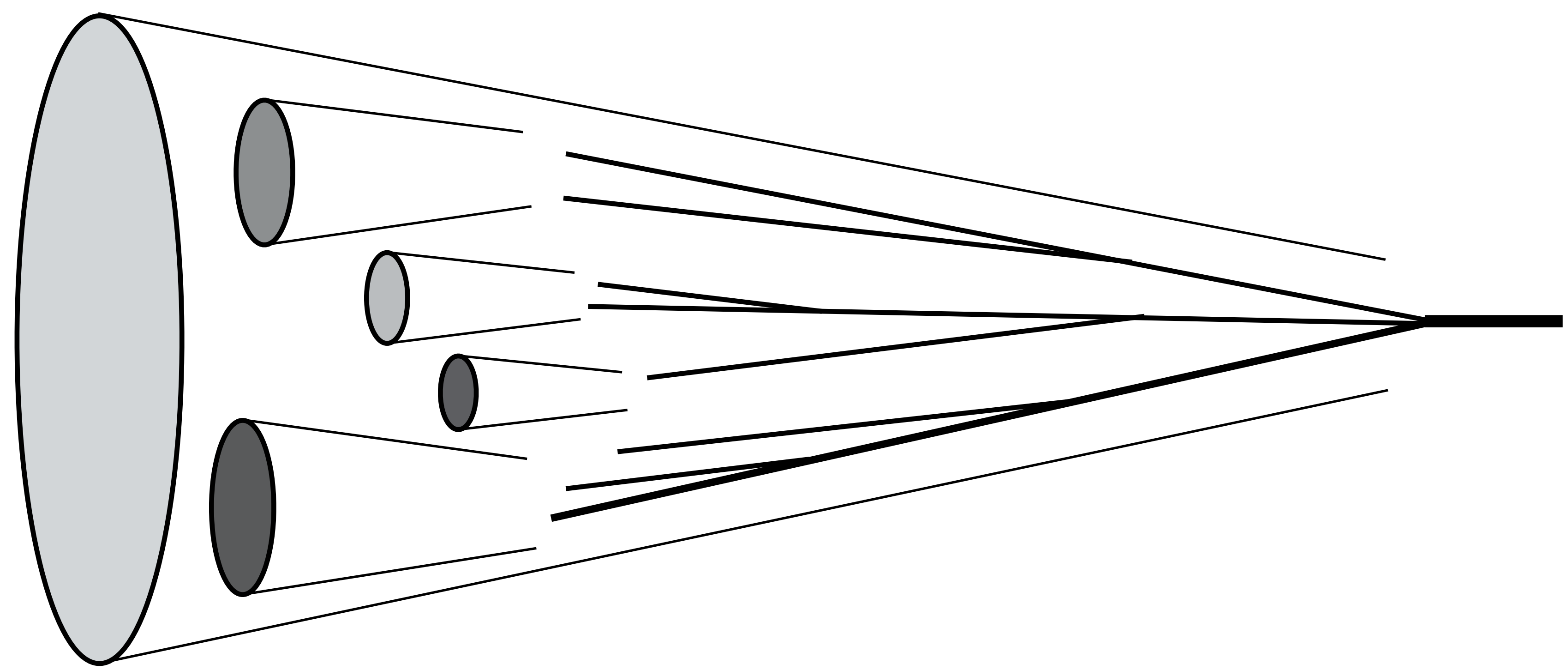
Jet substructure via angular correlations



Martin Jankowiak **Stanford/SLAC**

based on 1104.1646, 1201.2688 (with Andrew Larkoski)

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Outline

- introduction: why jet substructure?
- the unclustering paradigm
- angular correlation function
- top-tagging
- underlying event

Jet substructure

- the excellent resolution of the ATLAS & CMS detectors means that we can "peer inside" jets and measure how energy is distributed within jets

What is this good for?

- as a probe of QCD
- event discrimination

Jet substructure

as a probe of QCD

- make jet substructure measurements in data and compare to perturbative QCD calculations
- use to tune Monte Carlo event generators

Jet substructure
for event discrimination

- the LHC inverse problem:

  how do we connect what we measure (jets) to the hard scattering ?

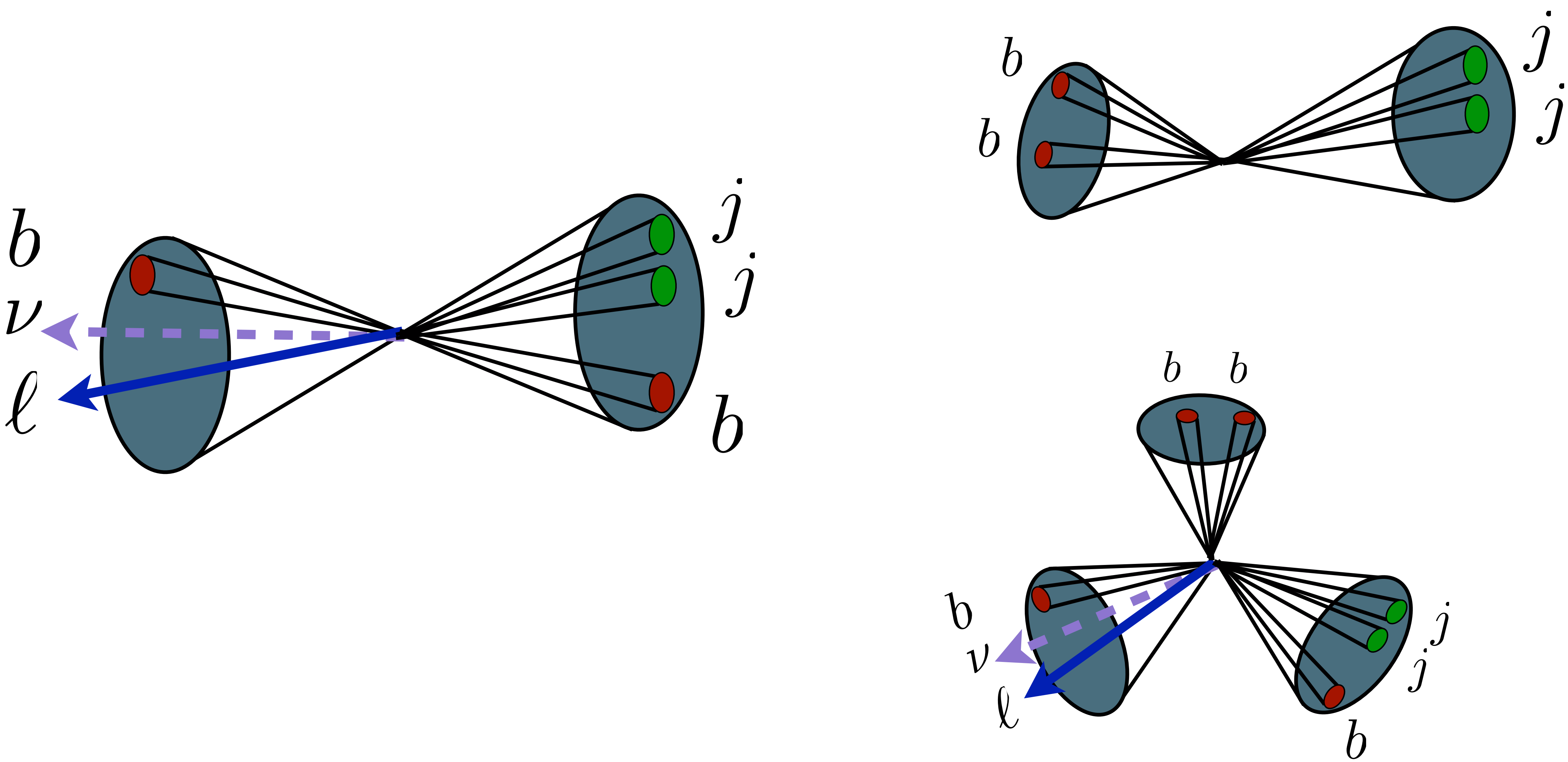
- use the characteristic energy distribution of signal jets (e.g. top jets) to discriminate against background jets (e.g. QCD jets initiated by light partons)

- especially relevant for boosted objects

Jet substructure

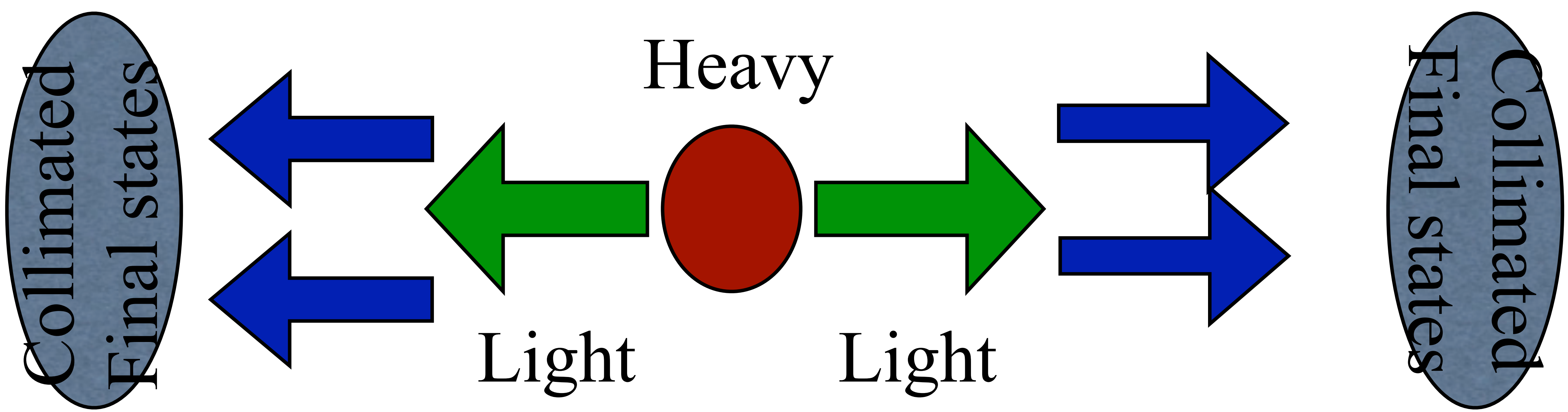
for event discrimination

want to separate complex signal topologies
from QCD backgrounds



Jet substructure
for boosted objects

The LHC has access to much higher energy scales:
cascade decays can lead to collimated final states



Jet substructure

for boosted objects

- requires rethinking cuts (e.g. isolation)
- a way of classifying complicated signatures
- reduces combinatoric backgrounds
- can be a unifying framework for peculiar signatures that were falling between cracks

Jet substructure

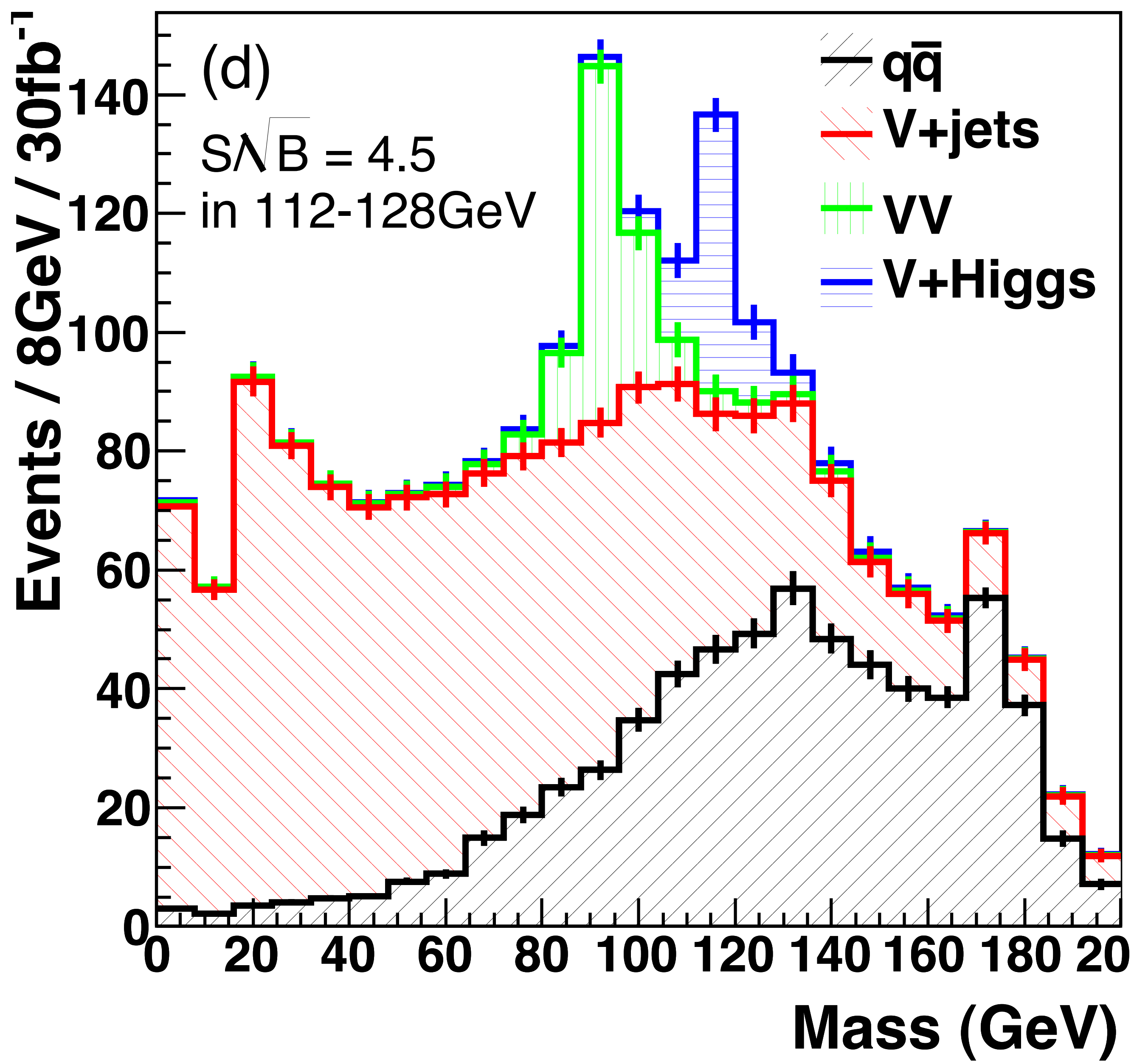
for boosted higgs

- for $p_T \gtrsim m_H$ the decay products of the higgs will typically be close together and reconstructed as a single jet
- about 5% of the cross-section for VH has $p_T > 200$ GeV
- backgrounds (V+jets, VV, top pairs) fall faster with p_T than the signal
- can pay to go to the boosted regime if substructure techniques can reduce backgrounds/combinatorics
- discovery for a light higgs with ~ 30 inverse fb

Jon Butterworth, Adam Davison, Mathieu Rubin, Gavin Salam arXiv/hep-ph:0802.2470

Jet substructure

for boosted higgs

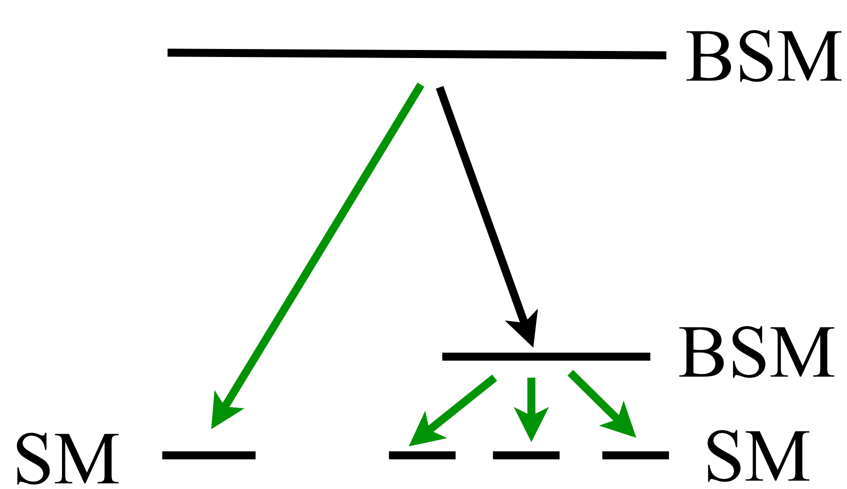


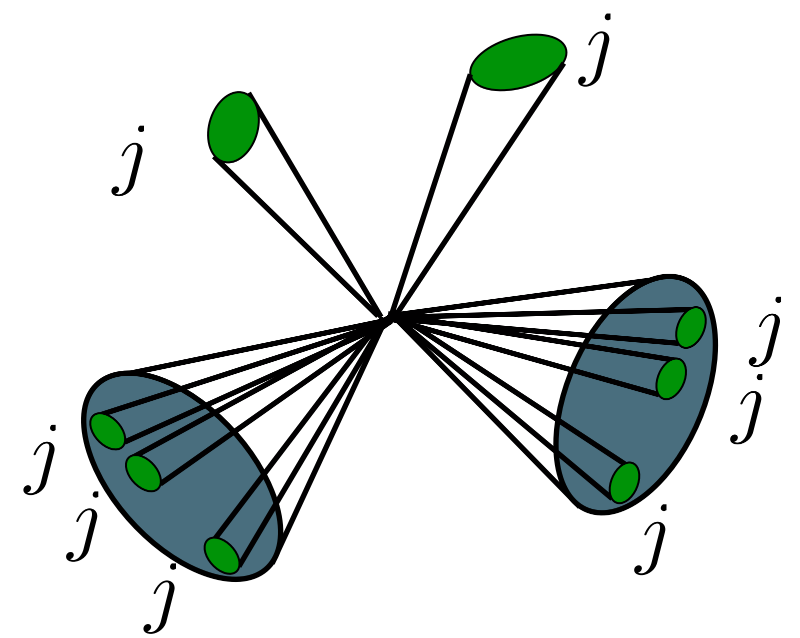
Jon Butterworth, Adam Davison, Mathieu Rubin, Gavin Salam arXiv/hep-ph:0802.2470

Jet substructure
for boosted bsm physics

R-Parity Violation $\tilde{q} \to \tilde{\chi}^0 q$ Butterworth et al. 0906.0728

$$W_{\mathrm{RPV}} = U^c D^c D^c \qquad \Longrightarrow \tilde{\chi}^0 \to 3q$$



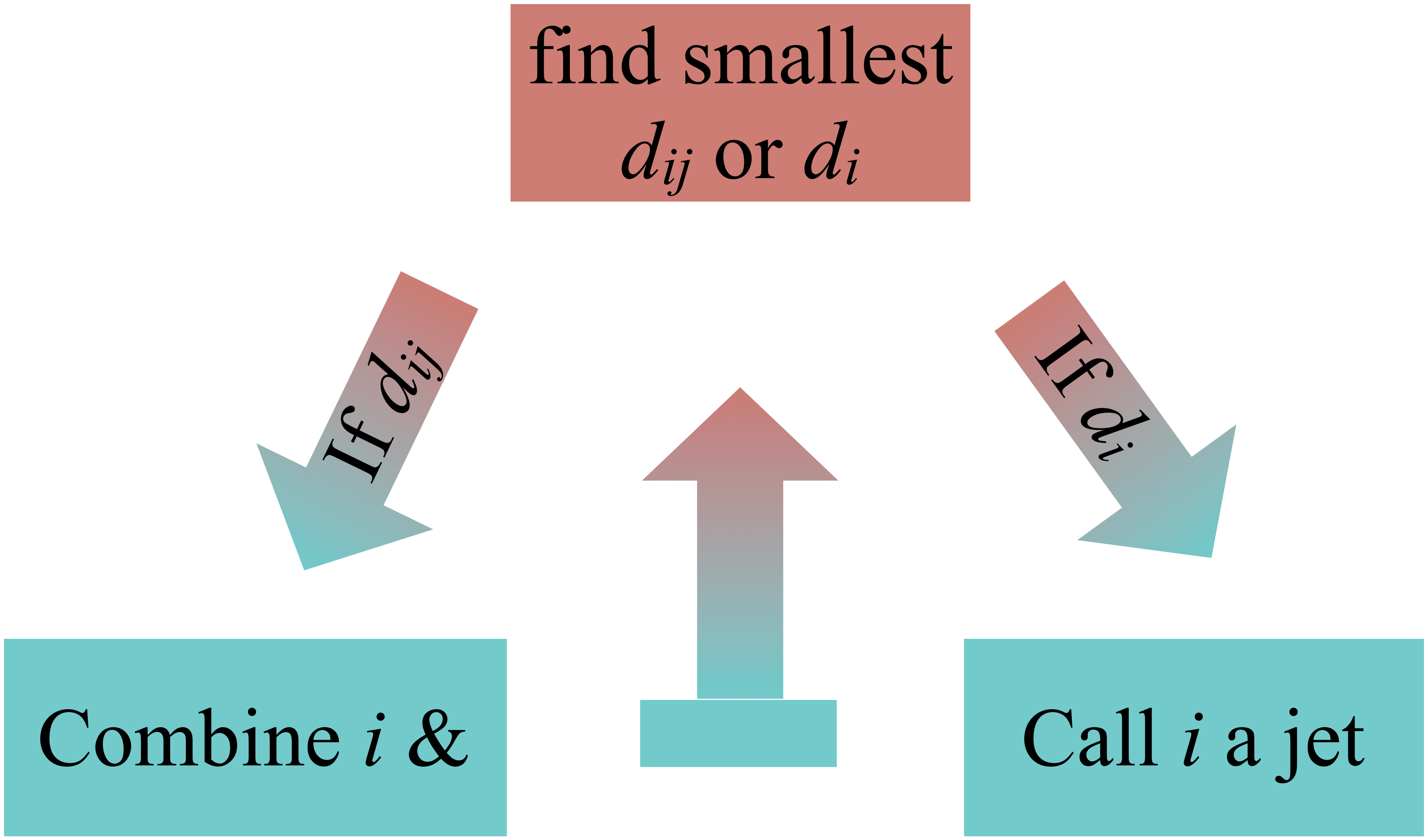


No significant MET, can reconstruct everything

Sequential jet clustering algorithms

- need a way to define jets from the four-momenta measured in the detector
- do this by sequentially combining four-momenta

Sequential jet clustering algorithms



$p = 0 \Rightarrow$ Cambridge-Aachen

$p = 1 \Rightarrow$ kT

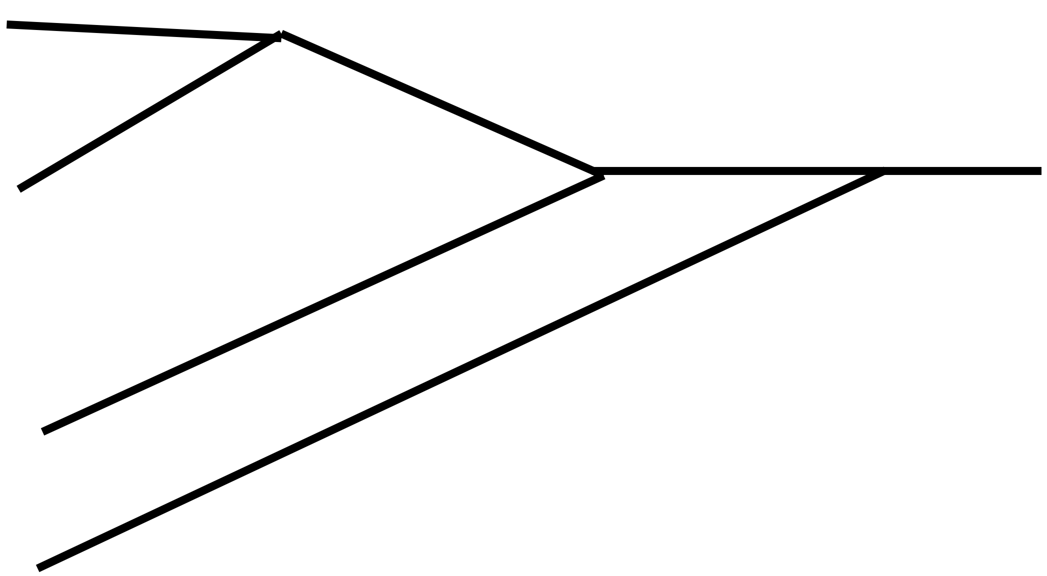
$p = -1 \Rightarrow$ anti-kT

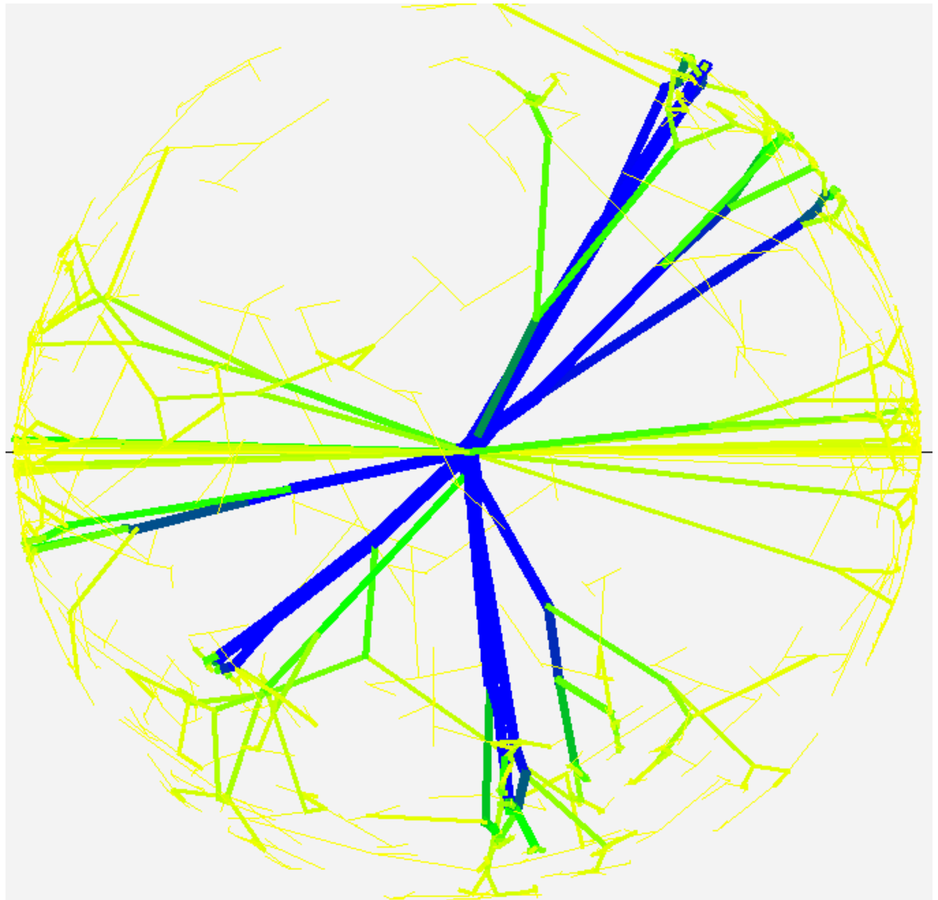
$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{ti}^{2p}$$

Unclustering

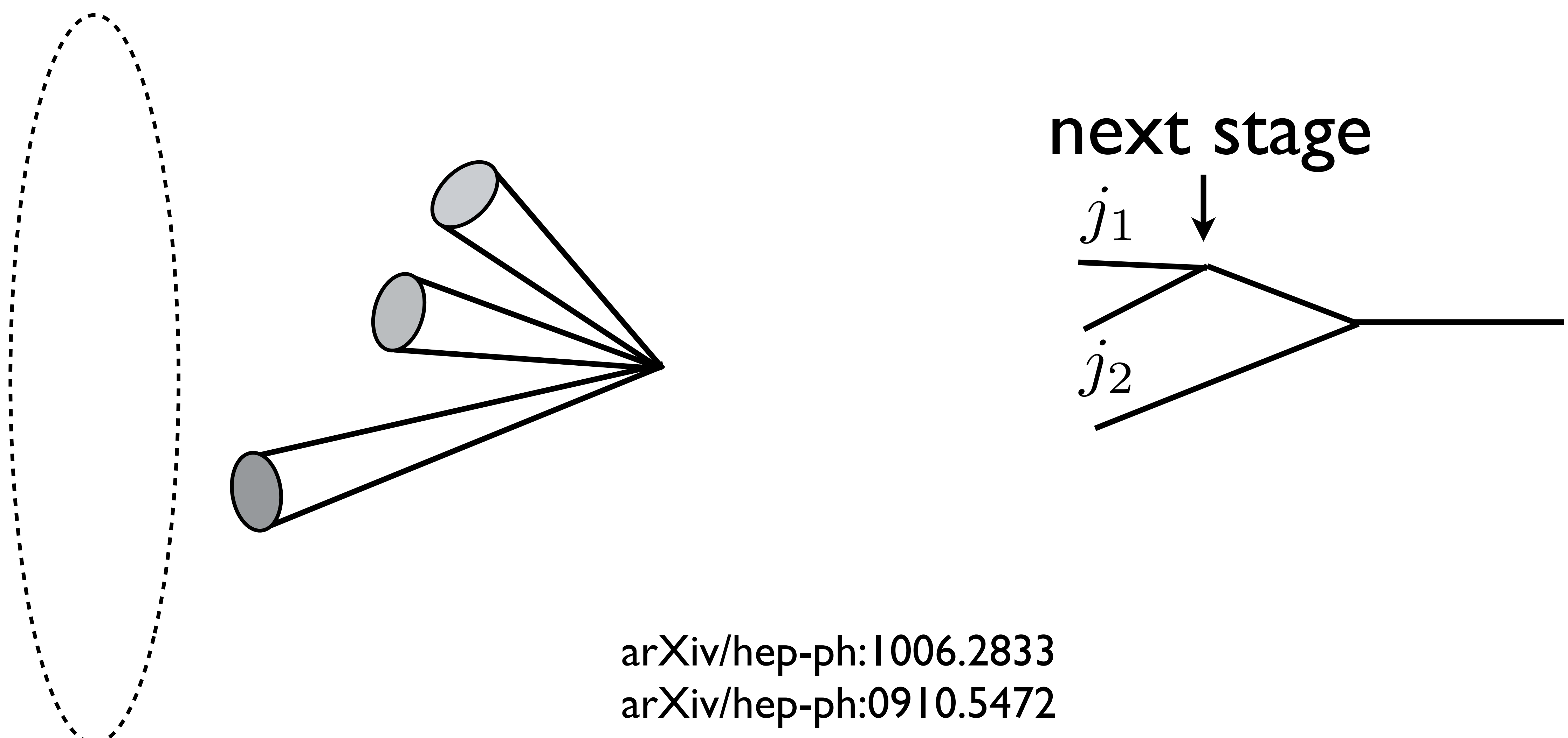
- sequential jet clustering algorithms give us more than a list of jet four-momenta
- they also give us a *clustering tree*: lots of information inside
- **main idea**: use the clustering tree to identify and characterize substructure in jets





HEPTopTagger

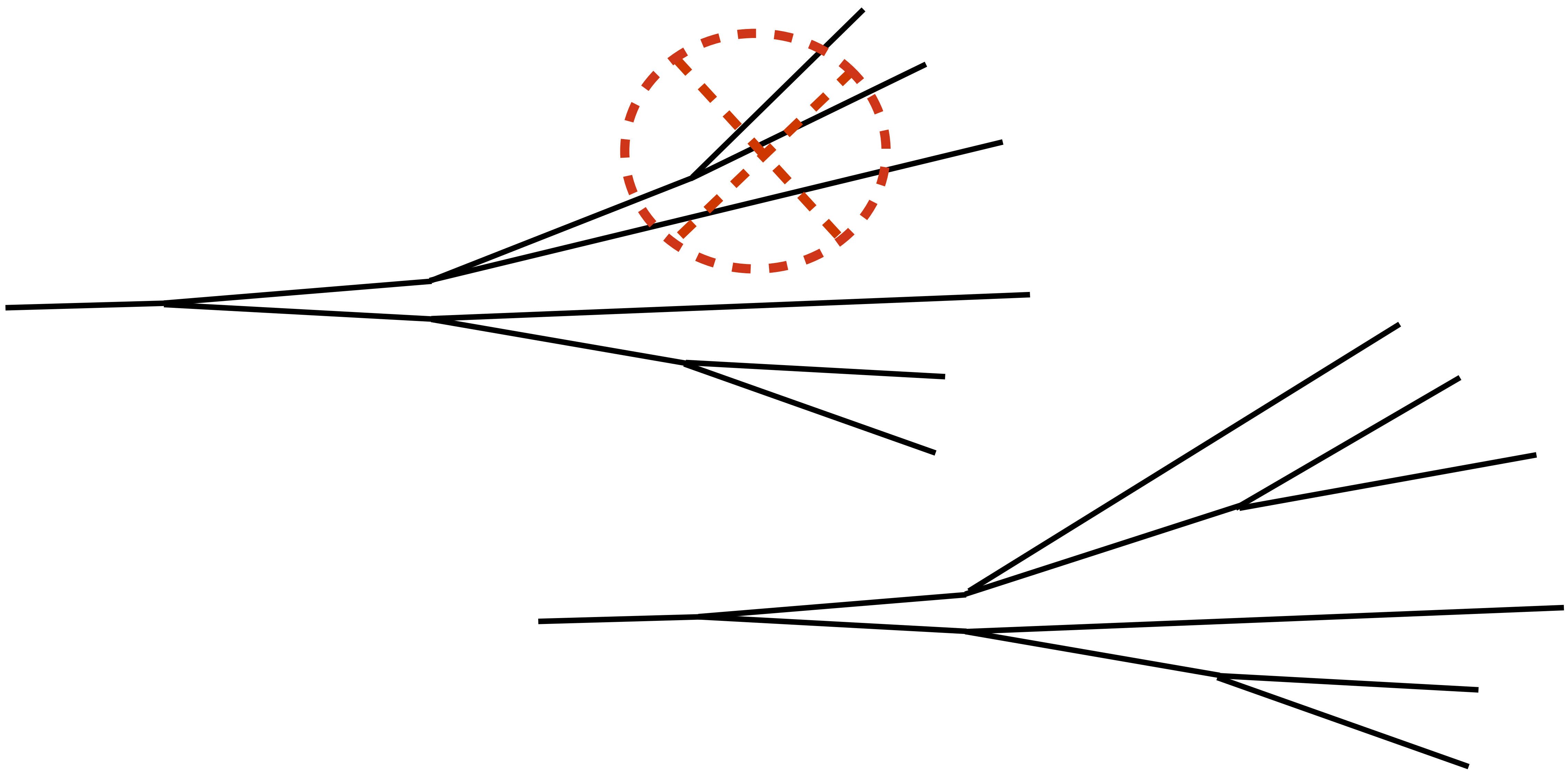
2. Break each fat jet into hard subjets using the following mass-drop criterion. Undo the last stage of clustering to yield two subjets j_1 and j_2 (with $m_{j_1} > m_{j_2}$), keeping both j_1 and j_2 if $m_{j_1} < 0.8 m_j$ and otherwise dropping j_2. Repeat this procedure recursively, stopping when the m_{j_i} drop below 30 GeV.



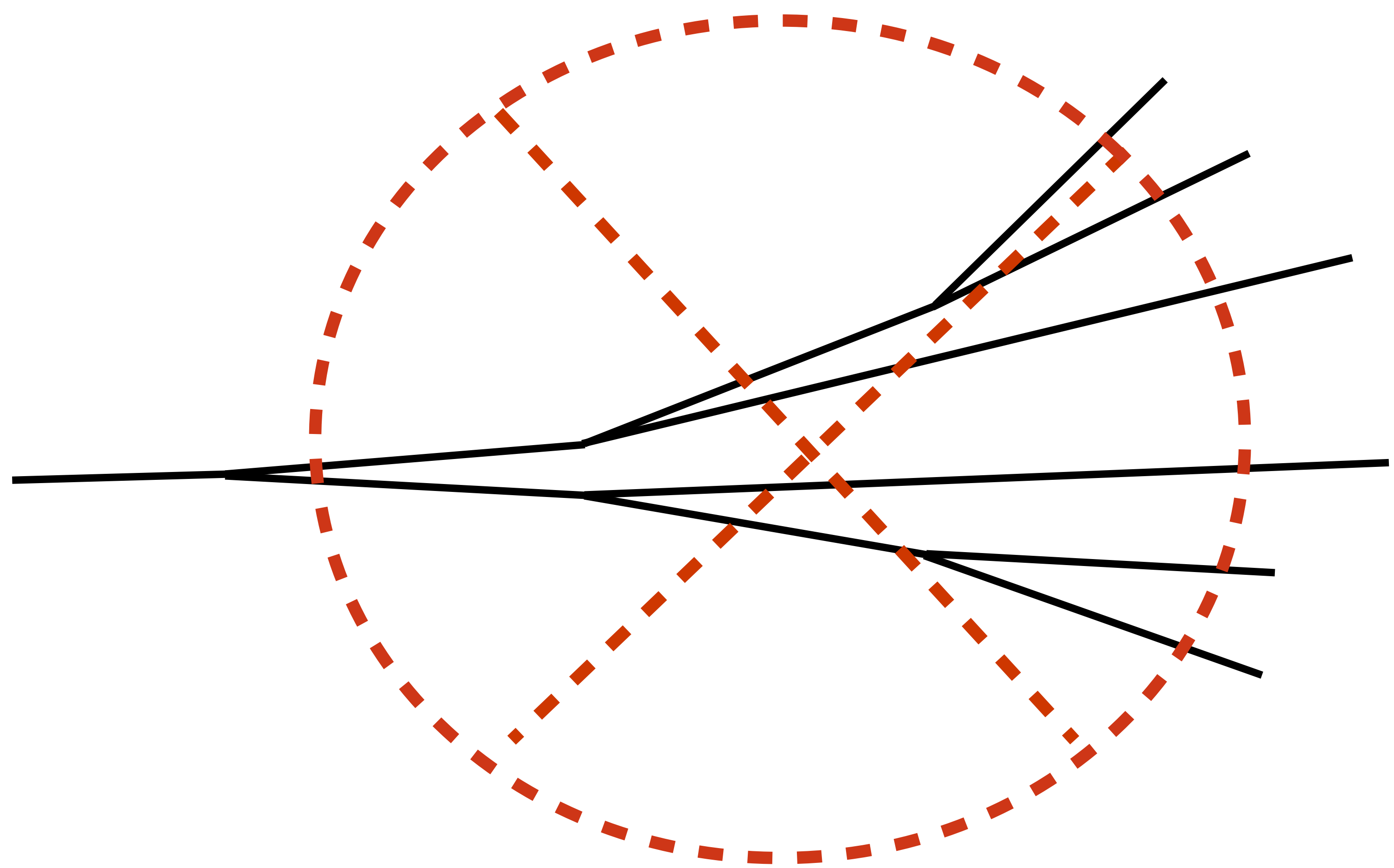
arXiv/hep-ph:1006.2833
arXiv/hep-ph:0910.5472
arXiv/hep-ph:1111.5034

Unclustering

we might worry that we've reconstructed the wrong parton shower history



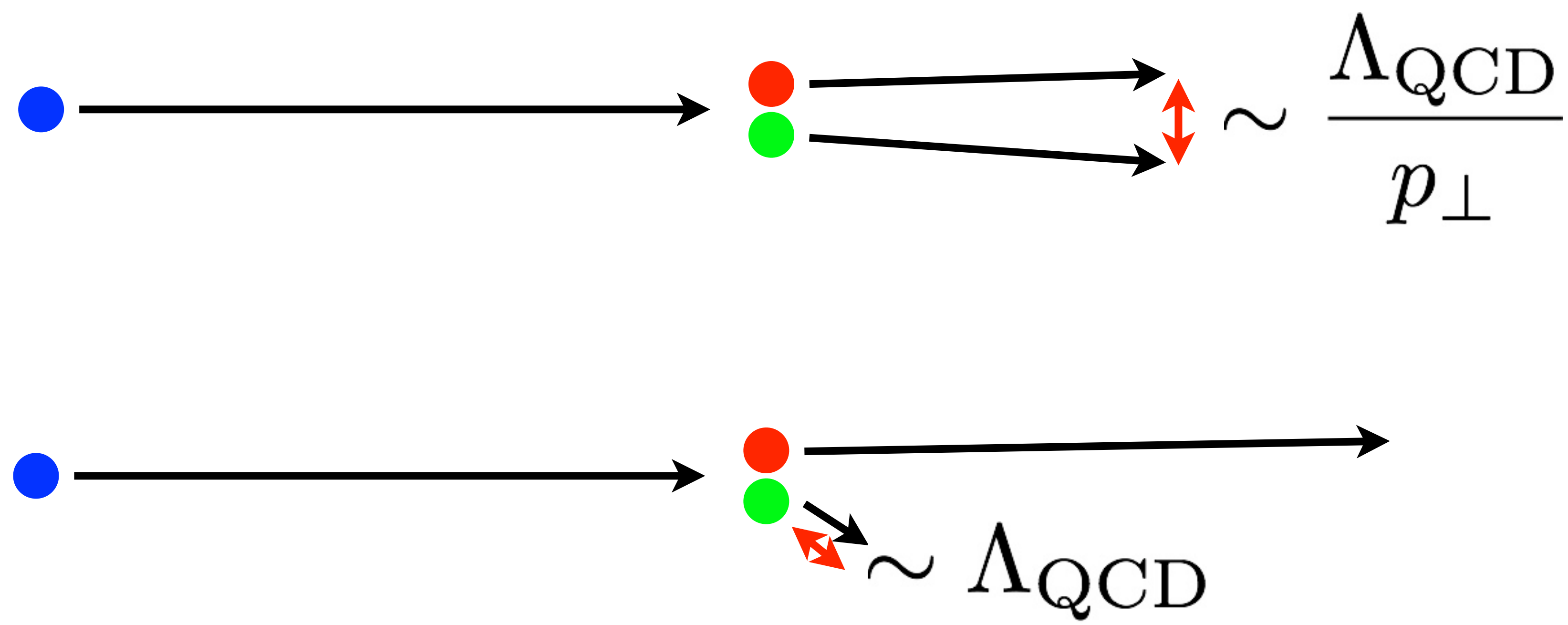
angular correlation function



“Jet Substructure Without Trees”

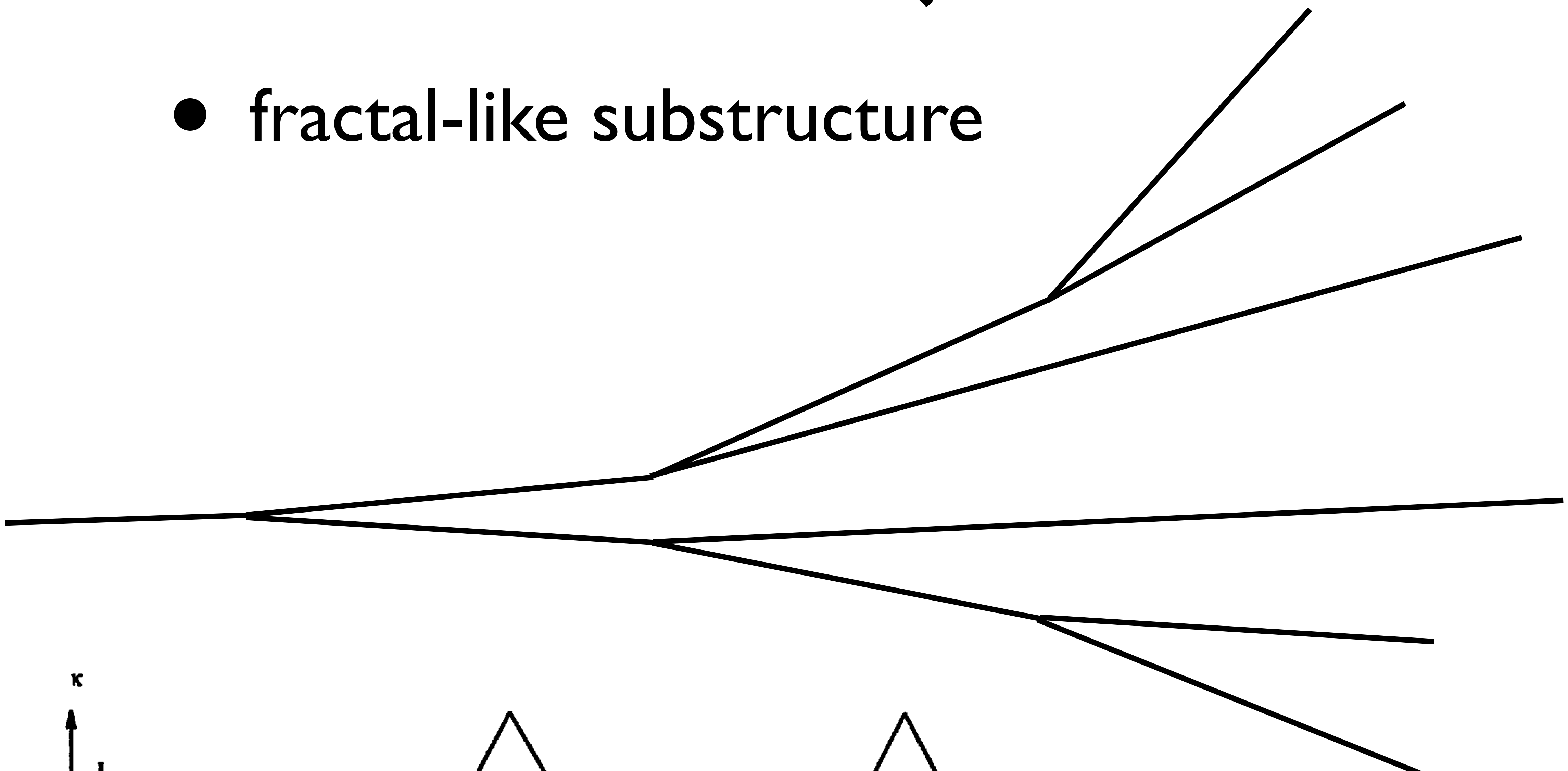
What are QCD jets like?

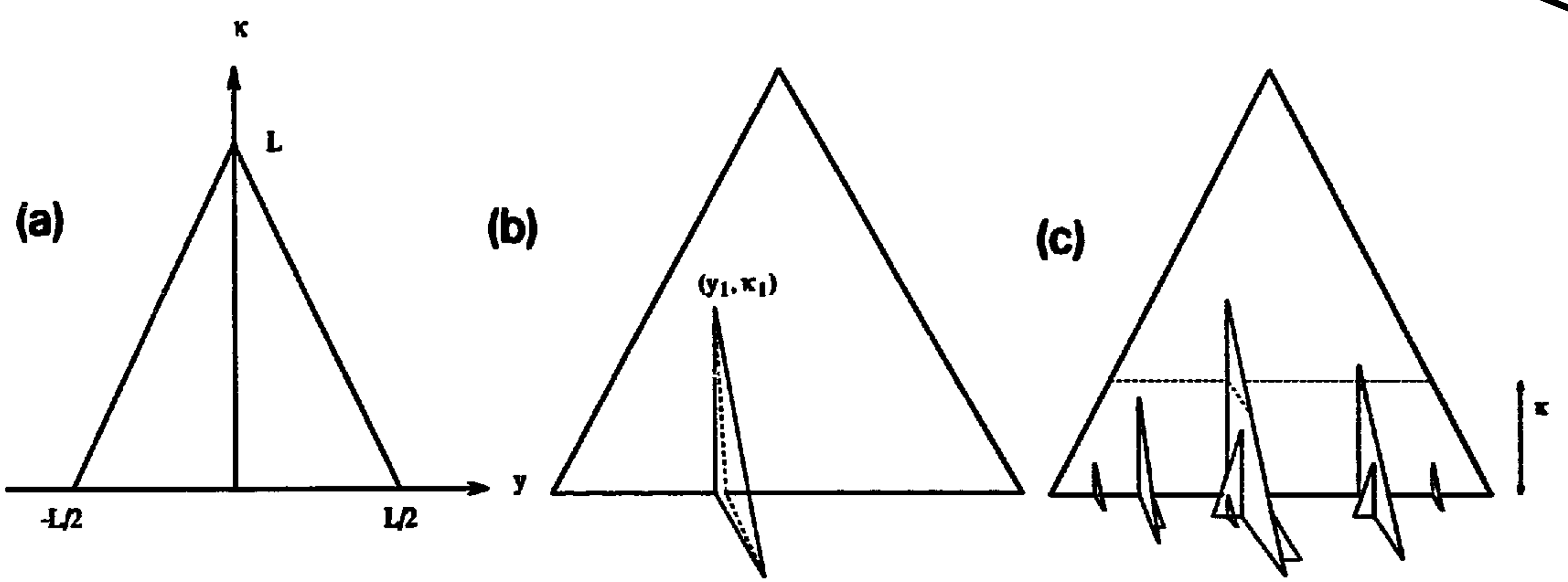
- QCD is an approximately scale-invariant non-Abelian gauge theory at high energies
  - consequences:
    - soft & collinear singularities



What are QCD jets like?

- fractal-like substructure





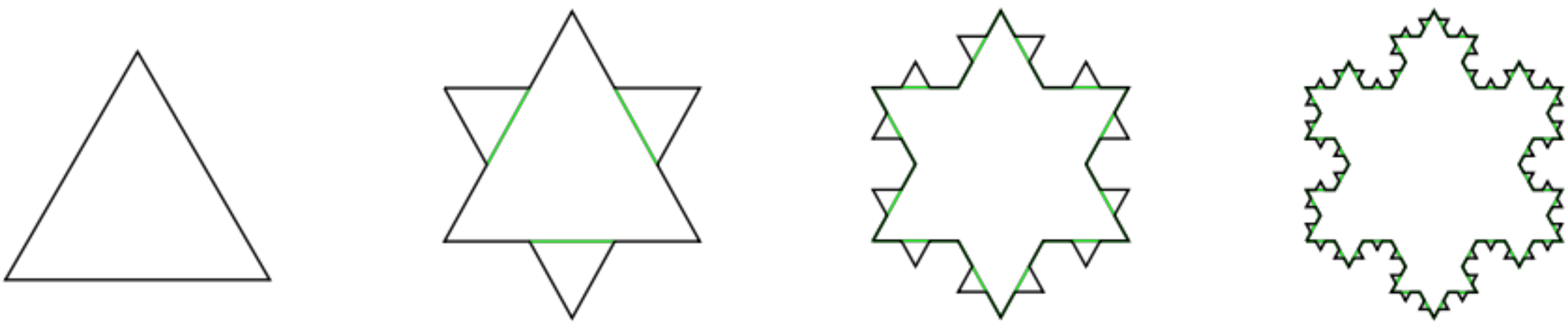
 Gustafson, Nilsson 1991; Bjorken 1992

Defining an Observable

- goal: define an observable that can distinguish between approximately scale invariant objects and objects that have an intrinsic, high energy scale
  - observable will be a function that encodes the scaling behavior of the system
  - the argument of the function is a resolution parameter

Defining an Observable

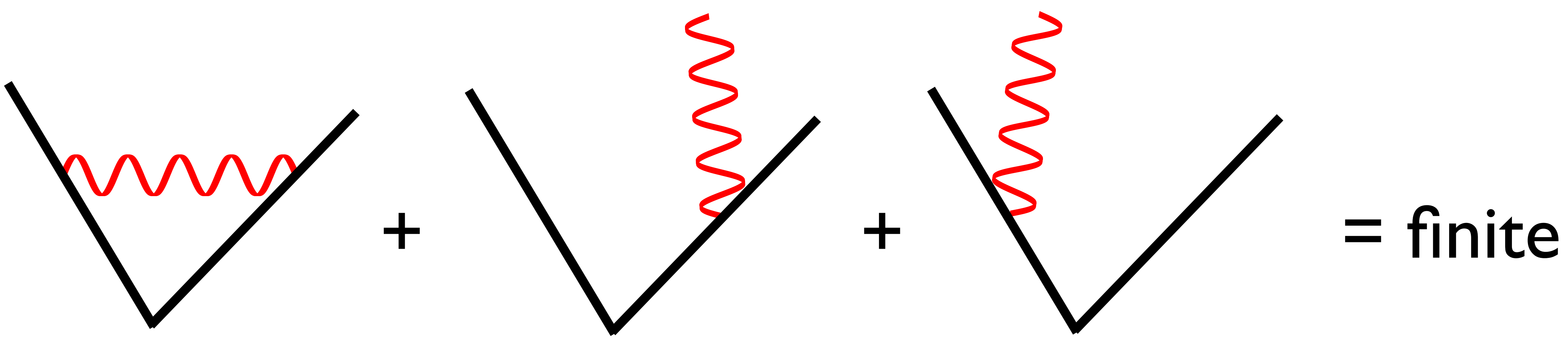
- define an angular correlation function between jet constituents



increasing resolution ⟶

Defining an Observable

- requirements from theory:
  - infrared and collinear safety
    - want to compute in pert. theory



Defining an Observable

- correlation function should be *z*-boost invariant
  - jet mass is the prototypical 2-particle 'correlation function'

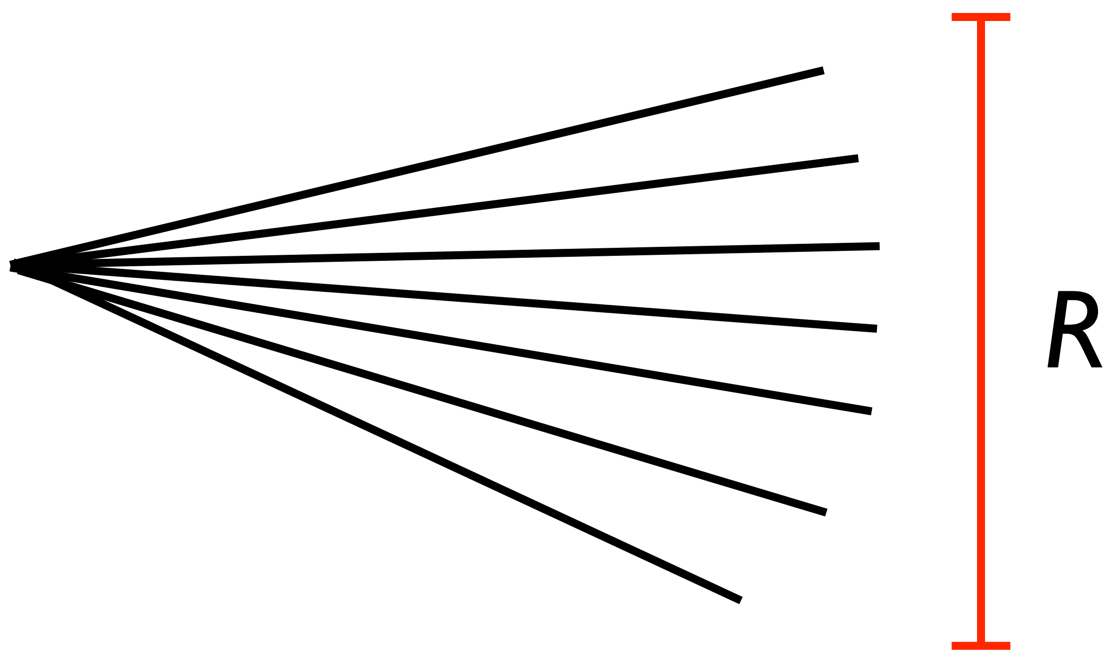
$$\mathcal{G}(R) \equiv \sum_{i \neq j} p_{\perp i} p_{\perp j} \Delta R_{ij}^2 \Theta[R - \Delta R_{ij}]$$

$$\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

- angular correlation function (ACF)

Angular Correlation Function

- expectations
  - ACF in QCD ~ R^2



Angular Correlation Function

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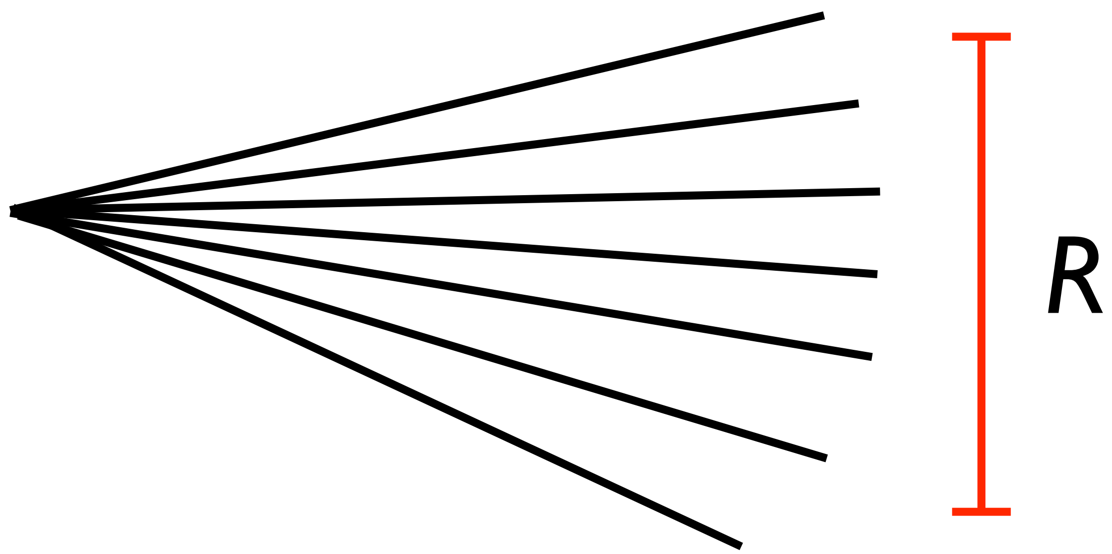

Angular Correlation Function

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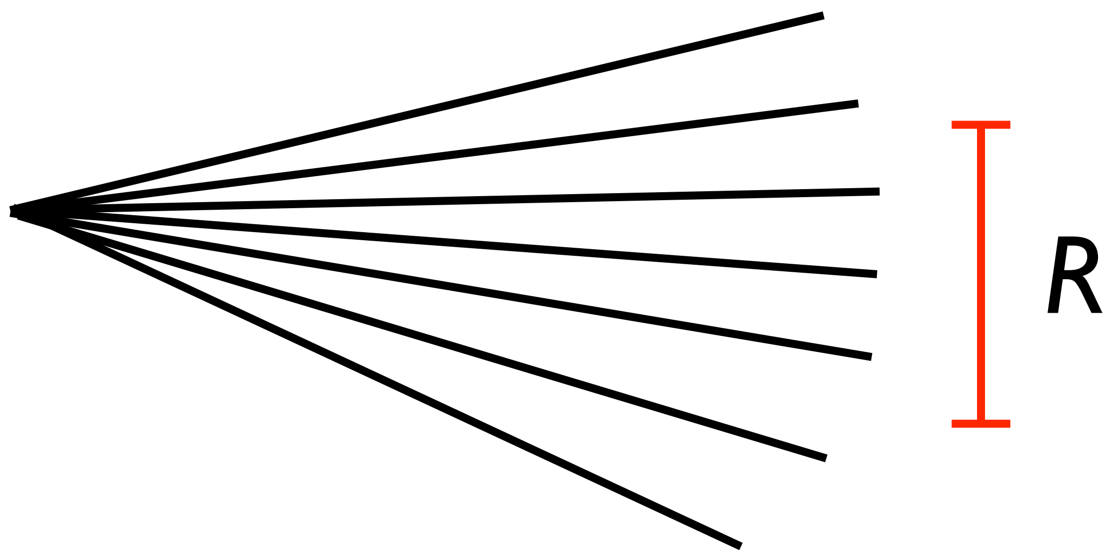
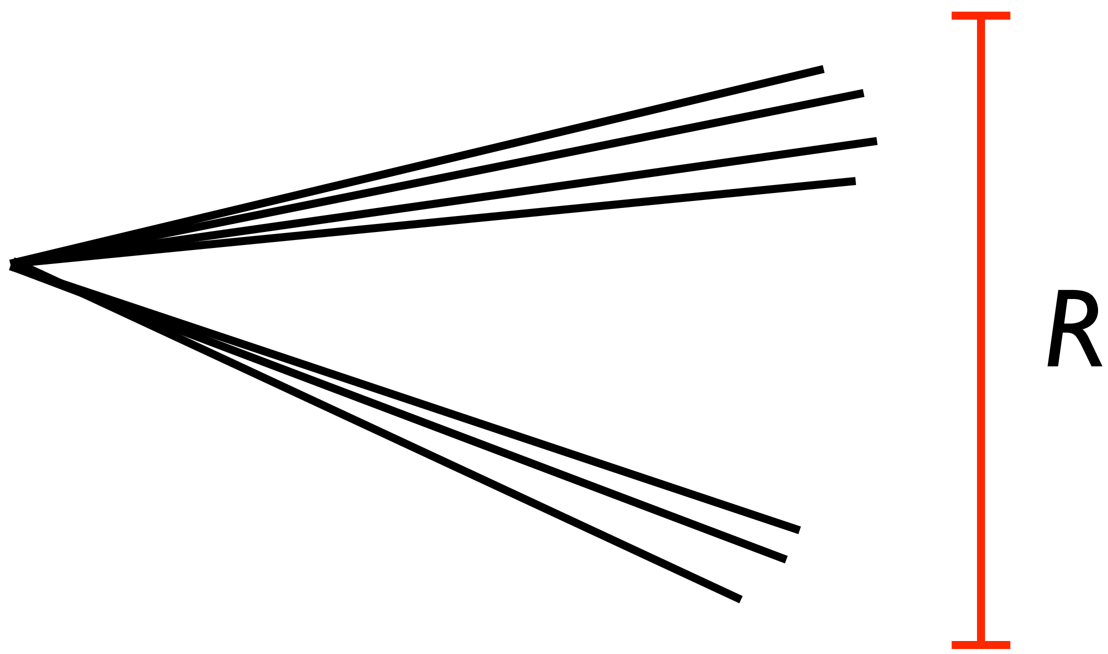


Angular Correlation Function

- expectations
  - ACF for heavy particle jet will have “cliffs” at characteristic values of R



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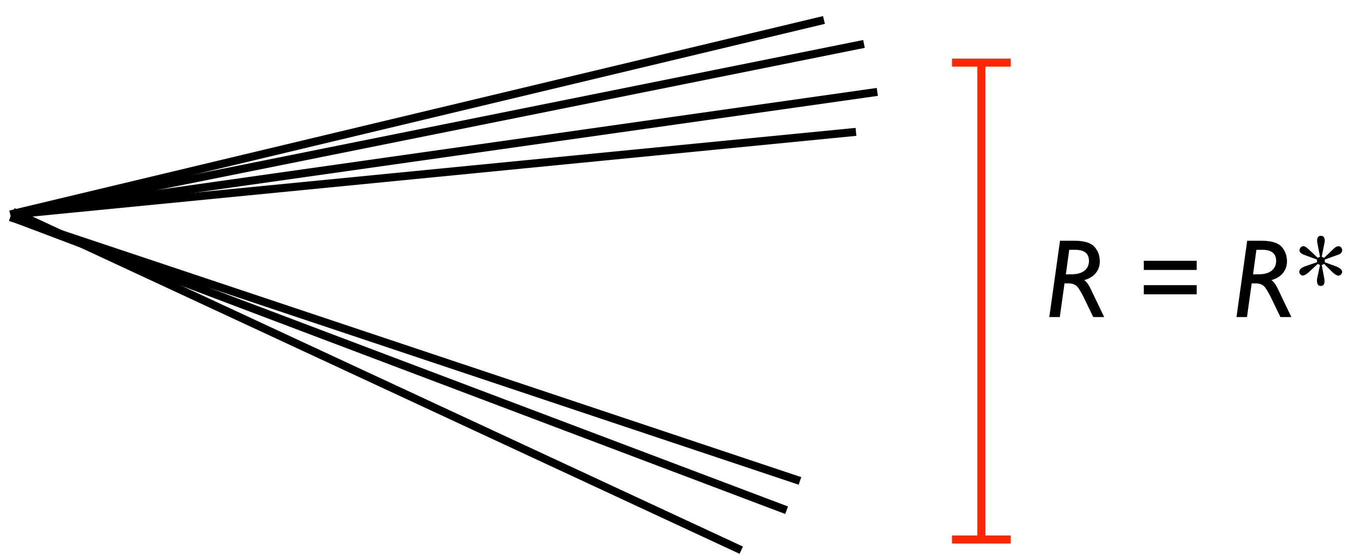

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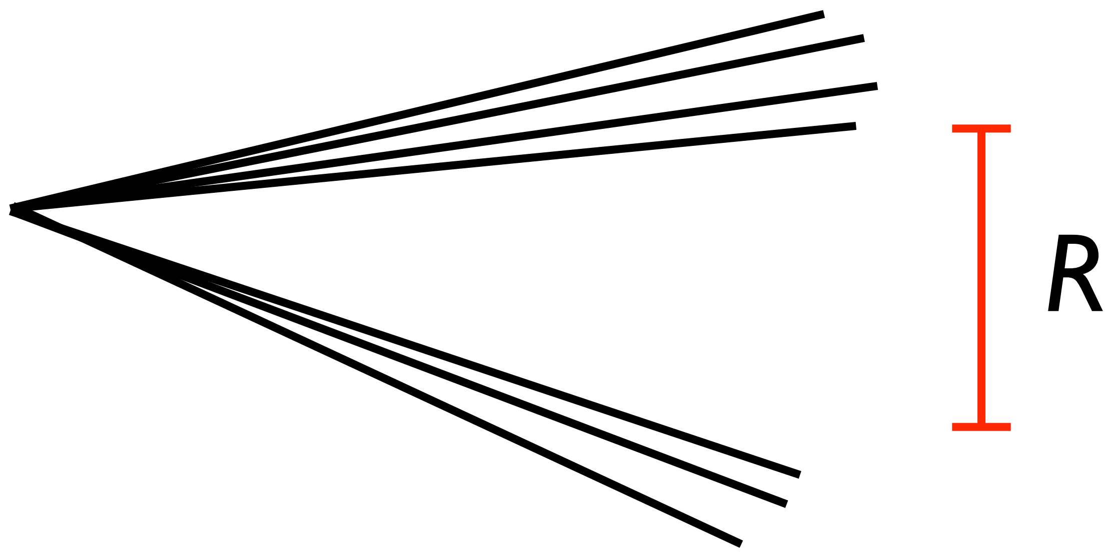
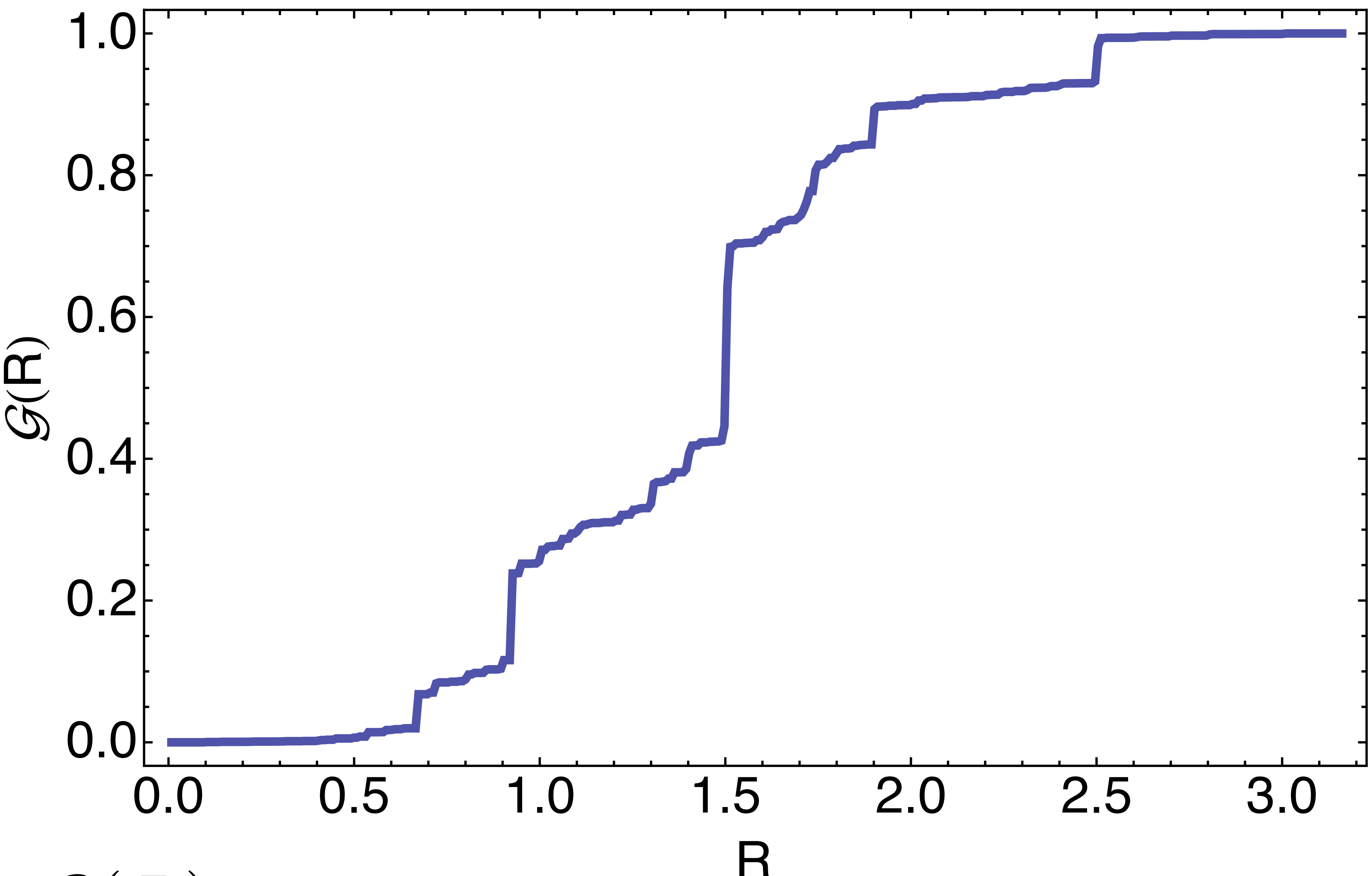


- cliffs in $\mathcal{G}(R)$ = separation of hard subjets



- $\mathcal{G}(R)$ for a top quark jet

Angular Structure Function

- how to extract a dimension:
  - "standard way":

$$D = \lim_{R \to 0} \frac{\log \mathcal{G}(R)}{\log R}$$

  - problem: can't access this limit!

Angular Structure Function

- how to extract a dimension:
  - better: take a derivative

$$D = \frac{d \log \mathcal{G}(R)}{d \log R}$$

  - benefits: defined for all R, cliffs in ACF manifest themselves as peaks in derivative

Angular Structure Function

- define angular structure function (ASF):

$$\Delta\mathcal{G}(R) \equiv \frac{d\log\mathcal{G}(R)}{d\log R}$$

$$= R\frac{\sum_{i\neq j} p_{\perp i}p_{\perp j}\Delta R_{ij}^2\delta[R-\Delta R_{ij}]}{\sum_{i\neq j} p_{\perp i}p_{\perp j}\Delta R_{ij}^2\Theta[R-\Delta R_{ij}]}$$

Angular Structure Function

- delta-function is inappropriate for finite data
- smooth ASF by replacing delta-function:

$$\Delta\mathcal{G}(R) = R\frac{\sum_{i\neq j} p_{\perp i}p_{\perp j}\Delta R_{ij}^2 K[R-\Delta R_{ij}]}{\sum_{i\neq j} p_{\perp i}p_{\perp j}\Delta R_{ij}^2 \Theta[R-\Delta R_{ij}]}$$

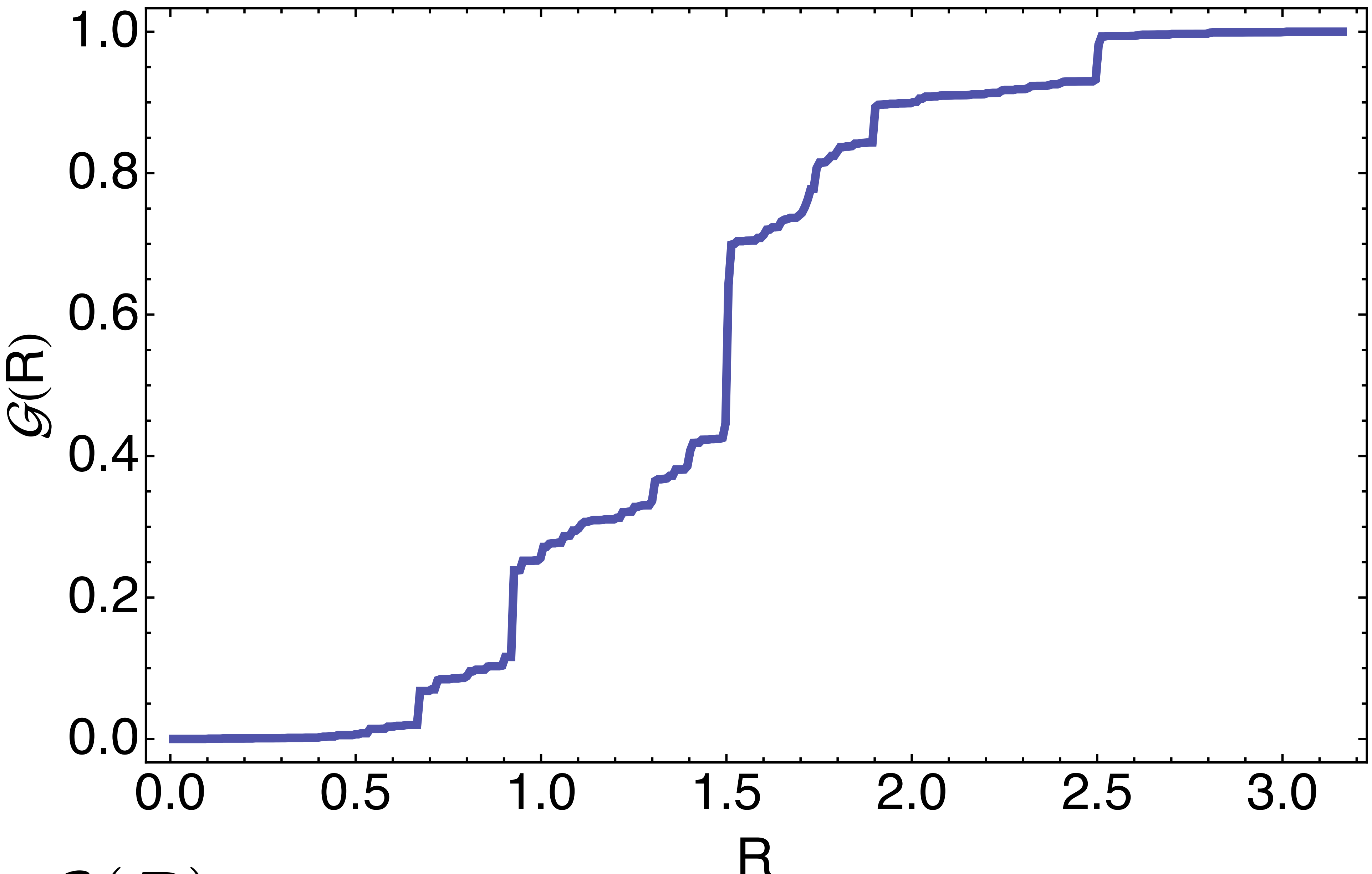
- *K* is taken to be a smooth gaussian kernel:

$$\delta(R-\Delta R_{ij}) \simeq \frac{e^{-\frac{(R-\Delta R_{ij})^2}{2dR^2}}}{dR\sqrt{2\pi}}$$

first application

ASF event by event:
Top Tagging

- cliffs in $\mathcal{G}(R)$ = separation of hard subjets



- $\mathcal{G}(R)$ for a top quark jet

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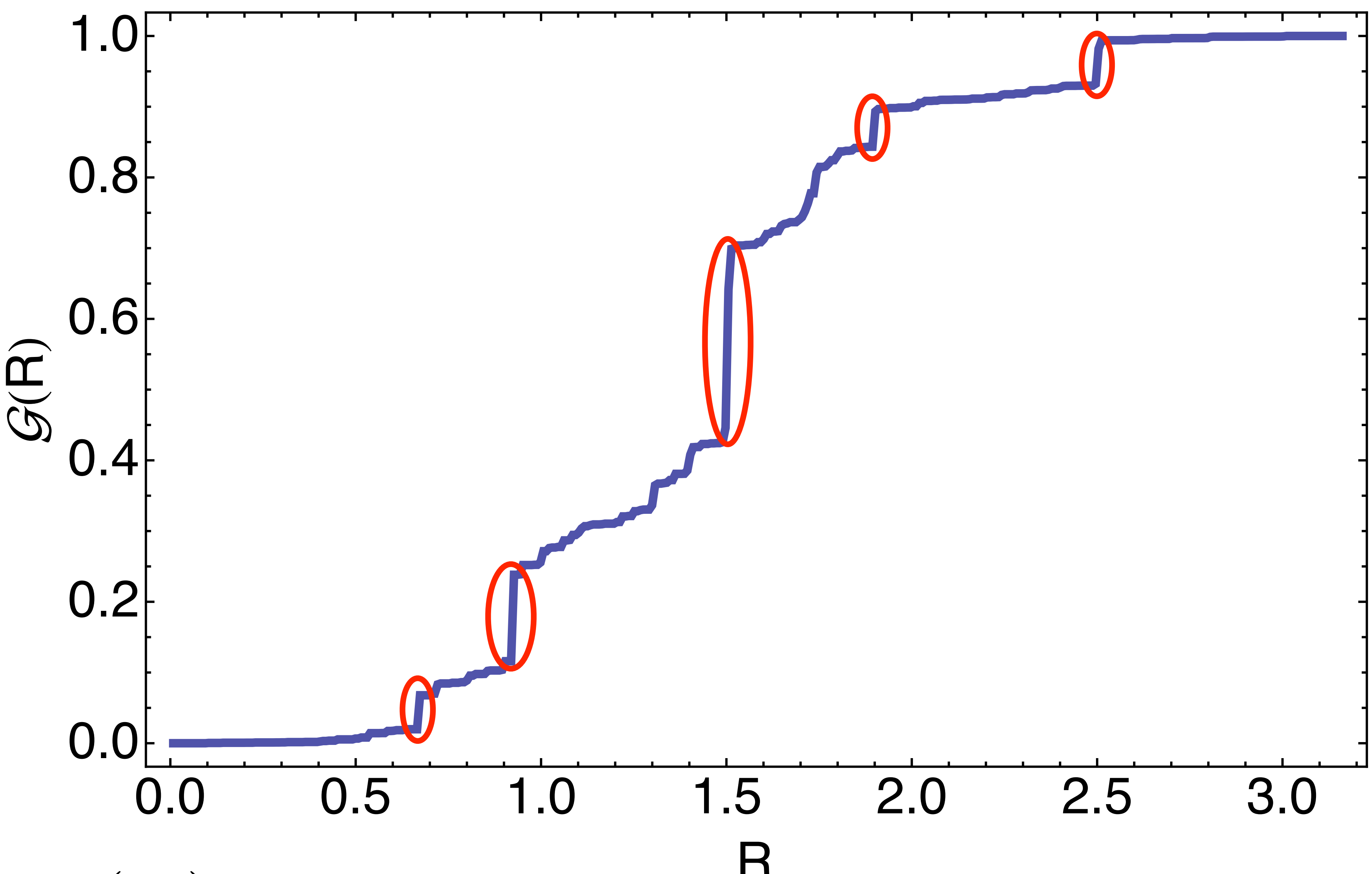
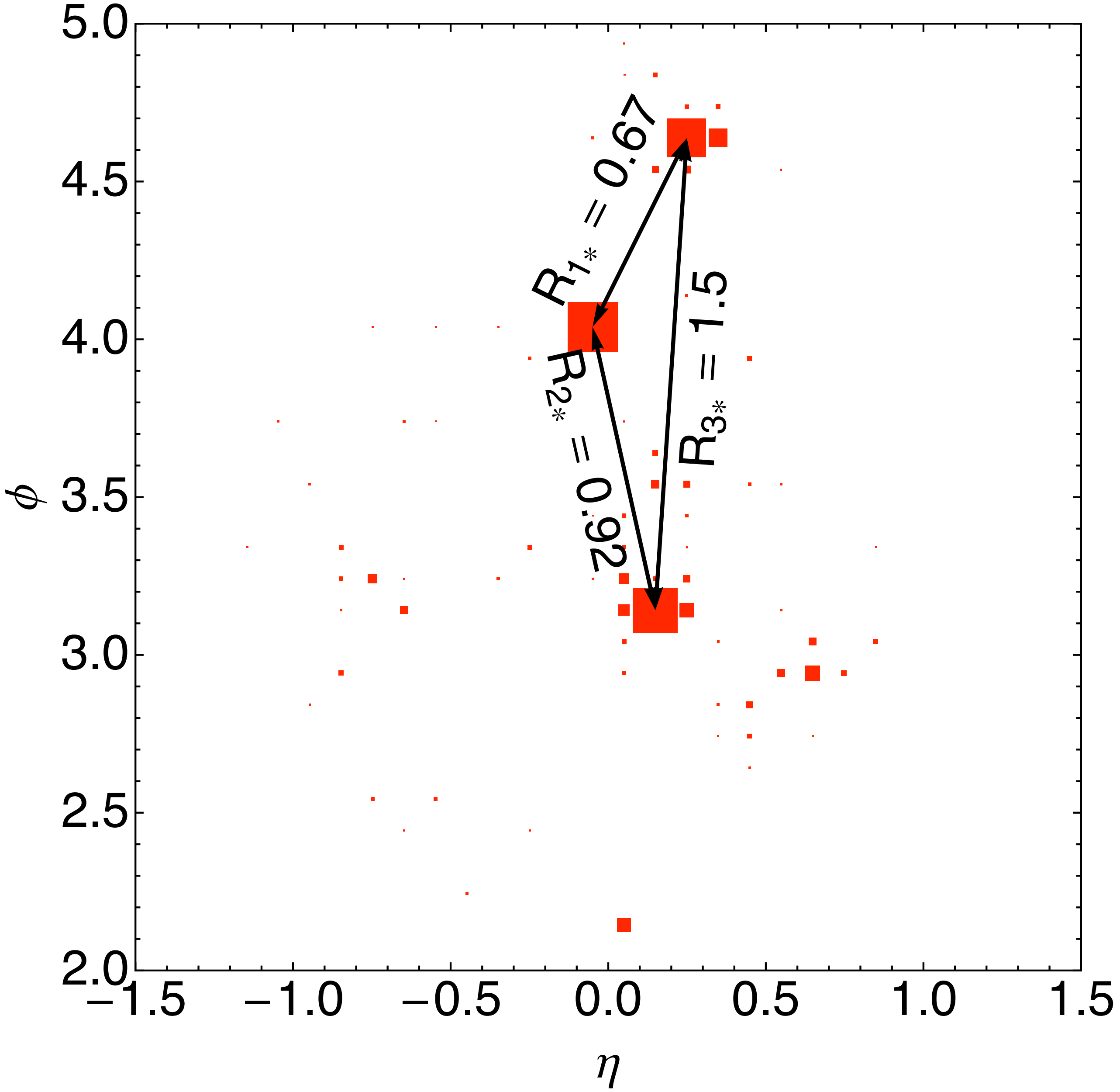
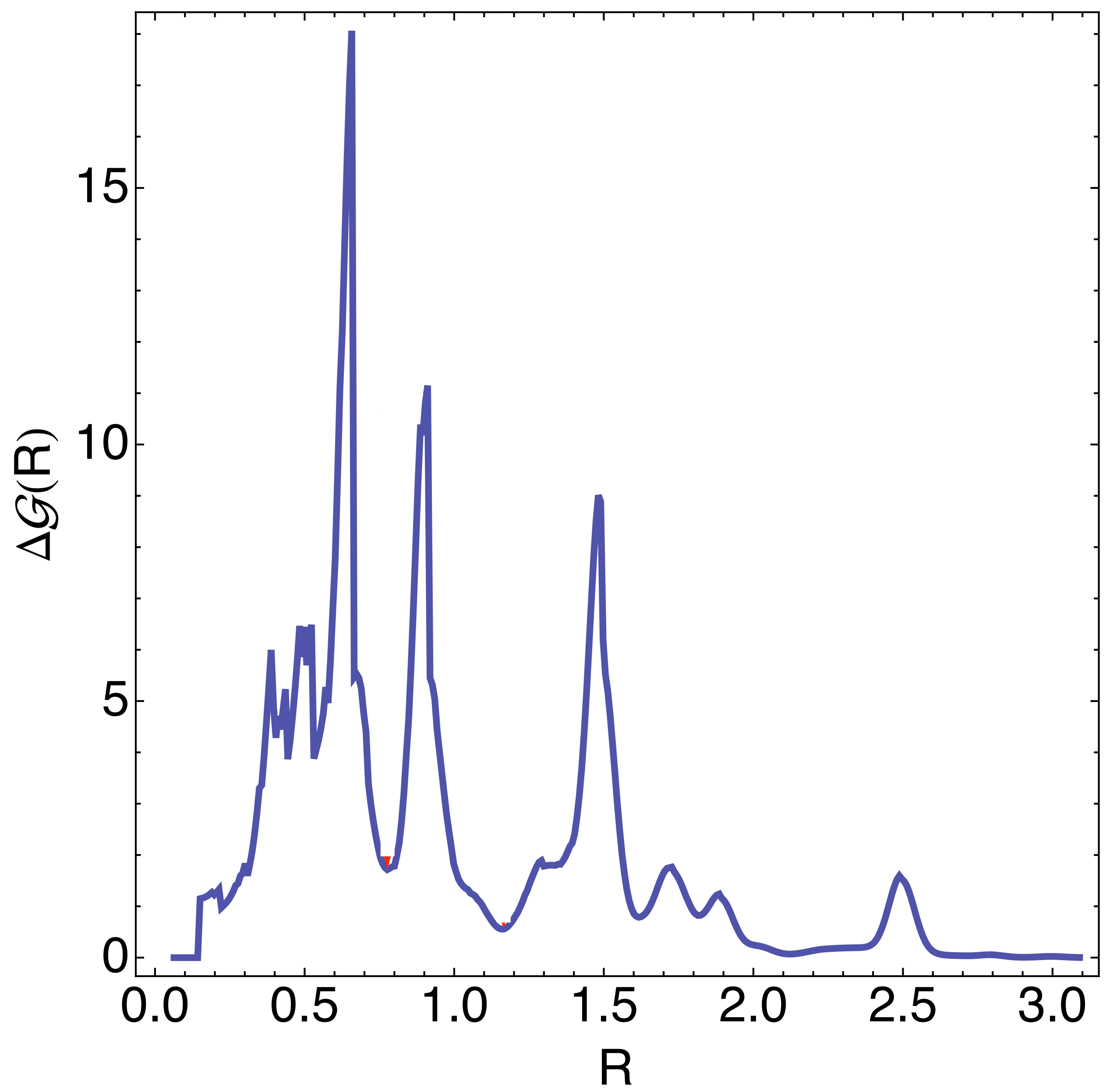


- $\mathcal{G}(R)$ for a top quark jet

“Jet Substructure Without Trees”

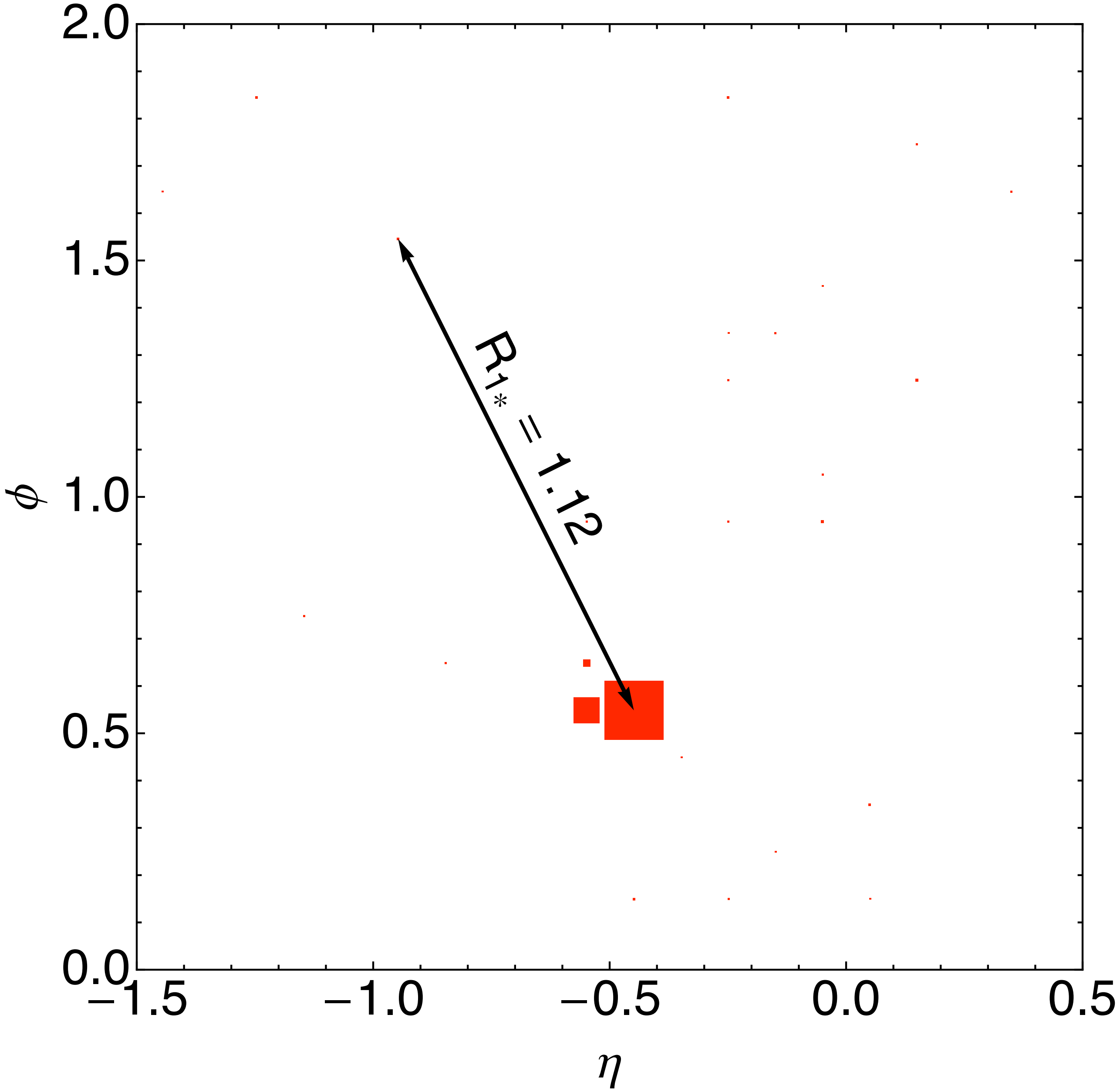
Top Jet

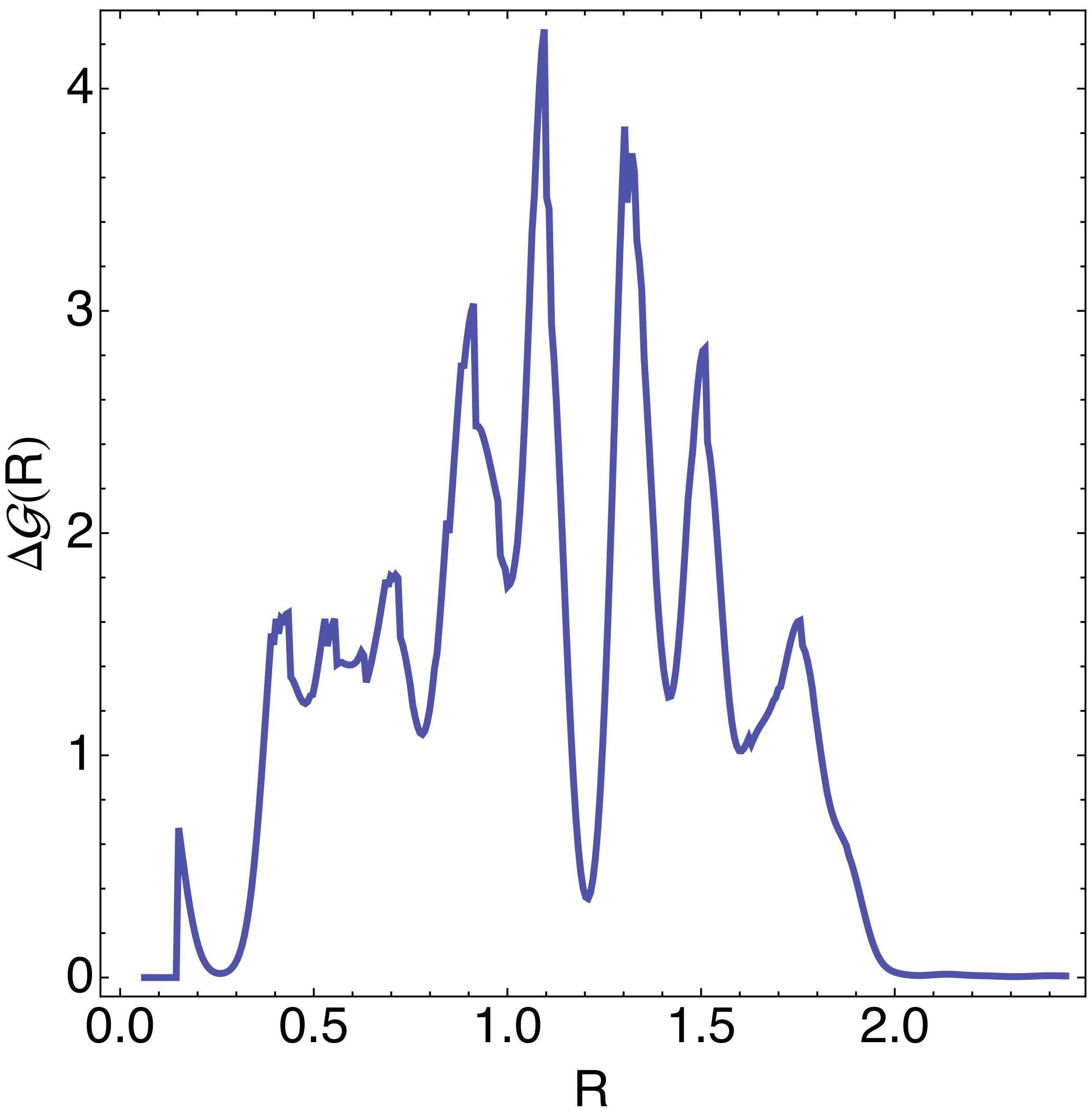




“Jet Substructure Without Trees”

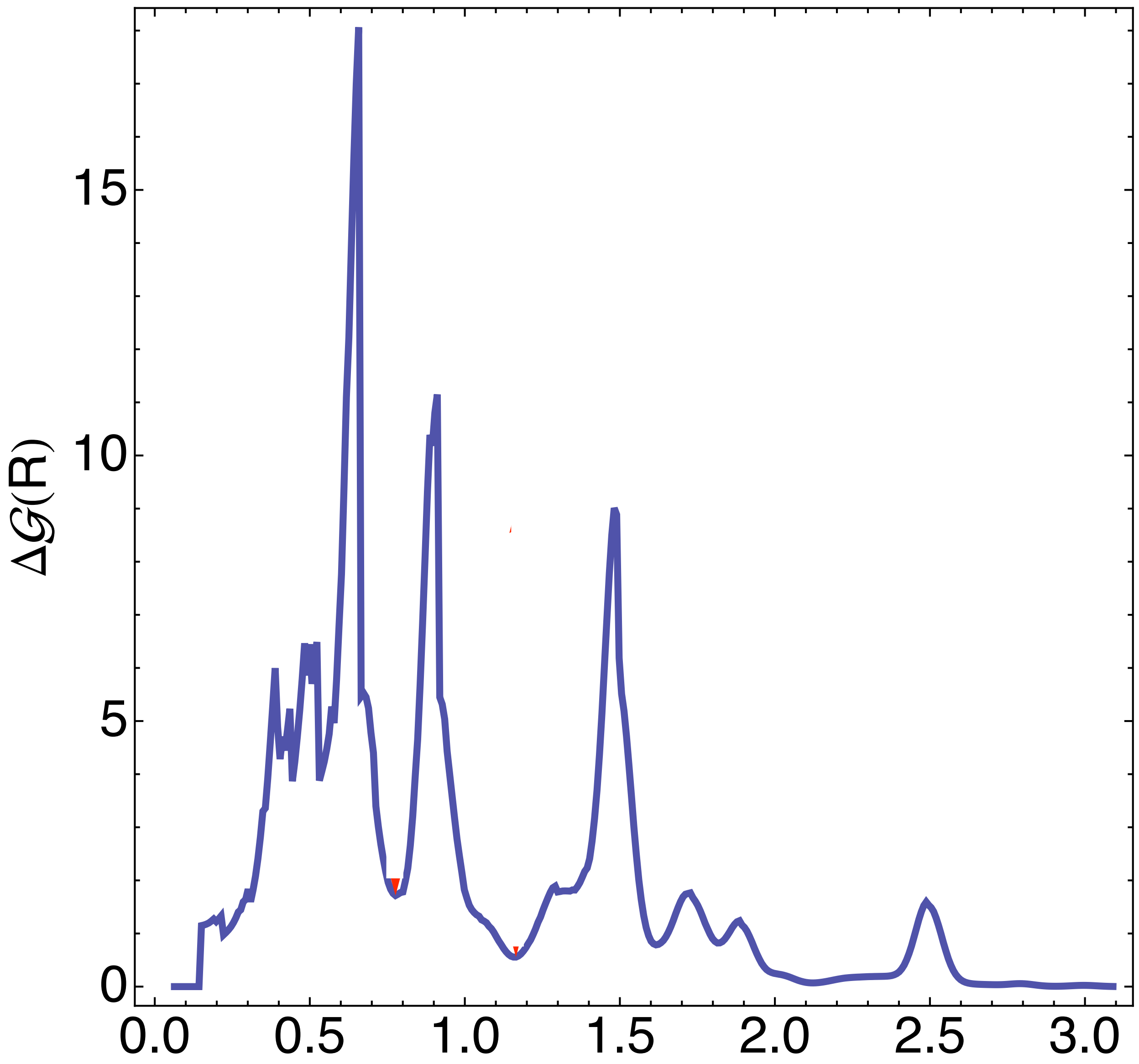
QCD Jet





Defining Observables

- IRC safe observables from $\Delta\mathcal{G}(R)$:



Defining Observables

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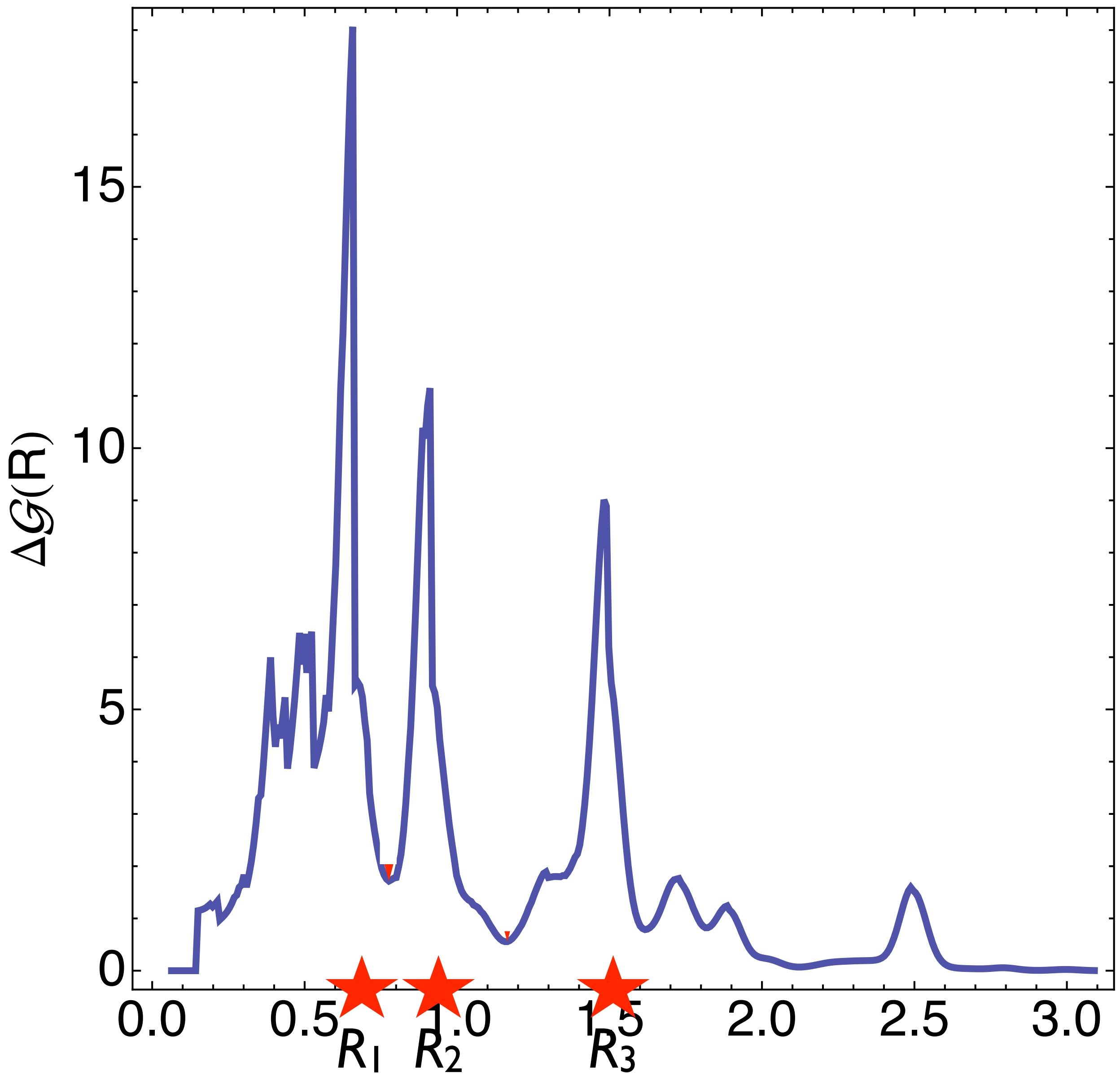
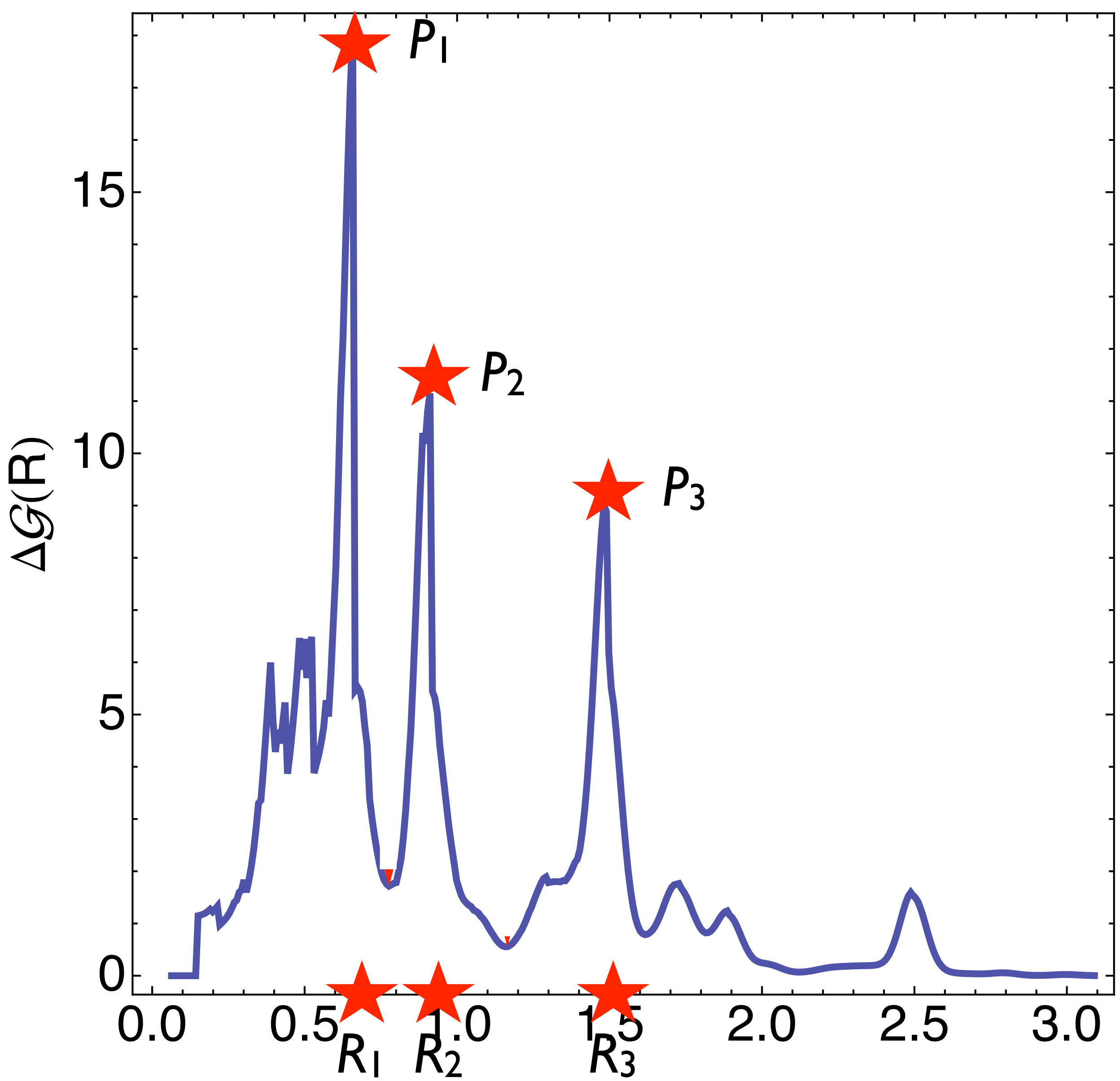


- location of peaks in *R*

Defining Observables

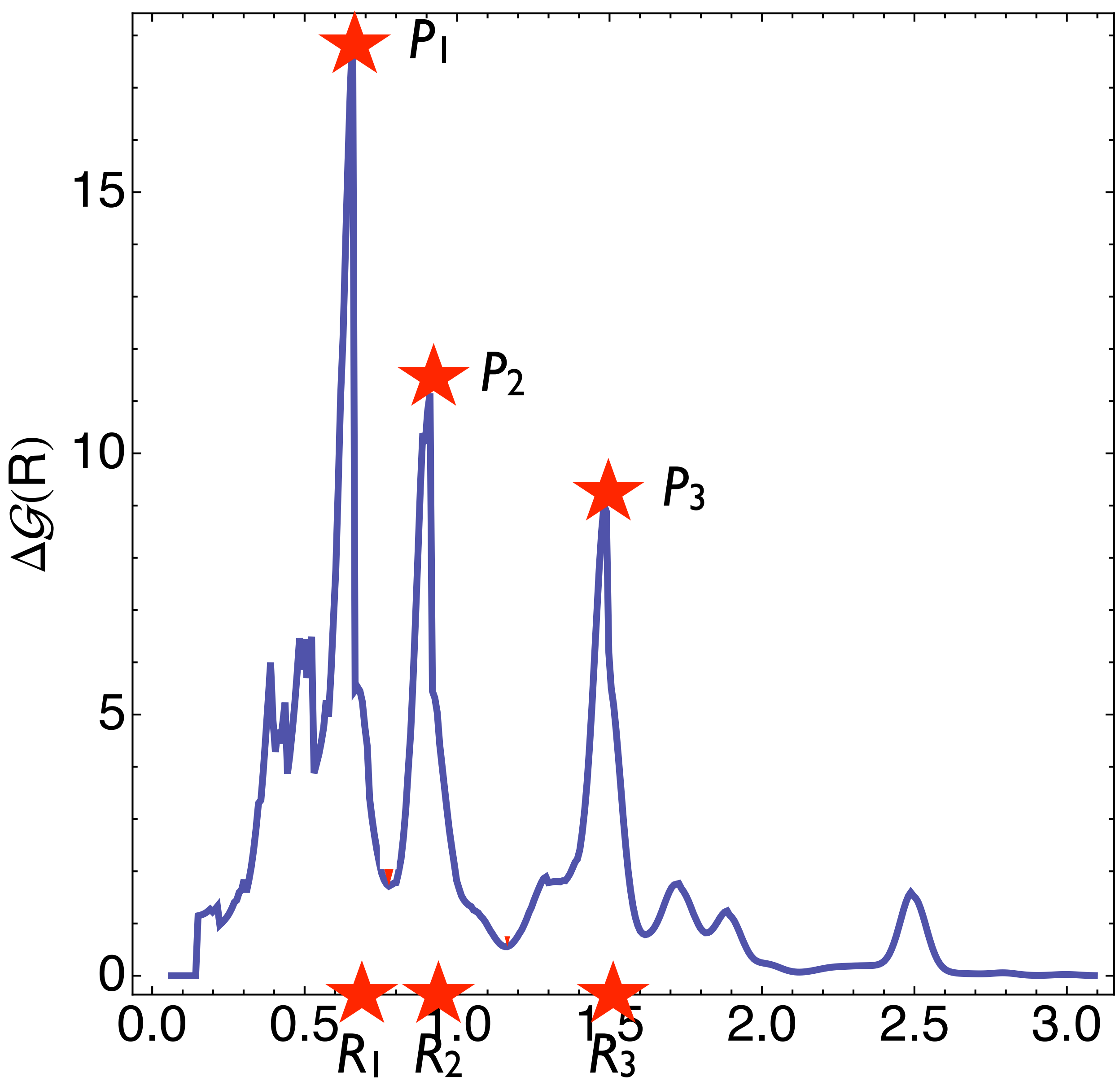
- IRC safe observables from $\Delta\mathcal{G}(R)$:



- location of peaks in *R*
- height of peaks

Defining Observables

- IRC safe observables from $\Delta\mathcal{G}(R)$:



- location of peaks in R
- height of peaks
- number of peaks

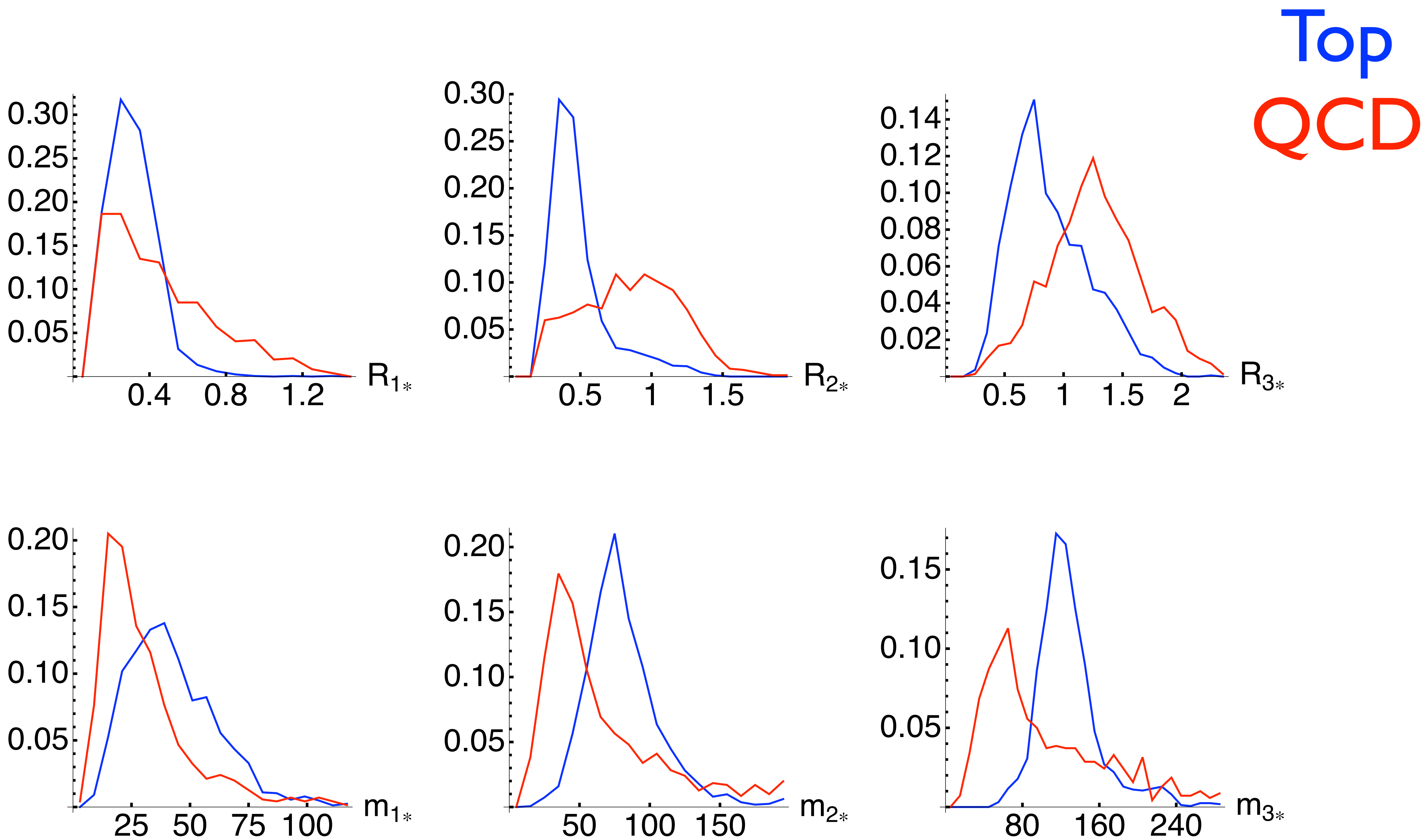
Top Tagger

- top tagging approach:
  - bin jets by the number of peaks
  - in each bin place rectangular cuts on the available observables (mass and angular scales)

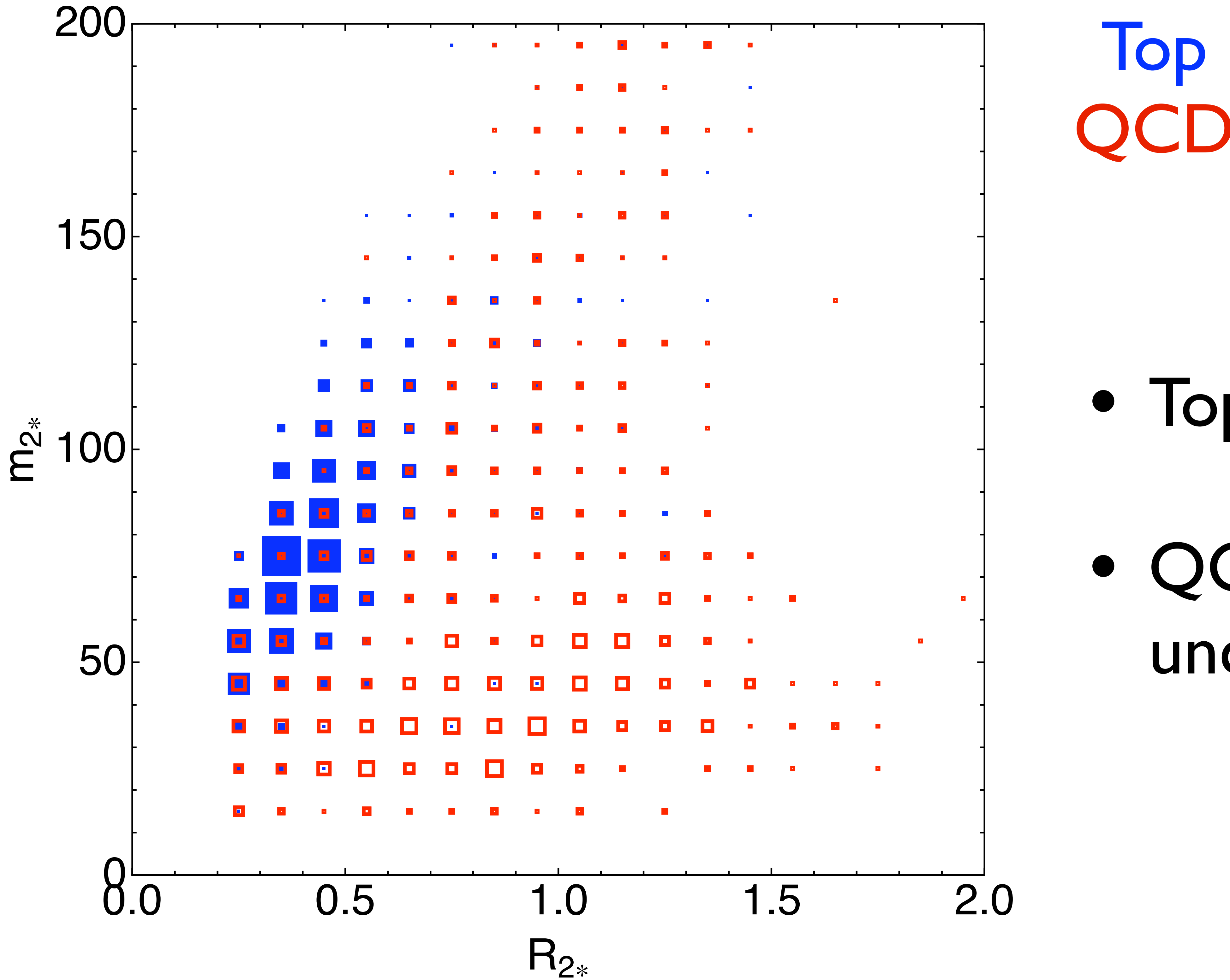
$$m_{R_*}^2 \equiv \mathrm{Numerator}[\Delta\mathcal{G}(\mathrm{R}_*)] = \sum_{i \neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2 K(R_* - \Delta R_{ij})$$

Top Tagger

- observables for dR = 0.06, min height = 4.0, npeaks = 3



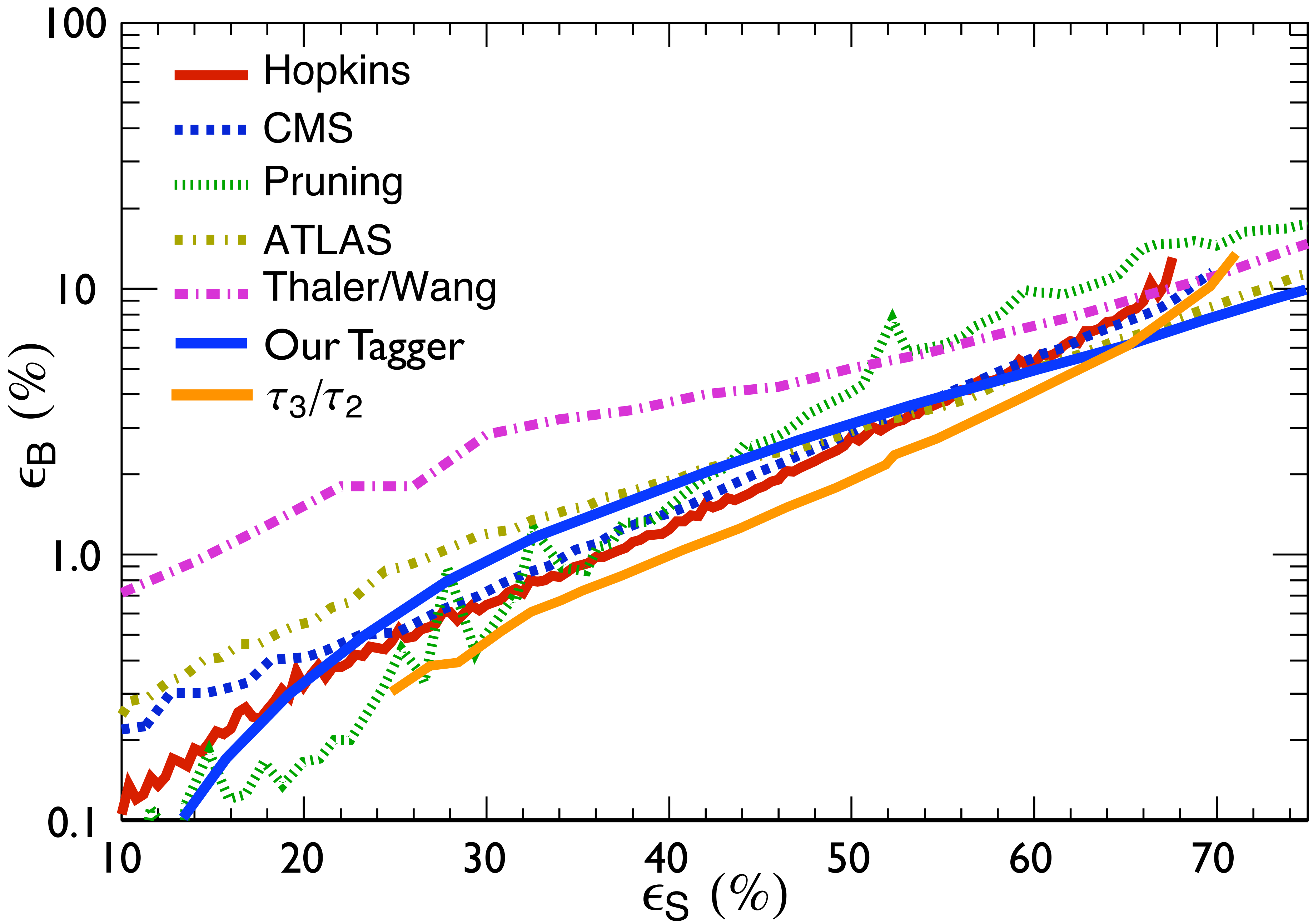
Top Tagger



- Top: m ~ R
- QCD: m, R uncorrelated

Top Tagger

- comparison to other top taggers



second application

ensemble averaged ASF:
the underlying event

Ensemble Averages

average ACF

$$\langle \mathcal{G}(R) \rangle \equiv \frac{1}{n} \sum_{k=1}^{n} \mathcal{G}(R)_k$$

average ASF

$$\begin{aligned}
\langle \Delta\mathcal{G}(R) \rangle &\equiv R \frac{\frac{d}{dR} \langle \mathcal{G}(R) \rangle}{\langle \mathcal{G}(R) \rangle} \\
&= R \frac{\sum_{k=1}^{n} \mathcal{G}'(R)_k}{\sum_{k=1}^{n} \mathcal{G}(R)_k} \\
&\equiv R \frac{\sum_{k=1}^{n} \sum_{i \neq j} p_{Tk,i} p_{Tk,j} \Delta R_{ij}^2 \delta_{\mathrm{dR}}(R - \Delta R_{ij})}{\sum_{k=1}^{n} \sum_{i \neq j} p_{Tk,i} p_{Tk,j} \Delta R_{ij}^2 \mathrm{erf}(R - \Delta R_{ij})} \\
&\neq \frac{1}{n} \sum_{k=1}^{n} \Delta\mathcal{G}(R)_k
\end{aligned}$$

Simple calculation

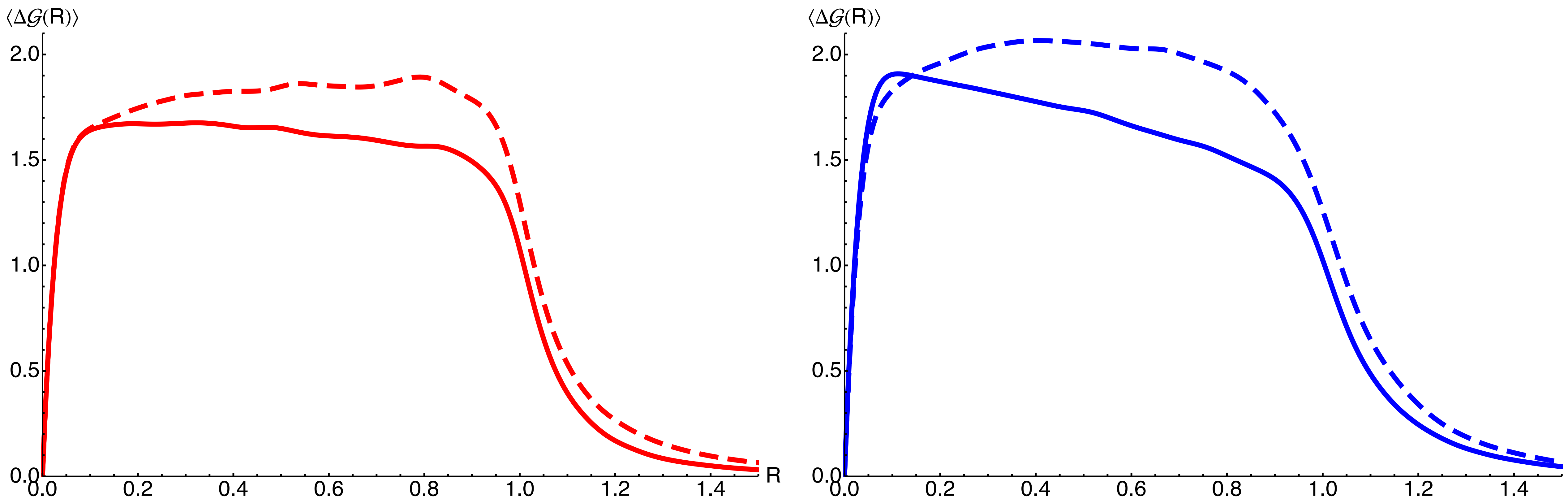
$$\langle \mathcal{G}(R) \rangle \simeq \frac{\alpha_s}{2\pi} \int^{R_0^2} \frac{d\theta^2}{\theta^2} \int dz P(z) p_T^2 z(1-z)\theta^2 \Theta(R-\theta)$$

$$\langle \mathcal{G}(R) \rangle = \frac{\alpha_s}{2\pi} p_T^2 R^2 \begin{cases} \frac{3}{4} C_F & \text{quark jets} \\ \frac{7}{10} C_A + \frac{1}{10} n_F T_R & \text{gluon jets} \end{cases}$$

$$\langle \Delta \mathcal{G}(R) \rangle = 2$$

expect higher order effects to be $\mathcal{O}(\alpha_s) \sim 10\%$

Monte Carlo



Pythia8 (solid) vs. Herwig++ (dashed): no UE or ISR

red = quark jets

blue = glue jets

Simple calculation continued

- leading order integral can be computed analytically with a running coupling

$$\alpha_s(p_T\theta(1-z)) = \frac{\alpha_0}{\log\left(\frac{p_T\theta(1-z)}{\Lambda_{QCD}}\right)}$$

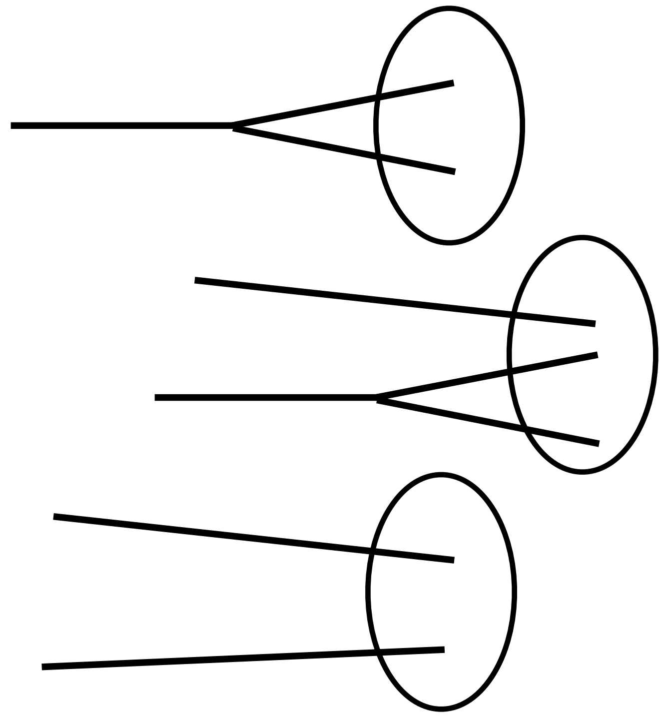
$$\langle \Delta\mathcal{G}(R)\rangle \simeq 2 - \frac{1}{\log\left(\frac{p_T R}{\Lambda_{QCD}}\right)} + \mathcal{O}\left(1/\log^2\left(\frac{p_T R}{\Lambda_{QCD}}\right)\right)$$

Contributions from the underlying event

- schematically, the ACF can be written as:

ACF = (Pert-Pert correlations) +
(Pert-UE correlations) +
(UE-UE correlations)

- Red ~ p_T^2
- Blue ~ $p_T \Lambda_{UE}$
- Green ~ Λ_{UE}^2

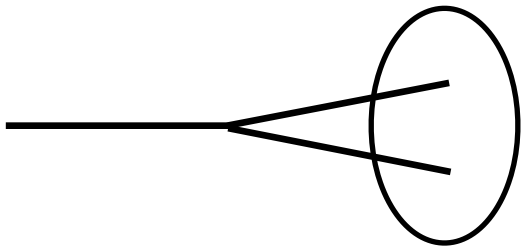


Contributions from the underlying event

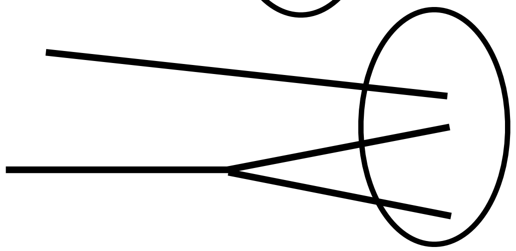
- schematically, the ACF can be written as:

ACF ~ (Pert-Pert correlations) +
(Pert-UE correlations)

- Red ~ p_T^2



- Blue ~ $p_T \Lambda_{\mathrm{UE}}$



Contributions from the underlying event

- Correlation between jet and UE:

$$\langle \mathcal{G}(R)_{\text{jet-UE}} \rangle = p_{\perp\text{jet}} \Lambda_{\text{UE}} \int_0^{2\pi} d\phi \int_0^R R' \; dR' \; R'^2 = \frac{\pi}{2} p_{\perp\text{jet}} \Lambda_{\text{UE}} R^4$$

- ACF including UE ansatz:

$$\langle \mathcal{G}(R)_{\text{with UE}} \rangle = \langle \mathcal{G}(R)_{\text{no UE}} \rangle + \frac{\pi}{2} p_{\perp\text{jet}} \Lambda_{\text{UE}} R^4$$

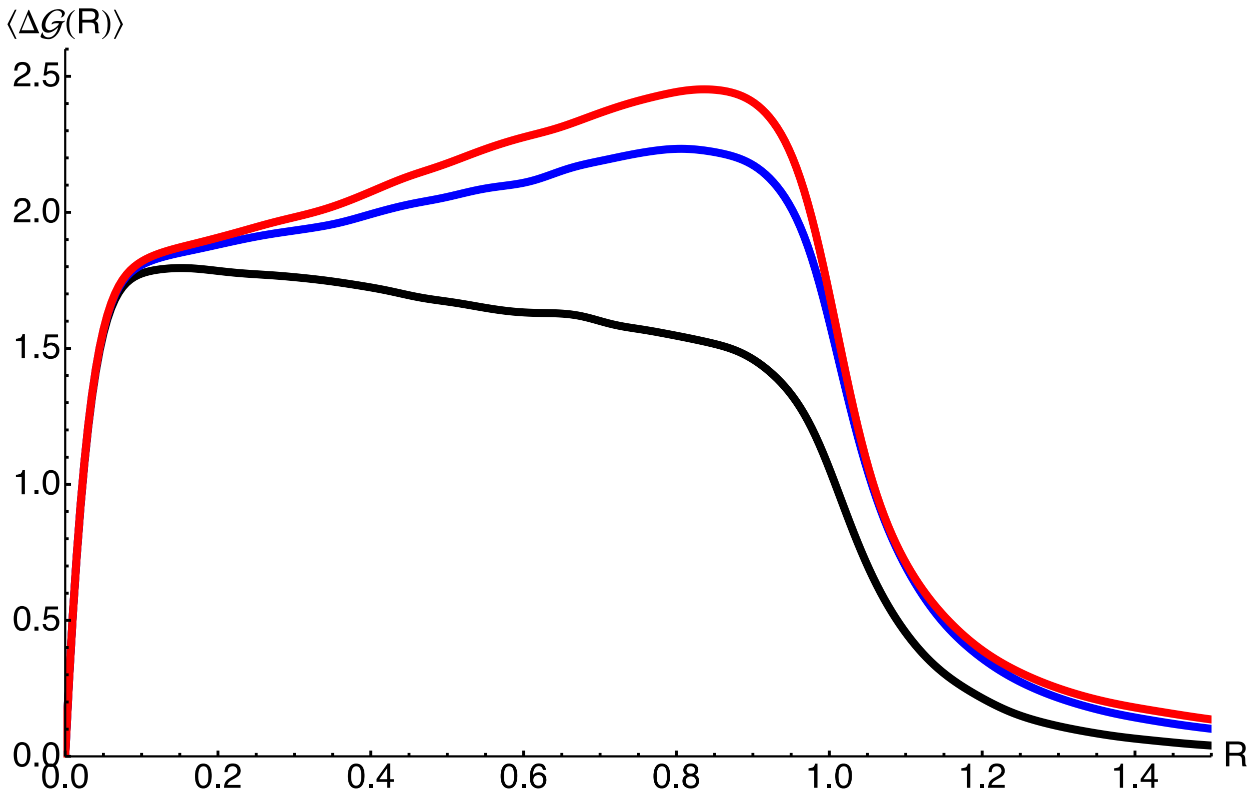
$$\langle \Delta\mathcal{G}(R)_{\text{no UE}} \rangle = \frac{R \langle \mathcal{G}'(R)_{\text{with UE}} \rangle - 2\pi p_{\perp\text{jet}} \Lambda_{\text{UE}} R^4}{\langle \mathcal{G}(R)_{\text{with UE}} \rangle - \frac{\pi}{2} p_{\perp\text{jet}} \Lambda_{\text{UE}} R^4}$$

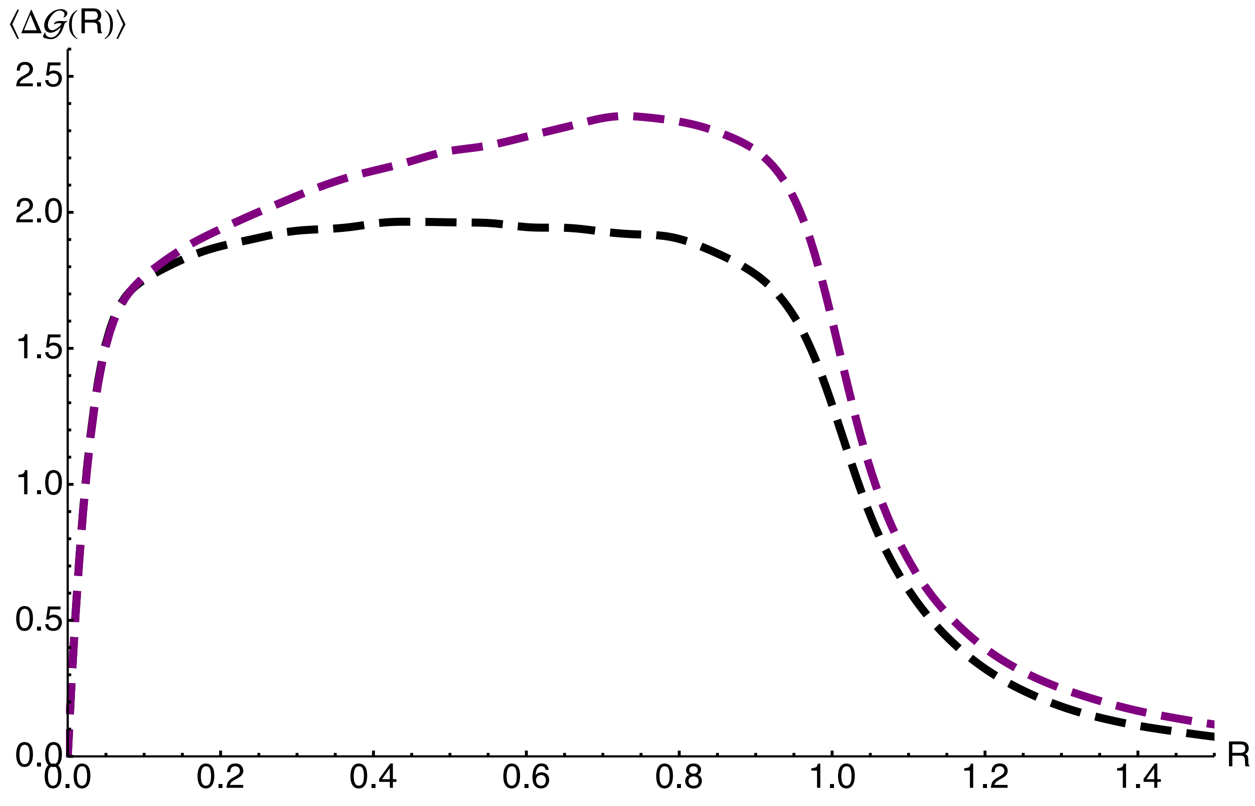
Extracting UE Energy Density

$$\Lambda_{\mathrm{UE}} = \frac{2\langle \mathcal{G}(R)_{\mathrm{with\ UE}} \rangle}{\pi p_{\perp \mathrm{jet}} R^4} \frac{\langle \Delta\mathcal{G}(R)_{\mathrm{with\ UE}} \rangle - C(R)}{4 - C(R)}$$

- *C*(*R*) is the ansatz for perturbative ASF
- Data-driven approach:
  - Match *C*(*R*) to ASF at small R
  - Compute UE energy density function
  - Flatness of UE energy density validates ansatz

Extracting UE Energy Density





Pythia8: with UE & ISR (blue, red);

red = 2x MPI cross section;

Tune 4C

Herwig: with UE & ISR (purple);

Tune LHC7-UE-2

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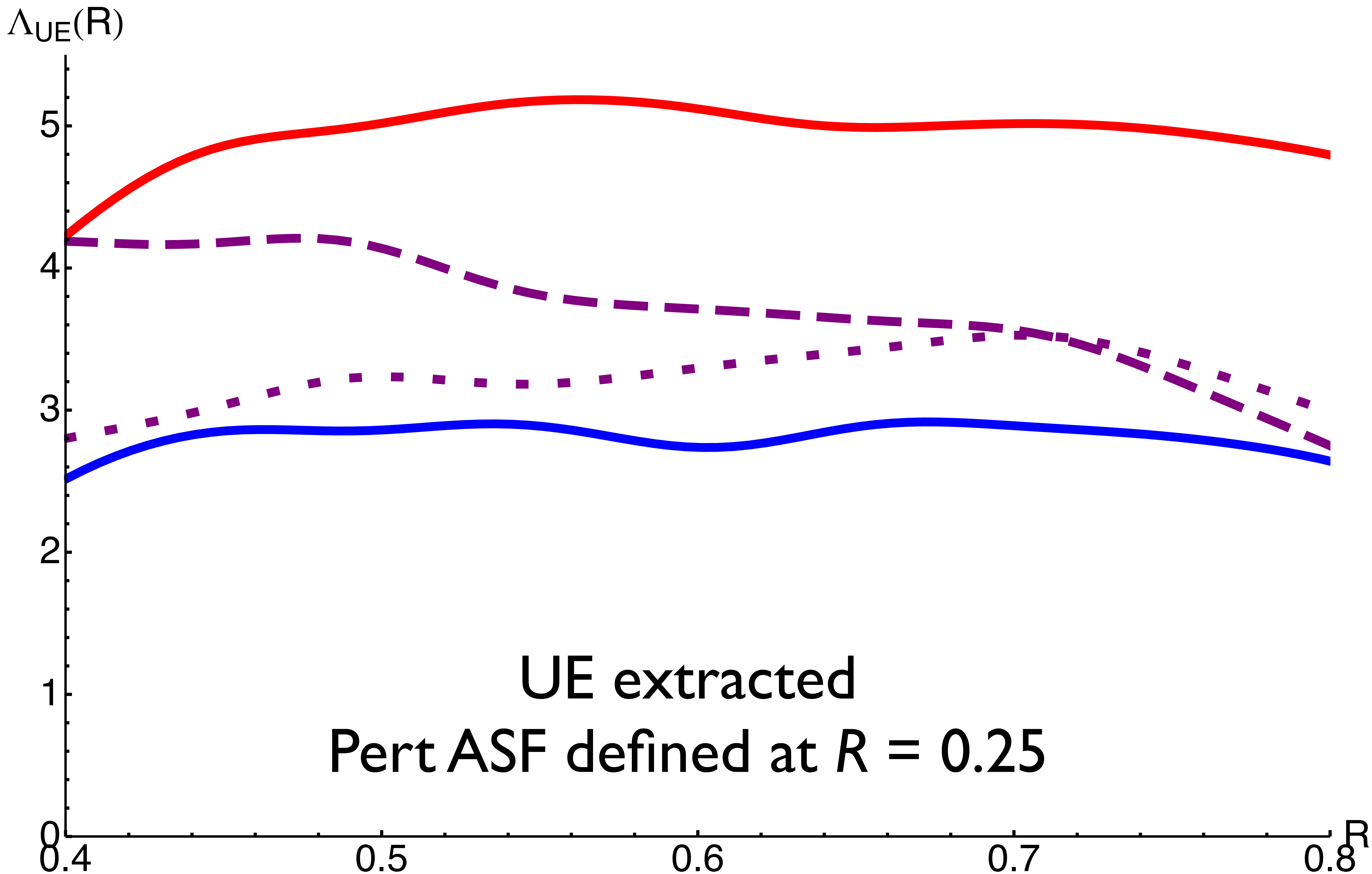

Conclusions

- worth thinking about alternatives to the clustering paradigm
- ASF offers interesting event-by-event observables
- average ASF is an interesting observable sensitive to the whole of a jet’s dynamics (parton shower, underlying event, ISR, ...)

Conclusions

- many jet substructure techniques proposed to date - time to see them validated at the LHC
- so far focus has been on simpler topologies (e.g. top tagging). how well can we probe more complicated signals?
- more broadly: should searches for "spectacular" signatures fail to find anything, can we use jet substructure to increase sensitivity to and (especially) coverage of new physics?

thank you