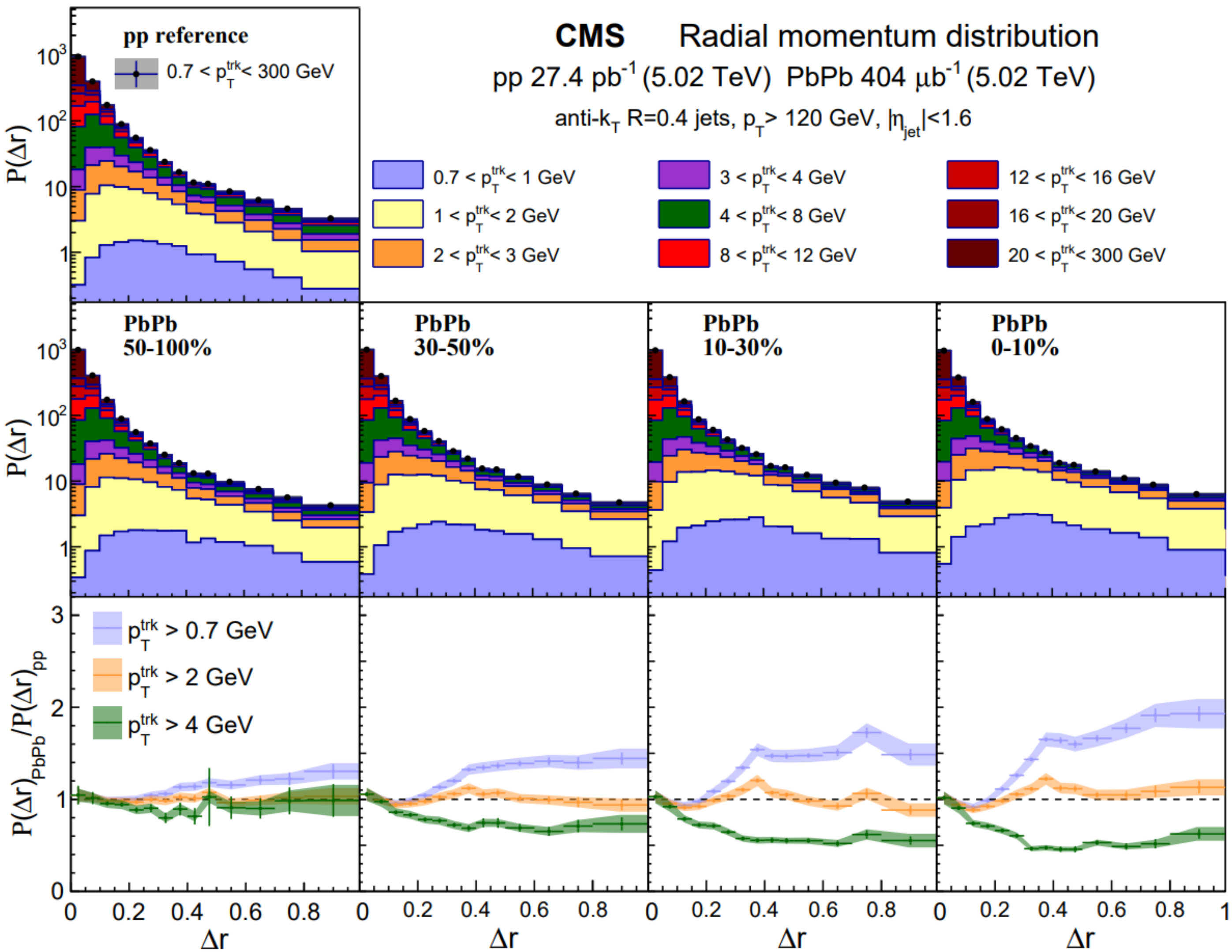
**Motivation and a simple model**

- (weakly coupled) jet energy interacts strongly with QGP
- From production (pQCD) to strings to null geodesics in AdS
- Goal is to provide energy loss formalism valid for flowing plasma

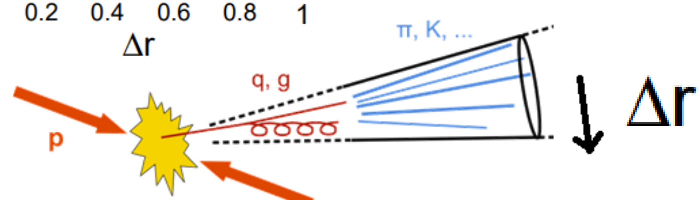
**Jet shapes and (holographic) dijet systems**

- Dijet asymmetry interesting: path length & fluctuations essential
- Study leading and subleading shape modifications
- Observable: dijet asymmetry for different subleading jet width

# TRENDS IN JET ANALYSIS



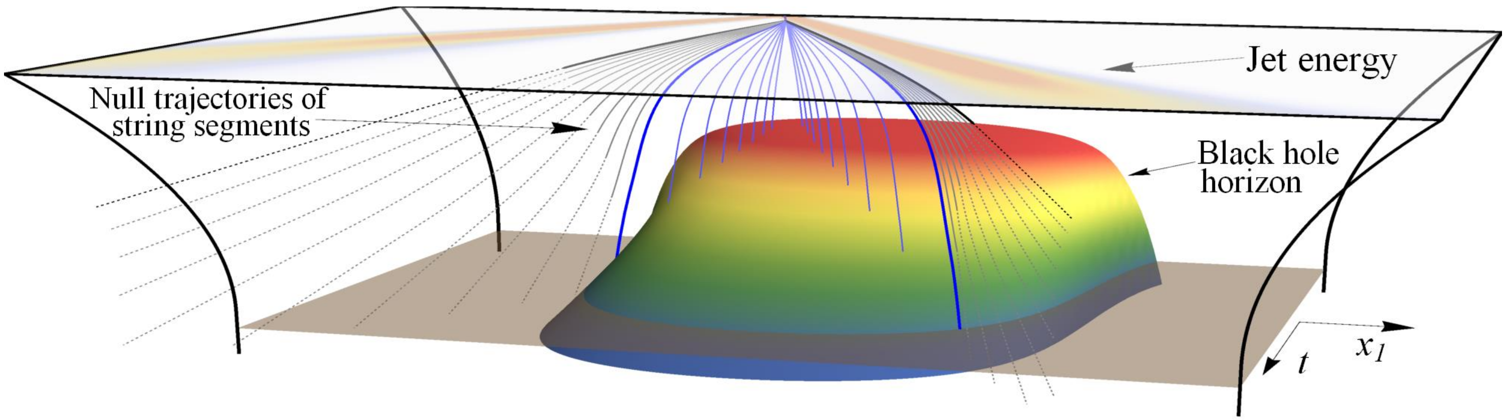

$p_T$ cut separates medium effects from jet physics




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

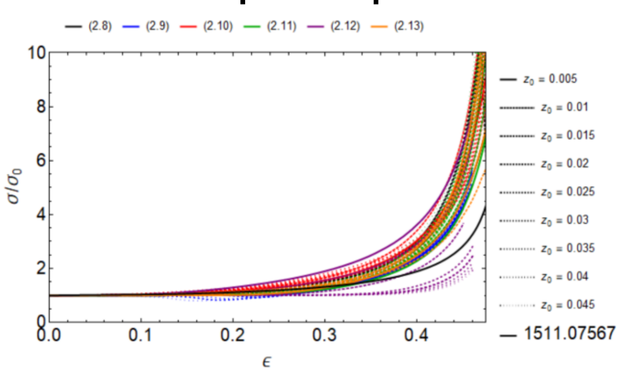
# JET ENERGY LOSS IN ADS/CFT

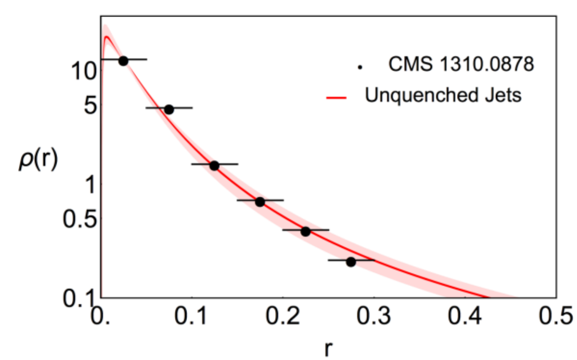
## Quark-antiquark pairs ~ strings in AdS geometry




## 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
- Final shape depends on specific evolution




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

# FLOW AND IDEAL HYDRODYNAMICS

**Final formula for geodesics in ideal hydrodynamics, including flow:**

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

- *Z* is holographic coordinate string segment, *T* and *v* depend on ($\tau$, $x_\perp$)
- Initial position close to zero, initial *Z'* related to jet width

**Flow had not yet been included**

- Formula can have analytic solutions for constant temperature
- Varying temperature is non-trivial (even when gradients are small)
- Effects of gradients is relatively small (upcoming work)
- (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)

# 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 4)
- 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)

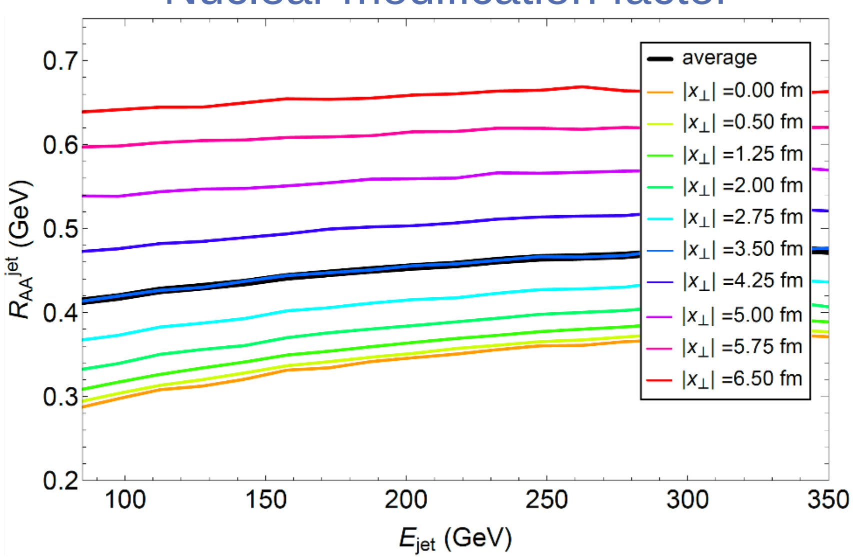
# DIJET ASYMMETRY

**Two sources of (extra) imbalance in heavy ion dijet asymmetry:**

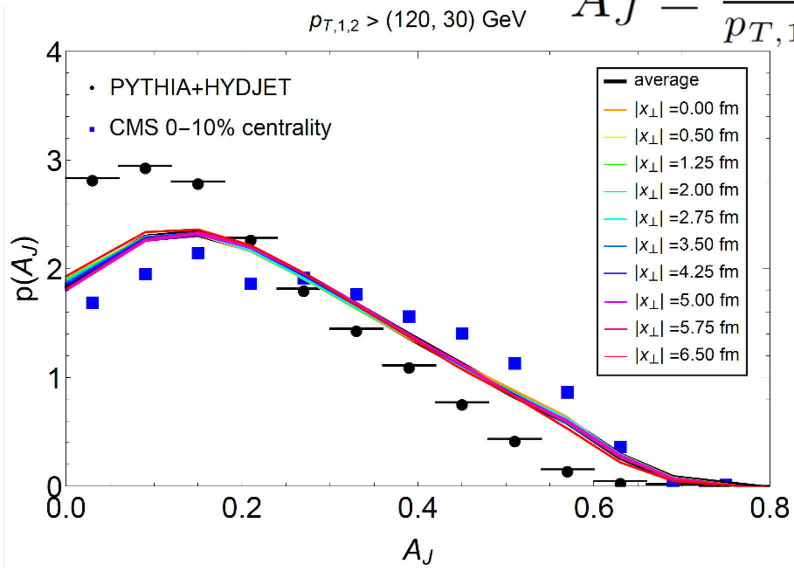
- Path length: different path length → less balanced
- Fluctuations of energy loss: jet width fluctuations (our model)

- Nice trick to turn off path length imbalance: start all jets at center
    - Turns out that in our model (and in JEWEL) $A_J$ is insensitive to position

Nuclear modification factor




$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$




Guilherme Milhano and Korinna Zapp, Origins of the di-jet asymmetry in heavy ion collisions (2015)

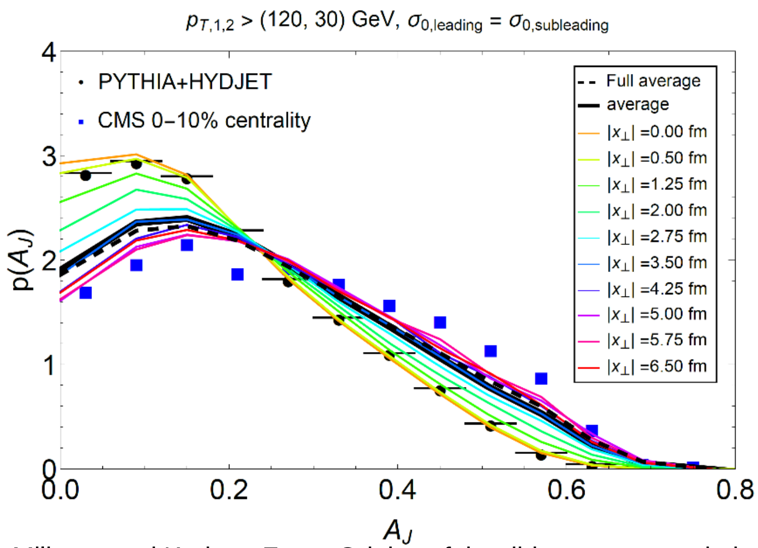
# DIJET ASYMMETRY

**(Artificial) way of turning off independent energy loss fluctuations**

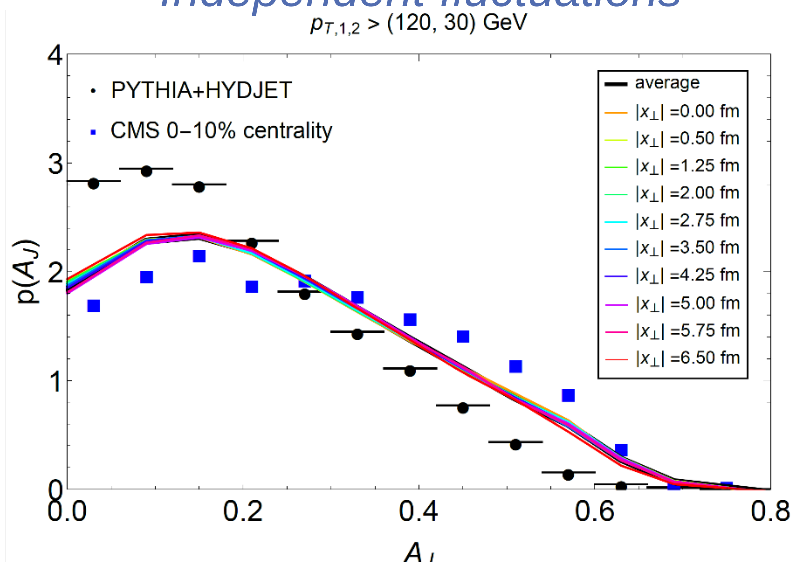
- Select subset of dijets in sample that have equal jet widths
- Relative energy loss fully determined by path length imbalance

- Now indeed dijet asymmetry of jets produced at center is unmodified
    - Curiously average dijet asymmetry agrees with full result

*No independent fluctuations*




*Independent fluctuations*



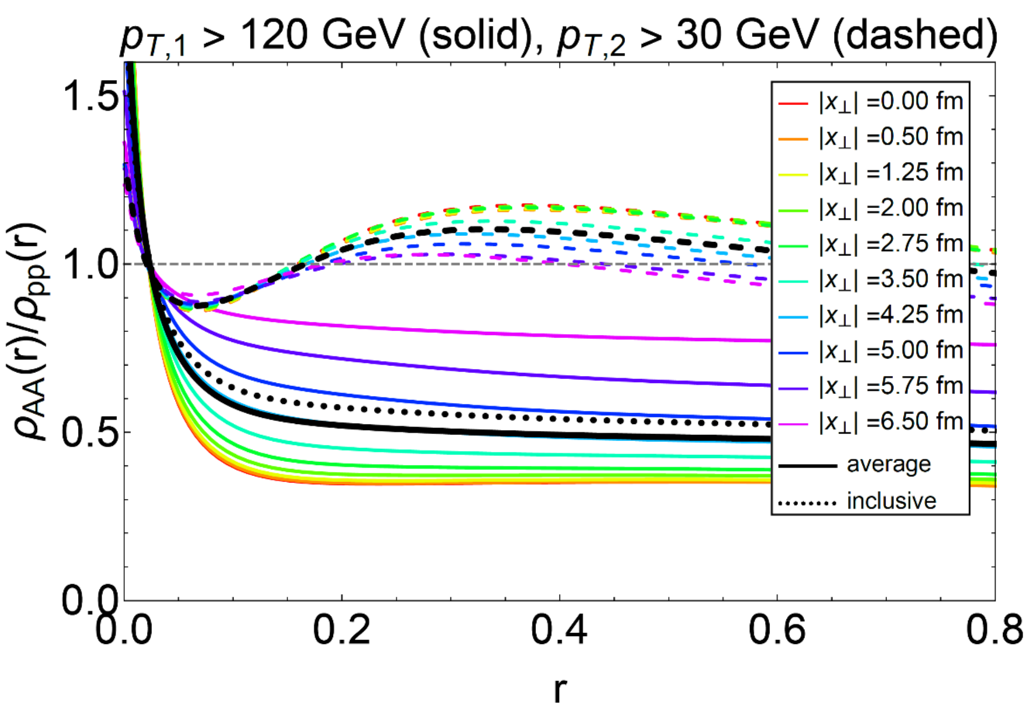

Guilherme Milhano and Korinna Zapp, Origins of the di-jet asymmetry in heavy ion collisions (2015)
Jasmine Brewer, Andrey Sadofyev and WS, Jet shape modifications in holographic dijet systems (2018)

# JET SHAPE MODIFICATIONS

**Two clear lessons:**

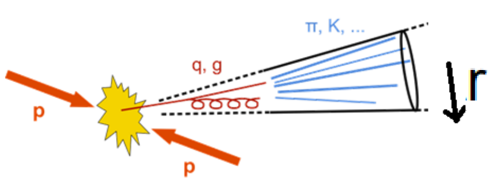
- Influence of path length imbalance and fluctuations `cancels'
- Dijet asymmetry is uninformative on where a jet was produced
- Jets from center lose more energy, hence larger fluctuations

**Jets at center are also more heavily modified:**




**Leading and subleading (dashed) modifications**

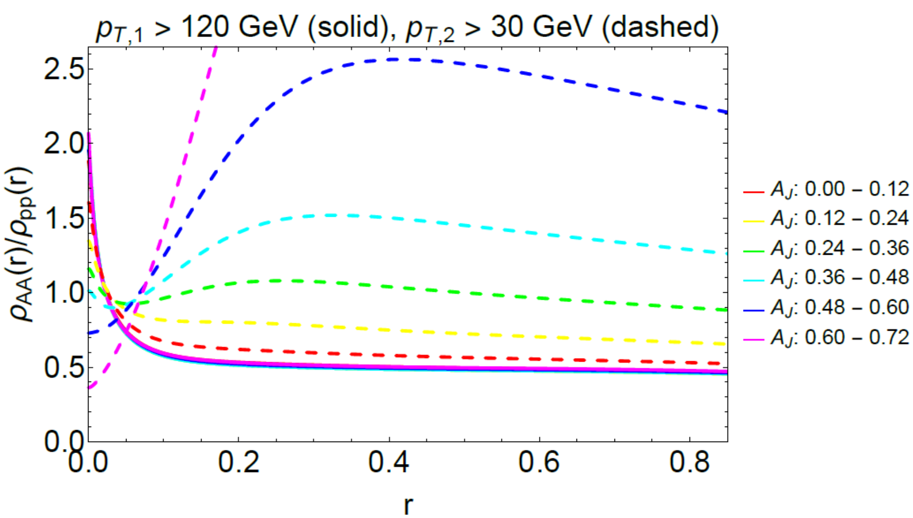
- Jets from center more strongly modified
- Leading jet much narrower
- Subleading jets seem wider (but subtle in our model)

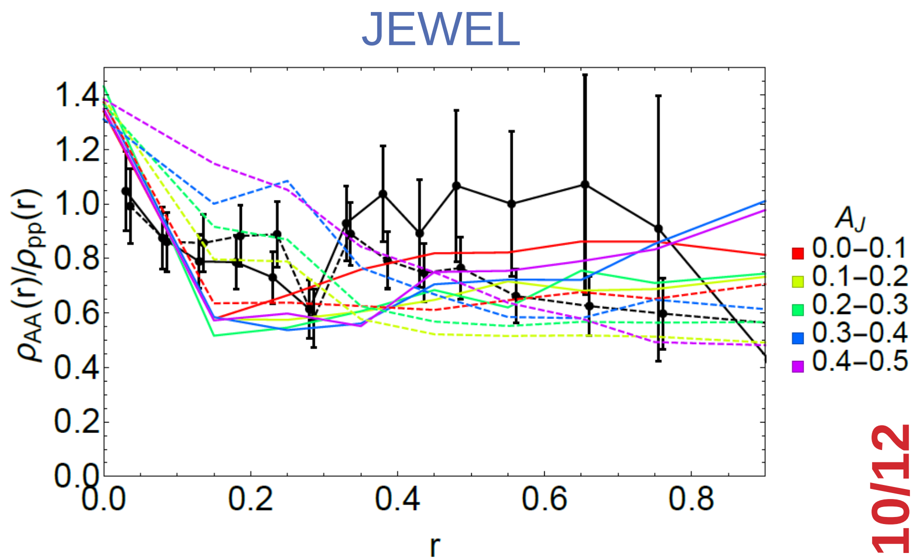


# JET SHAPE MODIFICATIONS

**Can these differences be probed experimentally?**

- *Select jet shapes according to dijet imbalance*
- Compare with JEWEL, matches qualitatively
- Includes CMS data with $p_T$ > 3 GeV, to exclude thermal particles
- Subtlety for subleading: rather large contribution from 3rd jets and incoherent partons (included in JEWEL, not in our model)



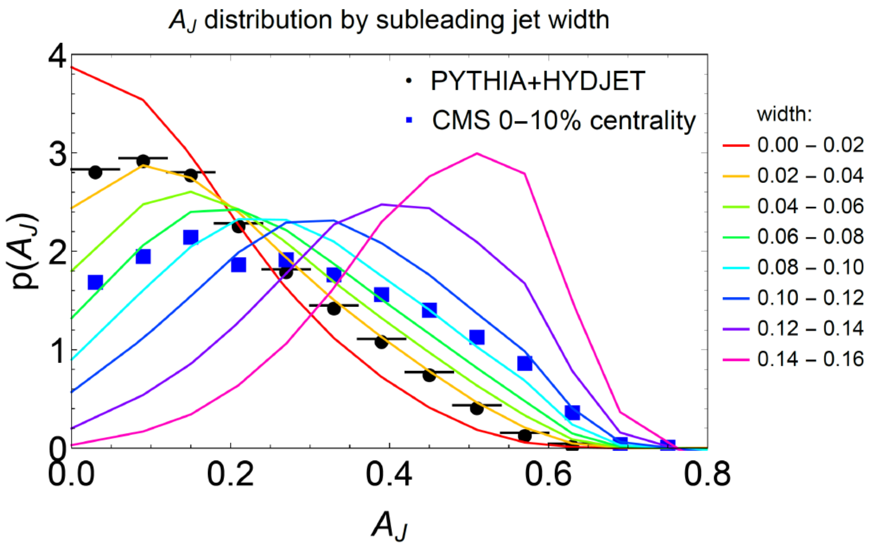

CMS, Measurement of transverse momentum relative to dijet systems in PbPb and pp collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (2015)

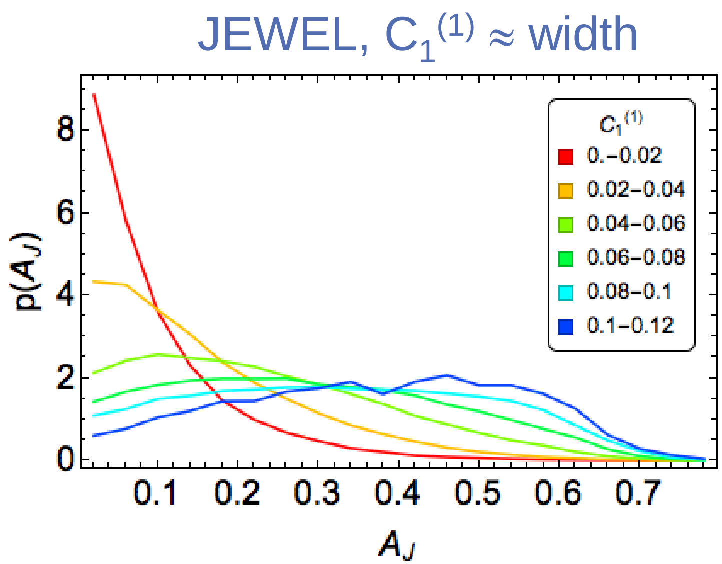
# A NEW OBSERVABLE?

**Dijet asymmetry is very sensitive to subleading jet width**

- Large subleading width leads to imbalanced dijet
- JEWEL effect is a bit stronger for small width, weaker for large width

- Quite intuitive: large subleading width → large energy loss → large $A_J$




CMS, Measurement of transverse momentum relative to dijet systems in PbPb and pp collisions at $\sqrt{s_{NN}}$= 2.76 TeV (2015)

# DISCUSSION

**The model**

- Take initial conditions of strings from pQCD
- Treat evolution in holography: medium interaction is strongly coupled
- Currently oversimplified: no hadronisation, back-to-back jet, medium etc

**Jet shape modifications and dijet asymmetry**

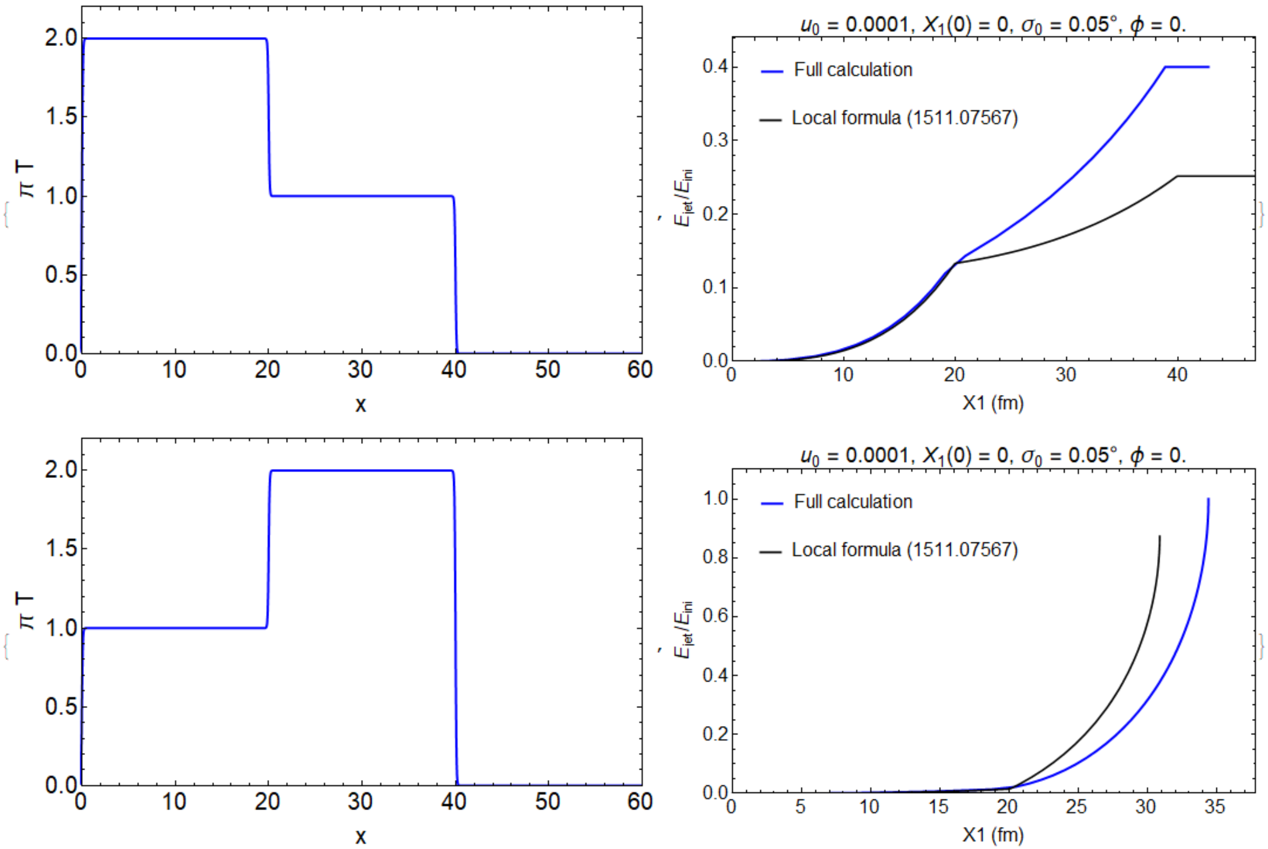
- Confirmed dijet asymmetry does not depend on starting position
- Jet shape modifications strongly depend on position
- Leading jet shape narrower, independent of $A_J$
- Subleading jet shape increasingly wider for increasing $A_J$
- Observable: dijet asymmetry for different subleading jet width?

**Outlook**

- Implementation in Monte Carlo?
- Full understanding initial condition string: 3-jets etc
    - Can have important effects on subleading jet at large r
- Not quite related: back-reaction lost energy on medium: where does E/p go?

# VARYING TEMPERATURE

**Energy loss depends on temperature evolution non-linearly:**

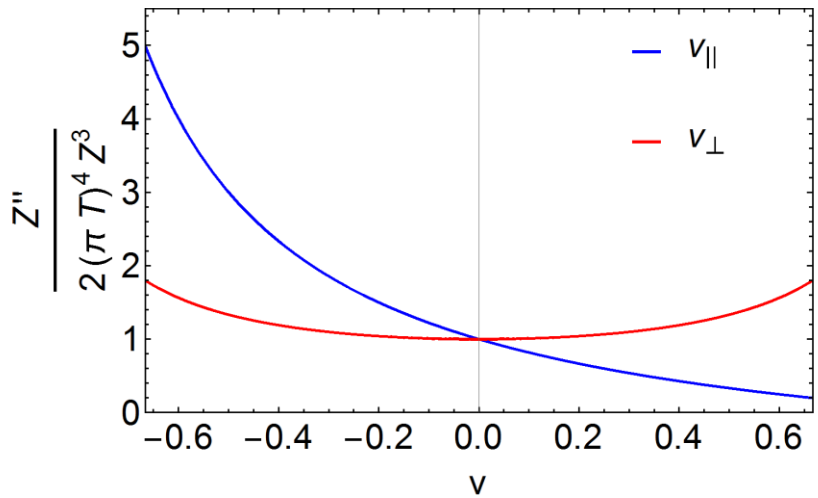



- First phase agrees with (ultra)local formula (Chesler, Rajagopal)
- Interesting: (final) energy loss much bigger for 2nd profile
- Illustrates `memory-effect': wave function remembers evolution

# SECOND EFFECT: FLOW

**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)

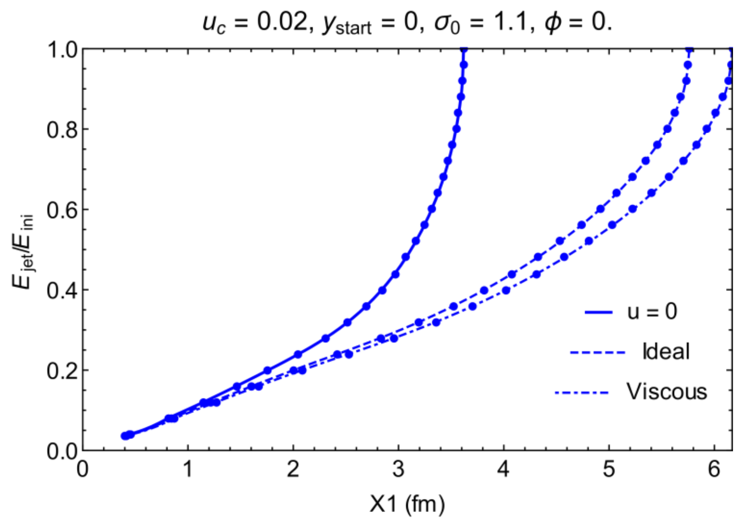
**Corrections due to viscosity:**

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

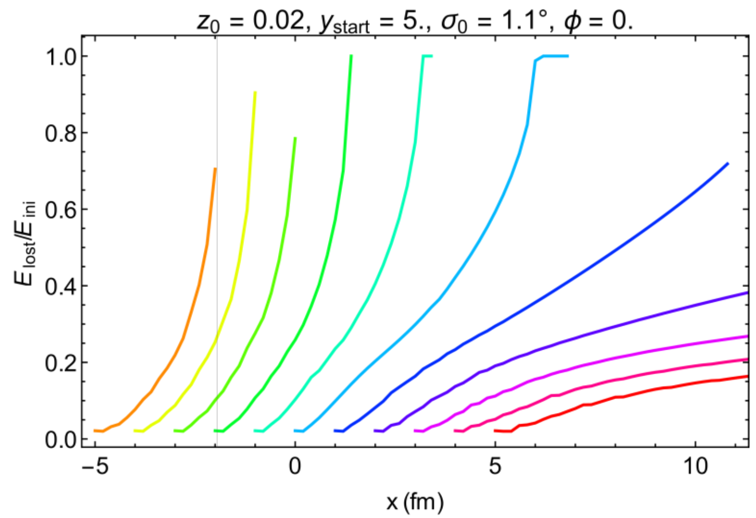
# RESULTS IN GUBSER FLOW

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

Compare no flow, ideal and viscous




different starting points



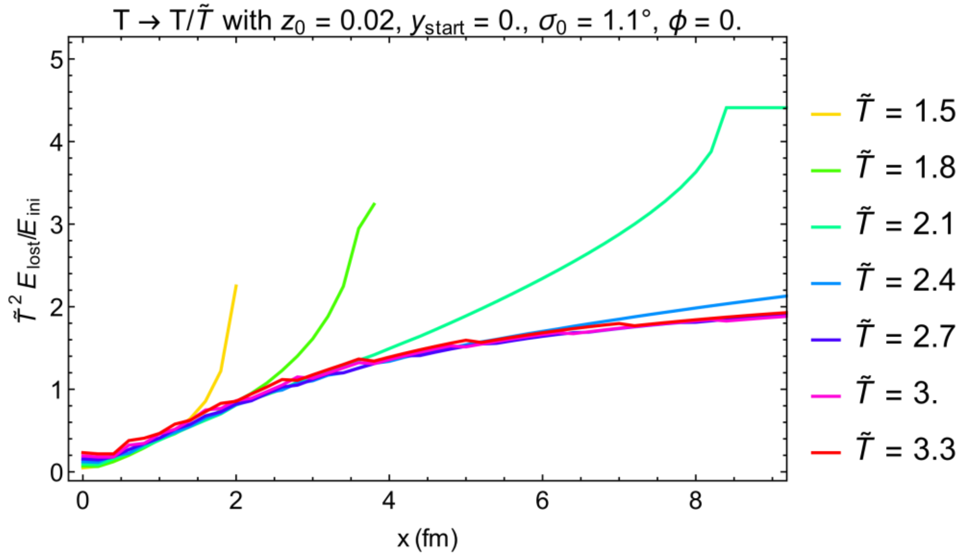

- Flow has extremely important effect, doubling stopping distance
  - Recall old result: $\Delta x_{\rm stop} = \left[\frac{2^{1/3}\,\Gamma\left(\frac{5}{4}\right)}{\sqrt{\pi}\,\Gamma\left(\frac{3}{4}\right)}\right] \frac{1}{T} \left(\frac{E_*}{\sqrt{\lambda}T}\right)^{1/3}$
- Corrections due to gradients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

# 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 $T^3$)

# MODIFIED JET WIDTH DISTRIBUTIONS

**Jet shapes become narrower: jet width distribution**

- Can also compare with original pp 'truth' jet width
- Even individual jets can become narrower
  - Only for intermediate widths and intermediate energy losses