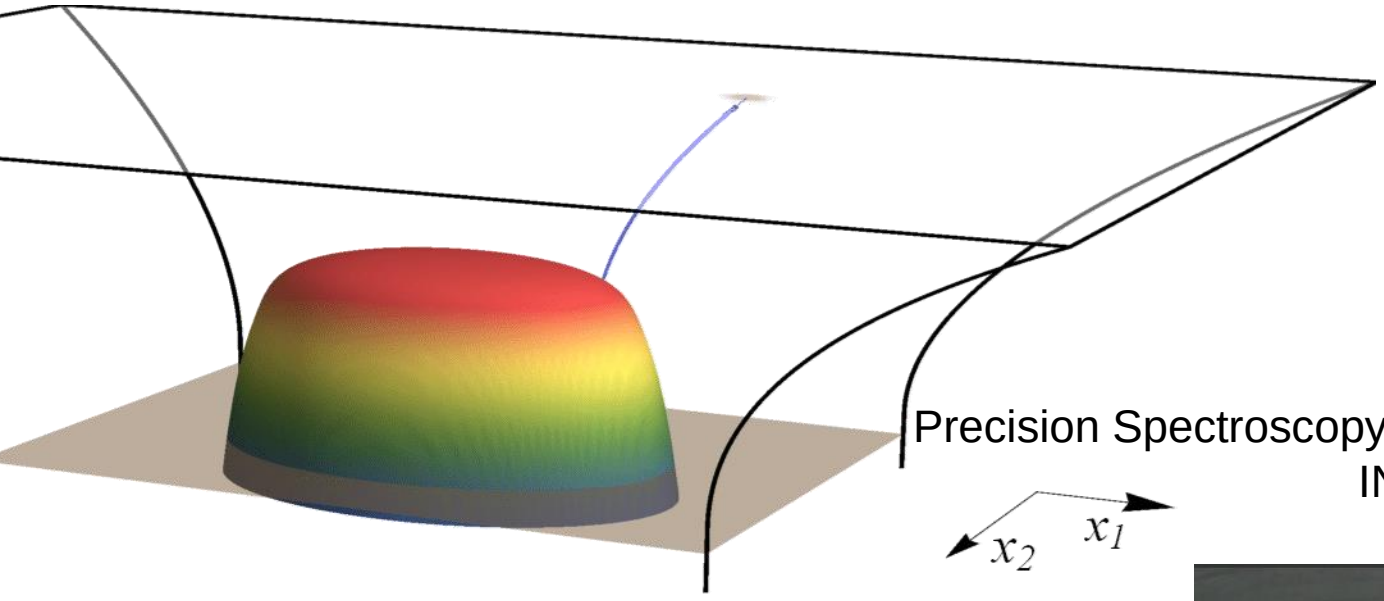
Universiteit Utrecht

JETS IN STRONGLY COUPLED PLASMA

PART 1: TRANSLATING VACUUM QCD TO ADS/CFT

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



(slowed down by 10^{23})

Wilke van der Schee

Precision Spectroscopy Jets and Heavy Quarks
INT Seattle, 10 May 2017

Center *for* Theoretical Physics

OUTLINE

Introduction and interesting jet observables

- Jet width, $C_1^{(\alpha)}$ and jet shapes
- Some background (literally)

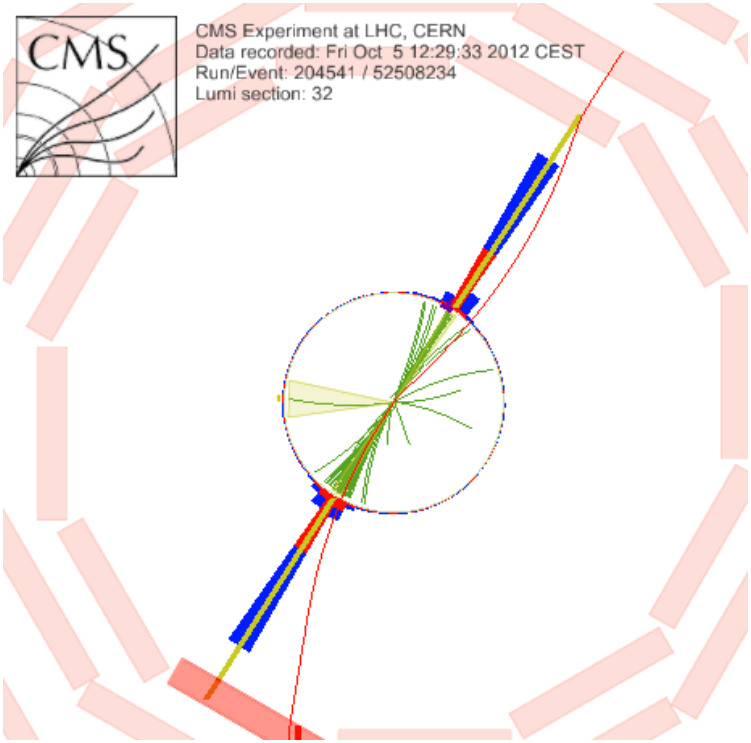
A perturbative initial state

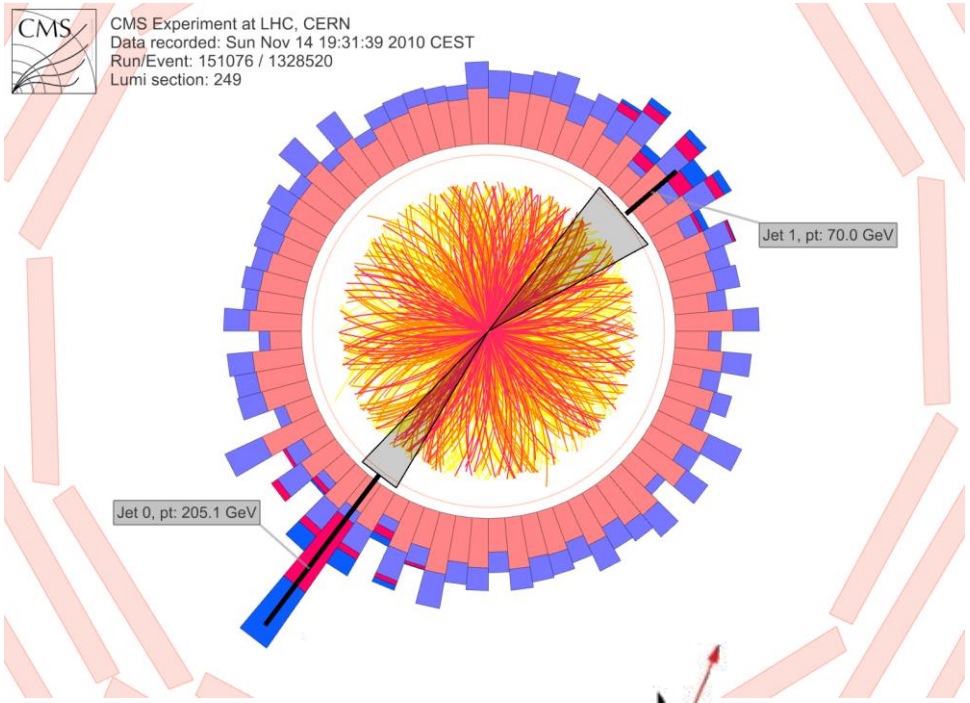
- Creation of jet is well described by perturbative QCD
- Interaction with plasma requires strong coupling
- Quark-antiquark has clear AdS dual: fundamental string
- Mimic ensemble of strings to match perturbative QCD

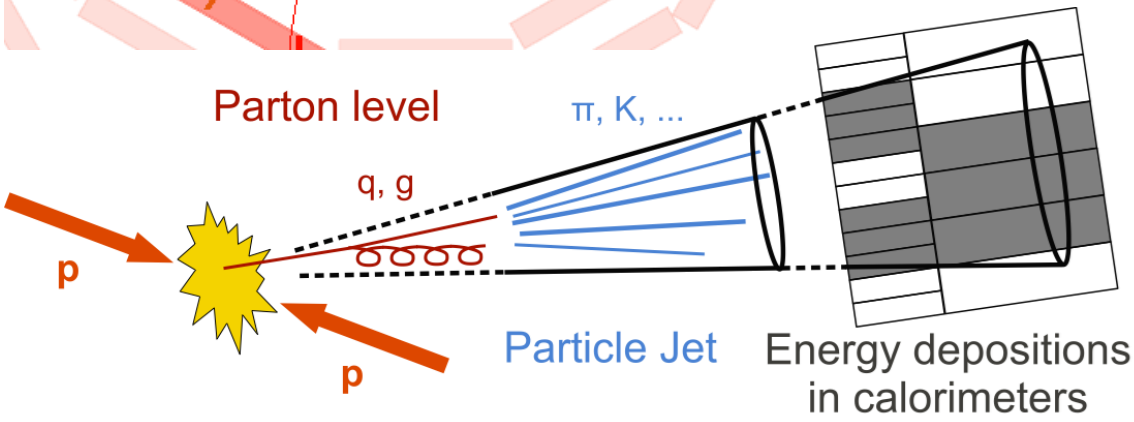
Strongly coupled evolution

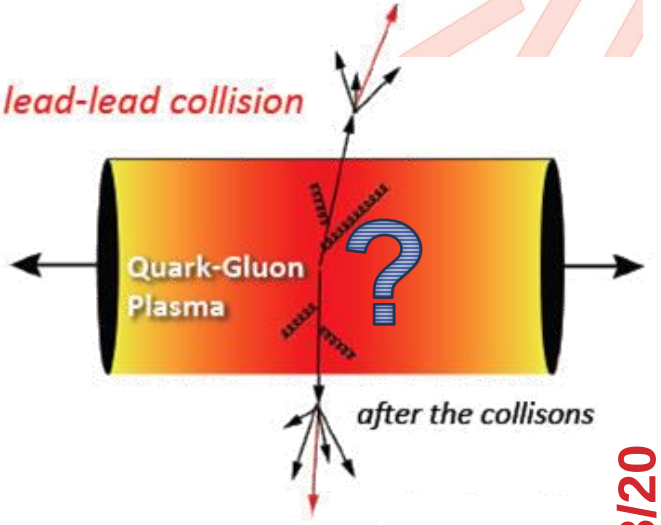
- Shoot ensemble through expanding and cooling black hole
- → Andrey

JETS IN QGP









CMS PAPER EXO-12-059

JET ESSENTIALS

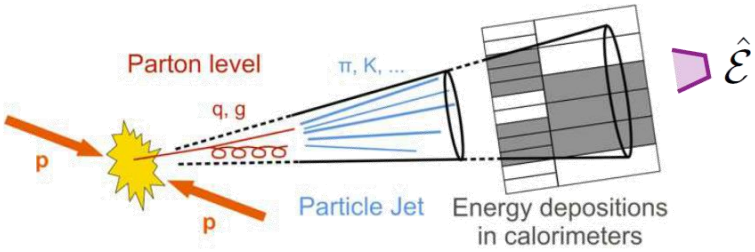
A priori: event with set of particles

- Define jet using a jet finding algorithm
- anti-k_T: group particles around energetic cores

Measurement consists of n-point function of energy flow:

- Measure energy flow (direction)
- 1-point function:

$$p_T^{\text{jet}} \simeq \sum_i p_{Ti}$$



- Rescale energies: $z_i \equiv \dfrac{p_{Ti}}{\sum_j p_{Tj}}$

$$\hat{\mathcal{E}}(\theta,\phi,v) \simeq \lim_{t\to\infty} \hat{n}_i T^{0i}(t, vt\hat{n})$$

energy flowing to infinity

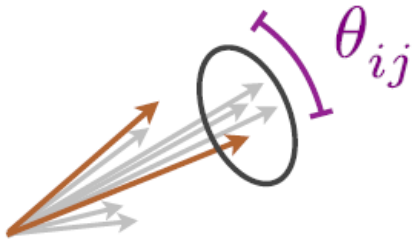
- Becomes trivial: $e_1 = \sum_i z_i = 1$
- Interesting substructure in higher point functions

J. Thaler, Jet Substructure from Protons to Ions (presentation 2016)

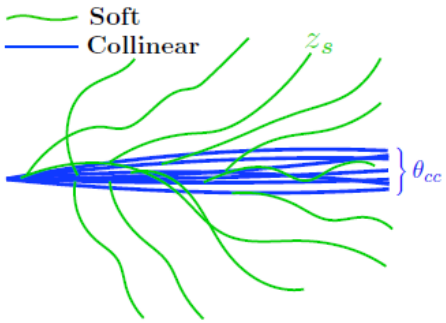
JET ESSENTIALS

2-point Correlators

2-point: $e_2^{(\beta)} = \sum_{i<j} z_i z_j \theta_{ij}^{\beta}$



Similar information to radial moments



soft dominated	$\beta = 2$	$\approx$	thrust	*a.k.a. m^2/p_T^2*
equal weight	$\beta = 1$	$\approx$	width	*a.k.a. broadening, girth*
collinear dominated	$\beta = 0.5$	$\approx$	"Les Houches Angularity"	

[see also Berger, Kucs, Sterman, hep-ph/0303051; Ellis, Vermilion, Walsh, Hornig, Lee, 1001.0014; Larkoski, Salam, JDT, 1305.0007; Larkoski, Neill, JDT, 1401.2158; Larkoski, JDT, Waalewijn, 1408.3122; Soyez, JDT, Freytsis, Gras, Kar, Lönnblad, Plätzer, Siodmok, Skands, Soper, 1605.04692]

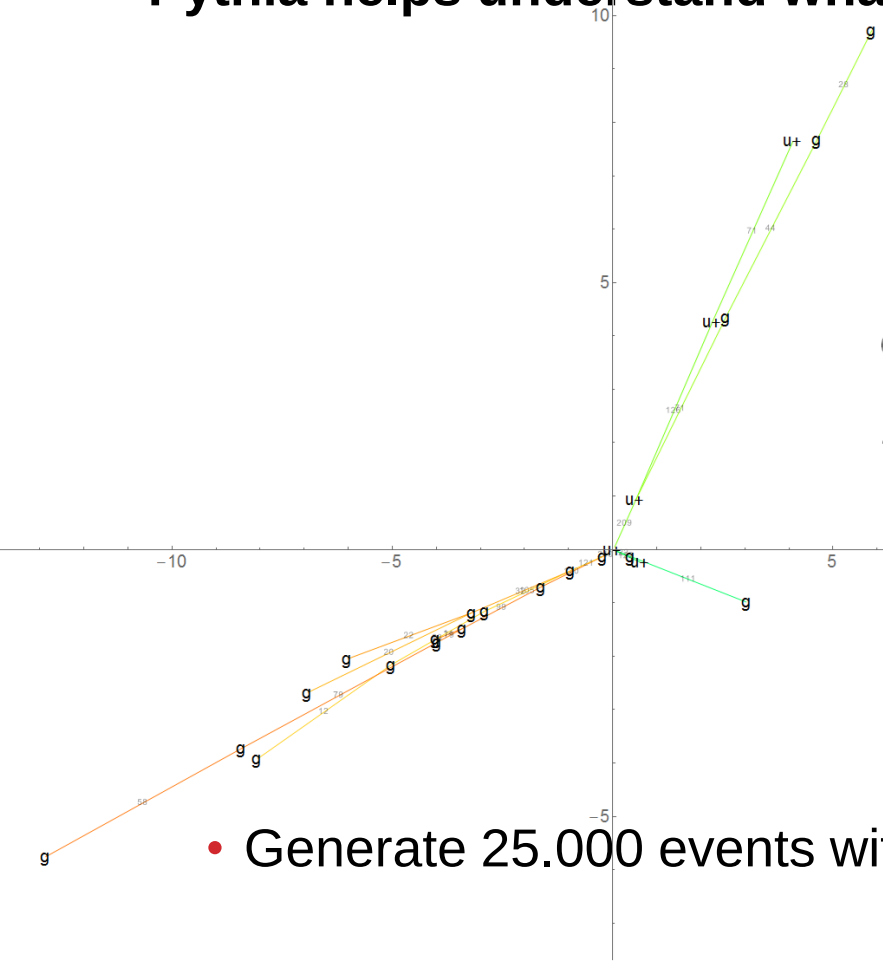
Also works with energy distributions as opposed to only particles (z_g)

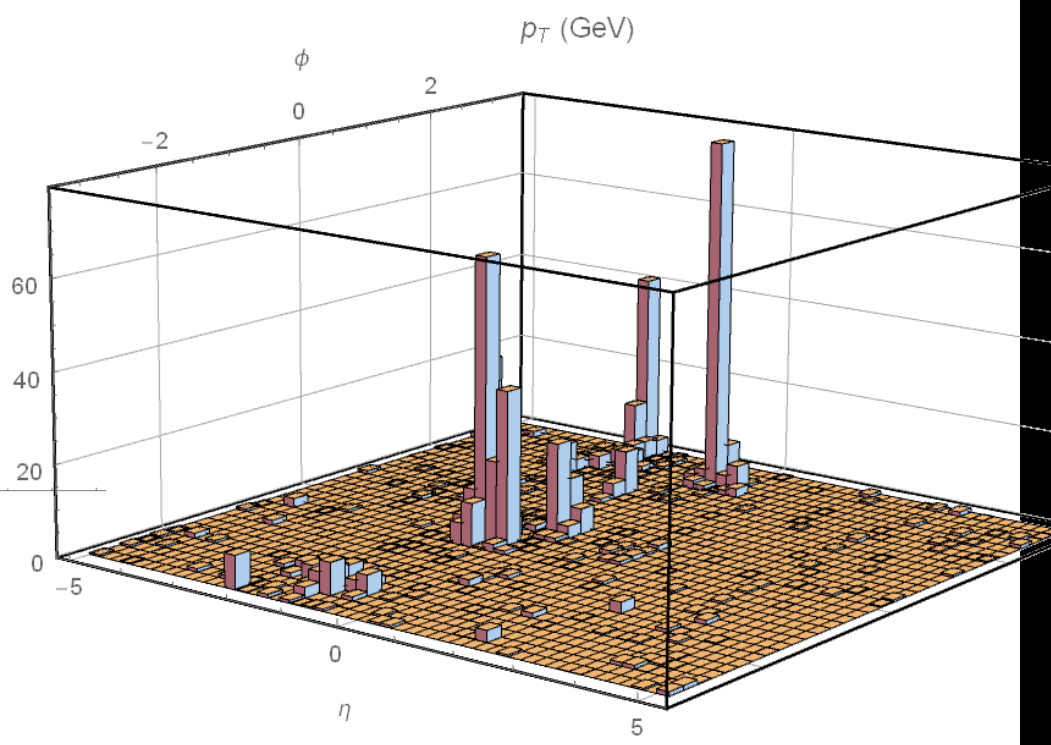
JET ESSENTIALS - SHAPES

Jet shapes, jet width depend on jet axis

- More non-linear than 2-point function

Pythia helps understand what we need to understand ☺



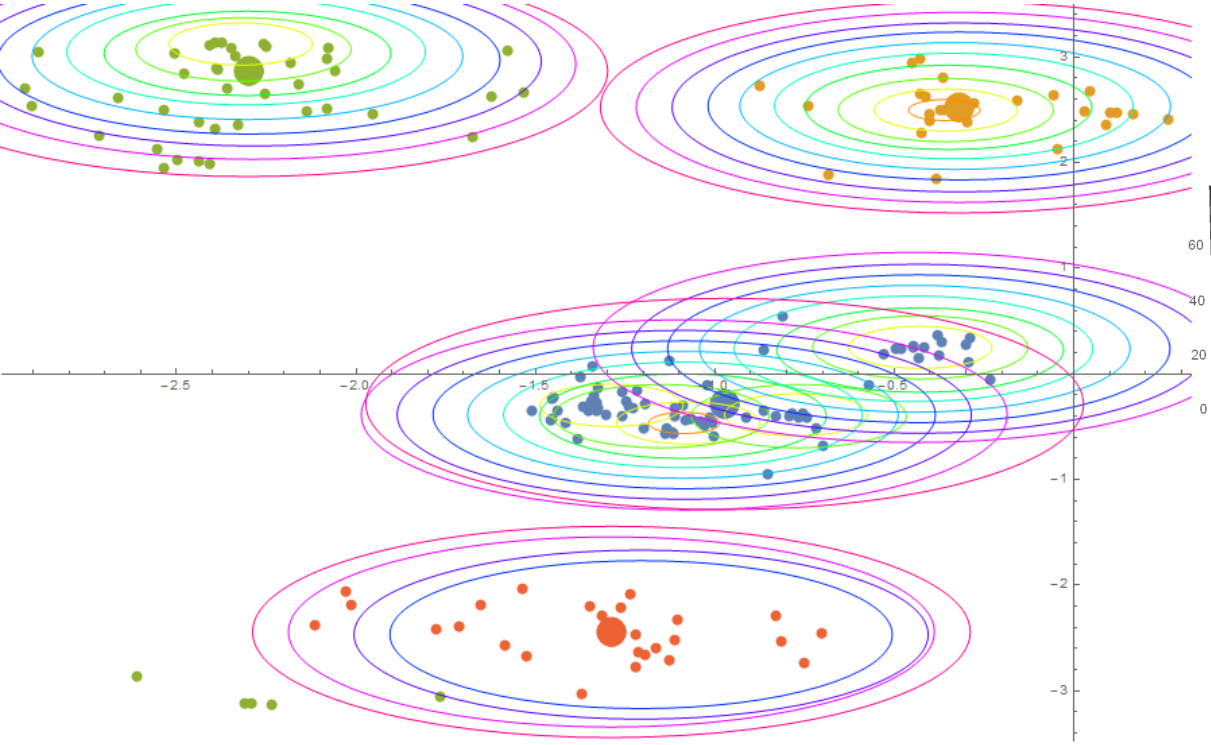


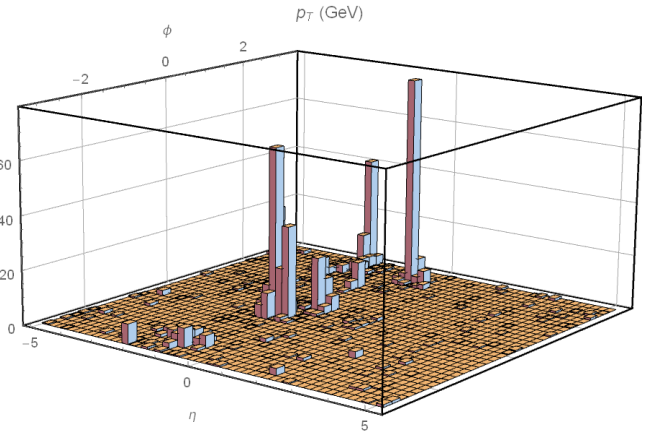
- Generate 25.000 events with 120 GeV jets and analyse

JET ESSENTIALS - SHAPES

Find jets using anti k_T

- Can be interesting to look at different jet radius R (different colours)



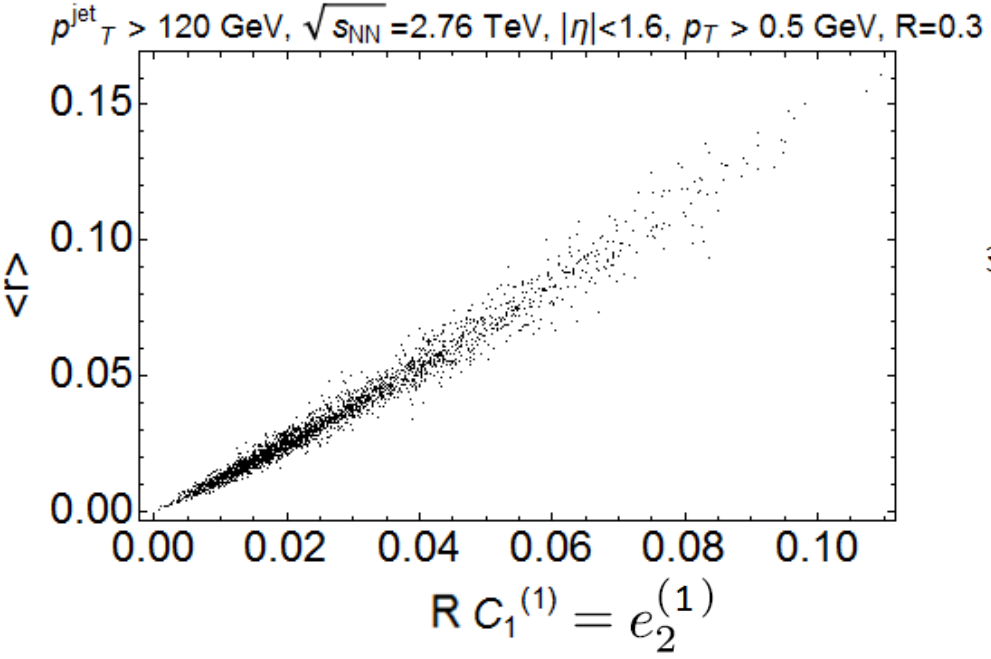


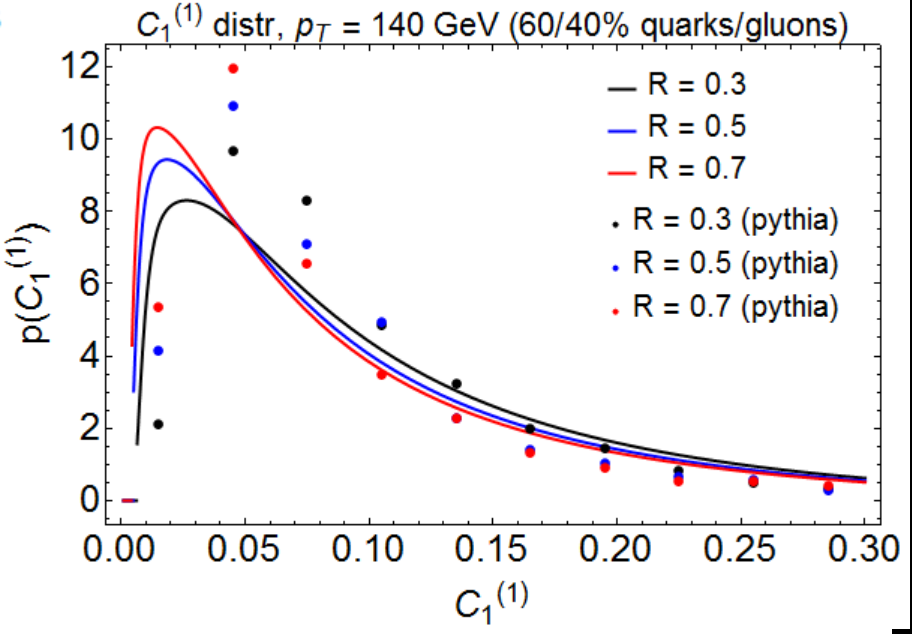
evnt	R	i	pT	y	phi	mult	chgmult	photons	hardest	pTinneutral
2852864	1.	0	244.398	-0.974	-0.284	74	39	31	pi+	41.581
2852864	1.	1	111.52	-0.321	2.526	28	12	14	pi-	6.121
2852864	1.	2	101.157	-2.297	2.87	46	21	21	gamma	6.055
2852864	1.	3	47.922	-1.289	-2.444	26	15	7	pi+	8.193

JET ESSENTIALS - SHAPES

Can now study correlation $C_1^{(1)}$ and jet width:

- Relatively high p_T means relatively narrow jets
- Can also be compared to analytic formula (see Andrey's talk also)



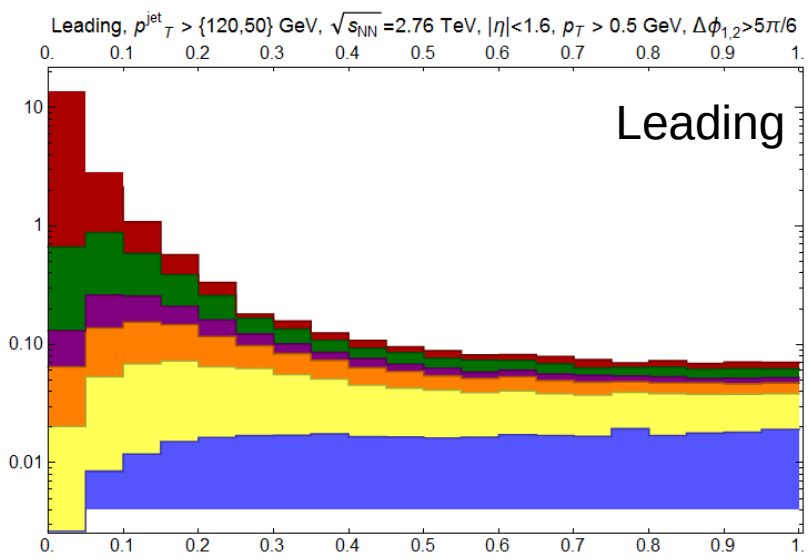


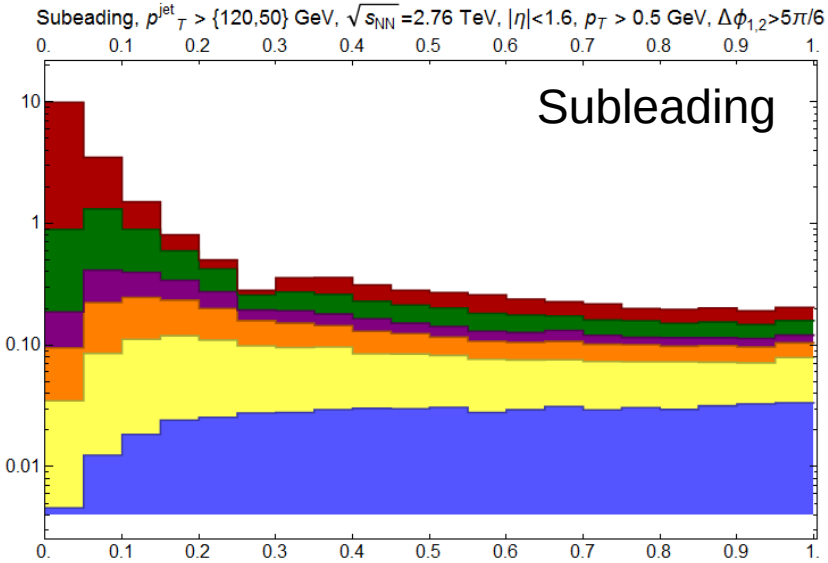
A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft drop (2014)

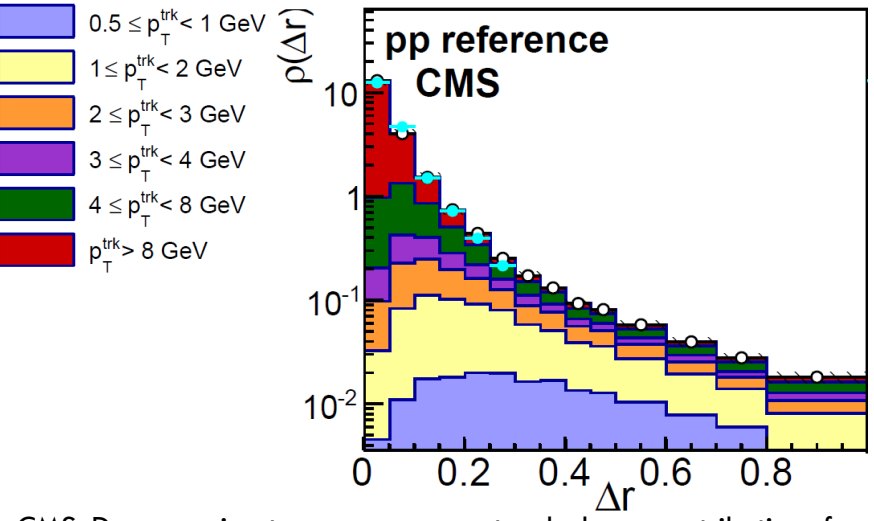
JET ESSENTIALS - SHAPES

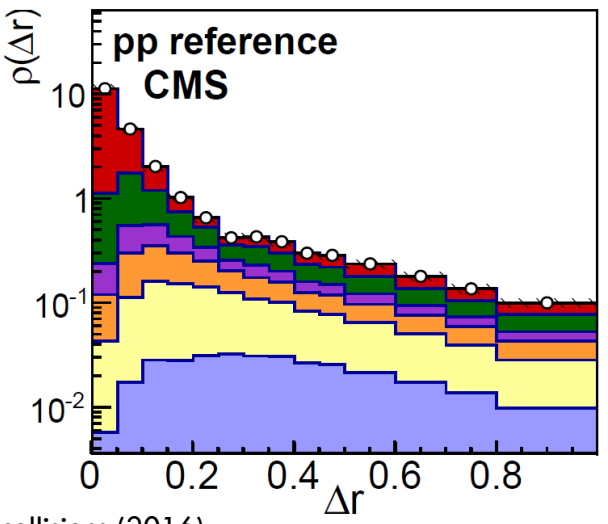
Ready to look at jet shapes, energy around axis, decomposed

- There is a problem at larger radii: background subtraction in pp! 3rd jet







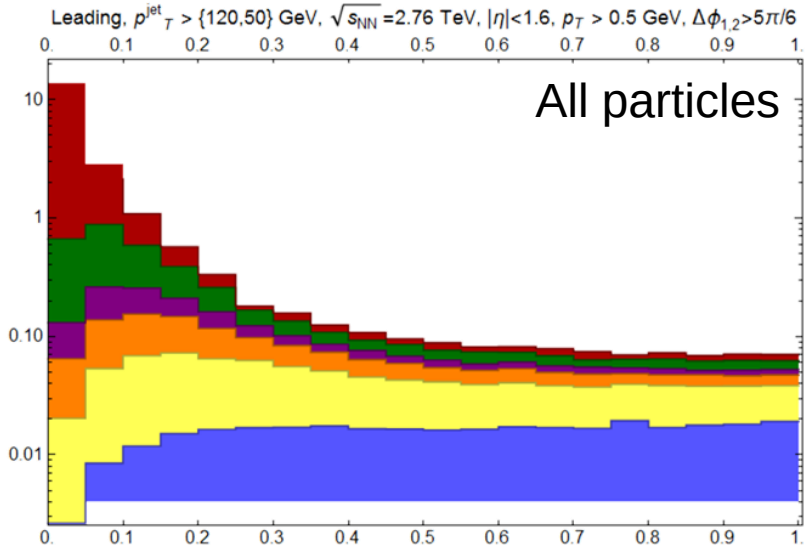


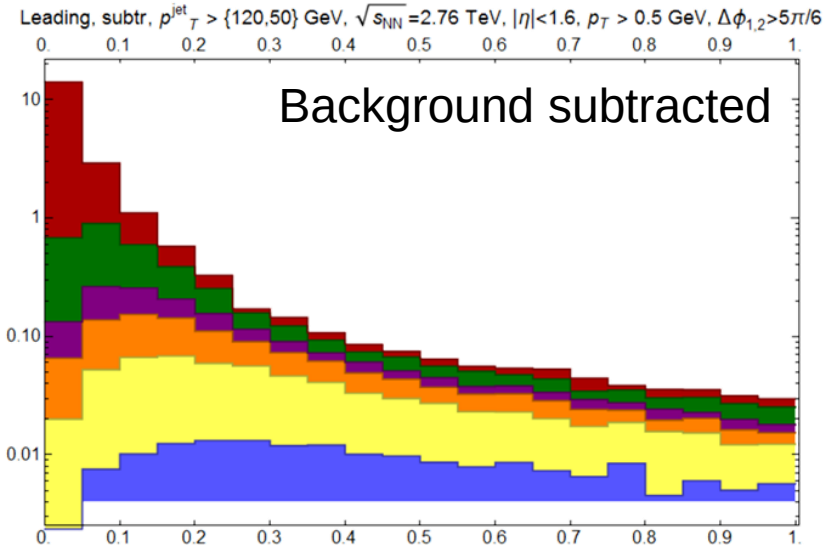
CMS, Decomposing transverse momentum balance contributions for quenched jets in PbPb collisions (2016)

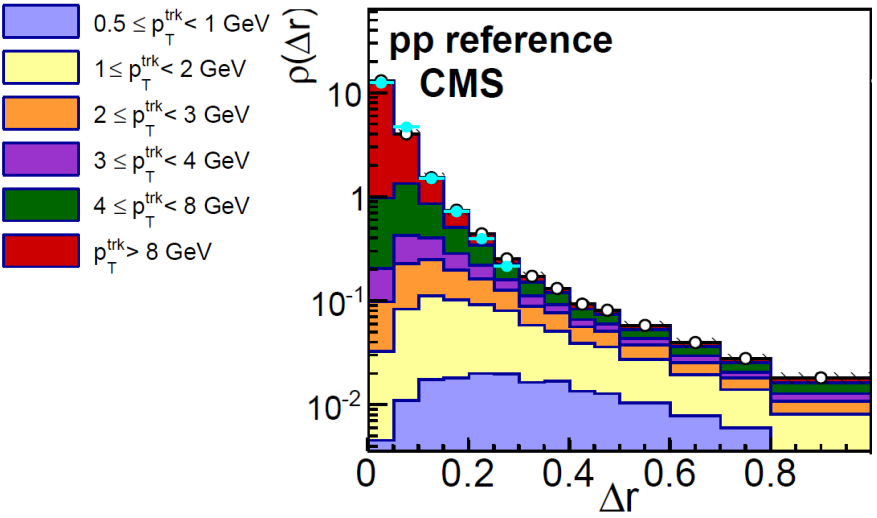
JET ESSENTIALS - SHAPES

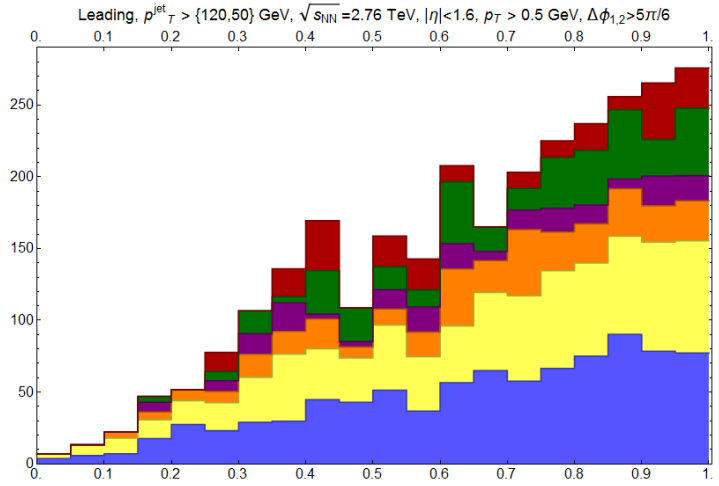
Ready to look at jet shapes, energy around axis, decomposed

- There is a problem at larger radii: background subtraction in pp! 3rd jet





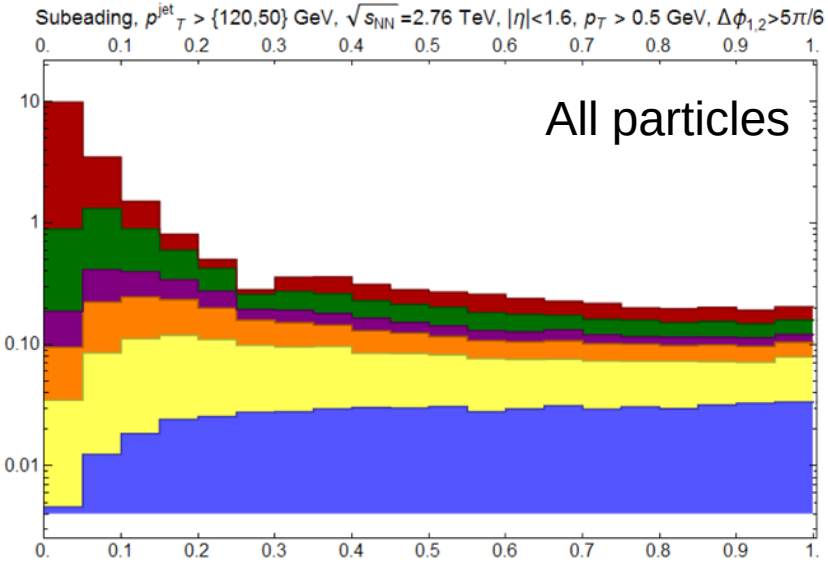


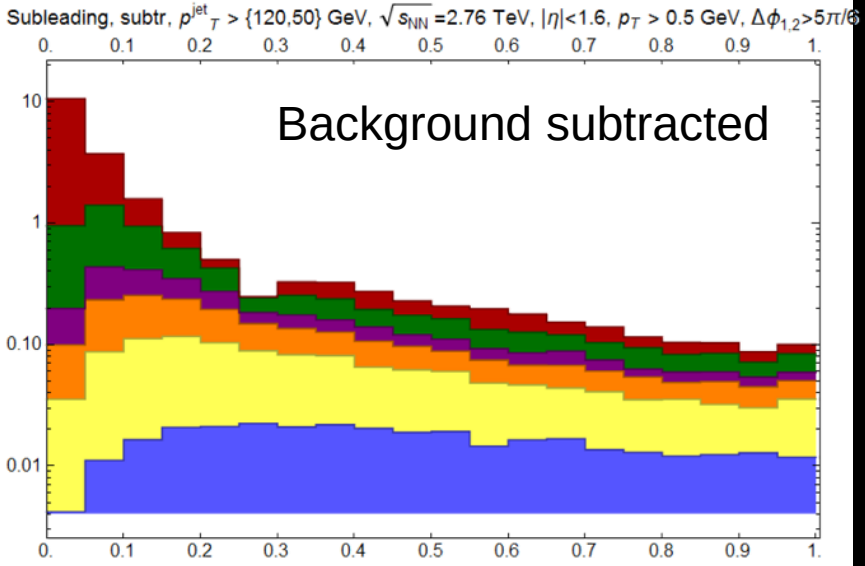


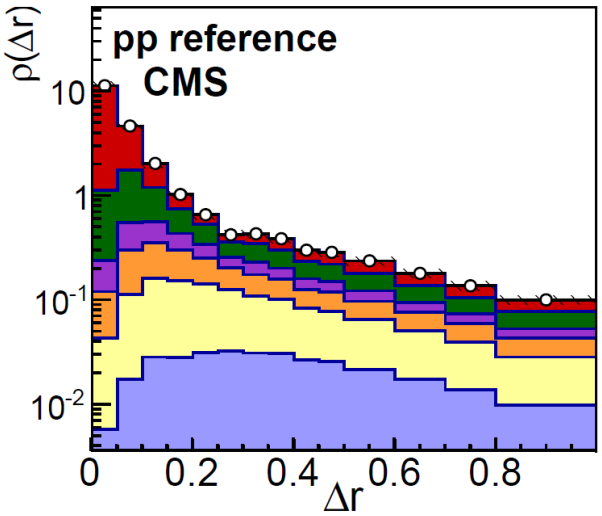
JET ESSENTIALS – SHAPES SUB

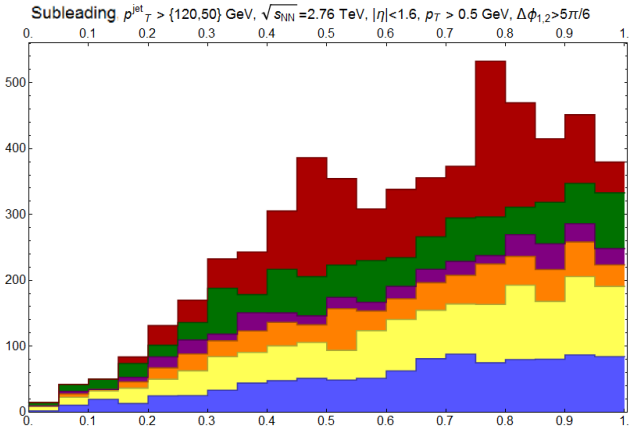
Ready to look at jet shapes, energy around axis, decomposed

- There is a problem at larger radii: background subtraction in pp! 3rd jet





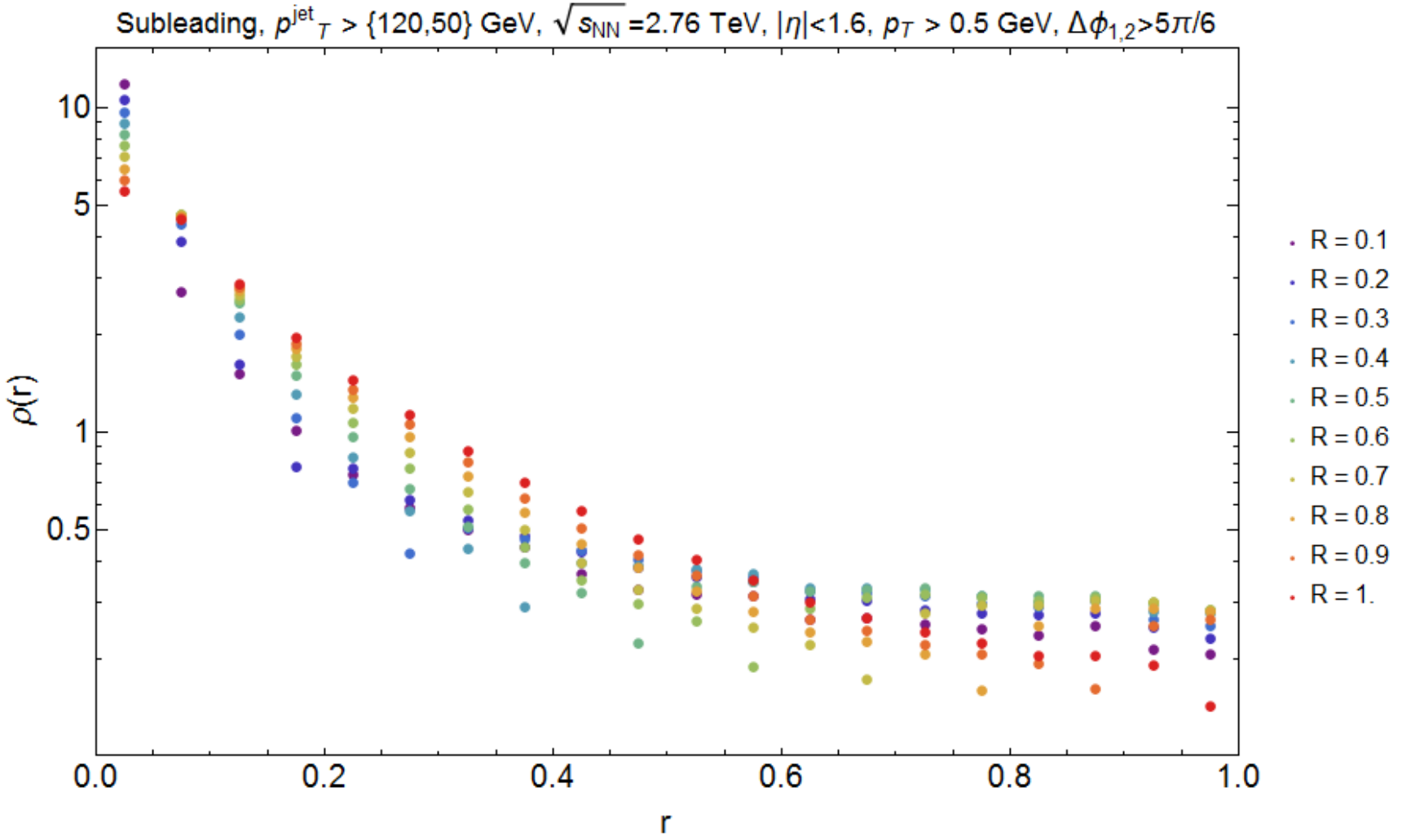




FUN FACT

Jet axis and hence jet shapes not very well behaved observable

- Particle `at the edge' shifts axis, changes jet shape
- Plot jet shape for different R:

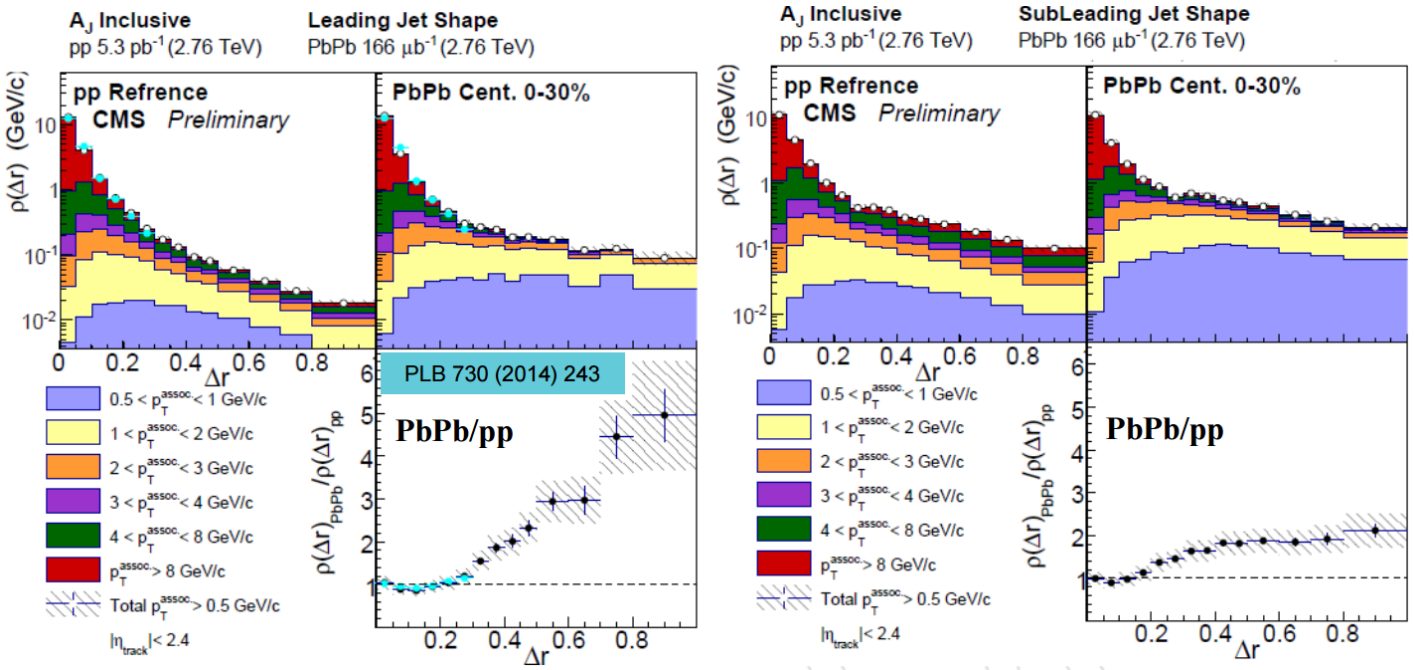


RECAP JET SHAPES

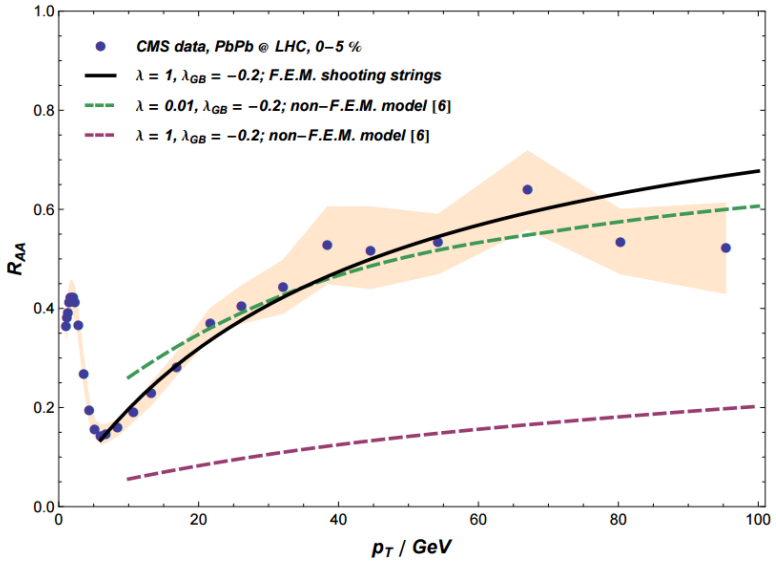
Jet shapes are somewhat complicated, especially at large *r*

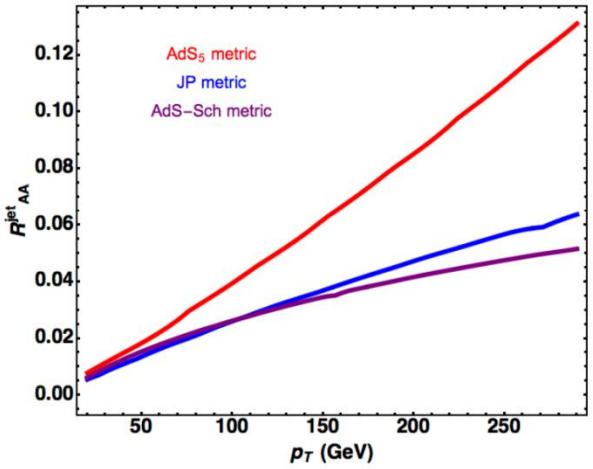
- In AA we have to subtract background, same way in pp
- Background can however be correlated, 3rd jet in pp
  - If 3rd jet is modified in QGP then this affects jet shape modification
- Cleaner observables, as $C_1^{(1)}$, but not as intuitive + similar issues

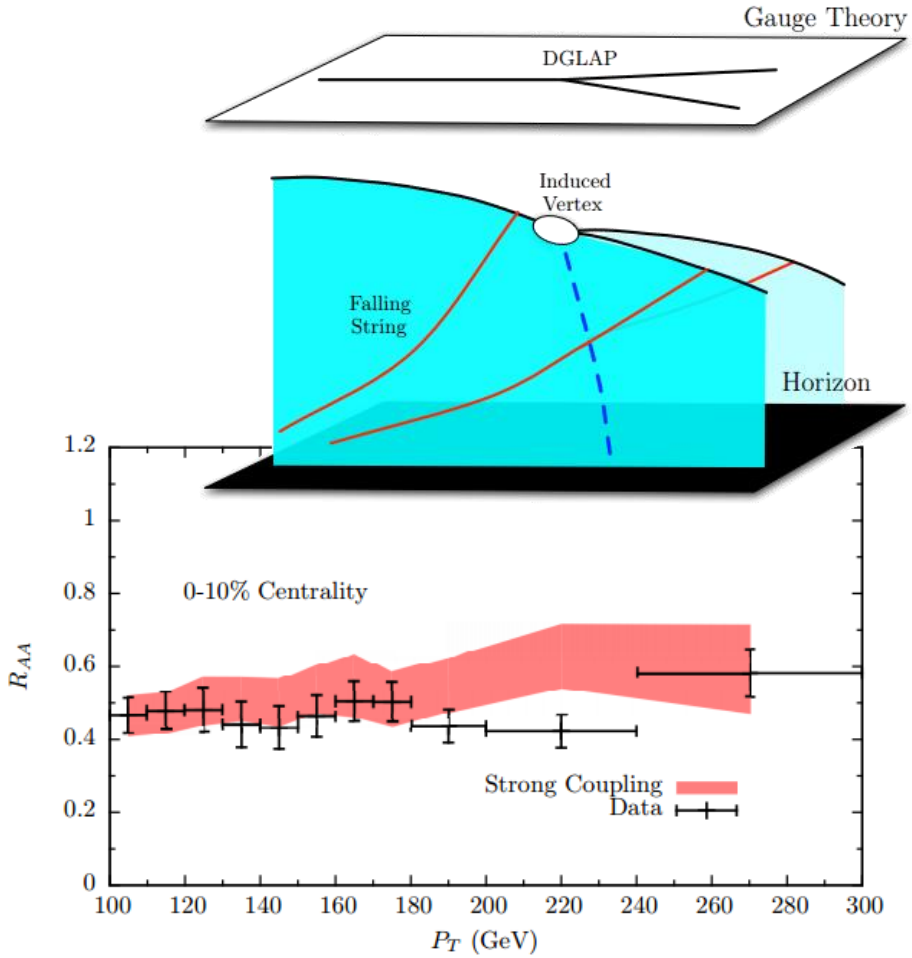
Interesting observable: jet shape modifications:



HOLOGRAPHIC STUDIES WITH REAL DATA



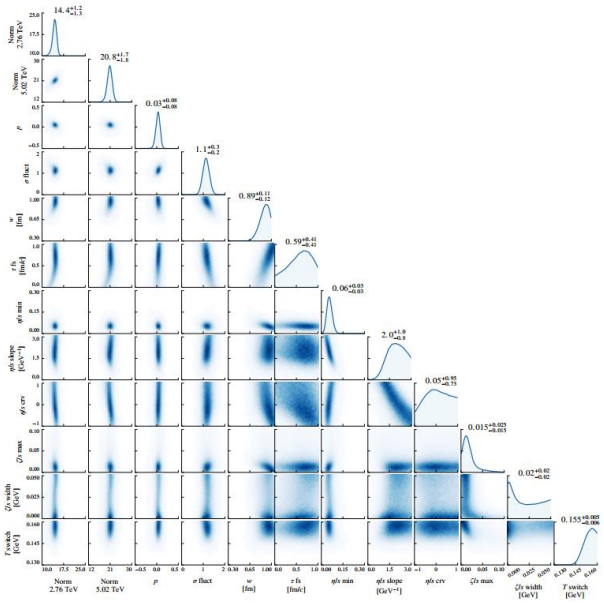


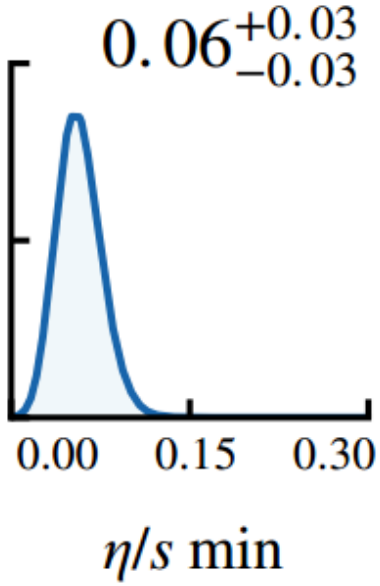


J. Casalderrey, D. Can Gulhan, J. Guilherme Milhano, D. Pablos and K. Rajagopal, A Hybrid Strong/Weak Coupling Approach to Jet Quenching
R. Morad, W.A. Horowitz, Strong-coupling Jet Energy Loss from AdS/CFT (2014)
A. Ficnar, S.S. Gubser and M. Gyulassy, Shooting String Holography of Jet Quenching at RHIC and LHC (2013)

ADS/CFT VISCOSITY REVISITED?

New experimental estimate for shear viscosity QGP: $\eta/s = 0.03 - 0.09$





Skipping/stressing many caveats applying N=4 SYM to QCD:

- Infinite coupling limit (QCD = intermediate coupling?)
- SYM vs YM, no confinement, what to collide?, jet production?

Idea: get strong coupling benchmark/intuition + improve model

Steffen A. Bass, Jonah Bernhard and J. Scott Moreland, Determination of Quark-Gluon-Plasma Parameters from a Global Bayesian Analysis (2017)

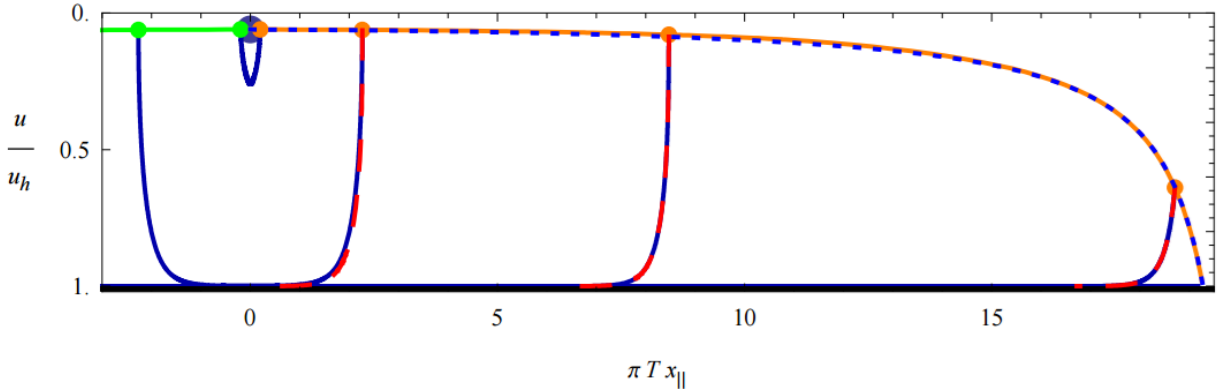
JET PRODUCTION

Typical philosophy:

- Jet is result of hard event, as prescribed in pQCD
- Energy loss, through soft modes, and non-perturbative
- Understood quite precisely: energy fallen into horizon = thermalised

In AdS/CFT: jet = (classical) string

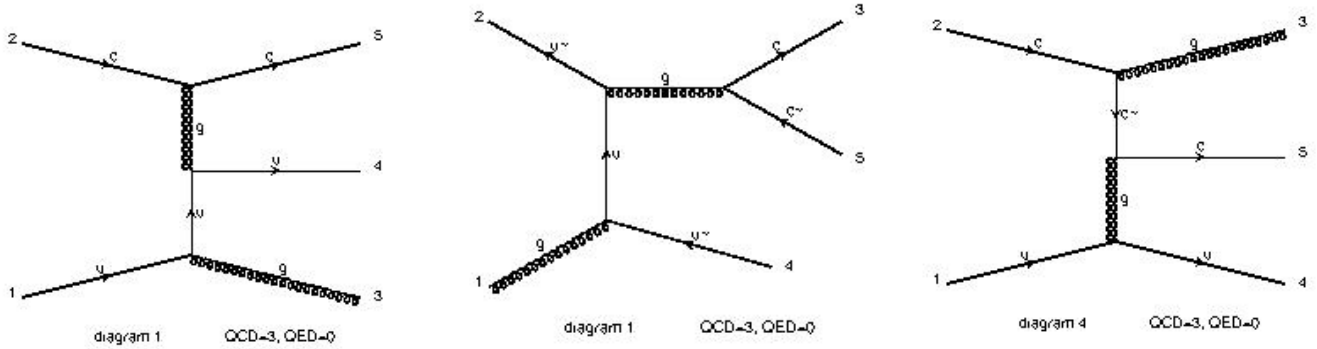
- Create string (quark-antiquark pair) with `jet-like' properties
  - Problem: initial condition string is 2 functions (position, velocity)



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)

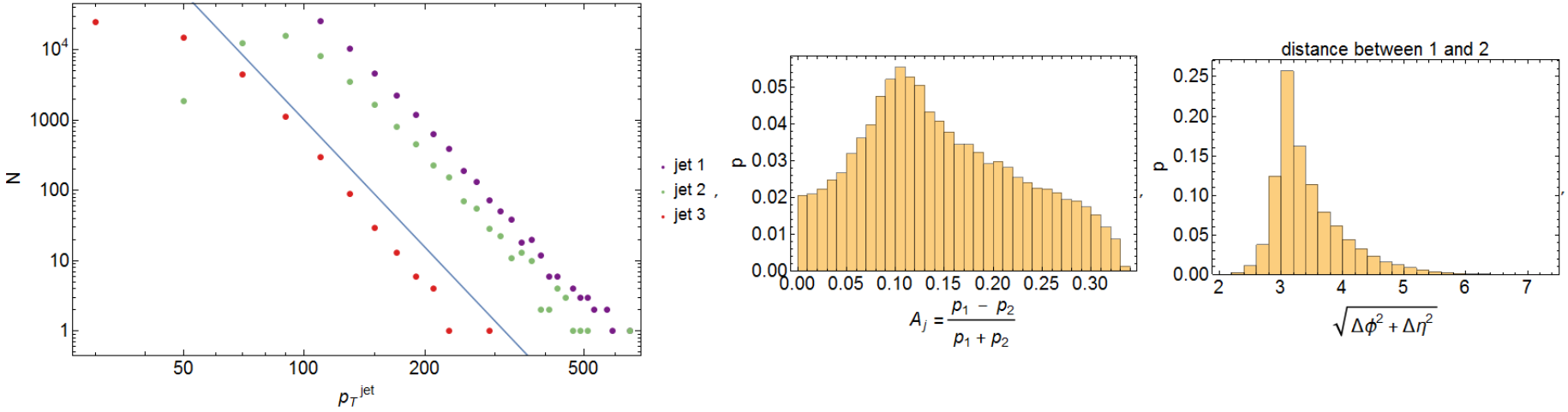
IN AN IDEAL WORLD

Use MadGraph to simulate hard creation of 3 partons:



+1390 other diagrams

Extract distributions of energies and angles:

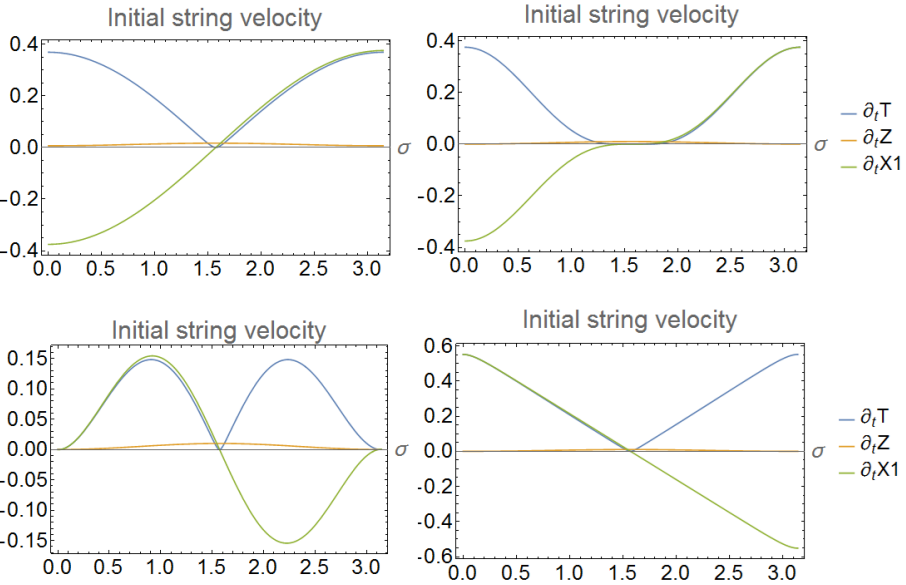


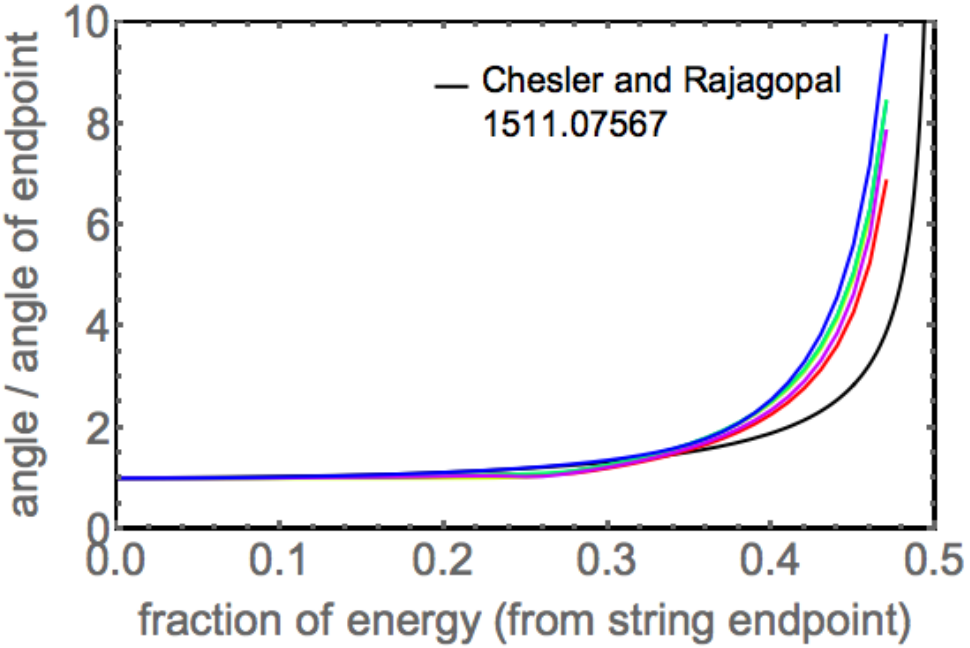
- Try and create string ensemble that looks behaves similarly

STRING PROFILE

Back-to-back string evolution

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



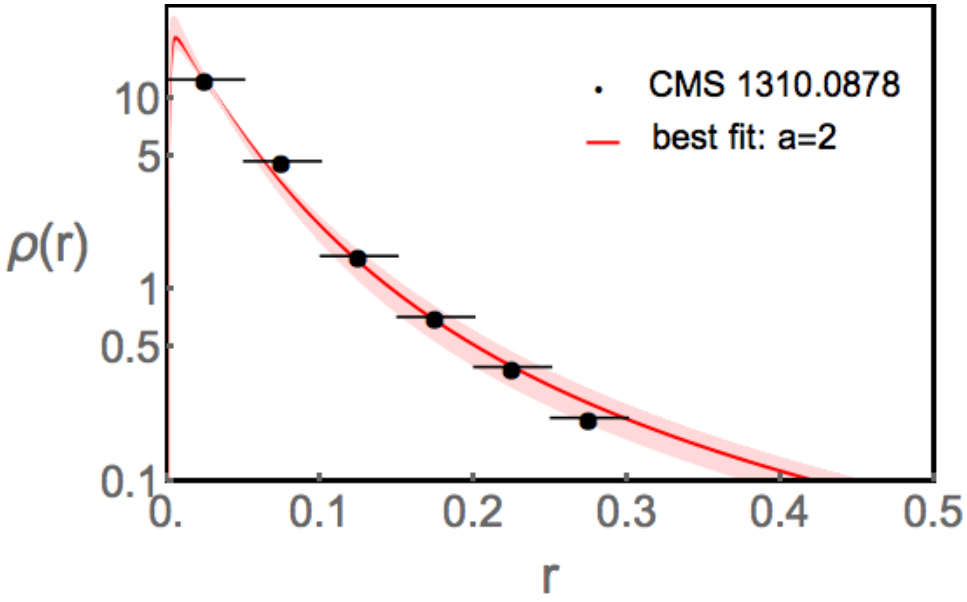


- This can reasonably model a single jet, with opening angle determined by $C_1^{(1)}$

LINKING STRINGS TO JET SHAPE

Construct the string ensemble

- Take representative curve from previous slide
- Energy distribution from QCD (E^{-6})
- Endpoint angle distributed as jet width distribution (pQCD or Pythia)
  - Free parameter needs to be fixed
- Compute jet shape (AdS/CFT prescription)
- Compare with CMS to fix parameter



DISCUSSION

Review of jet observables

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

Constructing an ensemble of jets

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

Now ready to study strongly coupled interaction with plasma (Andrey)

- Shoot ensemble through plasma (black hole)
- How does the ensemble change?

Outlook

- Use R-differentiated measurement to distinguish narrow/wide jets? (Peter Jacobs)
- Finite coupling corrections in more realistic settings?