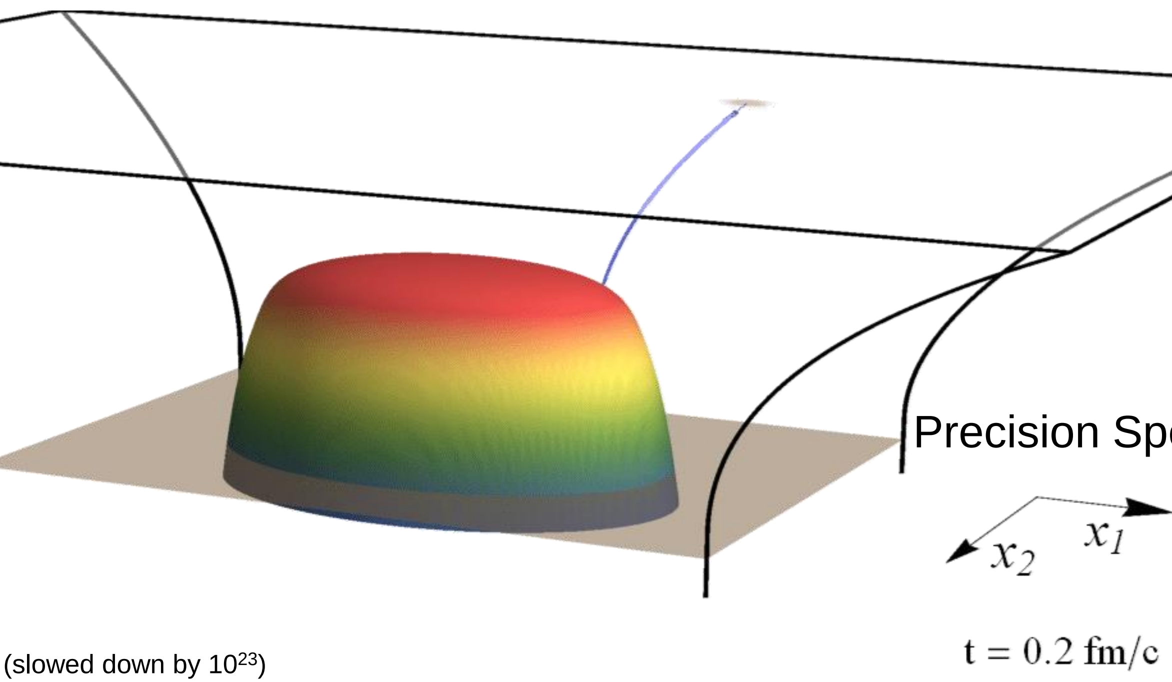
Universiteit Utrecht

JETS IN STRONGLY COUPLED PLASMA

ENERGY LOSS IN ADS/CFT

with Jasmine Brewer, Krishna Rajagopal and Andrey Sadofyev
1602.04187, 1704.05455, to appear



Wilke van der Schee

Precision Spectroscopy Jets and Heavy Quarks
INT Seattle, 15 May 2017

Center *for* Theoretical Physics

(slowed down by 10^{23})

OUTLINE

Overview of jets in AdS/CFT

- Strings and jets
- Uncomplete, skipping i.e. parts as presented by Will and Dani

Making an ensemble of jets

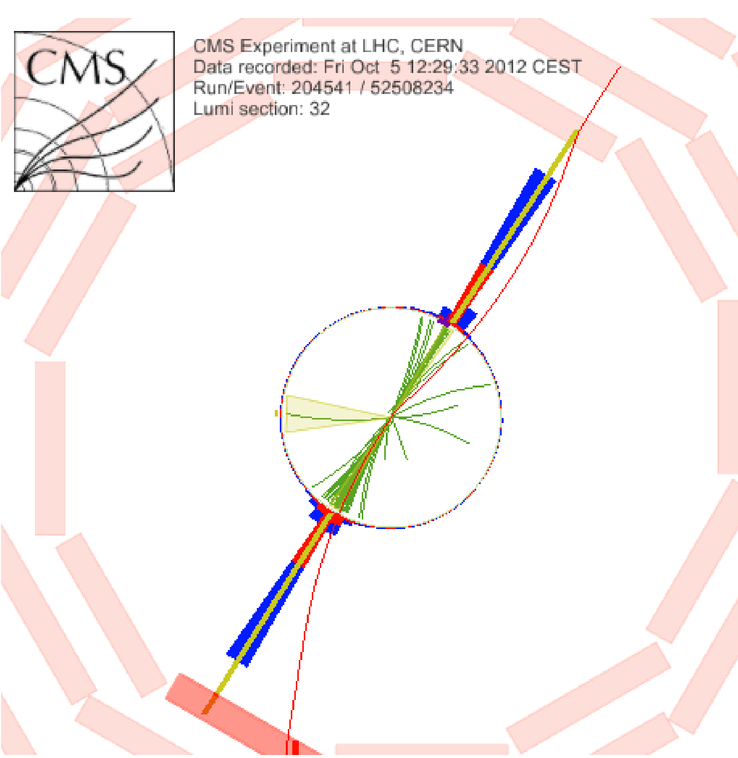
- Fluctuating initial conditions

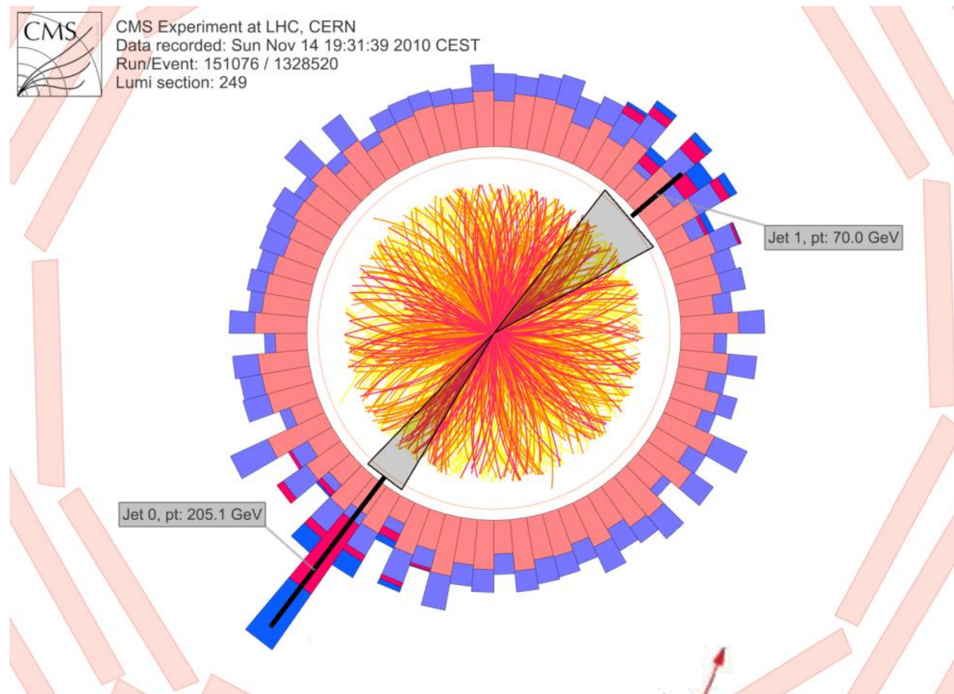
Resulting distributions

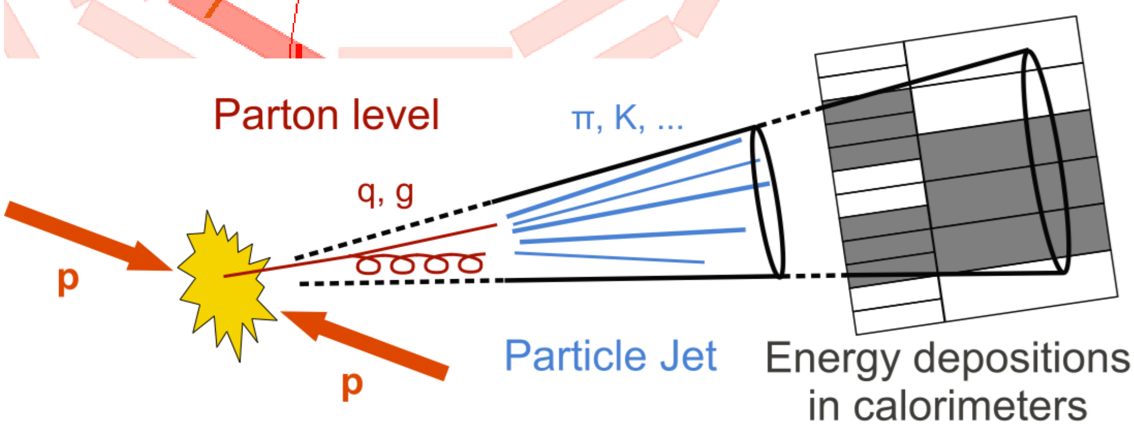
- Shoot ensemble through expanding and cooling black hole
- Jet width, jet shapes and dijet asymmetry

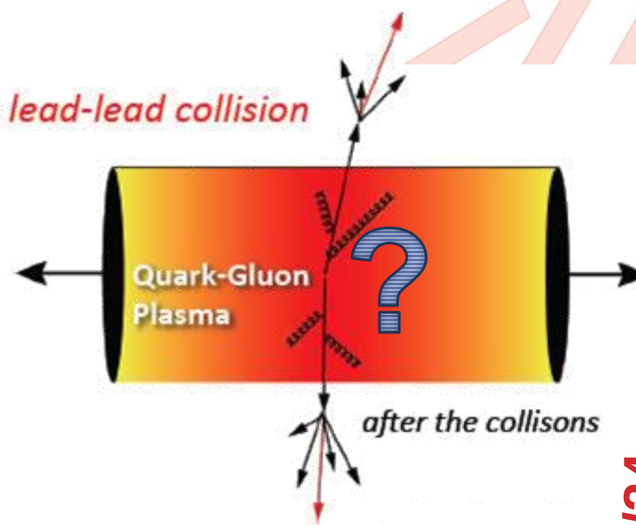
(tried to minimise overlap with last week, but not entirely possible ☹)

JETS IN QGP









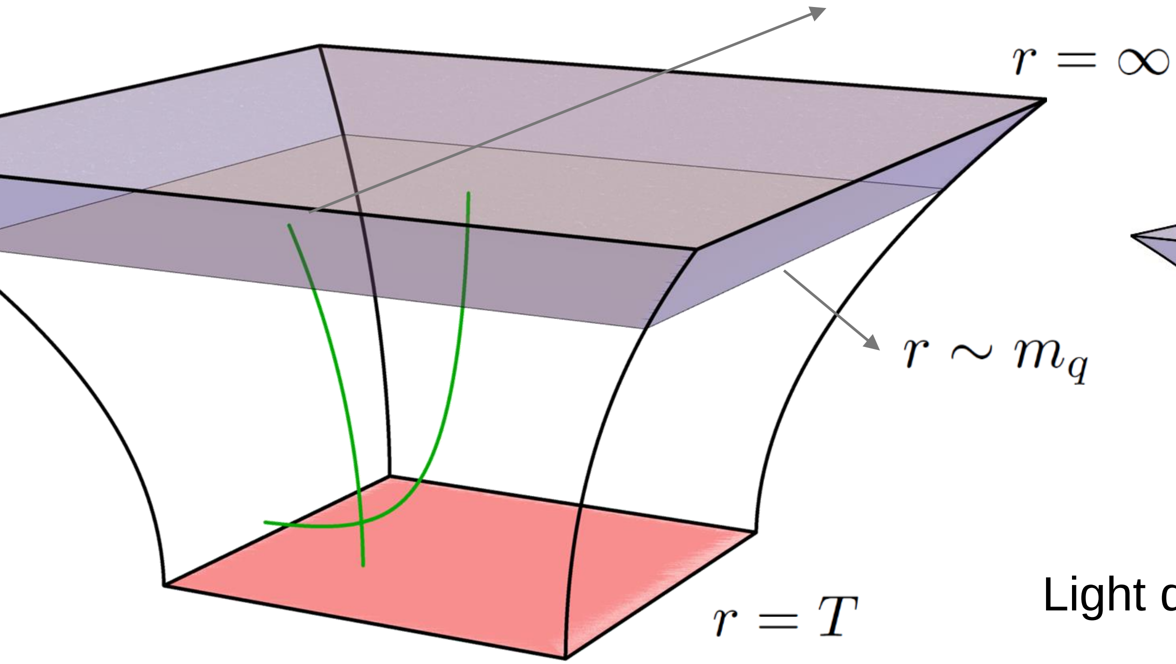
CMS PAPER EXO-12-059

QUARKS IN ADS/CFT

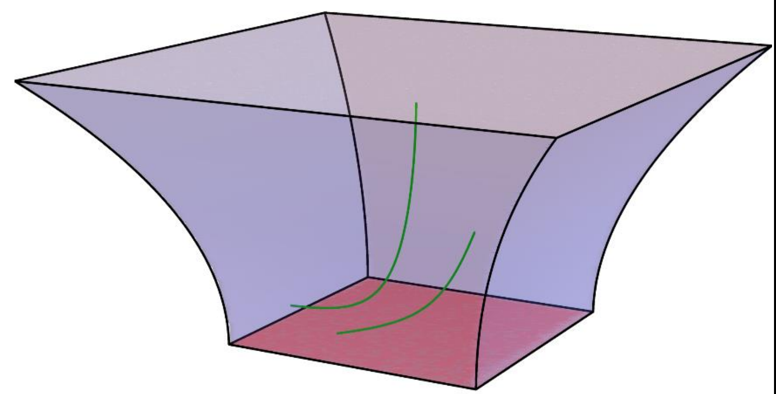
AdS/CFT allows to add fundamental quarks to N=4 SYM

- Classical open strings, but energy proportional to $\sqrt{\lambda}$

Endpoint has to stay on D7-brane, cannot fall



Heavy quarks, if mass>temperature



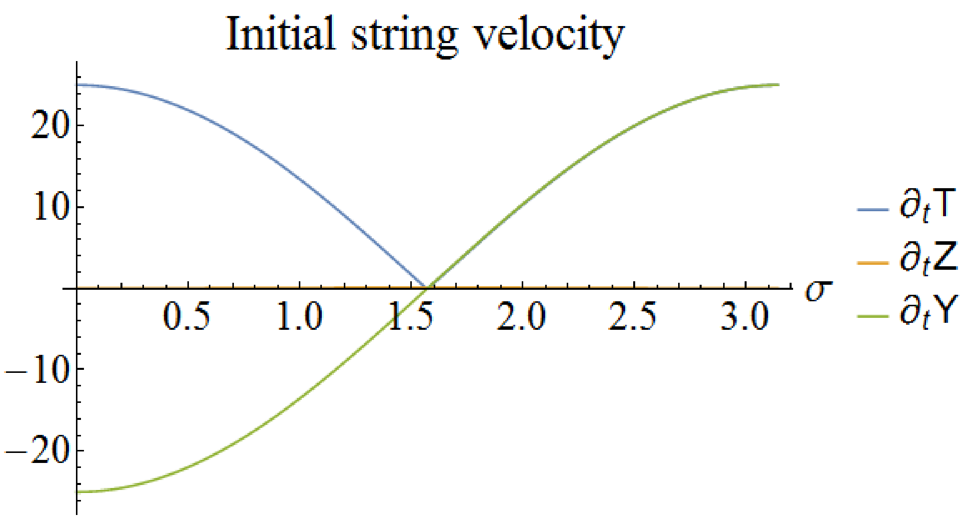
Light quarks; strings falls into black hole

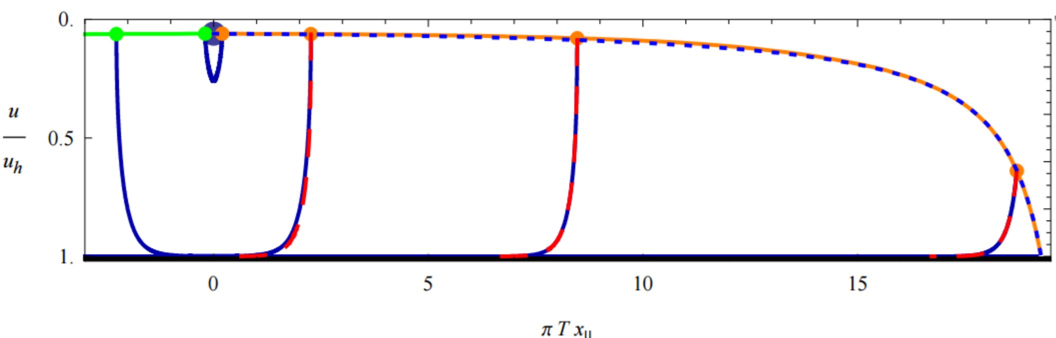
Andreas Karch and Emanuel Katz, Adding flavor to AdS/CFT (2002)

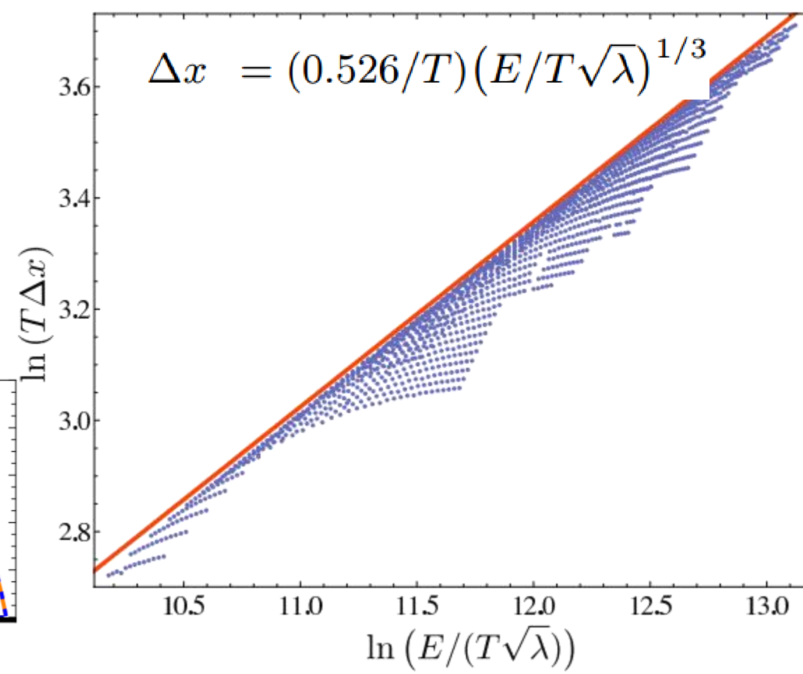
EARLY WORK

$$\partial_\tau Y(0,\,\sigma) = A\, z_0 \cos(\sigma)$$
$$\partial_\tau Z(0,\,\sigma) = z_0(1-\cos(2\sigma))\sqrt{f(z_0)}$$
$$A = 500,\ \ z_0 = 1/20,\ \ f(x) = 1 - x^4$$

Initial string at point, velocity profile → stopping distance







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)

ENERGY LOSS BY A SLAB OF PLASMA

Old problem: how to define energy loss in terms of string?

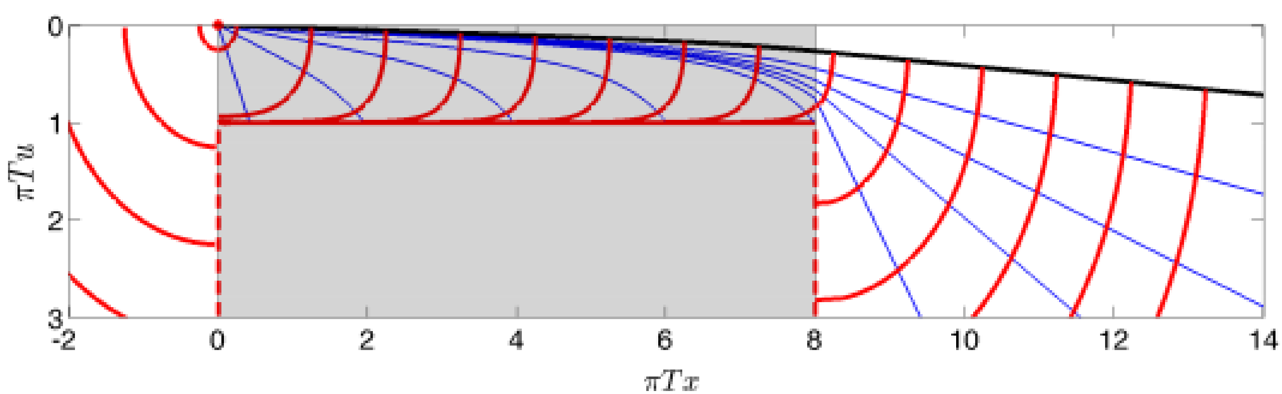
- In particular, real jets lose order 10% energy
- Natural definition: size black hole = size QGP, shoot jet through

Model evolution more realistically

- Part of string falls in black hole: dissipates into hydro modes

Attractive: final string in vacuum AdS is well understood

- Angle in AdS ≈ jet angle (?)

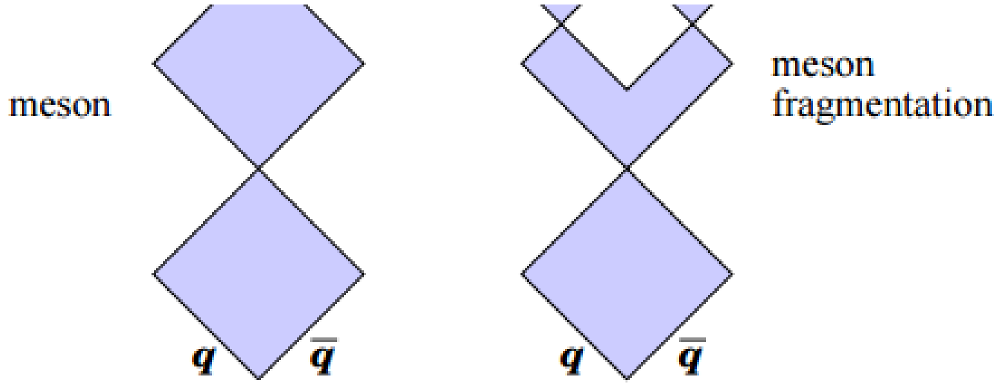


P.M. Chesler and K. Rajagopal, Jet quenching in strongly coupled plasma (2014)

A LUND MODEL IN ADS

Put all initial energy/momentum at endpoint (≈quark)

- Natural from Lund model perspective
- EOM: endpoint follows null geodesic, losing energy gradually
- Attractive: removes *functional* freedom of initial conditions



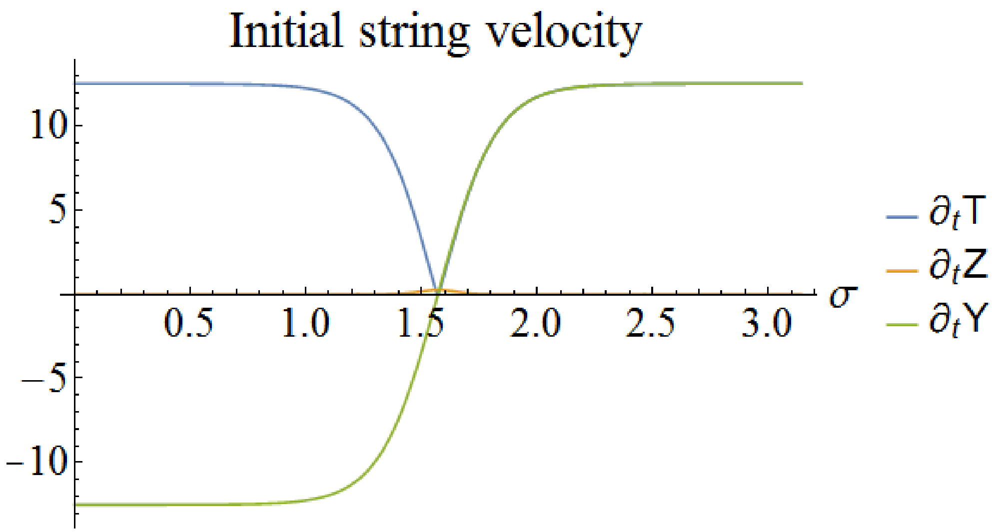
Revisiting stopping distance: $\Delta x_{\text{stop}} = \left[\frac{2^{1/3}}{\sqrt{\pi}}\frac{\Gamma\left(\frac{5}{4}\right)}{\Gamma\left(\frac{3}{4}\right)}\right]\frac{1}{T}\left(\frac{E_*}{\sqrt{\lambda}T}\right)^{1/3}$

- Finite endpoint momentum strings do not become stationary
- Possible to go about 19% further (already 11% in 0804.3110)

A. Ficnar and S. Gubser, Finite momentum at string endpoints (2013)

A TYPICAL EXAMPLE

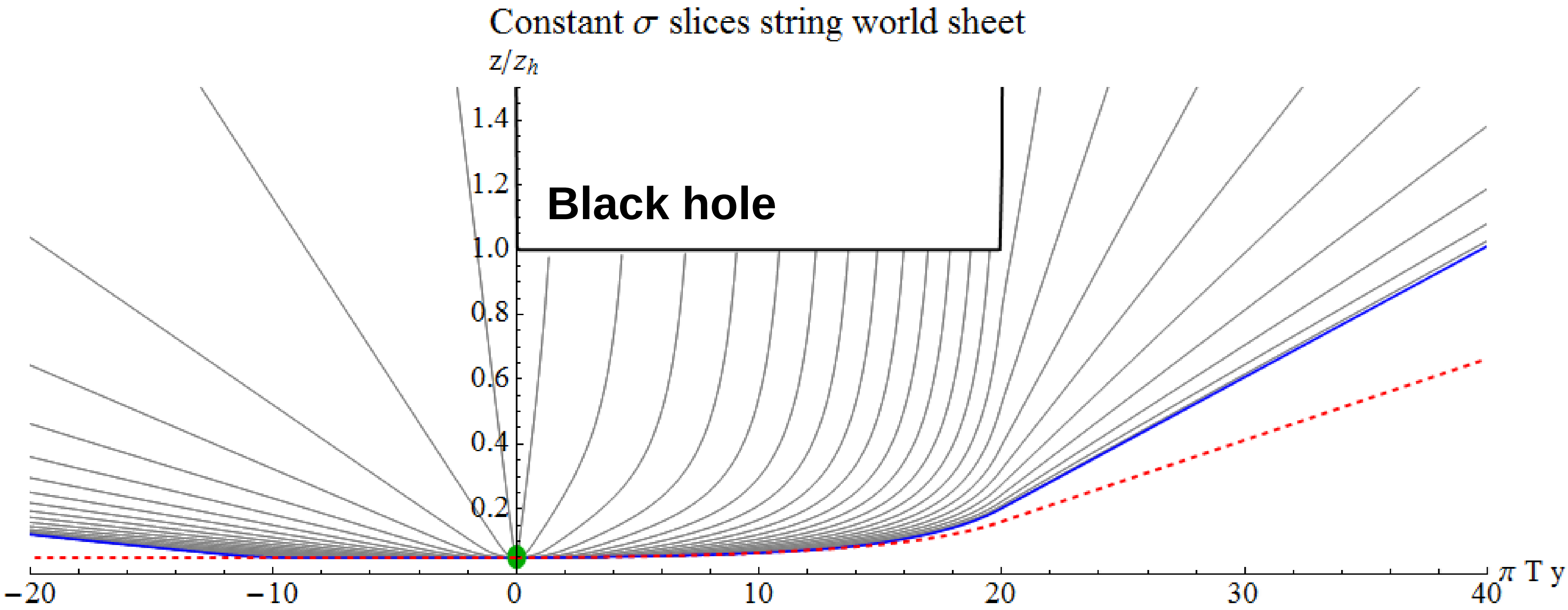
Try simulate string (regularised finite endpoint string):



Shoot through slab of plasma (or dynamic spacetime)

- constant 300 MeV plasma, length 4fm, create at edge
- Little bit of freedom: start at 5% from boundary-horizon distance
- `t Hooft coupling 5.5, gives jet energy of 1.6 TeV

STRING EVOLUTION

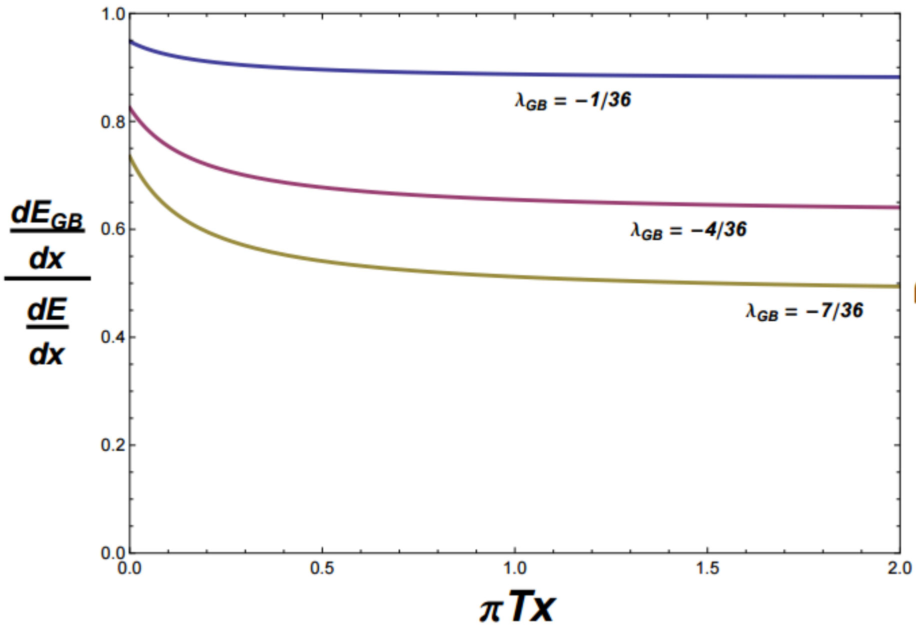


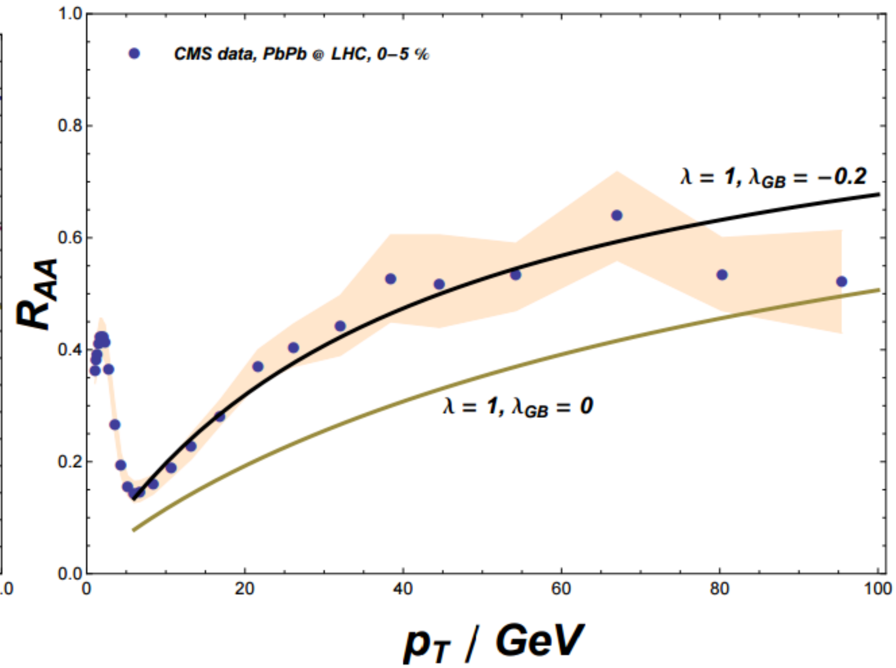
String endpoint (blue) follows null trajectory initially (red dashed)

String endpoints change direction when energy vanishes

- `Snapback’: especially relevant when string is moving upwards

WITH FINITE COUPLING CORRECTIONS





Study Gauss-Bonnet gravity (i.e. weaker coupling $\eta/s = 1.8/4\pi$)

Fits qualitative or even quantitative R_{AA}

- Optimistic parameters for formation time, freeze-out temperature, coupling constant and string dynamics…

Andrej Ficnar and Steven Gubser and Miklos Gyulassy, Shooting String Holography of Jet Quenching at RHIC and LHC (2013)

INCLUDING FLUCTUATIONS

So far strings were optimised to minimise energy loss

- Phenomenologically well motivated, but not so realistic

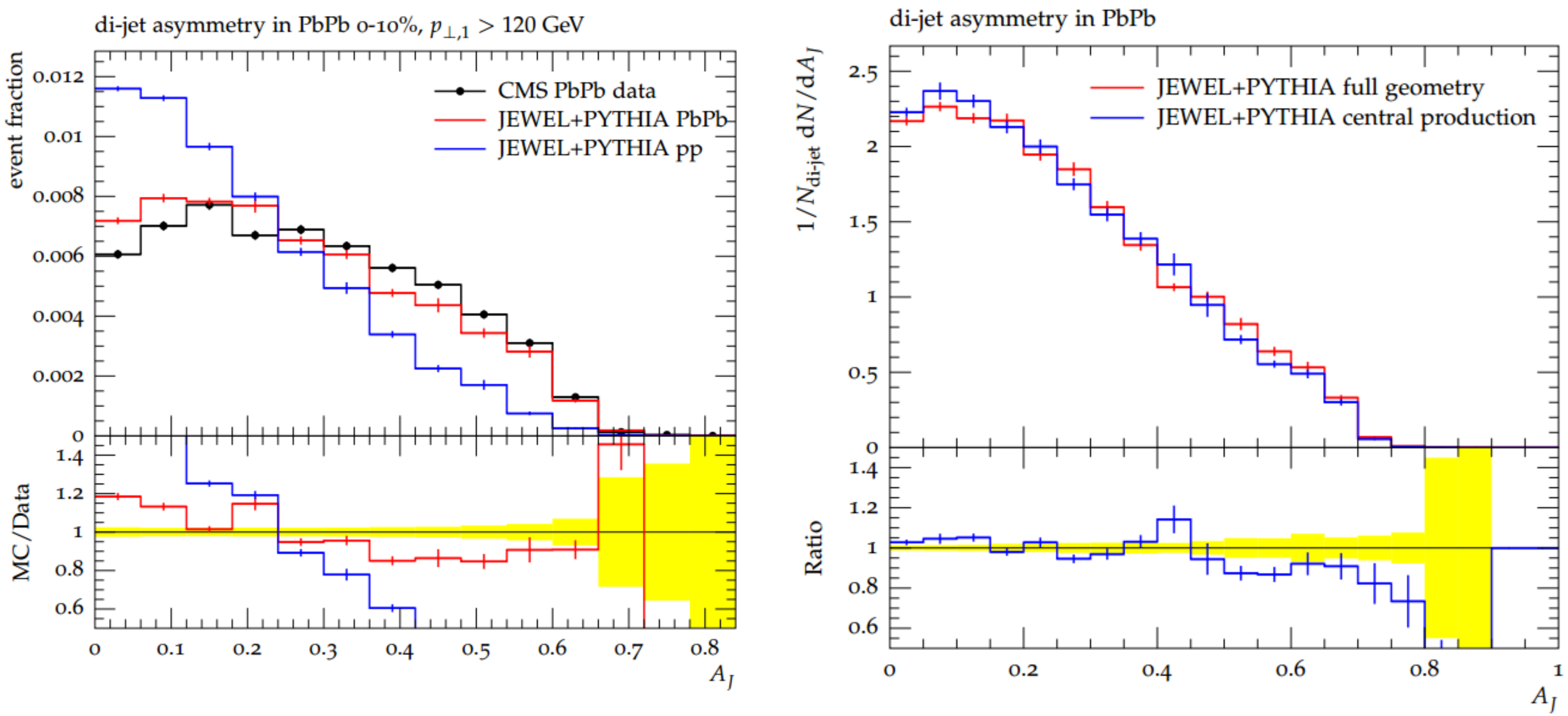
Try including more realistic string initial conditions

- Jets fluctuate, have probability distribution for energy loss
- Not necessarily straightforward at large N and strong coupling
    - Jets are not spray of particles before hadronization; more properly energy flow with energy correlators
- Different jets, however, characterised by different string profile
- Ignoring 1/N and 1/coupling effects for now…

FLUCTUATIONS IN JEWEL

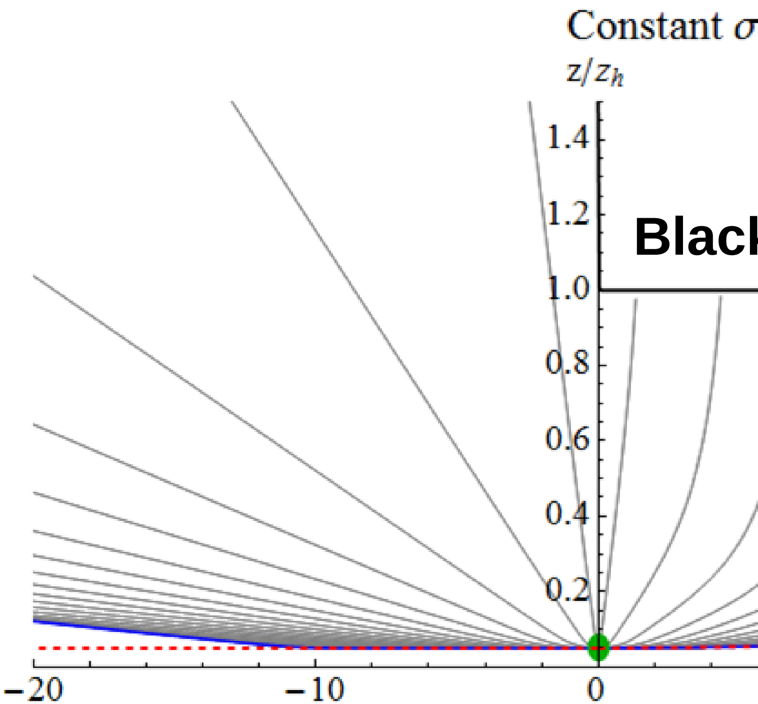
Jet dijet modification thought to arise from path length fluctuations

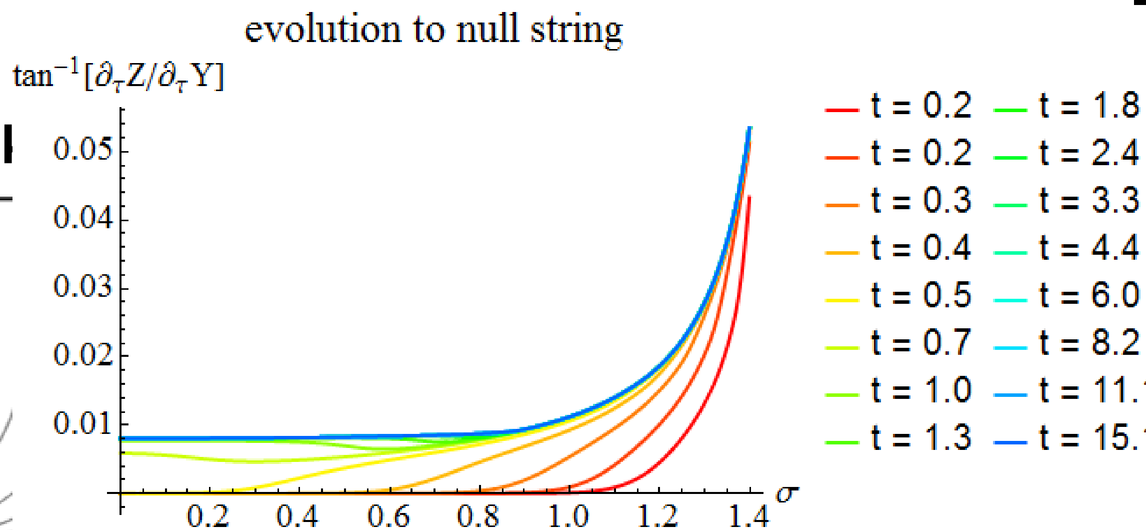
- One jet loses more energy than other jet: larger asymmetry
- Intuition turns out not to be quite right: single jet fluctuation dominates
    - Compare r=0 central jets, to regularly distributed jets



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

TOWARDS A SIMPLER MODEL





After a while the string becomes a null string (1 fm/c should be ok?)

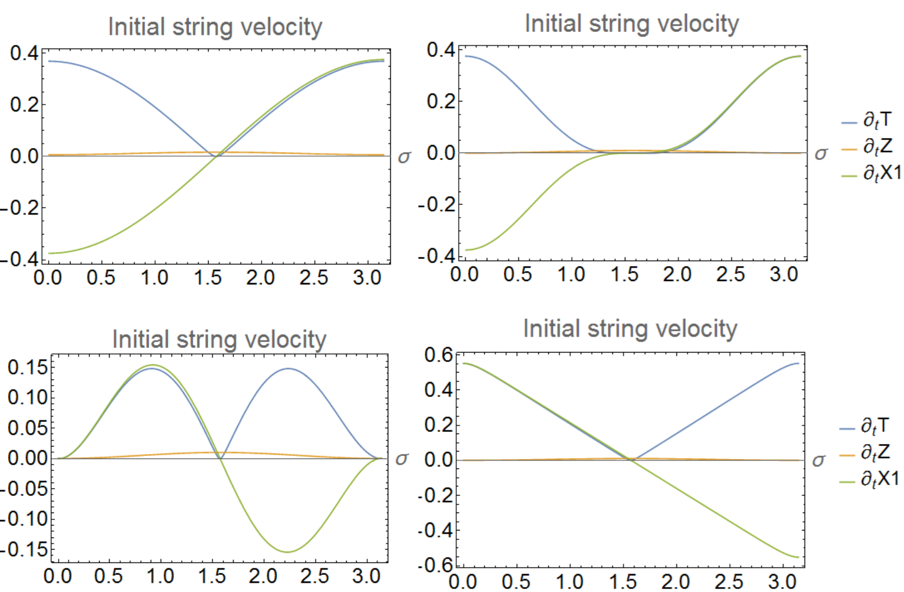
Evolution of string = independent evolution of null string segments

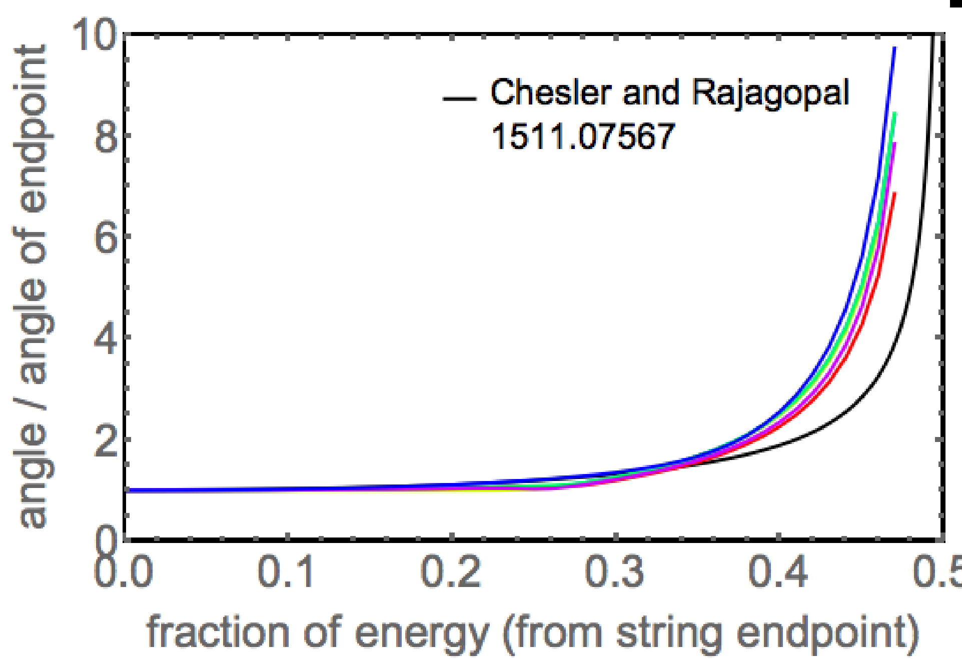
- Need to know where which string bit goes with how much energy

STRING PROFILE

Back-to-back string evolution

- Try several initial profiles
- Endpoint angle and energy determine profile
- Can change when considering 3D evolution (Andrey)



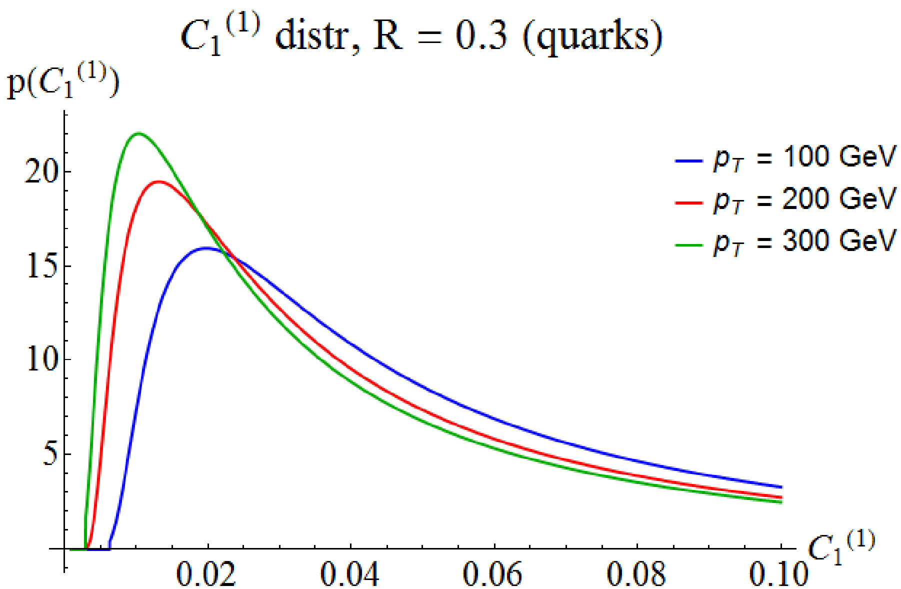


- This can reasonably model a single jet, with opening angle determined by $C_1^{(1)}$

INITIAL CONDITIONS WITH JET WIDTHS

Would like to mimic distribution of real QCD jets

- Extra motivation: how is distribution affected by QGP?
- Take from pQCD (compares quite well with PYTHIA)



$$C_1^{(\alpha)} \equiv \sum_{i,j} z_i z_j \left(\frac{|\theta_{ij}|}{R}\right)^{\alpha}$$

z_i: fraction of jet energy
θ_{ij}: angle between particle *i* and *j*
R: jet radius parameter

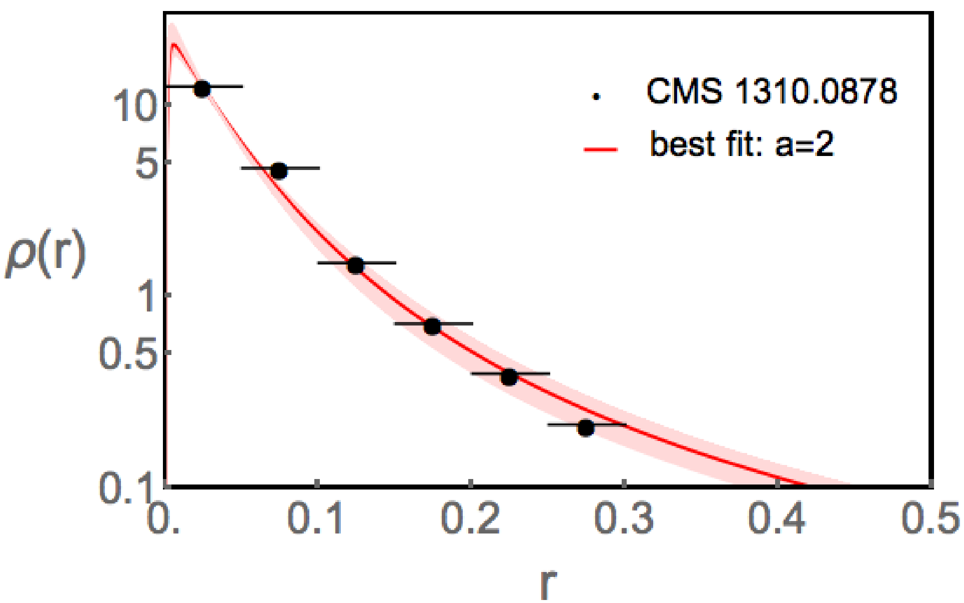
Link opening angle $C_1^{(1)}$ **to AdS angle:** $C_1^{(1)} = a\,\sigma_0$ **(*a* fixed next)**

A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft drop (2014)

LINKING STRINGS TO JET SHAPE

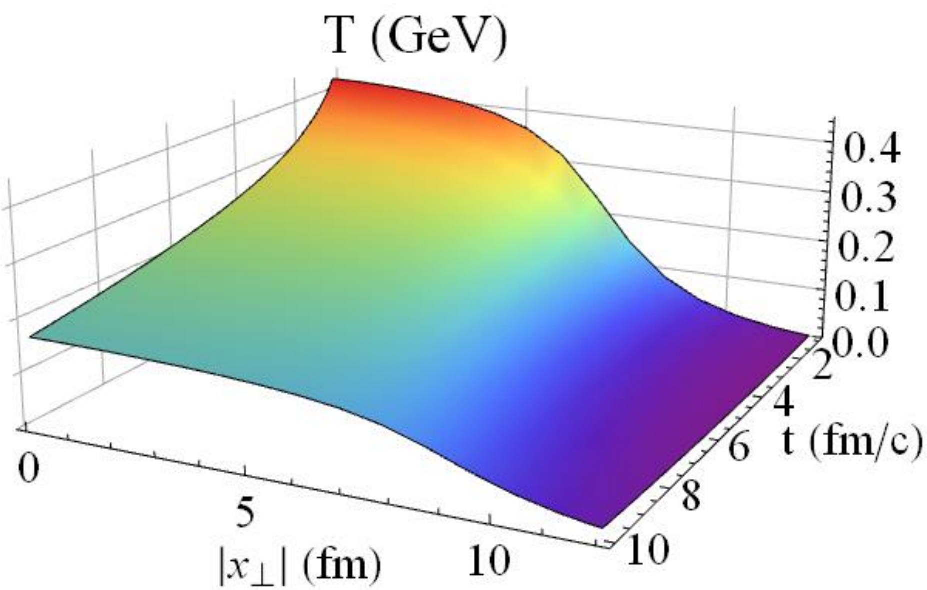
Construct the string ensemble

- Take representative curve from two slides back
- Energy distribution from QCD (E^{-6})
- Endpoint angle distributed as previous slide
- Compute jet shape (AdS/CFT prescription)
- Compare with CMS to fix parameter



TEMPERATURE PROFILE

Simple semi-analytic hydrodynamic temperature profile:



$$T(\tau, \vec{x}_\perp) = b \left[\frac{dN_{\rm ch}}{dy} \frac{1}{N_{\rm part}} \frac{\rho_{\rm part}(\vec{x}_\perp / r_{\rm bl}(\tau))}{\tau \, r_{\rm bl}(\tau)^2} \right]^{1/3},$$

$$r_{\rm bl}(\tau) \equiv \sqrt{1 + (v_T \tau / R)^2}$$

(*b* measures N_{ch} per S, given EOS)

Neglect initial dynamics (1 fm/c) + hadronization + confinement

Start string at single point at boundary

- Distribute according to binary scaling and $(E_{\rm jet}^{\rm init})^{-6}$
- Free parameter *b*: to get reasonably energy loss ((coupling) $\mathcal{N} = 4 \neq \mathrm{QCD}$)

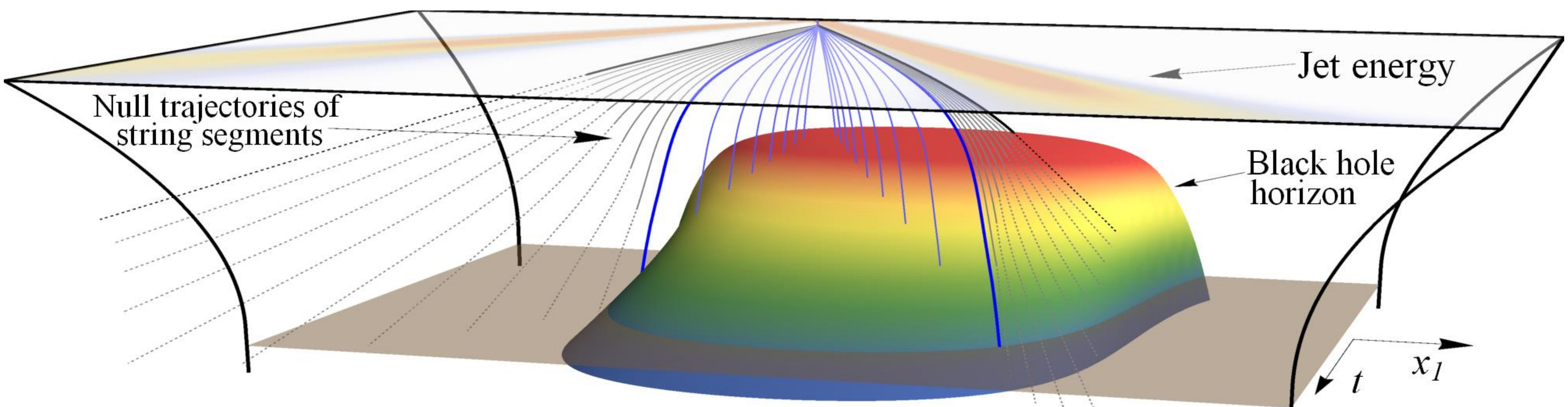
A. Ficnar, S.S. Gubser and M. Gyulassy, Shooting String Holography of Jet Quenching at RHIC and LHC (2013)

ALGORITHM

- **Scan parameter space: energy, angle, position, direction**
  - Compute null geodesic endpoint → new angle
  - Find null geodesic which barely escapes black hole (freeze-out)
  - → energy loss

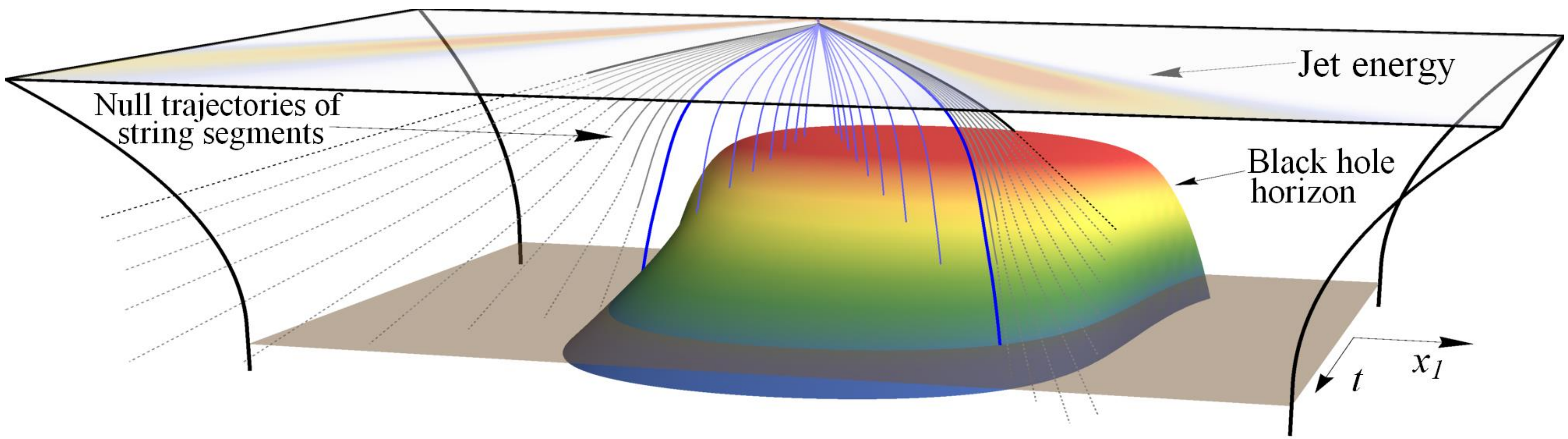
- **Use original distributions in parameter space**
  - Bin final parameters (energy + angle)
  - Average over parameter space, taking weight factor

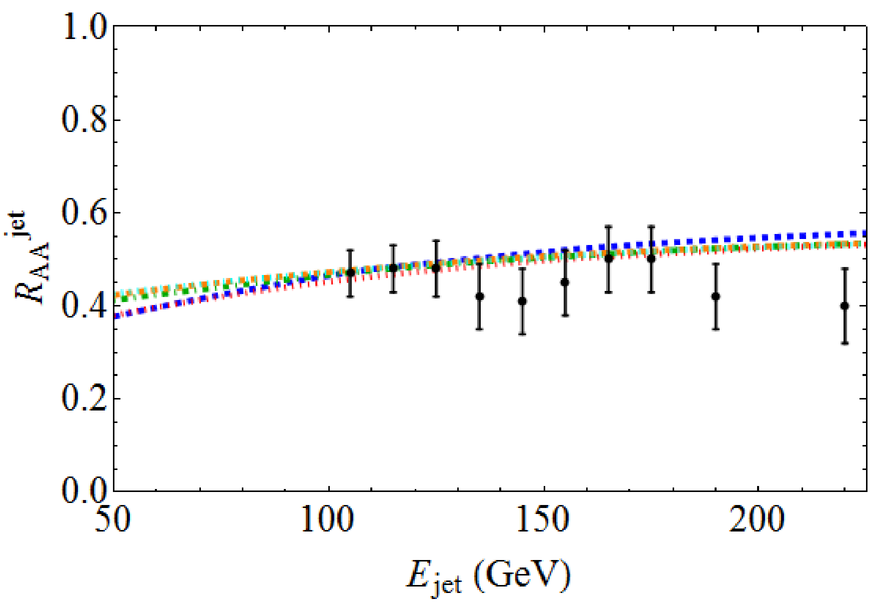
- **Compare initial with final distributions ☺**



RESULTS

Shooting about 50.000 jets through plasma



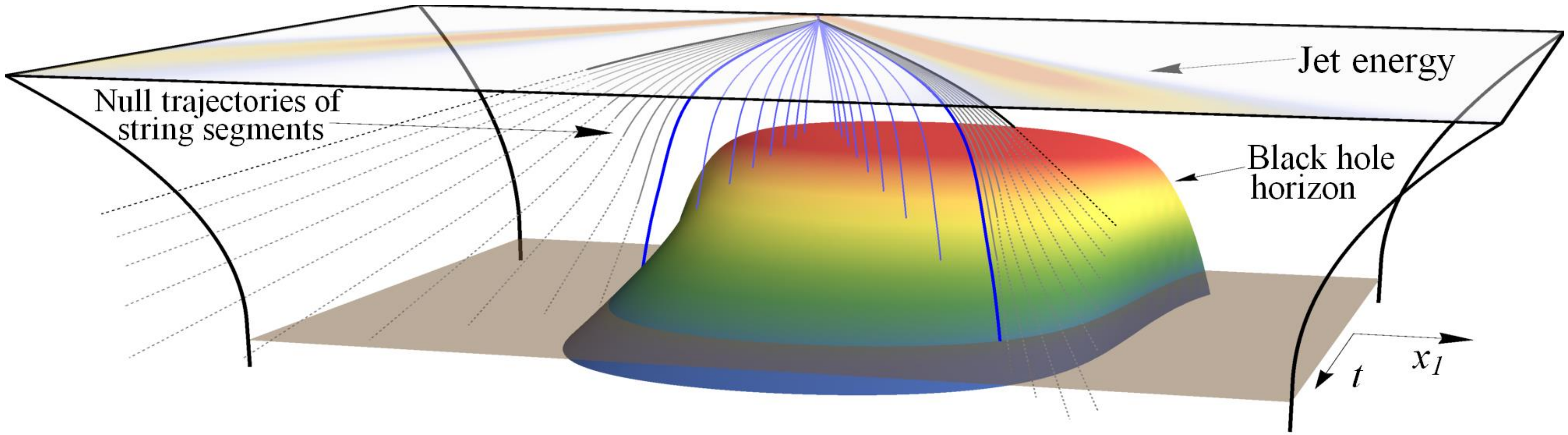


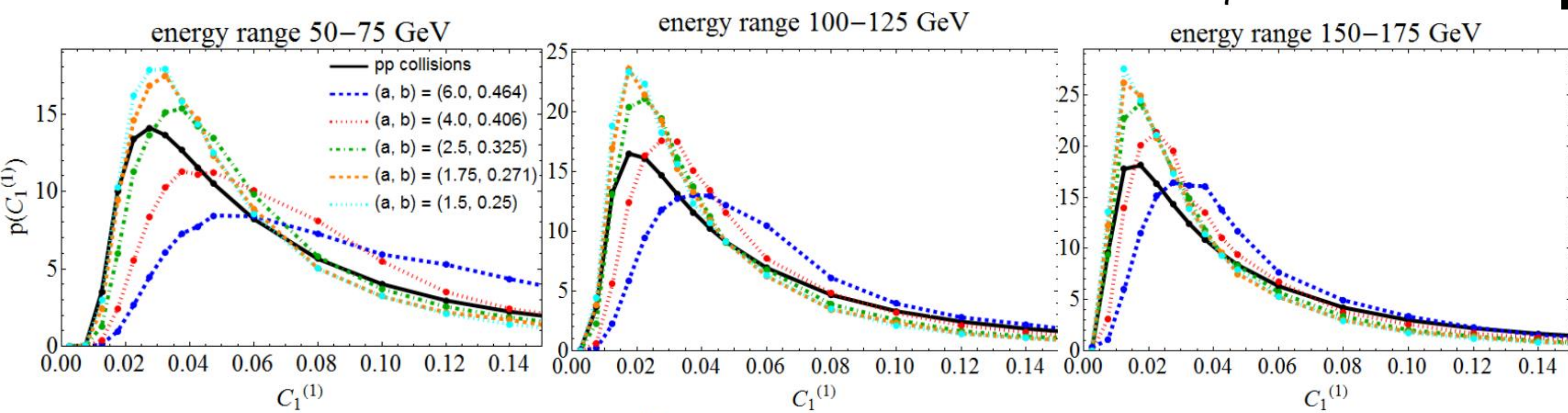
- (a, b) = (7.0, 0.464)
- (a, b) = (4.5, 0.406)
- (a, b) = (2.5, 0.325)
- (a, b) = (2.0, 0.271)
- (a, b) = (1.5, 0.25)

Naïve QCD: $a \sim 1.7, \quad b \sim 0.78$

FIRST EFFECT: JETS WIDEN

Change of probability distributions of jet opening angle

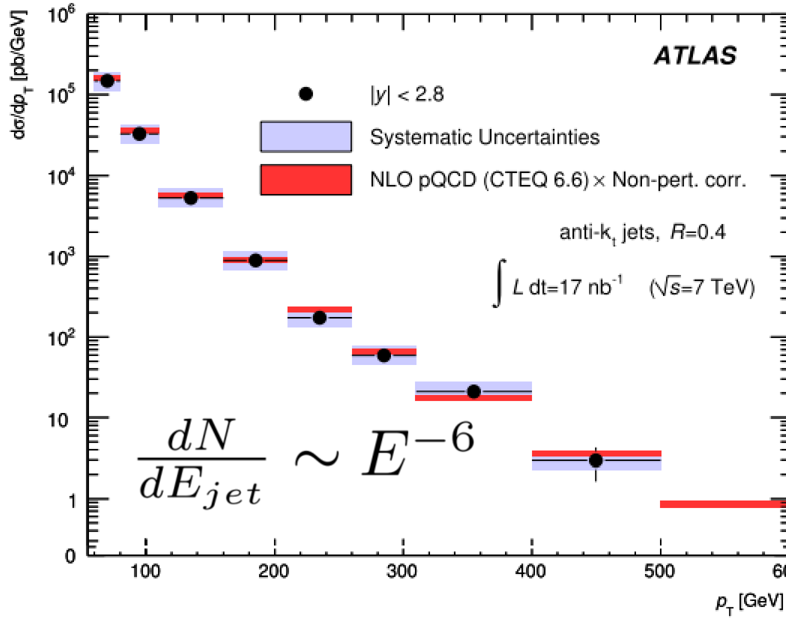


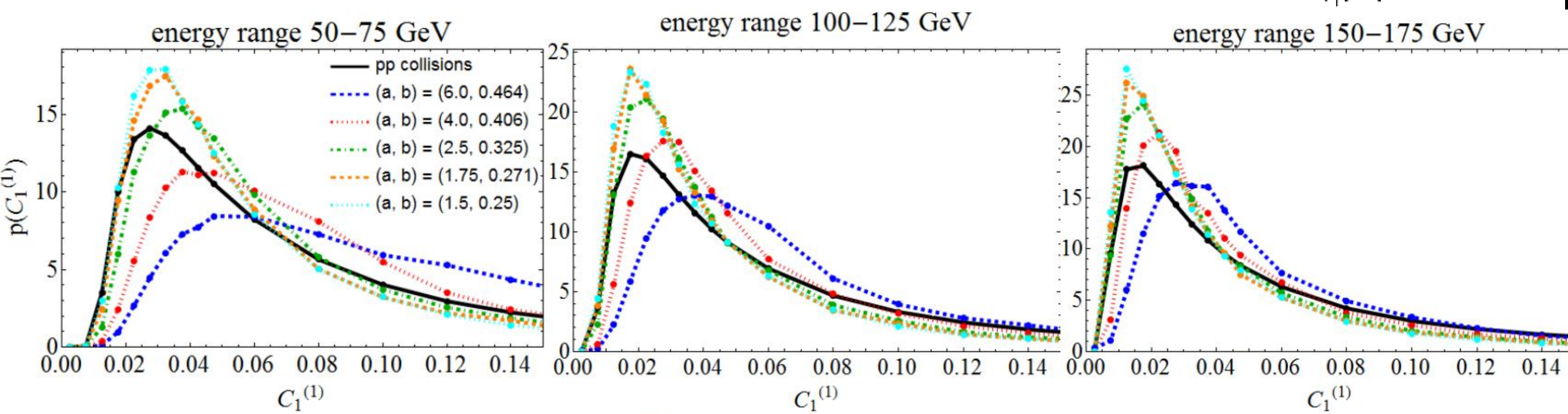


Has not been measured ☺ (could/should be possible)

SECOND EFFECT: NARROWER JETS

- **Energy distribution falls steeply (~E^{-6})**
- **Wide jets lose (much) more energy**
- **→ selection bias on narrow jets**





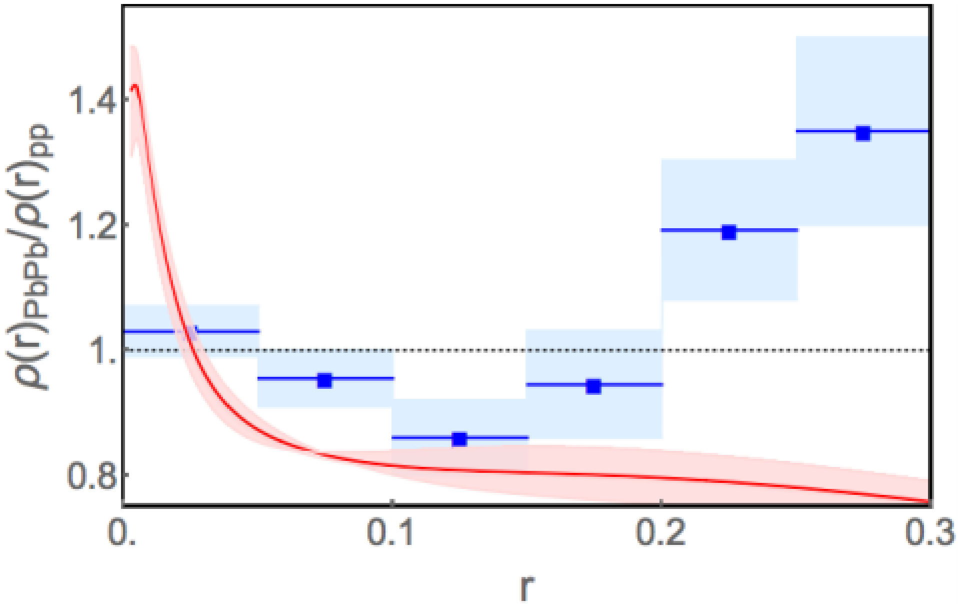
ATLAS, Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy (2011)

JET SHAPES

Improved model also allows to see change in jet shapes

- Jet shapes have some subtleties, especially 3rd jet at intermediate r

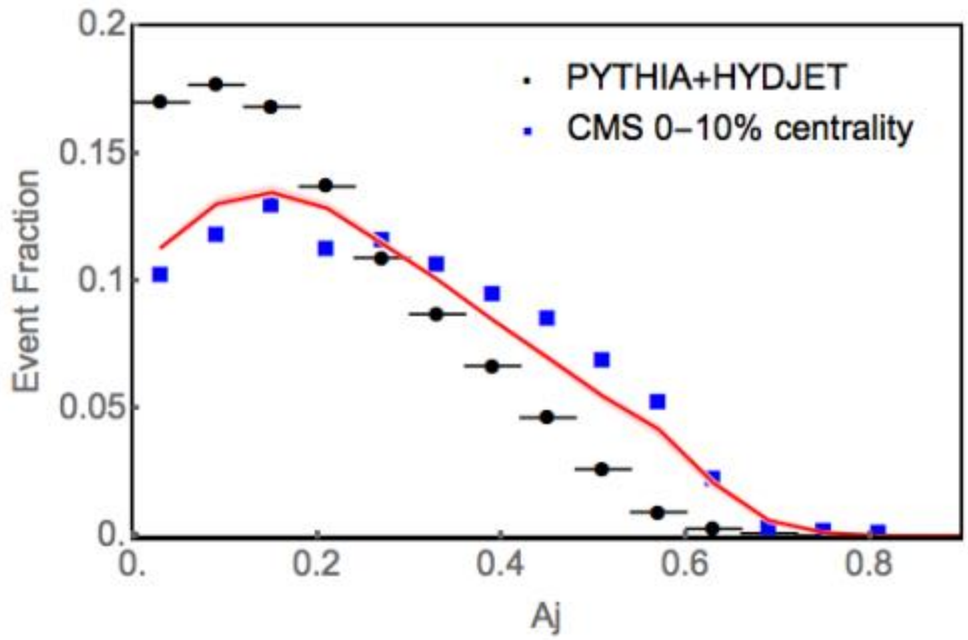
Fails at larger r (no hydro backreaction included)



DIJET ASYMMETRY

Dijet asymmetry a bit subtle: only back-to-back jets

- Take `half' back-to-back jet to model single jet
- Fit dijet distribution to Pythia+hydjet data
- Run through plasma to see change



DISCUSSION

Constructing an ensemble of jets

- Strings are dual to quark-antiquark
- Obtain initial ensemble of jets from pQCD (or Pythia)
    - → construct ensemble of strings
- Included fluctuations

Study modification of jets

- Jet shapes and dijet asymmetry

Outlook

- Use R-differentiated measurement to distinguish narrow/wide jets? (Peter Jacobs) (likely requires 3-jet events)
- Finite coupling corrections in more realistic settings? More realistic fitting parameter? A splitting function analogue?